MATHEMATICAL MODELLING AND IMPROVEMENT OF OPERATING PRACTICES OF SUN DRYING OF RICE

PYSETH MEAS

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MATHEMATICAL MODELLING AND IMPROVEMENT OF OPERATING PRACTICES OF SUN DRYING OF RICE

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សូមឧទ្ទិសស្នាដៃនេះជូនចំពោះអ្នកម្ដាយ លន់ កន

To my mother (Kân Lun)

ព្រមទាំង វិញ្ញាណក្ខន្ធ៍លោកឪពុក មាស សៀង

& spirit of my father (Sieng Meas),

This humble manuscript is lovingly dedicated

ABSTRACT

In Cambodia, sun drying of rice has always been of great importance for preserving rice. The main goal of this study was to find the conditions for sun drying that maximise the throughput while minimising quality loss.

A whole-bed approach was taken to investigate the conditions of the grain and the air at different layers during the drying process. Seven sets of sun-drying experiments were conducted in Cambodia using a range of methods practiced by rice farmers. These methods included drying with different bed depths (2 to 6 cm), with the bed on different pads (water-proof tarpaulin, mat, net, polystyrene or rice husk), and with different bed tempering methods (stirring regularly or shading and/or covering the bed around midday) for four Cambodian rice varieties (Pka Knhey, CAR11, Masary and IR66).

The grain temperature was found to be more affected by the solar intensity than the temperature of the ambient air. Fastest drying was achieved when the bed was thin, less compacted, stirred regularly but not shaded or covered around midday, dried on a pad which allows some air and moisture movement and with high or strong solar intensity.

Only the mechanical impact (MI) and milling tests of the rice quality provided useful results. Higher quality was found for grain that was dried in thin beds, stirred regularly, shaded with or without covering around midday and dried on pads with less air circulation.

Among the methods used to determine the glass transition temperature of the grain, only the Differential Scanning Calorimetry method gave meaningful results. The glass transition temperature data were highly variable but generally decreased with increasing moisture content and compared quite well with the published glass transition temperatures for other varieties of rice.

To provide additional detail on the local conditions within the bed, to better understand the drying process and the interactions between variables and to predict alternative parameters that might be used to correlate with the head rice yields (HRYs), a mathematical model for heat and moisture transport within the bed was developed. The model covered all the drying methods/conditions studied experimentally. A lumped parameter approach to energy and mass transfer in individual kernels was used in the bed model.

The model was validated against experimental data. The predicted drying time, temperatures, moisture contents and water activities (relative humidity of the air within the bed) were found to compare very well with the experimental data except when a polystyrene pad was used. The model proved to be a very good mechanistic tool with advantages of simplicity and practical accuracy in the design and management of the sun drying system.

A number of parameters related to postulated grain damage mechanisms were derived from the predicted conditions within the bed during drying. The best predictors of the grain quality were found to be rewetting the kernels when the grain is bulked (especially when the kernels are partly below and partly above critical moisture content) grain temperature and distance from the glass transition temperature line.

It was concluded that in order to get the fastest drying conditions rice should be sun dried with thin bed, stirring, not shaded or covered around midday and dried on a pad with air circulation. For the highest quality grain, that is grain which would have the least breakage during milling, rice should be sun dried with a thin bed, stirring, shaded or covered around midday and dried on a pad with less air circulation. The optimal drying conditions to get the best quality combined with the fastest practical drying rate, the drying conditions should be drying with 2 cm bed depth, stirring the grain bed every hour, shading or covering the bed around midday and using a tarpaulin or net pad placed directly on the ground.

ACKNOWLEDGEMENTS

Like most of my compatriots, I have suffered intolerable pain and misery through the conflicts in Cambodia. I lost my loving father in my childhood and have had to almost totally rely on my mother, brother and some relatives. Due to the fighting, shelling and many wild fighters, I have had many relocations and my mum was always scared to let me be away or out of her reach. During this, I had a lot of time to observe what she was doing. One of her businesses was to buy paddy grain, get it milled and graded and sell it to make a small profit.

What I saw was that the grain is produced in a very hard way with a high percentage of broken grains in the milled rice. Farmers in the country still do not have many chances to ease their hard work by the means of improved machinery or technology and rely almost totally on the weather for drying. In the end, they do not have good grain for their own consumption and my mother and Cambodian rice farmers can not sell the rice they have produced for a good price due to its low quality. As a result, Cambodia still remains one of the poorest nations. This led me into choosing to look at the effects of sun drying of rice on the quality of milled grain as the subject of my PhD.

I have been very fortunate to have had tremendous support and assistance from a number of countries and organisations and to be in very safe hands of many people to complete some useful work in the determining of better ways to use the sun for the drying of rice so that the grain quality is not compromised. I, therefore take this opportunity to gratefully thank:

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Chapter 1

INTRODUCTION

1.1 INTRODUCTION

Rice (*Oryza sativa*) is the most important cereal crop in the developing world and is the staple food of over one half the world's population (Juliano, 1993). The crop is second only to wheat in terms of annual production for food use. It is the main staple food for about 60% of the world's population. About 90% of the world's rice is produced and consumed in Asia (Marshall and Wadsworth, 1994). It is generally considered as the main source of carbohydrate to supply food energy in the diet (Riahi and Ramaswamy, 2003).

Contrary to other cereals, rice is preferably consumed as whole grains (Kamst *et al*., 2002). Thus, maximizing the head rice yield (HRY), which is usually expressed as a weight percentage of whole and broken white rice kernels that are larger than 3/4 of the kernel to the paddy, is a priority. The economic value of the crop is largely determined by the yield. Arora *et al*. (1973), Steffe and Singh (1980), Webb *et al*. (1986), Muthukumarappan *et al*. (1992), Siebenmorgen *et al*. (1992), Siebenmorgen (1994), Cnossen and Siebenmorgen (2001), Zhang *et al*. (2003a) and Cnossen *et al*. (2003) claimed that the typical value of broken rice is about one third to one half of that of whole rice.

This head rice yield depends not only on variety and crop management but also on the management of post-harvest operations and of the drying conditions used to dry the rice in particular (Brooker *et al*., 1992 and Abud-Archila *et al*., 2000). The yield is especially sensitive to the mode of drying and is usually used to assess the success or failure of a rice drying system (Siebenmorgen, 1994; Izadifar and Mowla, 2003).

Scientific research has been remarkably successful in increasing the quantity and quality of rice grain through the application of improved drying technologies. Most of the studies, however, have been focused on mechanical drying and little on sun drying. Sun drying is still the most common practice in Cambodia and many other developing countries, as solar radiation is usually convenient for at least several months of the year. Also, the method is simple and very economical.

The royal government of Cambodia, in its agricultural strategies and policy framework for sustainable food security and poverty alleviation, has recognized the importance of the postharvest technologies where the losses of basic foodstuffs are a result of poor handling practices. It makes more sense and is economical to safeguard the crops that have been harvested, instead of trying to make up for losses through increases in production. To focus its attention on agro-products for export, the government is also very concerned that agricultural products often have to be distinguished by high quality, which ensures success in the competitive markets.

Unfortunately, postharvest losses of agro-products in Cambodia, in general and of food grains in particular, are relatively high. The losses of rice grain remain high due to inefficient harvesting, handling, drying and processing techniques. Anecdotal estimates of the losses for various traditional systems include harvest (3-5%), threshing (3-4%), transport (10%), and storage (7-30%). Current evidence indicates that sound kernels of white rice range from 15-45% of the paddy, which means that a high proportion of the harvest is downgraded prior to marketing (both local and export) and this represents a loss in income to the rural farmers. This high incidence of handling damage also contributes to the low seed establishment rate (45% maximum) that is common among farmers.

Despite the desire to store grain in order to cover food requirements and future cash needs, most farmers are forced to sell their grain immediately after harvest, when prices are low, due to a lack of adequate facilities, as well as expertise for timely and efficient harvesting, handling, drying, storage and processing.

Therefore, understanding all the effects of different parameters and methods on drying performance and on the dried grain quality in the sun drying system of rice is very important, as it can help many rice farmers to optimize the drying process.

1.2 RESEARCH GOAL

My research activities focussed on the area of postharvest handling of rice grain. They were aimed at understanding the effect of various sun drying and tempering treatments on the grain conditions and breakage/head rice yield reduction that can be used to provide rice producers and end-users with information to optimize their processing operations. These will also generate high quality rice to meet the demand of local and global markets by incorporating technology findings and recommendations into national policy and farmers' regular practices.

1.3 RESEARCH OBJECTIVES

The objectives of this research were to investigate the variables that affect the drying performance and head rice yield during the sun drying of rice. This was achieved by the following specific objectives:

1. Investigate the effects of the grain varieties and drying methods on
   a. The grain conditions
   b. The drying performance, especially drying time, and
   c. The dried grain quality (Chapters 2, 3 and 4).
2. During the experimental sun drying of a bed of rice, monitor the changes of
   a. The ambient air conditions such as the solar intensity, temperature and relative humidity (RH) and
   b. The grain and air conditions within the drying bed, such as the temperature, moisture content (MC) and RH or water activity (Chapters 3 and 4).
3. Measure the glass transition temperature (T_g) of four rice varieties used and generate a state or phase diagram mapping the conditions of the grain so that the effects of the grain state conditions during drying on the drying performance and the dried grain quality can be explained (Chapters 3 and 4).
4. Develop and validate a mathematical model of rice drying that can be applied to a range of sun drying systems (Chapters 5 and 6).
5. Confirm the theory that grain fissuring and other problems are mechanistically related to grain conditions during drying (Chapter 7) and

6. Use the model and knowledge gained to design a rice-drying system and improve operating practices by developing technology options for reducing losses of rice grain after harvest (Chapter 8).

Chapter 2

LITERATURE REVIEW

2.1 RICE GRAIN STRUCTURE AND CONSTITUENTS

A mature rice grain (or kernel) contains three components; from the outside, they are respectively: husk (or hull), bran (seed coats and germ) and endosperm (Laguë and Jenkins, 1991). The complete grain is so called paddy or rough rice. Brown rice is obtained by removing the hull. Removal of the bran by abrasive milling yields the final product called white, milled or polished rice (Fig 2.1). According to Kunze and Choudhury (1972), Srinivas *et al*. (1978) and Kunze and Prasad (1978), white rice absorbs moisture faster than brown rice, and brown rice faster than paddy rice. Aguerre *et al*. (1982) stated that it is reasonable to think that the moisture adsorption capacity will be different for each of the constituents, but they found that the non-homogeneity of the grain need not be considered in drying kinetic analysis.

Fig 2.1: Paddy, brown rice and milled rice

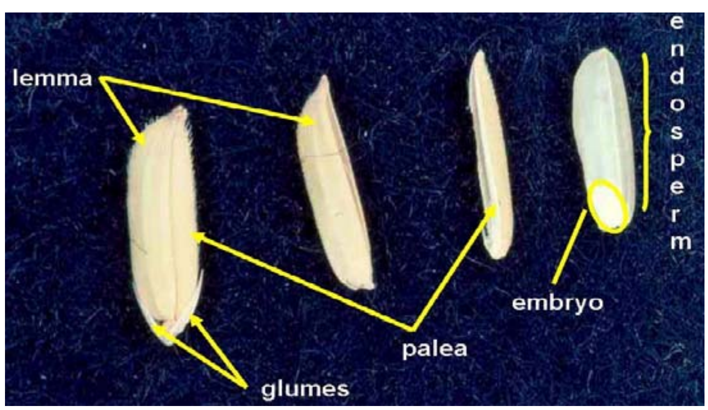


Figure 2.2: A dissected paddy grain
(Source: LSU AgCentre, 2005)

Because of the outer husk, paddy grain is different from most other grains. The husk, as shown in Fig 2.2, encloses the caryopsis during harvesting, drying and storage (Wongwises and Thongprasert, 2000; Riahi and Ramaswamy, 2003).

The most important components of the grain, according to Juliano and Bechtel (1985), Brooker *et al*. (1992), Hoseney (1994), Marshall and Wadsworth (1994), Gwinner *et al*. (1996), Lásztity (1996), Evers and Millar (2002), and Riahi and Ramaswamy (2003), are

- The husk or seed coat that is composed of two modified leaves: the palea and larger lemma, which protect the seed from many damaging influences. A tight husk may provide storage protection to the grain but may make the milling difficult. The husk is about 18 to 20% of the total kernel weight,
- The endosperm, which constitutes the nutritional reserves for the embryo. It consists largely of starch and a little aleurone. It is about 74 to 78% of the total kernel weight. It is the largest morphological component in all cereal grains and is the component with the greatest value, and
- The embryo or germ which is the most important grain component for the survival of the species as it is capable of developing into a plant of the next generation. It is very small and is located on the central side at the base of the grain. It is particularly rich in oil, protein and vitamins.

The brown rice kernel consists of a pericarp (about 2%), seed coat and aleurone (about 5%), germ (2-3%), and endosperm (89-94%). As with other cereals, the aleurone is the outermost layer of the endosperm but is removed with the pericarp and seed coat during milling (Hoseney, 1994).

A rice kernel can be regarded as a composite consisting of several different biopolymers, and a brown rice kernel is primarily a mixture of starch and protein with a small quantity of lipids with moisture as a plasticizer (Sun *et al*., 2002; Zhang *et al*., 2003b). Rice and oats are the only two cereals with compound starch granules (i.e. a starch granule made up of many small granules) (Fig 2.3). Little or no matrix protein has been found in the rice endosperm. Other cereals contain large amounts of protein that exist as inter-granular matrix. By using a scanning electronic microscope to study the structure of a rice kernel after sun drying, Dong and Zhihuai (2003) found that most stress cracks are not only propagated along the edges of the starch granules, but also tear some starch granules, dividing them into two parts.

Starch makes up about 90% of the dry matter content of milled rice (Juliano, 1993; Juliano, 1998; Inprasit and Noomhorm, 2001; IRRI, 2002d). The individual rice starch granules are small (2-5 μm) and polygonal in shape (Fig 2.4). Many of the granules in tuber and root starches, such as potato and cassava starches, tend to be larger than those of grain starches and are generally less dense and easier to cook. Potato starch granules may be as large as 100 μm along the major axis (Wilkinson, 2000). Within the rice starch granule, amylose and the branching points of amylopectin contribute to the amorphous phase, while the outer chains of amylopectin contribute to the crystalline phase (Hoseney, 1994).

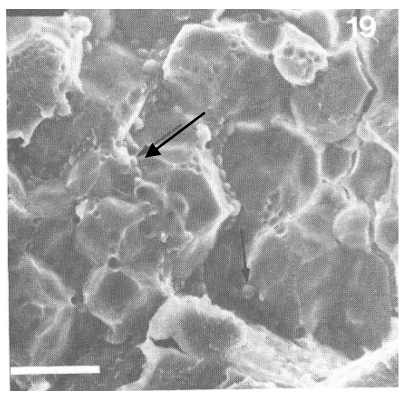


Fig 2.3: Compound starch granules and protein bodies (arrows) near the aleurone layer of a rice kernel. Bar is 10 μm *(Source: Hoseney, 1994)*

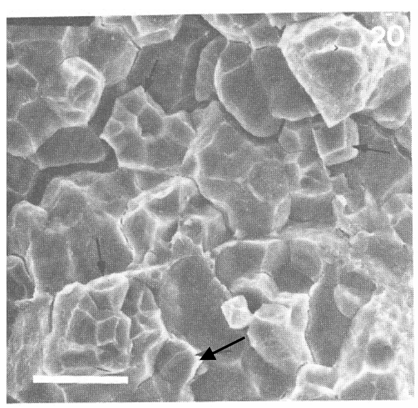


Fig 2.4: Compound starch granules near the centre of a rice kernel, with certain granules broken, showing individual granules (arrows). Bar is 10 μm *(Source: Hoseney, 1994)*

Wilkinson (2000) stated that amylose and amylopectin in starch granules are arranged radially making the granules contain both crystalline and non-crystalline regions in alternating layers, i.e. the starch granule is constructed like an onion with layers of amylose and amylopectin, but the layers cannot be peeled off (Fig 2.5).

Fig 2.5: A schematic model of the structure of a starch granule *(Source: Wilkinson, 2000)*

Fractions of amylose and amylopectin in starch granules, as shown in Table 2.1, are different for different rice varieties. Patindol *et al*. (2003) reported that a rice variety "Bengal" has a higher percentage of amylopectin but is lower in intermediate material and amylose content when compared with another rice variety "Cypress".

Table 2.1: Percentage (± standard deviation) of starch molecule size of two rice varieties *(Source: Patindol et al., 2003)*

Starch molecular sizes	Bengal (medium grain)	Cypress (long grain)
Amylose	16.07 ± 0.42	26.20 ± 0.33
Amylopectin	77.37 ± 0.64	58.33 ± 0.51
Intermediate material	6.57 ± 0.31	15.47 ± 0.62

Note: Starch fractions were categorised into amylopectin, intermediate material, and amylose base on the retention time because of their differences in molecular size.

Protein is the second most important rice component after carbohydrates. It is unevenly distributed in the grain kernel and acts as a bio-adhesive that binds the discrete cell structures and starch granules (Zhang *et al*., 2003a). There are greater concentrations in the bran and periphery of the endosperm and smaller quantities towards the centre of the grain. Accordingly, milled, polished rice has a lower protein content than brown rice; about 82% is retained after milling. Chemical interactions between protein and starch may also influence rice quality. Protein bodies remain intact upon cooking (Juliano and Bechtel, 1985).

2.2 RICE GRAIN QUALITY

Different rice grains are demanded by different customers and markets, depending on their preferences and the intended end use (Brooker *et al*, 1992). Most consumers prefer the best quality they can afford (Bakker-Arkema and Salleh, 1985). Long-grain (higher-quality) rice is sold mostly in Europe and the Near East, medium-quality long-grain rice in the deficit countries of Asia, the short-grain rice in various special-demand areas, high-quality parboiled rice in the Near East and Africa, and the lower-quality parboiled rice in special markets in Asia and Africa. Aromatic rice is demanded mostly in the Near East. Waxy rice meets market needs in Laos, while smaller volumes go to other countries (Juliano, 1993).

To the rice farmers, grain quality refers to quality of seed for planting and dry grain for consumption, with minimum moisture, microbial deterioration and spoilage. Millers or traders look for low moisture, variety integrity and high milling and Head Rice Yields (HRYs). Market quality is mainly determined by physical properties and variety name, whereas cooking and eating quality is determined by physico-chemical properties, particularly the amylose content (Juliano, 1993; IRRI, 2002d).

There are few quality-measuring methods in the literature that are specific to rice. Some methods that are now used in the food industry are adapted from other cereal products. Some procedures, such as moisture determinations, are taken directly from standard methods (Kohlwey, 1994). Rice quality in Japan is evaluated using sensory tests and physicochemical measurements. The sensory test, which measures appearance, aroma, hardness, stickiness and overall quality, is the basic evaluation method, although it requires a large number of samples and many panellists. The physico-chemical measurements are an indirect method of estimating eating quality based on chemical composition, cooking quality, and gelatinisation and physical properties of cooked rice (Ohtsubo *et al*., 1998). Although sensory evaluations by laboratory panels and consumer panels give some indication on important criteria for rice quality, they do not reflect the properties for which consumers will actually pay a price premium in the retail market (Juliano, 1993).

The quality characteristics of rice that are to be maintained during the drying process include HRY, colour, and subsequent cooking qualities (Zhang *et al*., 2003a).

2.2.1 Quality characteristics

Quality characteristics of rice grain, according to IRRI (2002a), are either subjective or objective. Subjective characteristics are determined by individual preference, whereas objective characteristics are independent of personal opinion. The subjective characteristics can be

- Taste
- Appearance
- Smell etc.

The objective characteristics are

- Physical (texture, colour) and
- Chemical (nutritional value).

The growing place and the growers of the grain crop can also be classified as objective characteristics.

2.2.1.1 Physical characteristics of paddy grain

Simulation of heat and moisture transfer phenomena during drying and storage of the grain requires physical, thermal and moisture-transport properties of the grain. Accurate knowledge of the true value of the properties is a requirement for good engineering design of the machines, equipment or methods for processing and handling (Wratten *et al*, 1969; Morita and Singh, 1979).

Many physical characteristics have been described and used for rice grain, including kernel weight, sphericity, roundness, size, volume, shape, surface area, bulk density, kernel density, fractional porosity, static coefficient of friction against different materials, angle of repose and equilibrium moisture content (MC_e) etc. These properties vary widely, depending on MC, temperature, and density of cereal grains (Sablani and Ramaswamy, 2003). According to Bakker-Arkema and Salleh (1985) and IRRI (2002c), there are six main physical characteristics used to determine the quality of paddy rice:

a. Moisture content, MC

MC has a significant influence on all aspects of paddy rice quality. Details of this characteristic are described in Section 2.4.

b. Maturity

Immature rice kernels are very slender and chalky and result in the production of excessive bran, broken grains and brewers' rice (see its definition in Section 2.2.1.2).

c. Varietal purity

A mixture of varieties in a sample or bulk of paddy grain (Fig 2.6) causes difficulties in milling and usually results in reduced milling capacity, excessive breakage, lower milling and HRYs.

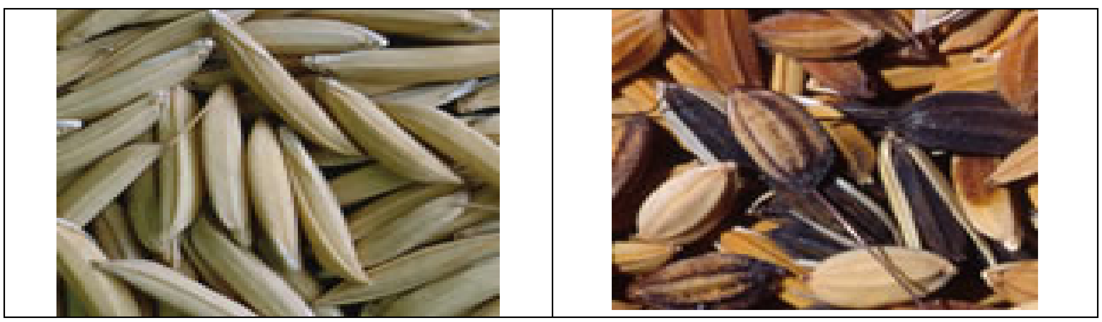


Fig 2.6: Paddy rice sample with single variety and mixed varieties *(Source: IRRI, 2002c)*

d. Dockage

Dockage includes chaff, stones, weed seeds, soil, rice straw, stalks and other foreign matter. These impurities generally come from the field or from the drying floor (Fig 2.7).

Fig 2.7: Clean paddy grain and the grain mixed with dockage *(Source: IRRI, 2002c)*

e. Discoloured

Water, insects and heat exposure can cause the grain to deteriorate through biochemical changes in the grain which may result in the development of off-odours and changes in physical appearance.

f. Cracks

Mechanical impact and overexposure to fluctuating temperature and moisture conditions may lead to the development of cracks in individual kernels. Cracks lead to easy infestation and development by mould and insects and because of the breaks in the endosperm tissue, the nourishment that the embryo can get is reduced so as to reduce the vitality of the seeds (Dong and Zhihuai, 2003).

2.2.1.2 Physical characteristics of milled rice

The following are six physical characteristics that, according to IRRI (2002d), are used to determine the quality of milled rice:

a. Head rice yield (HRY)

In rice milling, quality of the grain is often associated with the head rice yield (Bautista *et al*., 2000). Head rice refers to the whole grains of milled rice that can be obtained from a given quantity of clean paddy after complete milling. Broken rice particles that are larger than 3/4 of the kernel are also considered as head rice. The yield is usually expressed as a weight percentage of paddy rice (Siebenmorgen *et al*., 1992). It can vary from as low as 25% to as high as 65% depending on the quality of the grain itself and of the milling machine (IRRI, 2002d).

Since rice is consumed mostly in the form of whole grains and because of the greater economic value of head rice, increasing the HRY in production is a universal goal (Sharma and Kunze, 1982). Reduction in the yield decreases the grain value since broken kernels are typically worth half the value of head rice (Arora *et al*., 1973; Webb *et al*., 1986; Muthukumarappan *et al*., 1992; Siebenmorgen *et al*., 1992; Siebenmorgen, 1994; Cnossen and Siebenmorgen, 2001; Zhang *et al*, 2003a and Cnossen *et al*., 2003).

Research has found HRY to be especially sensitive to the mode of drying and is usually used in assessing the success or failure of the drying system (Brooker *et al*., 1992 and Abud-Archila *et al*., 2000). It is difficult to ascribe reduction in the yield to a single cause. However, it is generally believed that the yield is strongly related to internal cracking or fissuring (Stermer, 1968; Velupillai and Pandey, 1990). Research has indicated that some breakage in the grain occurs because the kernels have previously been weakened by stress cracks (fissures) caused by rapid moisture adsorption or desorption (Kunze, 1977 and Cnossen *et al*., 2003).

The efforts of rice breeders to develop new varieties, improvements in design of shelling and milling equipment, improvements in drying conditions, and treatments (parboiling, extractive milling) of the grain prior to, or during, milling have resulted in reducing the fissuring and breakage. However, further means for minimizing the damage would benefit rice millers and farmers more (Matthews and Spadaro, 1976).

A number of standardizing testing methods have been developed and applied by different groups of researchers to determine the HRY. Depending on the method and instruments used, the yield obtained from the same sample can be significantly different (Reid *et al*., 1998; Yadav and Jindal, 2001; and Lloyd *et al*., 2001).

b. Brewers' rice

Brewers' rice refers to the small pieces of broken rice that remain in the milled rice after milling. Its extent depends on the magnitude of the grain damage.

c. Damage

Before milling, paddy rice can be deteriorated through natural biochemical changes in the grain or by insect, mould, water, or heat which can create off-odours and changes in physical appearance. The result is damaged grains (Fig 2.8) that are fully or partially darkened.

Fig 2.8: Damaged grains *(Source: IRRI, 2002d)*

d. Chalkiness

The endosperm chalkiness or opacity, as shown in Fig 2.9, is due to the loose packing of starch granules in the region caused by interruption of final filling of the grain. Excessive chalkiness downgrades the quality and reduces the grain milling and HRYs. Chalkiness, however, disappears upon cooking and has no direct effect on cooking and eating qualities (Juliano and Bechtel, 1985).

Fig 2.9: Chalky grains *(Source: IRRI, 2002d)*

e. Red/Red streaked

Red and red-streaked grains (Fig 2.10) occur when part of the bran layer remains clinging to the surface of the grain after milling. Rice consumers almost universally desire well-milled rice because of its better appearance. Therefore, the presence of red and red-streaked grains suggests a lower degree of milling, and subsequently, a less desirable appearance.

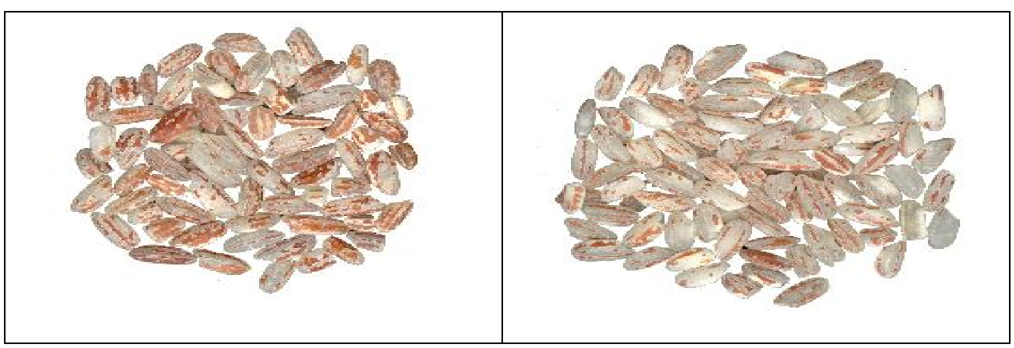


Fig 2.10: Red and red-streaked grains *(Source: IRRI, 2002d)*

f. Appearance

Whiteness, translucency, and milling degree influence the appearance of milled rice. Rice that is not attractive to the consumer will have a lower value in the marketplace. In other words, improving the appearance of the rice grains through proper milling increases their value (Bakker-Arkema and Salleh, 1985; IRRI, 2002d).

Fig 2.11: Discoloured milled rice *(Source: IRRI, 2002d)*

Discoloured milled rice grains (Fig 2.11), in many cases, referred to as the yellowing problem, often make the grains unattractive (Dillahunty *et al*., 2001). Chemical and physical transformations, induced by heating and translocation of colour from rice husk and rice bran to endosperm, cause the discolouration (Inprasit and Noomhorm, 2001; Dillahunty *et al*., 2001). Delayed threshing causes yellowing of the grain in the field; it can be increased during drying and storage from 0 to 5.5% or even 30% (Brook, 1992 and Brooker *et al*., 1992).

g. Aroma

Aroma of the grain (from paddy through to cooked rice) has become one of the most important factors for grain attractiveness, and drying the grain at high temperature has been reported to lower the concentration of the grain key aroma compound, 2-acetyl-1-pyrroline (Wongpornchai *et al*., 2004).

2.2.1.3 Chemical characteristics of milled rice

According to Juliano (1971), Bakker-Arkema and Salleh (1985), Ohtsubo *et al*. (1998), and IRRI (2002d), the following three chemical characteristics are most commonly used to determine the quality of milled rice:

a. Amylose content

This is the characteristic that affects the cooked rice quality or influences the eating quality of rice. When the content is high, the amount of cooking water absorbed by milled rice increases; the cooked rice will show high volume expansion (not necessarily elongation) and a high degree of flakiness (easy to loosen or separate). The rice will also be dry, less tender, and become hard upon cooling. When amylose is low, the cooked grain will be moist and sticky.

b. Gelatinisation temperature

This is the temperature that determines the amount of water and time required for cooking. The grain with a high gelatinisation temperature requires more water and a longer cooking time (Juliano, 1971; Juliano, 1985; Juliano and Perez, 1993). At this temperature, the grain kernels absorb water and starch granules swell irreversibly, with the core of the grain becoming translucent or gelatinised in hot water.

c. Gel consistency

Gel consistency is the chemical characteristic that affects the cooked rice tenderness. It measures the tendency of cooked rice to harden on cooling. When gel consistency is hard, the cooked rice tends to be less sticky. Harder gel consistency is associated with harder cooked rice and this feature is particularly evident in high-amylose rice. In contrast, when gel consistency is soft, the cooked rice has a higher degree of tenderness (softness).

2.2.1.4 Thermal and moisture-transport properties

Thermal and moisture-transport properties affect the rates of heat and moisture transfer during drying and storage of grains. The properties which are mainly considered in the phenomena are specific heat capacity, thermal conductivity, thermal diffusivity, moisture diffusivity and latent heat of vaporisation. While most studies have reported thermal properties of cereal grains as a function of MC, some studies have evaluated the influence of temperature and composition on thermal properties of grains (Wratten *et al*., 1969; Sablani and Ramaswamy, 2003).

a. Specific heat capacity, c_p

The specific heat capacity of a substance or material indicates the amount of energy a body stores for each degree increase in temperature, on a unit mass basis (J/kg.^{o}C).

Table 2.2: Equations and values describing the specific heat as affected by its MCs from 16.28 to 28.21% db (or 14 to 22% wb)

Equation	**Value calculated,** *J/kg.^{o}C*	**Grain type**	**Source**
1000 (1.0509 + 0.03835 MC_{db})	1665 - 2125		Kunze and Wratten, 1985
33.5 MC_{db} + 1189.9	1735 - 2135		ASAE, 2003[a],2004[a],2005[a]
39.2 MC_{db} + 1039.7	1678 - 2145	medium	ASAE, 2003[a],2004[a],2005[a]
23.6 MC_{db} + 1372.1	1756 - 2038	short	ASAE, 2003[a],2004[a],2005[a]

Wratten *et al* (1969) reported the specific heat of paddy grain (c_{pp}) of 2010.85 J/kg.^{o}C while Kunze and Wratten (1985), Oshita (1992), ASAE (2003a), ASAE (2004a) and ASAE (2005a) declared the specific heat changed under the effect of the grain MC (Table 2.2). Rahman (1995) also declared a change with grain composition and temperature. Mohapatra and Bal (2003) reported the specific heat of rice varies from 1230 to 4340 kJ/kg.^{o}C with temperature varying from -10 to 150^{o}C for MC of 13 and 12.4%, respectively.

b. Thermal conductivity, λ

According to Brooker *et al*. (1992), thermal conductivity of paddy kernel is a measure of the resistance to the conduction of thermal energy (heat) within an individual kernel. The authors reported a value for the conductivity within a rice kernel of 0.106 W/m.^{o}C.

Kunze and Wratten (1985) proposed that the thermal conductivity of a paddy kernel changes linearly with its *MC*:

$$\lambda_p = 0.0894 + 0.000958.MC_{db} \qquad \dots (2.1)$$

Laguë and Jenkins (1991) also reported the change in the conductivity under the effect of the *MC* but presented a different relationship:

$$\lambda_p = \frac{0.0637 + 0.0958.MC_{db}}{0.656 - 0.475.MC_{db}} \qquad \ldots (2.2)$$

Chakraverty and Singh (2001) claimed that thermal conductivity of bulk paddy grain or the effective thermal conductivity is 3 to 4 times smaller than that of the single grain kernel. The thermal conductivity of a single paddy grain, according to them, varies from 0.35 to 0.70 W/m.^{o}C, whereas the effective thermal conductivity varies from 0.12 to 0.17 W/m.^{o}C, which is due to the presence of air space in it. The thermal conductivity of air is 0.023 W/m.^{o}C.

Yang *et al*. (2003c) claimed that bulk or effective thermal conductivity increases with increasing MC and temperature. They reported that the conductivity ranged from 0.082 to 0.138 W/m.^{o}C in the temperature range of 6 to 69ºC and moisture range of 9.2 to 17.0%. These workers also found that the conductivity was relatively constant from around room temperature to the glass transition temperature (T_g), decreased with decreasing temperature below room temperature and increased dramatically after the temperature went above T_g. When the conductivity of the grain of 0.09 W/m.^{o}C is compared with the conductivity of other materials, Kawamura *et al*. (2001) claimed the grain is like a thermal insulating material.

c. Thermal diffusivity, α

Thermal diffusivity (expressed in m^2/s) is a measure used to indicate how fast heat can propagate through the material under transient heat-transfer condition. Physically, it relates the ability of a material to conduct heat with its ability to store heat (Sablani and Ramaswamy, 2003):

$$\alpha = \frac{\lambda_p}{\left(\rho.c_p\right)} \qquad \ldots (2.3)$$

2.2.1.5 Grain viability

Grain viability is defined as the capacity of seed grain to germinate under favourable conditions provided that any dormancy in the grain is “broken” before testing for germination (Basu, 1994). To be highly acceptable, seed grain requires a high proportion of individual grains with germination properties (Bakker-Arkema and Salleh, 1985).

Grain destined for use as seed must be dried in a manner that preserves the viability of the seed (Teter, 1987). Seed embryos are killed by temperatures greater than 40-43^{o}C (Brooker *et al*., 1974; Bakker-Arkema and Salleh, 1985; Trim and Robinson, 1994; IRRI, 2002d). Exposing paddy rice to 60ºC for one hour can reduce the seed germination rate from 95% to 30% and two hours at the same temperature will reduce the germination rate to 5% (Bakker-Arkema and Salleh, 1985). In some grains, rapid drying leads to the shrinking of the grain coat, which becomes impervious to the movement of moisture. This is known as case-hardening, a condition which can prevent further drying and can produce dormant seeds (Brooker *et al*., 1974).

Thompson and Foster (1963) found some relationship between stress cracks (fissures) after drying and seed germination. A high percentage of “checked or crazed” kernels in maize samples almost assures low germination. However, the absence of stress cracks did not assure high viability, since low germinating power may be caused by conditions other than those that cause stress cracks.

During storage, ambient air temperature and grain MC have profound effects on rice seed viability. The lower the MC of the seed at the beginning of storage, the longer the seed remains viable. If the storage temperature averages 26^{o}C, grain with a MC of 12% should maintain viability for a year; whereas grain with 22% MC would be unsatisfactory for seed after about a week. If seed is to be stored for more than a year, the moisture should, therefore, be reduced to 10% and kept at that level during the storage life (Teter, 1987; IRRI, 2002b). The seed can be safely stored in sealed containers (Bakker-Arkema and Salleh, 1985; IRRI, 2002b).

Teter (1987) presented an equation to estimate the number of storage weeks for 50% germination to be lost:

$$\textit{Number of storage weeks} = 10^{(5.686 - 0.069\,T - 0.159\,MC)} \quad \dots (2.4)$$

2.2.2 Losses in quality

Starting with certain quantity and quality levels at harvest time, subsequent practices in post-production can only lead to losses. Thus, the objective of grain management and the handling or campaign should be to minimize the losses at each and every point of postproduction (Juliano, 1993; Bell *et al*., 1999; Rickman, 2001).

Studies conducted by the International Rice Research Institute (IRRI) in Cambodia, the Philippines, and Indonesia, have found that the losses occur similarly in these countries, caused mainly by spoilage and wastage at farm level. The losses result in less and lower quality rice for consumption or sale, smaller returns to the farmers, higher prices for consumers, and greater pressure on the environment, as farmers try to compensate by growing more rice (Rickman, 2003).

Losses in grain quality, according to Coker (1994), occur in various forms:

- Changes in colour (e.g. yellowing of rice)
- Changes in smell
- Changes in taste
- Loss in nutritional value (degradation of proteins and vitamins)
- Loss in cooking, milling or baking quality
- Contamination of stored produce with mycotoxins or pathogenic agents and
- Loss of germination power in seeds.

Often several qualitative changes occur at the same time, usually in connection with weight losses. Losses in quality are much more difficult to assess than losses in quantity, as they cannot always be easily recognized (e.g. loss in nutritional value) (Gwinner *et al*., 1996). Moreover, there is a lack of quality standards in many countries and individual consumers may assess quality changes differently (Clarke and Orchard, 1994).

2.2.3 Grading of rice grain and standards

To make life simpler and to increase the reliability and effectiveness of the goods and services, standards have been developed at a national level in many countries. At the same time, the International Organization for Standardization (ISO) has published standards for international use. The standards are documented agreements containing technical specifications or other precise criteria to be used consistently as rules, guidelines or definitions of characteristics, to ensure that materials, products, processes and services are fit for their purpose. With rice, these standards ensure that when people are discussing the grain, they can have a common understanding of the terms being used and of the standards that various rice qualities must reach (Bakker-Arkema and Salleh, 1985; Clarke and Orchard, 1994; IRRI, 2002e).

These workers listed the following three types of standards:

- Standard specification which defines and specifies a subject
- Standard test method by which a specification is tested
- Grading standard which allows a subject to be classified into more than one category.

The establishment of quality and grading standards for producers and users, according to Clarke and Orchard (1994), can be beneficial in the following ways:

- Graded grains are likely to be more equably priced than non-standardised grains. This will bring stability not only to market prices but also to the quality offered
- Prices quoted against a recognized grade assist producers and traders to market their products. This will also benefit consumers of grain, providing more stable prices with assured quality
- Greater conformity in quality through standardisation will provide the millers, bakers and other processors with the consistency necessary for optimum performance
- Standards reveal clear variations in quality and indicate the opportunities for improvement and the potential rewards to be obtained, and

- The sanitary hazards associated with the inter-country movement of grain can be reduced if clearly defined standards are enforced, particularly in relation to the prevention of the spread of serious storage pests like the Larger Grain Borer.

However, the use of standards can have its disadvantages, namely

- National standards may reflect local end-uses and hinder export to areas that have differing requirements.
- The establishment of standards and the quality assurance practices to regulate and enforce them carries compliance costs which have to be carefully considered to avoid imposing unnecessary expense for little improvement in quality.

2.3 POSTHARVEST HANDLING OF RICE

The postproduction system is a very important component for the rice industry, and proper harvesting, threshing, cleaning, drying and storage are integral parts of the system (Sahay and Gangopadhay, 1985). When considering the system, the scope should eventually cover all operations and processes, beginning with characterising the state of the grain at harvest and progressing through sensory evaluation at the final consumption stage (Siebenmorgen, 1998). Improper handling of the grain after it is harvested has been found to cause significant losses (Meullenet *et al*, 2000).

2.3.1 Harvest

Harvest is a major operation in rice production and handling activities. Instead of being considered as the last step in production, it should rather be approached as the first in the postproduction system, because of its influence on subsequent processing and preservation of the grain. In this operation, two main alternatives exist: separate harvesting and threshing, or combined harvesting and threshing (Cruz and Havard, 1994).

2.3.1.1 Optimum harvesting time for the grain yield and quality

Rice, like most cereal grains, should be harvested at the optimal time or MC to minimize potential loss caused by bad weather, shattering, insects and fissuring (Fig 2.12). The fissures (internal fractures) are usually found to happen across the longitudinal axis of the kernel and develop from the centre to the outside. Individual fissures develop to their full extent within a fraction of a second (Kunze, 1979 and Lan and Kunze, 1996b).

Fig 2.12: Fissures in a rice kernel as seen through a red light filter
(Source: IRRI, 2002b)

Other than measuring its MC, the readiness of the grain for harvest is indicated by (Bal and Ojha, 1975; IRRI, 2002b):

- Colour - when 80 to 85% of the grains are straw or golden yellow coloured (the sign of maturity) and the grains in the lower part of the panicles are in the hard dough stage
- Number of days after flowering – 28 to 36 days
- Firmness of the grain - the grain should be firm but not brittle when squeezed traditionally between teeth.

Optimum MC at harvest gives not only the highest yield but also the highest milling yield. Harvesting of the grain when MC is in the range of 20 – 24% has been suggested and increasingly practiced in many rice producing countries. If harvesting is done when the grain has higher MC, reductions in the milling and HRYs would likely occur due to the presence of immature kernels; if the grain is allowed to dry to have MC of less than 15% in the field, the chances of reducing the grain and HRYs would also increase (Teter, 1987; Zhang *et al*., 2002; IRRI, 2002b).

Unfortunately, fissuring of the grain can not be totally avoided simply by having the proper MC. While the target MC level is an average, the kernels may still have different levels of MC due to their location on the panicles and in the field. The drier kernels could be subject to fissuring from rewetting by mixing, or, if it rains while they are still in the field (Hellevang, 2004). Srinivas *et al*. (1978) reported that drying of the grain in the field under sun as well as wetting by dew induced cracks in the grain especially for the kernels that were ripe or have low MC (lower than the critical MC of about 16%).

Overexposure of the mature grain to fluctuating temperature and moisture conditions in the field results in adsorption and desorption of moisture by the rice kernels (Kunze, 1977; Kunze, 1979; Calderwood *et al*, 1980; Chau and Kunze, 1982; Velupillai and Pandey, 1990; Lu *et al*., 1994; Lan and Kunze, 1996a; Kunze, 2001), and these were postulated to be the main reason for the fissuring. The paddy and brown rice kernels with large fissures broke easily during milling and handling. They observed that a 10% level of fissured grains in paddy grain caused the HRY to reduce by 8–9%, and increasing the fissured kernels in paddy to 30% caused the yield to reduce by 20%. The yield reduction was found to be approximately the same in all varieties tested.

This yield reduction was even more when rain fell between ripening and harvest, especially when the MC decreased to 15% or lower before rain (Siebenmorgen *et al*., 1992). Delayed harvest in rainy weather and the crop lodging frequently leads to grain sprouting on the panicles. The incidence of heavy rain during the harvesting season can even create mould contamination of the rice crop (Juliano, 1993).

2.3.1.2 Manual harvesting

In developing countries, this method is generally the most widely applied. In Cambodia, for example, rice crops are manually cut and tied into sheaves. These sheaves are usually placed on top of the standing stubble for some time to dry before they are transported to threshing sites. The crop is usually cut about 30 – 40 cm below the panicle so as to have the bundles long enough for grapping during manual threshing and to leave straw in the field in amounts large enough to produce grazing for cattle (Rickman *et al*., 1997). Such practice is labour intensive. Rickman *et al* (1995) reported that around 30 man days are needed for cutting the crop in one hectare.

2.3.1.3 Mechanised harvesting

Although harvesting and threshing are still frequently done by hand in many countries, mechanisation has begun to be introduced, especially where the crop is for commercial purposes (Trim and Robinson, 1994). Combine-harvesters, as the name implies, combine the actions of reaping and threshing the crop. Either the "through-flow" or the "hold-on" principle of threshing may be employed; the reaping action is basically the same. The main difference is that combine-harvesters of the Western ('through-flow') type are equipped with a wide cutting bar (4-5 m) while the working width of the Japanese ('hold-on') units is small (1 m). According to the type of machine used, and especially their working width, the machines can harvest the crop in 2 to 15 hours per hectare (Cruz and Havard, 1994).

Such machines are being increasingly used in some tropical countries despite their poor suitability for some small-sized fields. In Thailand, in particular, local manufacturers have transformed the IRRI thresher into a combine-harvester, so as to reduce the labour requirement. The unit can harvest 5 ha per day and seems to have been rapidly adopted (Cruz and Havard, 1994).

Andrews *et al* (1992) reported that a reduction of less than 2% in HRY was found in the combine-harvested rice samples of two long-grain varieties, "Newbonnet" and "Lemont", when compared to hand-harvested samples.

2.3.2 Threshing

Threshing is usually applied to the harvested crop to remove the grain kernels from their panicles. The operation should be done immediately or as soon as possible after cutting due to the chance of the grains to be exposed to insects, birds and rodents, disease, and moulds. The grain can change its colour and the milled rice will yellow. Unwanted germination can also occur if the grain is very wet (Bakker-Arkema and Salleh, 1985; IRRI, 2002b).

2.3.2.1 Traditional threshing

Traditional threshing of rice is usually done after the cut sheaves are sun-dried on the bund or in the field to make the grains more easily removed. It is generally done by hitting the sheaves against a hard element (e.g., a wooden bar, bamboo table or stone). The outputs are 10 to 30 kg of grain per man-hour according to the variety of rice and the method applied (Cruz and Havard, 1994).

Threshing or removing the grain from the straw by trampling or treading has been recognised to be the best method in maintaining the grain quality if enough labour is available. Farmers usually use this method to gain the threshed grain as seed. The outputs can be 5 to 15 kg of grain per man-hour according to the grain variety and yield. In some other cases, the crop is threshed by animal tread or vehicle action. The animals or vehicle are driven in circles (15 to 20 m in diameter) over the stack of paddy sheaves. The output can be a few hundred kg per hour. Some losses can occur when applying this method, due to the grain being broken or buried in the earth (Cruz and Havard, 1994; IRRI, 2002a).

2.3.2.2 Mechanised threshing

From an historical viewpoint, threshing operations were mechanised earlier than harvesting methods, and were studied throughout the 18th century. In the 1970s, the International Rice Research Institute developed an axial flow thresher (Fig 2.13), which has been widely adopted and manufactured in many rice producing countries at a local level. In Thailand, Cambodia and Vietnam, several thousands of these units have been put into use with the capacity ranging from 200 kg to 3 tons per hour (Rickman *et al*., 2001).

Fig 2.13: Axial-flow rice thresher *(Source: Cruz and Havard, 1994)*

The 'hold-on' thresher of Japanese design is so-called because the sheaves are held by a chain conveyor which carries them and presents only the panicles to the threshing cylinder, keeping the straw out. According to the condition of the crop, work rates can range between 300 kg and 700 kg per hour (Iseki model). The main disadvantage of these machines is their fragility (Cruz and Havard, 1994).

2.3.2.3 Performance and effects on the grain quality

MC of the grain and threshing machine settings have been found to affect the threshing performance, yield and quality of the harvest. MC of the grain suitable for threshing by machine is in the range of 20 to 25%. When the grain is too wet, the threshing will be slow and will cause some damage to the outer husk. On the other hand, when the grain is too dry, the threshing can create a lot of fissures and cracks in the kernels.

Drum tip speeds for peg tooth threshers should be set from 12 to 16 m/sec, or approximately 600 rpm. Higher speeds result in higher levels of grain damage while lower speeds increase the amount of grain kernels retained in the panicles or sheaves (Bakker-Arkema and Salleh, 1985; and IRRI, 2002b).

2.3.3 Cleaning and grading

Threshed grain contains all kinds of dockage (impurities), which should be removed as soon as possible after threshing and certainly before storage because clean grain (IRRI, 2002b)

- Improves the storability of grain,
- Improves milling output and quality,
- Has a higher value than grain that is contaminated with the dockage, and
- Reduces price penalties at the time of selling

Cleaning of the grain before drying increases the efficiency of drying and reduces the problems of handling. Clean grain causes less clogging and improves the flow in different parts of the handling machines (Teter, 1987).

The simplest traditional cleaning method is winnowing, which uses the wind to remove light or foreign elements from the grain. Some farmers produce the air current or artificial wind using an old car-radiator fan powered by batteries.

Manual cleaning methods are generally simple and cheap but not suitable for separating or removing materials (such as stones) that have a similar shape, size and density as the clean grain. Moreover, they can not be used to grade the grain based on its kernel length or width. Some mechanical cleaners are capable of separating or grading the grain, based on the kernel shape, length and thickness, with very high outputs (several tens of tons of the grain per hour) (Cruz and Havard, 1994).

2.3.4 Drying

After harvest and threshing, to keep the deterioration of grain below the acceptable level, its MC, temperature, presence of micro-organisms and/or insects, gaseous environment, and acidity, must be controlled and the following techniques have been used (Teter, 1987):

- Refrigeration by either mechanical cooled air or by using naturally cold air,
- Exclusion of oxygen from the bulked grain,
- Natural pickling by allowing *Lactobacillus* specimens to increase grain acidity,
- Chemicals to increase or decrease the pH to levels where micro-organisms cannot grow, and
- Drying.

Toğrul and Pehlivan (2004) stated that among these methods, drying of grain and other agricultural products has always been of great importance for the preservation of food. It is commonly practised for freshly harvested rice to lower its MC to a safe level before it can be stored safely for some months prior to milling (Fan *et al*., 1999; Izadifar and Mowla, 2003). According to IRRI (2002b), the safe MC level is about 14% and lower, and methods for drying rice differ greatly between on-farm and commercial systems. In either situation, it is essential that drying occurs immediately after harvest, but slowly, if high HRYs are to be achieved in the milling process. Delayed and inappropriate drying of wet grain leads to problems with insect, moulds, and crack damage (Gwinner *et al*., 1996; Olmos *et al*., 2002; Tiwanichakul *et al*., 2003). In ideal and efficient drying situations, paddy grain should be dried uniformly (Teter, 1987) and quickly, but its end-use quality should not be badly affected (Patindol *et al*., 2003).

During the grain drying, heat and mass transfer takes place. Heat is transferred from the drying air to the liquid water and water vapour in the grain, whereas mass is transferred out of the grain in the form of vapour (evaporated liquid) (Noomhorm and Verma, 1986).

2.3.4.1 Sun drying

Sun drying has been used since the beginning of human life to dry grains, plants and other agricultural products (Toğrul and Pehlivan, 2002). It is still the most common practice in Asia and other tropical and subtropical countries. Bakker-Arkema and Salleh (1985), Zaman and Bala (1989), Garg and Kumar (1999), Imoudu and Olufayo (2000), and Jain and Tiwari (2003) claimed that the method is simple and very economical but requires more labour and, on the average, produces paddy with lower quality than other methods of drying. However, controlled sun drying may result in a HRY comparable or even better than some artificial or mechanical drying methods.

Large-scale production can limit the use of the method for lack of ability to control the drying process properly, weather uncertainties, high labour and large area requirements, insect infestation, and mixing with dust and other foreign materials (Basunia and Abe, 2001; Toğrul and Pehlivan, 2002; Toğrul and Pehlivan, 2004).

Due to a non-controlled source of energy in the drying system, Mulet *et al*. (1993) claimed that experiments are difficult to compare. The drying rate in open sun depends on several factors. Firstly, it depends on incident solar radiation or solar intensity. The intensity will affect the ambient air temperature and RH, thus influencing its drying potential. Wind speed or velocity is another important factor that is indirectly related to solar radiation in a particular location. It is the result of more global factors. These workers, therefore, suggested investigating the advantages of a particular set up as well as the climatic influences. The drying experiments should contain a control trial, allowing the comparison of different drying methods or strategies.

a. Procedure

In the sun-drying method, rice grain is usually spread in a thin layer on horizontal ground and exposed directly to the sun, wind and other atmospheric conditions (Fig 2.14). In this system, heat and mass transfer occur simultaneously: the heat is transferred by the solar radiation and from the ambient air to the exposed surface of the grain bed. A part of this heat is transferred to the bed interior to raise the kernels temperature and the remaining heat is utilised to evaporate the moisture near the surface to the surrounding air. Some of the heat can also be lost by conduction to the ground below the grain bed (Garg and Kumar, 1999).

To protect the grain from dirt and absorbing any soil moisture, sheets or mats are usually used. In order to ensure good and even drying, the thickness of the grain should not exceed 8 cm and the grain should be turned over from time to time. Stirring or mixing the grain is considered not only important for increasing the rate of drying, but also for maintaining good grain quality (Teter, 1987). Nindo *et al*. (1995) reported that a non-stirred bed of 3 cm dried as fast as a 6 cm stirred bed, although MC was not uniform in the former case. The most common method for stirring is to use fingers or feet. Sometimes, some simple hand tools are used. The tools can be rakes or notched boards of about 1 m long, attached and braced to a convenient pulling or pushing pole. On larger drying floors, tractors or other motor vehicles mounted with stirring boards are common practice (Hellevang, 2004). At the end of drying day, farmers usually collect and bag or pile and cover the grain by the sheets or mats and placed under shade if drying need to be continued for the next day(s).

Fig 2.14: Sun drying of rice

b. Solar intensity

In the countries where the method is commonly practised, solar radiation is usually convenient for at least several months of the year (Toğrul and Pehlivan 2004). The mean level of solar intensity (solar irradiation) upon the ground can be more than 500 W/m² (Imoudu and Olufayo, 2000). At mean earth-sun distance, outside of the atmosphere, the intensity (called solar constant) or the energy from the sun, per unit time, received on a unit area of surface perpendicular to the direction of propagation of the radiation, is around 1353 W/m^2 (Duffie and Beckman, 1991). Cruz and Havard (1994) calculated the amount of the heat available on earth to be 21.6 MJ/m², assuming a 12 hour/day, which is theoretically sufficient to evaporate 9 kg of water.

Mahamed (1990) stated that the intensity of solar energy, or solar radiation, decreases with greater distance from the sun. The sun is not at the centre of the earth's orbit, so the earth's distance from the sun varies during the year and so does the intensity of the radiation reaching the earth. The energy available on the earth also depends on the time of day, the time of year, the weather, the latitude of the site and the site's tilted angle. To estimate the amount of heat available for drying, climatic sunshine or solar radiation should, therefore, be recorded.

Mahamed (1990) also stated that the solar intensity increases from zero just before dawn to some maximum value at about noon and then decreases to zero again at sunset. As the earth's rotational axis is tilted at a 23.5^{o} angle from its place of orbit around the sun, there are different seasons in each year within which day lengths change. As a result, in some seasons the sun has a longer travel path across the sky, giving more hours of sunlight, and more total daily energy is available on the earth.

Some of the available energy from the sun is reflected back into outer space at the top of the atmosphere. Some is absorbed by the ozone layer, water vapour, carbon dioxide and other compounds making up the atmosphere. Another portion of the radiation is scattered by dust particles or water vapour and is not available for collection on earth. Early in the morning and late in the afternoon, when the sun is low in the sky, the sun's rays travel through much more of the atmosphere than at midday, so as to cause more energy to be absorbed and scattered in the atmosphere, and less reaches the earth's surface (Mahamed, 1990).

c. Rate of drying

Depending on the solar intensity, ambient air temperature and RH, wind velocity, the grain initial MC, variety and depth, the type of drying pad and the intensity of stirring; the grain is usually dried for 1 to 3 days after threshing. If the weather is cloudy and rainy, more days may be required. Air movement of 8 m/minute or more will promote drying. Air movement is almost always sufficient to give satisfactory sun drying (Zaman and Bala, 1989; Garg and Kumar, 1999; Rickman *et al*., 2001).

Under the atmospheric conditions at the time, Chancellor (1965) estimated the amount of water removed per hour from one square metre to be 0.433 and 0.250 kg for stirred and unstirred beds, respectively (Hellevang, 2004).

d. Size of drying floor

The size of the floor required for drying is usually determined by matching the drying rate with the amount of harvested grain. Since the grain should be dried soon after harvest, the amount to be dried is usually determined by the rate of harvesting, estimating the availability and intensity of solar radiation, estimating the daily hours of drying and computing the amount of the grain to be dried in one day on one square metre (Hellevang, 2004).

e. Drying pads

Drying pads should not permit water to stand from either condensation or rainfall. Woven mats, plastic nets, or coarsely woven cloth are found to be satisfactory for drying the grain. Solid plastic sheets can result in condensed water and tend to hold it in low places; therefore, they should not be used as drying pads. Such solid sheets should be used to temporarily cover the piled grain during rain storms or at night between the drying days (Hellevang, 2004).

f. Cost

The costs of the drying method includes fixed and variable (operating) costs. Investments in land, floor or pad and perhaps containers may be considered as the fixed costs in the sun-drying system. The variable costs are labour for drying and maintenance costs. Overall, the economics of the drying system or method depends very much upon the labour costs. It has been estimated that on average eight man hours is required to dry one ton of grain. (Hellevang, 2004).

g. Operation

The drying operation should be done to dry the grain as fast as possible but to still maintain its quality. The two main mistakes that have been found to result in excessive fissuring of the kernels with subsequent low HRYs are (Hellevang, 2004)

1. Creating too large a moisture variation and then mixing the dry kernels with the wet. This comes about when the grain bed is thick and is inadequately stirred. The grain kernels at the surface or the higher parts of the bed may become very dry while the other kernels below are quite wet, and fissuring results when they are stirred or bulked, and
2. Allowing the dry grain to be rewetted by rain or dew. Rain usually does little damage if the paddy is above 15% MC when it is rewetted, but if rain water or dew is allowed to fall or to form on the grain with lower MC, severe fissuring would easily happen.

Even achieving the appropriate level of MC is the key for successful handling of the grain; the majority of rice farmers do not have access to moisture meter. The farmers use different kind of different traditional methods such as feeling by hand or biting to estimate the grain MC and the drying time is decided mostly by the number of drying days.

Sometimes, solar dryers which are based on the principle of blowing air heated by solar collector(s) through the rice are used. The advantages of such dryers as compared to the sun drying method, according to Ozbalta and Dincer (1994), Gwinner *et al* (1996) and Pangavhane *et al*. (2002), are

- The possibility for air temperature and flow control to reach optimum levels suitable for dehydration and maintaining quality of different products,
- The protection of produce from adverse weather conditions and from infestation by pests,
- A shorter drying time, and
- Lower running costs.

Unfortunately, the dryers have not yet been established to the desired extent due to socio-cultural, technical and financial reasons. In addition, cloudy skies at the time of harvest also limit their use (Gwinner *et al*., 1996).

2.3.4.2 Mechanised drying

Mechanised drying refers to drying using artificial or mechanical dryers, which are a complete drying system made up of fan, heater, ducts and bin. The drying occurs in machined dryers by air of suitable RH and temperature passing through the grain until the desired reduction in MC is achieved (McLean, 1989).

2.3.4.3 General performance and effects on the grain quality

Some biological products, when dried as single particles under constant external conditions, exhibit a constant-rate moisture loss during the initial drying period, followed by a falling-rate drying phase. Cereal grains, however, dry entirely within the falling-rate period, meaning that the drying rate decreases continuously during the course of drying (Brooker *et al*., 1992). For rice grain, the drying rate is extremely fast during the initial drying stage, attributed mainly to a quick moisture release from the husk (Shei and Chen, 2002). Diamante and Munro (1993) described the drying mechanism for the constant and falling rates when solar drying sweet potato slices. During the constant rate period, drying takes place from a material surface saturated with water, and the drying rate is controlled largely by the air temperature and flow. In the falling rate period, water is no longer saturated on the surface and the drying rate is controlled by diffusion of moisture from the interior of the solid to the surface.

It is expected that the grain would reduce its volume when dried. Steffe and Singh (1980) estimated the shrinkage of white, brown and paddy rice by taking volume measurements at 30% and 15% MC using a commercial air-comparison pycnometer. They reported that on average the volume of each of the three rice forms decreased 12.3% with the 15% drop in MC. In contrast, Murthy *et al*. (1986) investigated the increase in paddy rice kernel volume during adsorption from 13.6% to 29.9% MC for five varieties, and found that the increase in volume was linearly related to the MC for two varieties and nonlinearly for the other three varieties. Muthukumarappan *et al*.

(1992) reported that although rice samples with an initial MC of 8.5% might have fissured during adsorption at 30^{o}C and 95% RH, the volume change due to fissure formation was negligible.

In general, the drying rate can be increased by using a higher air temperature and flowrate but these factors affect the dried grain quality. Cnossen *et al*. (2003) claimed that understanding the effects of the drying process on the grain fissuring is important to control and optimise drying conditions for maximising the drying output and the milling quality.

Improper drying has been found to cause a lot of damages (cracks or fissuring) to rice kernels. Rhind (1962), Indudhara and Bhattacharya (1979), and Bhattacharya (1980) showed that breakage of the grain during milling, or any other mechanical treatment, is directly related to the proportion of kernels in the crop that exhibit internal cracks. Such fissures produce lines of weakness along which the kernels are more likely to break when subjected to mechanical stress.

Because the typical value of broken rice is about one third to one half that of whole rice it is important for the growers to minimize the breakage during harvesting, handling, drying and processing of the crop. Understanding the effects of drying and tempering processes on rice kernel fissuring is, therefore, important. This understanding can be used to control and optimise drying and tempering conditions for maximising milling quality (Kunze and Hall, 1965; Kunze and Choudhury, 1972; Kunze, 1979; Steffe and Singh, 1980; Sharma and Kunze, 1982; Nguyen and Kunze, 1984; Bautista *et al*., 2000; Cnossen and Siebenmorgen, 2000; Sun *et al*., 2002; Cnossen *et al*., 2003; Mujumdar and Beke, 2003).

Several hypotheses have been proposed to explain the formation of fissures and the subsequent breakage of fissured kernels. Many workers reported the strong effects of temperature on grain quality and recommended not to dry rice and maize grain with an air temperature of over 40^{o}C, although doing so takes an extended length of time for drying (Nguyen *et al*., 1995; Zaman and Bala, 1989; Li *et al*., 1999; Abud-Archila *et al*., 2000; Davidson *et al*., 2000; Fan *et al*., 2000b; Wongwises and Thongprasert 2000; Yang *et al*., 2002; Patindol *et al*., 2003; Tirawanichakul *et al*., 2004). Sarker *et al*.

(1996) and Chen *et al*. (1997) found the grain quality was significantly influenced by drying conditions, variety, and initial MC. In maize grain, Meas (1999) found that the harvest or initial MC had a significant effect on the grain breakage. The grain damage was found generally to be associated with high MC. Fan *et al*. (2000b) claimed that high temperature can be used to speed up the drying process when the grain MC is over a critical point of around 15%. Only below this point can the grain quality be badly affected.

According to Hellevang (2004), rewetting has been found to be the main cause for the grain fissuring and HRY reductions. Therefore, care has to be taken to avoid mixing dry grain (MC less than 15%) with moist grain (MC greater than 18%). Siebenmorgen and Jindal (1986) reported that a number of studies indicated that the MC of around 15% is the critical level. Above that level, internal moisture migration does not readily induce cracking in the grain.

Moreover, Hellevang (2004) stated that during drying there is an imbalance in vapour pressure between the grain kernels and the drying air. If this vapour tension becomes too great, the kernel may fissure. According to this worker, shrinkage of the outer cells, caused by the rapid removal of moisture from the surface, would also induce stress within the kernels, thereby increasing the likelihood of breakage during milling.

2.3.4.4 Tempering research

Contrasting with the above reports, many workers, such as Kunze and Hall (1965), Kunze and Hall (1967), Beeny and Ngin (1970), Srinivas *et al*. (1977), Kunze (1977), Srinivas *et al*. (1978), Kunze (1979), Steffe *et al*. (1979), Sharma and Kunze (1982), Sharma *et al*. (1982), Nguyen *et al*. (1995), Nguyen and Kunze (1984), Aguerre *et al*. (1986), Banaszek and Siebenmorgen (1990), Zhang and Litchfield (1991), Soponronnarit (1995), Lan and Kunze (1996b), Sarker *et al*. (1996), Bonazzi *et al*. (1997), Shei and Chen (1998), Siebenmorgen et. (1998), Li *et al*. (1999), Soponronnarit *et al*. (1999), Abud-Archila *et al*. (2000), Bautista *et al*. (2000), Perdon *et al*. (2000), Cnossen and Siebenmorgen (2000), Chen and Wu (2000), Fan *et al*. (2000b), Cihan and Ece (2001), Yang *et al*. (2001), Cnossen *et al*. (2001), Kunze (2001), Shei and Chen (2002), Jia *et al*. (2002a), Jia *et al*. (2002b), Cnossen *et al*. (2002), Yang *et al*. (2002), Siebenmorgen (2003), and Cnossen *et al*. (2003), claimed that the grain quality is not affected to a great extent by the temperature but by the changes of MC and moisture gradient differences within the grain lot and within the individual kernels.

The thermal shock alone did not cause the grain kernel to fissure, and high drying temperatures can be used without reducing the grain quality, provided that the evaporating capacity of the air is low or that the RH of the air is high (Bonazzi *et al*., 1997; Abud-Archila *et al*., 2000). Kunze and Hall (1965) and Kunze and Hall (1967) found that a thermal gradient of 35^{o}C did not produce fissures in rice, as long as the grains were maintained at a constant MC. The maximum temperature gradient inside a rice kernel appeared within 20 seconds after the onset of drying, and the entire temperature gradient disappeared after 2 to 3 minutes drying (Yang *et al*., 2002).

Internal stresses are due to combined MC and temperature gradients but the MC gradient has a greater effect than the temperature gradient on stress creation. When paddy rice is heated at 40 and 60^{o}C for different periods in closed metal cups (where no significant variation of MC was observed), Aguerre *et al*. (1986) found that the HRYs of the dried samples were almost the same. In a similar study on maize, Ekstrom *et al*. (1966) reported that a temperature gradient of at least 79^{o}C must exist between the centre and the outer surface of the kernel for cracking to occur due to temperature gradient alone.

Believing that tempering (allowing the grain to cool for some time in a bin or bag) should be done in order to ease a possible contribution of MC gradients to hygroscopically induced fissuring, these workers extensively studied the effect of the tempering process on the drying performance (i.e. drying rate and energy utilisation) and the quality of dried rice and maize. According to them, rapid drying is a cause for the fissuring of rice grain, although much of this damage may not develop until after drying. Re-absorption of moisture from the air after drying results in stresses in the grain kernel which have much more effect on the fissure formation than drying itself and discontinuing the drying process with tempering can help decrease the stresses and the fissuring percentage.

When the MC declines after drying, moisture from the central portion of the kernel diffuses to the surface, causing it to expand while the internal portion contracts due to moisture loss. As the result, tensile stresses were created in the inner portion and compressive stresses in the outer portion of the grain. This situation would intensify if the surface is exposed to ambient air with high relative humidity (RH), as the surface would absorb more moisture from the air. When the maximum tensile stresses in the grain centre exceed its failure strength, the kernel will be fissured (Kunze, 1977; Sarwar and Kunze, 1989; Jia *et al*., 2002a). According to Bamrungwong *et al*. (1988), the tensile strength of the grain is usually 7 to 14 times smaller than the compressive strength. Li *et al*. (1999) postulated that the temperature and moisture gradient within the grain kernel during drying will also result in volumetric changes. This non-uniform expansion and contraction result in failure when the induced stresses exceed the failure strength of the grain material.

In a tempering process, grain is maintained in an insulated adiabatic environment so that the moisture inside the grain kernels can equalise between the centre and surface of the kernel at a constant temperature. Mainly diffusion phenomena exist, and the average temperature and MC of the kernel are kept constant. In practice, however, the temperature usually decreases gradually due to imperfect insulation (Jia *et al*., 2002a).

In addition to the improvement of the grain quality, Shei and Chen (1998), Chen and Wu (2000), Inprasit and Noomhorm (2001), Cihan and Ece (2001), and Shei and Chen (2002) claimed that more efficient drying (higher drying rates, shorter drying time and less energy utilised) can be achieved by tempering, as the moisture in the central portion of the rice kernel moves towards its outer parts during the tempering process, so as to greatly increase the drying rate in the following drying period. High tempering temperatures have been shown to be effective in maintaining high HRYs and decreasing tempering duration (Steffe *et al*., 1979; Cnossen and Siebenmorgen, 2000). Similar effects of tempering were also reported for maize (Gustafson *et al*., 1983; Meas 1999).

For these reasons, multi-pass drying is generally used to remove moisture from freshly harvested rice in commercial drying. Between drying passes, the grain is held in bins for a certain period of time to allow MC gradients within kernels, created during drying, to reduce; this holding process is referred to as tempering. The tempering practices, however, vary widely. Tempering durations between 6 and 24 h are used in the United States to ensure that the grain moisture within individual kernels has enough time to equilibrate (Soponronnarit *et al*. 1999; Cnossen and Siebenmorgen, 2000; Cnossen *et al*., 2001; Cnossen *et al*., 2003). Siebenmorgen (2003) reported that if a drying stage exceeds 4 to 5% MC reduction, tempering did not help prevent HRY reduction.

Significant MC gradients have also been found to occur within the grain bed or column in the mechanical drying system. In the system, the hot inlet drying air is changed to humid warm air as it passes through the grain mass. Grain ahead of the drying front may adsorb moisture and possibly fissure before the drying front reaches them (Kunze and Prasad, 1978).

In sun drying systems, the moisture-removing capacity of the air can be enough to cause serious damage to the grain. The grain temperature can exceed 50°C and this can cause fissuring and killing of the seed (Imoudu and Olufayo, 2000). When drying the grain under the sun by spreading it in about a 2.5 cm deep bed, Bhashyam *et al*. (1975) observed that when the ambient air temperature was high (40-45^{o}C) and its RH was low (less than 45%), the breakage level was high. They also found that continuous drying of the grain under the sun allowed the drying in a short period but caused higher breakage than when the drying was slowed down by tempering between drying steps. When the temperature was mild (25-32^{o}C), the tempering steps were not essential.

Like Bakker-Arkema and Salleh (1985), these workers claimed that the fissuring may be reduced if the grain is covered during the very hot times of the day as covering provides the grain with tempering effects. To keep the milling quality, they suggested two tempering steps for the whole drying time or to dry the grain to 17% MC with stirring at half hour intervals, followed by a two to three hour tempering under cover and final drying to about 14% MC. During the tempering phase, the grain can still be spread but has to be under cover from the sun. The type of the cover, according to them, is not highly critical and can be locally available materials, such as a tarpaulin, mat, straw or coconut leaf.

Stirring, turning or mixing the grain bed regularly has been found to cause the grain to dry uniformly, to avoid over-drying and to give a tempering effect (Bala and Woods, 1994).

On the other hand, for flavour impact, Champagne *et al*. (1997) recommended to dry the grain to 15% MC, as practised in Japan, rather than 12%, as commonly practiced in other countries. However, the high MC rice grain would require special handling (e.g., aeration) to prevent spoilage.

2.3.4.5 Variety resistance to the damage

In addition to growing and handling conditions, the grain variety could have a significant influence on the strength characteristics (Velupillai and Pandey, 1990). Optimum drying conditions are likely to differ from one cultivar to another (Patindol *et al*, 2003). Certain cultivars have shown significant resistance to severe fluctuations in environmental conditions providing flexibility in the grain handling after harvest (Bhattacharya, 1980 and Jodari and Linscombe, 1996).

Rice varieties with thicker kernels were reported to attain slightly lower average equilibrium MC than thinner kernels when exposed to uniform desorption conditions (Jindal and Siebenmorgen, 1994). Medium grain was found to be more susceptible to fissuring, caused by rapid moisture transfer, than long grain. The medium-grain kernels are thicker, and typically have greater minor and intermediate diameters. Thus, the distance from the surface to the kernel centre is greater, and moisture migration during and after drying into or out of the kernel cannot occur as rapidly as in the long grain (Lloyd and Siebenmorgen, 1999; Fan *et al*., 2000b). Likewise, Nguyen *et al*. (1995) reported slender grain fissured less than medium grain because its MC gradient after drying was low.

2.3.5 Storage

As it is produced on a seasonal basis, and in many places there is only one harvest a year, grain storage is a normal step between harvest and consumption (Chrastil, 1994). The main function of the grain storage in the economy is to even out fluctuations in market supply, both from one season to the next, by taking the grain off the market in surplus seasons, and releasing it back onto the market in lean seasons. This in turn, smoothes out fluctuations in market prices (Coulter and Magrath, 1994)

The quality of rice grain is set at harvest. Storage cannot improve the quality of the grain but the storage conditions and duration can have significant effects on the quality. During storage, a number of physico-chemical and physiological changes occur and are called 'ageing' which affect the grain functionality and eating quality (Zhou *et al*., 2003). Under improper storage conditions, grain quality can be reduced within a few hours (Juliano, 1985; Loewer, 1994; Loewer *et al*., 1994; Daniels *et al*., 1998; Ohtsubo *et al*., 1998; Fan *et al*., 1999; Zhou *et al*., 2002; Ranalli *et al*., 2003).

To store the grain successfully, grain and the atmosphere in which it is stored must be maintained under conditions that discourage or prevent the growth of micro-organisms that cause spoilage. The grain must have a MC of less than 13-14% and be protected from insects, rodents and from absorbing moisture from the atmosphere or rain. If the grain is stored for seed purposes, the MC should be reduced to 12% before storage (IRRI, 2002b). Pearce *et al*. (2001) investigated the effect of storage MC; the grain stored at 10% MC exhibited higher HRY than did the grain stored at 12 or 14% MC.

However, Manski *et al*. (2002) found that it is possible to store the grain at high MCs (from 20 to 25%) in sealed plastic containers for up to three months under storage temperatures varying from -9 to 4^{o}C without affecting the HRY. After storing rice grain at 15.4% MC at about -1.5^{o}C for eight months, Kawamura *et al*. (2001) found that the grain quality such as germination rate, free fat acidity and texturogram (hardness/stickiness ratio) could be preserved at a level similar to that of freshly harvested rice.

2.4 MC OF RICE GRAIN

2.4.1 Definition

MC of grain denotes the quantity of water per unit mass of either wet or dry grain, usually expressed on a percentage basis. Grain MCs (wet and dry basis) are generally defined as (Hall, 1980; McLean, 1989; Brooker *et al*., 1992; ASAE, 2001; ASAE, 2003c; ASAE, 2004c; ASAE, 2005c):

$$MC_{wb} = \frac{Weight\ of\ water}{Weight\ of\ grain} \times 100 \qquad \text{… (2.5)}$$

and

$$MC_{db} = \frac{Weight\ of\ water}{Weight\ of\ dry\ matter\ in\ grain} \times 100 \qquad \text{… (2.6)}$$

Jindal and Siebenmorgen (1987) defined the MC wet basis as the ratio of the weight of water that can be removed without changing the grain chemical structure to the initial weight of the grain. It is assumed in the use of reference methods that complete drying of material is achieved without any loss or decomposition of organic material.

2.4.2 Measurement

Determination of MC is an essential step in quality evaluation of cereal grains. MC is used perhaps more than any other property in managing rice from harvest to milling, as the behaviour of the grain in their handling stage is so dependent on MC. Many studies have used MC as a benchmark property in quantifying the effects of various harvest, drying, storage and milling practices (Kocher, *et al*., 1990; Siebenmorgen *et al*., 1990; Watson, 1991; Juliano, 1993; Siebenmorgen, 1994; Trim and Robinson, 1994; Chen, 2001; IRRI, 2002b).

MC above a certain safe limit is conducive to infestation with fungi and insects during storage, and makes the produce more perishable (Gwinner *et al*., 1996). When milling, MC was found to be the most significant variable in affecting the grain HRY. As MC decreased, bran removal became more difficult and the HRYs decreased (Andrews *et al*., 1992). MC also influences the keeping quality of flour and bakery products. The higher the MC, the worse can be the quality. The behaviour is also influenced by other factors such as temperature, oxygen supply, history and condition of the grain, length of storage and biological factors such as moulds and insects (Lorenz and Kulp, 1991).

There are two main methods usually used for measuring the MC of rice grain (IRRI, 2002c):

- The primary or direct method - often referred to as the oven drying method.
- The secondary or indirect method - which uses an electronic moisture meter.

The oven method, which is mostly used in laboratories, determines the amount of water in the grain by removing the moisture from the grain. The method is based on drying whole or ground grain in an oven over a fixed period of time. Sometimes the grain samples are ground but ASAE (1983) and Jindal and Siebenmorgen (1987) claimed that whole-grain samples can be used primarily for simplicity and avoiding possible moisture loss during grinding.

In the second method, the measurement of an electrical property of the grain (either conductance or capacitance) is required and moisture meters, as shown in Fig 2.15, are generally used. Lim *et al*. (2003) stated that because the dielectric constant of water is much greater than that of the dry material of grain, the dielectric constant of grain is correlated with its MC and that correlation forms the basis for the rapid determination method.

Fig 2.15: Electronic moisture meters used for grain *(Source: IRRI, 2002b)*

The MC can also be determined by the equilibrium RH and temperature of the air environment using some of the known isotherms (Chen, 2001).

2.4.3 Variation during handling

Non-uniformity or variation in MC has been described in Section 2.3.1.1 to be a problem in determining optimum harvesting time. It can also cause problems for storage as it shortens the permissible storage duration for rice grain. The presence of some grain kernels with MC above the average level of MC can reduce the safe storage life of the entire lot of grain (Teter, 1987). Like Kunze (1977), Teter (1987) stated that depending somewhat on their proportions and MCs after threshing and drying, the high moisture kernels in the mass can cause the low moisture kernels to fissure when they are mixed or bulked. As the MCs tend to equilibrate, the dry kernels become wetter and the wet kernels becoming drier. Rewetting of the dry paddy may create fissures. Spreading very wet paddy in the rain does not harm the grain quality; however, it does increase the drying time required.

It has been reported that usually large differences in individual kernel MCs exist throughout maturation and at harvest (Kunze and Prasad, 1978; Brooker *et al*., 1992). Rice kernels in a field, and even on the same panicle, do not reach a given maturity at the same time. As time progresses and the grain matures, both the number of kernels with high MCs and number of kernels with the lowest MC decreased (Kocher *et al*., 1990). Thus, at harvest, some kernels may already be well past maturity, while others may still be immature (Desikachar *et al*., 1973). Moreover, during normal weather conditions at harvest, the grain will lose moisture during the day but gain moisture at night because of the high RH. Rain will also cause a dramatic MC increase (Siebenmorgen, 1994).

Desikachar *et al*. (1973) reported that the average MC of their grain kernels from the whole panicle was 4 to 6% higher than that of the grains in the top portions. The grains at the top also had a tendency to shed easily from the panicle. Chau and Kunze (1982) summarized that when field MC of medium grain rice (Brazos) was 22%, variations of up to 46% MC were observed on a given day during the normal harvest season, between grains from the top of the most mature panicles and grains from the bottom of the least mature panicles.

Even after drying, the variation in the MC can still exist. For example, Hellevang (2004) stated that if grain kernels vary in moisture between 20 and 30% before drying, the variation may be between 12 and 18% after drying. There is, therefore, potential for variations of MC in stored grain, too. Studies have shown that even after drying and extended bulk storage to allow “full equilibration”, a wide range of kernel MCs remains (Siebenmorgen, 1998).

2.4.4 Equilibrium MC and isotherm

Rice is a hygroscopic grain and hence reacts with any environment with which it is not in equilibrium. A dry grain surface adsorbs moisture in a humid environment while a wet surface desorbs moisture in a relatively dry environment (Kunze, 1977; Kunze, 1979; Bakker-Arkema and Salleh, 1985).

If a grain sample is placed in a closed jar or any sealable container, water will move both from the grain into the surrounding air and from the air to the grain until equilibrium is reached. The grain MC in this condition is known as the equilibrium MC (MC_e), and the RH of the air is known as the equilibrium RH (RH_e) (Loewer *et al*., 1994; Newman, 1994).

Brooker *et al*. (1992) and Lan and Kunze (1996a) explained this phenomenon in terms of water vapour pressure by stating each kernel displays a characteristic water vapour pressure at a certain temperature and MC. The vapour pressure of cereal grain at the various MCs and temperatures determines whether it will desorb (lose) or adsorb (gain) moisture when exposed to moist air. When the vapour pressure of the water in a grain kernel is equal to the water vapour pressure of the surrounding air, the MC of the kernel is equal to the MC_e.

Table 2.3: MC_e of paddy rice *(Source: Teter, 1987)*

RH,%	**Temperature**, ^{o}C						
	22	**24**	**28**	**32**	**36**	**40**	**44**
50	11.2	10.9	10.7	10.5	10.2	10.0	9.9
55	11.7	11.5	11.2	11.0	10.8	10.6	10.4
60	12.3	12.0	11.8	11.6	11.4	11.2	11.0
65	12.7	12.6	12.4	12.2	12.0	11.8	11.6
70	13.5	13.3	13.1	12.8	12.6	12.5	12.3
75	14.3	14.0	13.8	13.6	13.4	13.2	13.0
77	14.6	14.3	14.1	13.9	13.7	13.5	13.4
79	14.9	14.7	14.5	14.3	14.1	13.9	13.7
81	15.3	15.1	14.9	14.6	14.5	14.3	14.1
83	15.7	15.7	15.3	15.1	14.9	14.7	14.5
85	16.1	15.9	15.7	15.5	15.3	15.1	15.0
87	16.6	16.4	16.2	16.0	15.8	15.6	15.5
89	17.2	17.0	16.8	16.6	16.4	16.2	16.1
91	17.9	17.7	**17.5**	17.3	17.1	16.9	16.7

It is very important to realise the practical significance of the MC_e. It is not possible to dry grain or any other product to a MC lower than the MC_e associated with the temperature and humidity of the drying air (Brooker *et al*., 1992). The data in Table 2.3 show that paddy rice can only be dried to a MC of 17.5% when exposed to air at 28°C and 91% RH. If a grain of MC of less than 17.5% is required, then either the temperature of the drying air has to be increased or its humidity reduced.

A variety of methods have been employed for determining the MC_e values of cereal grains. Most of the available data have been obtained by exposing a grain sample to water vapour in a moist-air environment. Atmospheric equilibrium MC determination techniques are either static or dynamic. In the static method, a grain sample is allowed to come to equilibrium in still, moist air. In the dynamic method, the air is mechanically moved. The static method can require several weeks before equilibrium is reached. At high relative humidities and temperatures, the grain may become mouldy before equilibrium is attained. The dynamic method is quicker and, thus is preferred (Brooker *et al*., 1992).

Table 2.4: Relative humidity (%) at different temperatures above a number of saturated salt solutions *(Source: Brooker et al., 1992)*

Tempe-rature	**Lithium Cloride**	**Magnesium Cloride**	**Magnesium Nitrate**	**Sodium Cloride**	**Ammonium Sulphate**	**Potassium Nitrate**	**Potassium Sulphate**
^oC	*LiCl*	*$MgCl.6H_2O$*	*$Mg(NO_3)_2.6H_2O$*	*NaCl*	*$(NH4)_2SO_4$*	*KNO_3*	*K_2SO_4*
10.0	13.3	34.2	57.8	75.4	81.8	95.5	97.9
32.2	11.9	32.6	51.9	75.6	80.0	90.0	96.5
48.9	11.5	31.6	47.3	74.8	79.1	85.3	95.8
68.3	11.1	30.3	42.2	73.2	78.0	78.0	95.0

RH in the closed environment above salt solutions has also been used mainly to calibrate RH meters or probes. Table 2.4 lists the RH values obtained by seven salt solutions at four temperatures. Greenspan (1977) listed RH values obtained by many more salt solutions for temperatures ranging from 0 to 100^{o}C.

Plotting the MC_e versus RH (holding temperature constant) for any grain results in a sigmoid-type (S-shaped) curve, which is called the equilibrium MC curve or isotherm (Brooker *et al*., 1992).

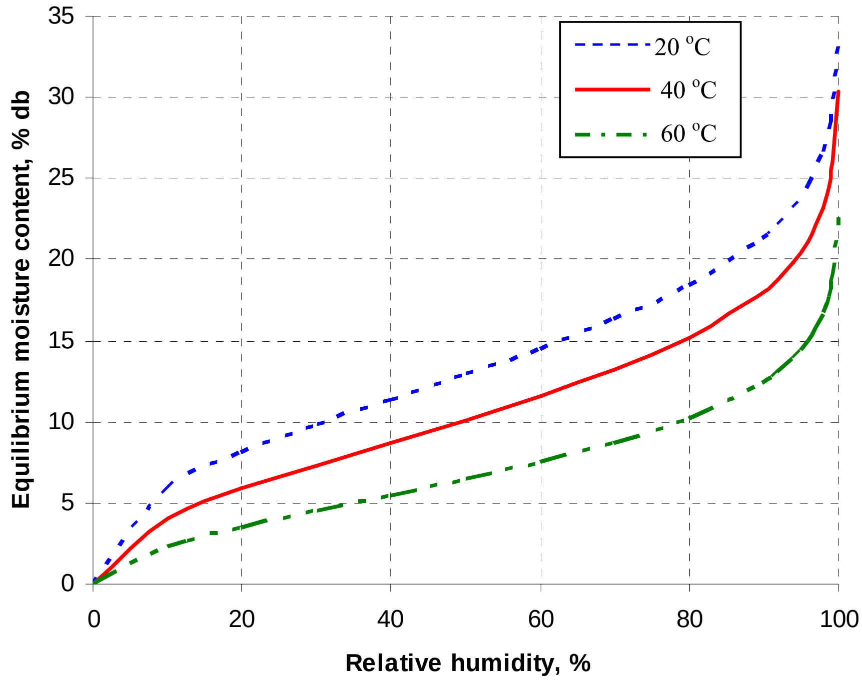


Fig 2.16: MC$_e$ curves or moisture equilibrium isotherms using the Zuritz and Singh equation

Teter (1987), Brooker *et al*. (1992), Fan *et al*. (2000a), and Reddy and Chakraverty (2004) found and stated that at the present time, the empirical modified Henderson (Equation 2.7) and Chung MC$_e$ equations (Equation 2.8) are recommended for use in grain drying calculations:

$$1 - \frac{P_v}{P_{vs}} = exp\left[-1.9187.\left(T + 51.161\right)\left(100.MC_e\right)^{2.4451}\right] \qquad \dots (2.7)$$

$$MC_e = 0.29394 - 0.046015.ln\left[-\left(T + 35.703\right).ln\left(\frac{P_v}{P_{vs}}\right)\right] \qquad \dots (2.8)$$

On the other hand, Basunia and Abe (1999) and Basunia and Abe (2001) stated that to fit the data of paddy rice, the most commonly used is the Modified-Chung–Pfost equation. Its results are adopted as ASAE Standards (ASAE, 2001; ASAE, 2003c; ASAE, 2004c and ASAE, 2005c). The form of the Chung–Pfost equation they recommended was:

$$MC_e = 29.394 - 4.6015.ln\left[-\left(T + 35.703\right).ln(RH)\right] \qquad \text{… (2.9)}$$

For the grain dried below 50°C, Brooker *et al*. (1992) also recommended another empirical relationship called the Zuritz and Singh model:

$$MC_e = 0.001\left[\frac{E}{F}\right]^G \qquad \text{… (2.10)}$$

where,

$E = - ln(1 – RH)\ \theta$

$F = 2.667\ \ 10^{-7}\left(1 - \frac{\theta}{641.7}\right)^{-23.438}$

$G = \frac{1}{4\ \ 10^5.\theta^{-2.1166}}$

2.5 GLASS TRANSITION IN RICE KERNEL

Solid materials can be subdivided into crystalline and amorphous solids. The crystalline form possesses an orderly array of aligned molecules, whereas an amorphous solid comprises disarrayed or disorderly arranged molecules. The crystalline form is tightly packed; therefore only radical or functional molecular groups on the external surface of the crystals can interact with external materials such as water (absorption). The molecules in an amorphous state are tangled, more open and porous; therefore, an individual molecule possesses more sites for external interactions; for example, an amorphous structure can absorb water easily. Therefore, an amorphous solid is sometimes referred to as a "solid solution" or also "glass" or a "vitrified solid" (Bhandari and Howes, 2000).

An amorphous solid can undergo structural change when its temperature is increased. Below a critical value, known as its glass transition temperature (T_g), amorphous materials are glassy with high viscosity, density and modulus of elasticity but low specific heat, specific volume, and expansion coefficient. Above the T_g, they are rubbery with a much higher specific heat, specific volume, and expansion coefficient, lower density and viscosity (Cnossen and Siebenmorgen, 2000, Perdon *et al*., 2000; Cnossen *et al*., 2001). The changes in volumetric expansion and specific volume during a glass transition will have an effect on rice kernel fissuring, while the changes in diffusivity will greatly affect the drying and tempering rates (Cnossen *et al*., 2002).

As the stability of foods is mainly dependent on the MC and because the T_g is also highly sensitive to this parameter, the glass transition concept appeared to be a powerful tool for understanding the mechanisms of processing food products and for controlling their storage life. The transition has and will continue to play an important part in the food technologists' understanding of storage stability and the role that non-equilibrium kinetics plays in that understanding (Schenz, 1995). Information on these transitions would help understand the structure-properties relationship of rice kernels, thereby helping to develop a more effective drying process (Perdon 1999; Bhandari and Howes, 1999; Cnossen and Siebenmorgen, 2000; Perdon *et al*., 2000; Sun *et al*., 2002).

Perdon *et al*. (2000) suggested that thermomechanical properties of rice kernels such as the glass transition temperature (T_g) are important to rice drying and fissuring behaviour. They stated that the state change of kernels, as they go through a glass transition, has an important role in rice drying and tempering in terms of kernel fissuring potential. However, with the current knowledge of grain drying, it is not entirely clear how the temperature and other transitions affect the drying and tempering processes of rice.

2.5.1 Relationship with MC

As water is a very effective plasticizer, the T_g is inversely related to the MC (Biliaderis *et al*., 1986; Zeleznak and Hoseney, 1987; Perdon *et al*., 2000). Plotting T_g against its corresponding MC (Figure 2.17) generates a state diagram that, according to Cuq and Icard-Vernière (2001) and Cnossen *et al*. (2001), can be used to predict the mechanical properties of rice kernels at a particular temperature and MC which can be a complimentary tool to improve the process parameters and the final quality of the product. At a given MC, the temperature of the material relative to its T_g will determine whether the material will be in the glassy or the rubbery state.

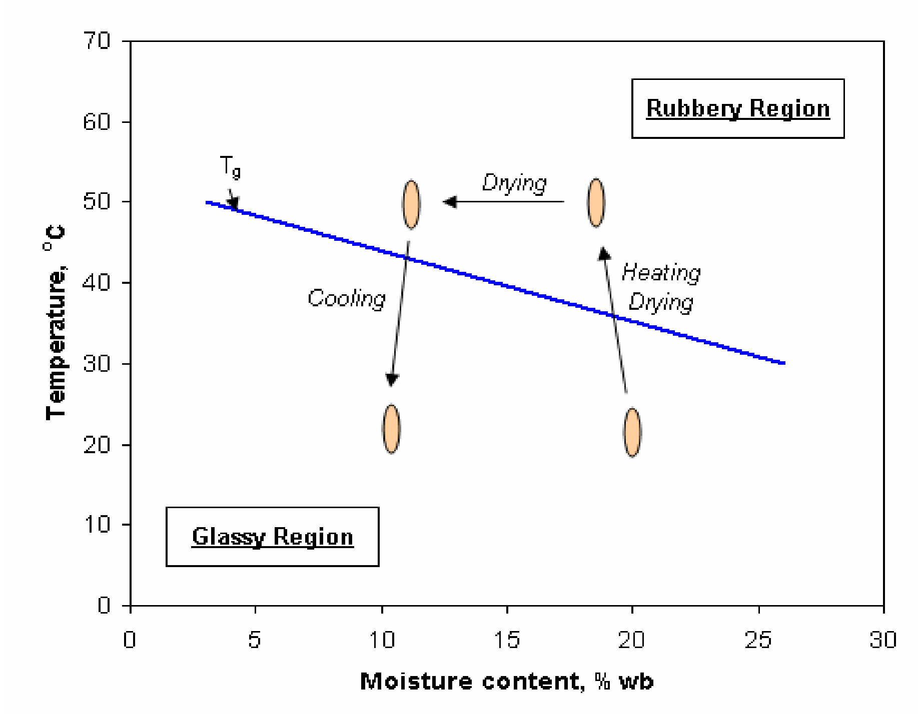


Fig 2.17: Brown rice state diagram (for Bengal and Cypress varieties combined)
plotted using the information reported by Perdon, (1999)

Patindol *et al*. (2003) claimed that different slopes of the T_g in the state diagrams can exist due to different components in different varieties (e.g amylose content, amylopectine), different bundles of amylose-lipid helices (somewhat spiral in form) and different physicochemical properties of the starch granules.

2.5.2 Measurement

The T_g has been measured by several thermal and differential thermal analyses (Mackenzie, 1970; Biliaderis *et al*., 1986; Sun *et al*., 2002). According to these workers, the thermal analyses can be classified as techniques that are dependent on

- Weight changes (thermogravimetry, isobaric weight change determination, isothermal weight change determination),
- Energy changes (differential thermal analysis, heating curves, differential scanning calorimetry),
- Dimensional changes (dilatometry), and
- Evolved volatiles (evolved gas detection, evolved gas analysis).

Differential thermal analysis, the difference in temperature between a substance and a reference material, as the two specimens are subjected to identical temperature regimes in an environment heated or cooled at a controlled rate, are recorded (Mackenzie, 1970). With constant heating, any transition or thermatically induced change in the sample is recorded as a peak or dip in an otherwise straight line. The different temperature versus the programmed temperature indicates the temperature of transition, whether the transition is exothermic (heat releasing) or endothermic (heat absorbing), and the magnitude of the transition (Pomeranz, 1994).

The differential scanning calorimetry (DSC), which measures heat flows and temperatures associated with both first-order (melting) and second-order (glass transition) transitions in materials, is probably the most widely used method of studying thermal properties of foods and grain (phase transitions, reactions, and specific heats) (Perdon, 1999). DSC can also be used to characterise phenomena such as amorphous/crystalline behaviour in polymers, purity and polymorphism in pharmaceuticals and thermal hazard potential for organic chemicals (Biliaderies, 1990; McLoughlin, 2001). In the method, the sample and reference material are subjected to a controlled temperature program. If a transition takes place in the sample, thermal energy is added to or subtracted from the sample or reference containers to maintain both at the same temperature. This difference of energy input is equivalent to the transition energy (Pomeranz, 1994).

The sensitivity of DSC can be low because polymers with relatively high crystalline structure content have low amorphous content. Many of the rice molecules are locked into crystallites. Furthermore, as the polymer chains are accommodated in the crystallites, the remaining non-ordered segments are under tension and thus do not possess the typical characteristics of a bulk amorphous phase (Biliaderis *et al*., 1986). Thus, the change in heat capacity at T_g becomes less conspicuous and more difficult to detect (Schenz, 1995; Champion *et al*., 2000; and Sun *et al*, 2002). For that reason, thermomechanical analysis (TMA) and differential mechanical analyses (DMA) are sometimes preferred for their sensitivity.

Perdon (1999), Perdon *et al* (2000) and Sun *et al*. (2002) claimed that a single technique usually would not be sufficient in determining the transition. These workers found the transitions in rice kernels using a combination of DSC and thermomechanical analysis (TMA). In the TMA method, the change in the physical dimension of a material is measured as a function of temperature. The expansion coefficient and specific volume of a material below and above its T_g can also be calculated using this method (Perdon, 1999).

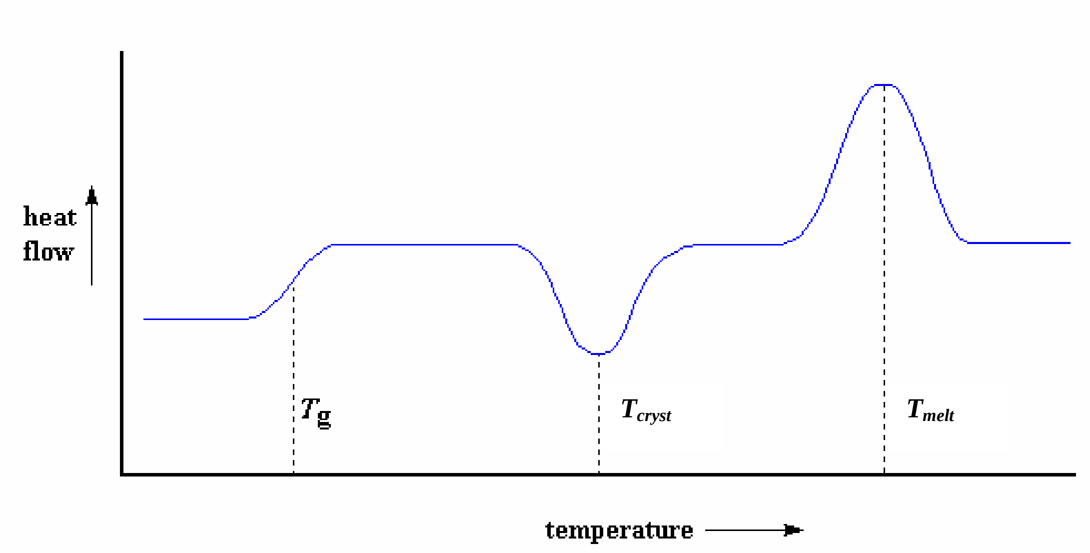


Fig 2.18: Entire DSC plot *(Source: DPSc, 1997a)*

Note: *T_g, T_{cryst} amd T_{melt} are glass transition, crystallization and melting temperatures, respectively*

Sun *et al*., (2002) conducted TMA tests on both brown rice kernel and pure rice starch and found that rice starch and the whole kernel underwent a distinct transition at almost the same temperatures. They found rice kernels experienced three thermomechanical transitions between 0 and 200^{o}C: a low temperature transition, an intermediate temperature transition and a high temperature transition. The low temperature transition was taken to be the T_g of rice kernels. The intermediate temperature transition was suggested to be related to rapid evaporation of moisture from the rice kernels. The high temperature transition was related to the melting of crystalline starch. All three transitions were inversely related to kernel MC. The researchers suggested that the transition of rice kernels was due to the T_g of rice starch but not the protein.

Ma *et al*. (1990); Perdon *et al*. (2000) and Patindol *et al*. (2003) claimed that the multiple thermomechanical transitions are closely related to the structure and morphology of the grain. Within the starch granule, amylose and the branching points of amylopectin contribute to the amorphous phase, while the outer chains of amylopectin contribute to the crystalline phase. For non-waxy rice starch, Ma *et al*. (1990) found thermomechanical-analysis volume expansion associated with the glass transition in the 50-70^{o}C range.

2.5.3 Application to rice drying

Some of the previous studies have reported the mechanism of grain breakage based on the glass transition concept. Sun *et al*. (2002) claimed that the melting temperature of rice starch plays little role in rice drying because drying temperatures usually do not reach the magnitude of the melting temperature (Fig 2.20), but the T_g of rice kernels can be very important. The drying air conditions that would be expected to cause the state transition (high temperature and low RH) are attainable in typical rice drying operations (35 to 50^{o}C, see Fig 2.17) (Perdon, 1999; Perdon *et al*., 2000; Cnossen and Siebenmorgen, 2000; Cnossen *et al*., 2002).

If the drying temperature is below the T_g, the rice starch exists in a glassy solid state, the starch granule is compact, and the water associated with the starch is relatively immobile. Therefore, the diffusion of moisture inside the rice kernel would be very slow, and it would take a longer time to dry rice kernels to a targeted MC. If the temperature were above T_g, the rice starch would exist in the rubbery state, rice starch macromolecules would have greater free volume, the starch would be more mobile and moisture could thus diffuse out of rice kernels much faster (Cnossen and Siebenmorgen, 2000; Cnossen *et al*., 2001; Cnossen *et al*., 2002). Cnossen and Siebenmorgen (2000) hypothesised that if rice is dried and tempered above the T_g line sufficiently long enough to reduce MC gradients, a state transition will not cause HRY reduction but that insufficient MC gradient reduction before a state transition will produce fissures and consequent HRY reduction.

When bulk samples are dried with air conditions near the T_g line, the average MC can fall within one region. However, some kernels may be in the rubbery region while others may be in the glassy region (Cnossen *et al*., 2002). These workers observed that the greater the number of kernels that were in the glassy region, the slower was the overall drying process. In addition, when the greater portion of the kernels was in the rubbery region but the kernels' surfaces were transitioned back to the glassy region, a slower drying process was also observed. Cnossen and Siebenmorgen (2000), Cnossen *et al*. (2001) and Cnossen *et al*. (2002) explained that when the surface of the kernel transitioned back from the rubbery to glassy region, the moisture diffusivity dropped so as to cause slower drying.

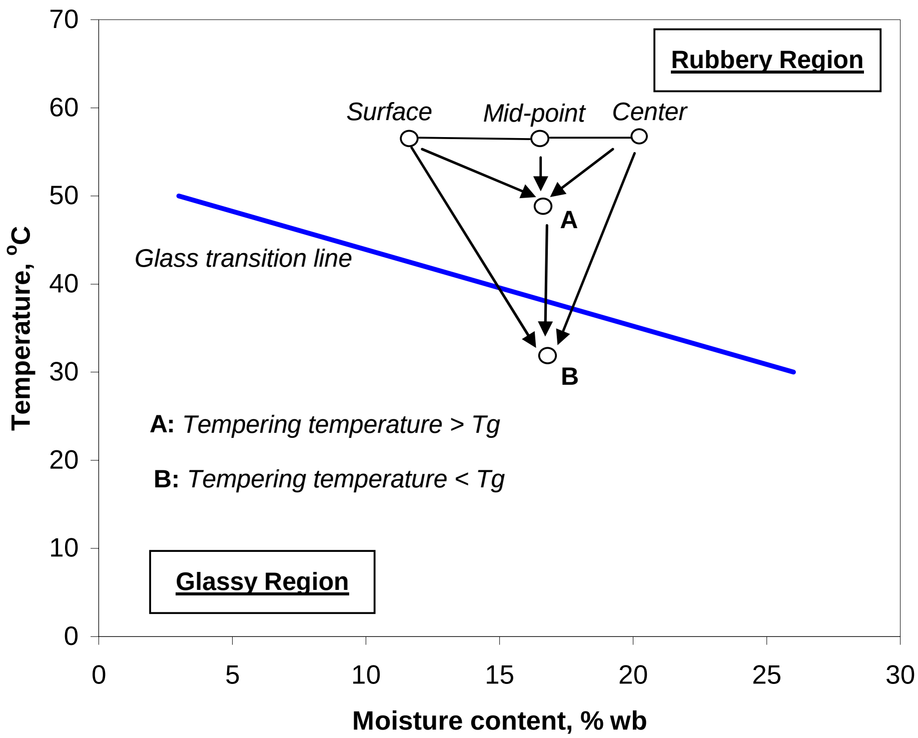


Fig 2.19: Hypothetical response of the various sections of a rice kernel during tempering for two tempering scenarios plotted using the information reported by Cnossen and Siebenmorgen (2001)

Drying air conditions that result in a low equilibrium MC (high temperature and low RH) in combination with high moisture removal rates per drying pass could be used without reducing milling quality if sufficient tempering at a temperature above the T_g is performed between the passes (Cnossen and Siebenmorgen, 2000; Cnossen and Siebenmorgen, 2001; Cnossen *et al*., 2001; Yang *et al*., 2001; Cnossen *et al*., 2002; Yang *et al*., 2002; Yang *et al*., 2003a; Yang *et al*., 2003b). Under these conditions, as much as 6% MC can be removed without reducing the HRY if a tempering duration of 3 h at 60°C is used before cooling. If the grain is tempered above the T_g line sufficiently long enough to reduce MC gradients (see Fig 2.19), a state transition will not cause fissuring in the kernels and consequent HRY reduction. These authors concluded that insufficient MC gradient reduction before the state transition will produce fissures. If the tempering temperature is below the T_g, on the other hand, the kernel will again go through the transition and become glassy as the kernel temperature decreases. As a result, a change of state of the starch happens and causes differential stresses within the kernel.

2.6 DRYING MODELS

2.6.1 Principles

Drying models have been developed and used as powerful and useful tools for describing complex drying systems such as predicting the MC and temperature distributions inside the grain kernels, within the drying bed and optimising the drying and tempering processes to improve the grain quality. They are helpful in designing new or improving existing drying systems or for the control of the drying operation (Sharma *et al*., 1982; Yang *et al*., 2001).

Various interactions of grain and ambient air conditions can be analysed by some approximate drying models. These basic models include (Chen and Wu, 2001)

- The physical properties of air and water vapour,
- The heat and mass transfer between grain and air,
- The equilibrium state of grain and ambient air, and
- The rates of heat and moisture transfer within the grain.

In many modelling cases, the solution of two or more coupled partial differential equations describing heat and mass transfer are required. Moreover, some algebraic equations used are nonlinear. These complexities make the analytical solution difficult and thus numerical solutions are preferred. According to Bronlund (1997), Bronlund and Davey (2003) and Cleland *et al*. (2003), the most common methods available to solve the models numerically are

- Explicit finite differences schemes,

- Implicit finite difference schemes, and
- Finite elements methods.

Each of these methods has advantages and disadvantages. The easiest method to implement is the explicit finite difference scheme within which the predictions of the dependent variables are made based on known values. This method can lead to numerical instability problems, however, especially if changes in the variables are occurring quickly.

Under that situation, the implicit finite difference method should be used. In this method, the predictions are based not only on known values but also future values of the variable. For that to happen, the series of equations must be solved simultaneously.

The finite element method is especially powerful and useful for solution of problems where the geometry of the system is irregular. It has been successfully used to obtain approximate solutions of complex problems in heat transfer, fluid mechanics and solid mechanics (Jia *et al.*, 2002c). The method involves the division of a continuous domain into a finite number of simple sub-domains, the elements, and the use of variational concepts to approximate any continuous quantity (temperature, MC, displacement) over that domain by collection of simple piecewise continuous functions defined over each element. It is more difficult to implement and most often an existing package is used.

2.6.2 Previous works

Reid and Siebenmorgen (1998) explored the relationships between the grain surface temperature, amount of moisture removed and harvest MC and HRY reduction and developed a model describing the yield reduction as a function of these variables.

In 1991, Laguë and Jenkins developed two finite element models to predict pre-harvest stress-cracking of rice kernels. The rice kernel was approximated as an axisymmetric body and the coupled diffusion of heat and moisture in the grain was calculated. Results show that the modelled kernel went through daily cycles of global day-time (diurnal) drying and night-time (nocturnal) rewetting. The drying phases generated surface shrinkage of the kernel and compressive stresses in the endosperm while rewetting has the opposite effect.

Considering that the paddy grain has the outer husk cover and a bran layer present during drying and storage, Wongwises and Thongprasert (2000) claimed that the heat and mass transfer processes occurring in the grain are different from other cereal grains. Shei and Chen (1999) used a single-term diffusion model in their drying study and reported the model did not appear to be adequate for rice drying at the beginning of the drying period.

Queiroz *et al* (2000) developed a model to simulate the moisture diffusion during the drying process of the grain using finite element analysis. The simulated model could predict the temperature of the air and grain and the moisture movement inside the rough rice kernel.

Abud-Archila *et al*. (2000) constructed a simulation tool capable of predicting the HRY during mechanical drying, so that the design of industrial rice dryers can be improved. Relationships were established between the yield and both MC gradient and kernel temperature.

Izadifar and Mowla (2003) developed a mathematical model to simulate the drying of moist paddy in a cross-flow continuous fluidised bed dryer. The model was based on the differential equations, which were obtained by applying the momentum, mass and energy balances to each elemental part of the dryer and also on the drying properties of the grain.

2.6.3 Thin-layer model

Thin layer in this context refers to the thin thickness of a grain bed within which all the kernels have almost the same exposure to the drying medium. According to ASAE (2003b), ASAE (2004b) and ASAE (2005b), material in a thin layer is exposed fully to an air stream during drying and the depth (thickness) of the layer should be uniform and should not exceed three layers of particles.

Thin layer models describe the drying phenomena in a unified way, regardless of the controlling mechanism. They have been used to estimate drying times of several products such as tea (Temple and Boxtel, 1999), rapeseed (Corrêa *et al*., 1999), apricots (Toğrul and Pehlivan, 2002) and to generate drying curves. In their development, the MC of the material at any time after it has been subjected to a constant RH and temperature conditions is generally measured and correlated to the drying parameters (Toğrul and Pehlivan, 2004).

The validity of a deep-bed model was found to depend on the goodness of fit of the thin-layer drying model as the deep beds of grain have been assumed to be composed of many thin layers. Thus, the thin-layer drying models that help to define the mass and energy transfer mechanisms contribute to simulation of and optimising the design of drying and storage equipment (Noomhorm and Verma, 1986; Wongwises and Thongprasert, 2000; Chen and Wu, 2001; Iguaz *et al*., 2003).

Several thin layer models are available in the literature and vary widely in nature. In their study, Shei and Chen (1999) and Chen and Wu (2001) selected four empirical thin-layer drying models, namely the exponential equation (Equation 2.11), the Page equation (Equation 2.12), the Wang and Singh equation (Equation 2.13), and the two-compartment equation (Equation 2.14) to fit with the MC of their paddy grain samples:

$$MR = \frac{MC - MC_e}{MC_i - MC_e} = e^{-k.t} \quad \ldots (2.11)$$

Where the *MCs* are expressed in decimal, dry basis.

$$MR = e^{-k.t^n} \quad \ldots (2.12)$$

$$MR = 1 + E.\,t + F.\,t^2 \quad \ldots (2.13)$$

$$MR = E\,.\,exp\,[-F\,.\,t] + G.\,exp\,[-M.\,t] \quad \ldots (2.14)$$

When drying paddy at temperatures from 35–60°C with RH from 10 to 50%, Chen and Wu (2001) concluded that the two-compartment model (Equation 2.14) with two-term exponential function was the best model to fit the experimental data and was recommended as the thin-layer drying model for paddy rice. Similarly, Sharma *et al*. (1982) concluded that the grain drying could be described by a single equation similar to the above rather than the full model.

2.7 CAMBODIAN RICE VARIETIES AND CLIMATE

2.7.1 Rice varieties

Rice is the staple food for Cambodia. The grain provides about 60 to 70% of daily calories in the diet of the average rural household and absorbing about 30% of household expenditure. It is mainly produced in the wet season (May to December). Because of its long history of cultivation and selection under diverse environments, the crop has acquired a broad range of adaptability and tolerance so that it can be grown in a wide range of water/soil regimens from deeply flooded land to dry hilly slopes.

The medium and late maturing varieties account for about three-quarters of the total area planted. Floating rice and upland rice represent approximately 4 and 2%, respectively, of the planted area and are diminishing and being replaced by plantings on receding water tables. These proportions can vary from year to year depending on prevailing rainfall patterns. Because the dry season yield is about double that of the wet season, dry season production has increased to around 11% of the total area harvested (FAO and WFP, 1997).

Rice varieties in Cambodia are classified broadly as traditional and modern. Most of the farmers grow the traditional varieties that, unlike modern high-yielding-varieties (HYVs), are photosensitive (respond to a short photoperiod, e.g. daylength longer or shorter than a critical period for flowering) and can succeed on poor land with few modern inputs. These varieties usually bring higher prices than the HYVs, because of their higher quality and preference by local consumers.

Within the two groups of rice, different varieties have different physical and chemical characteristics. Some of the varieties

- Have short and medium type kernels, which are more rounded and thicker than the other long ones. Goodman and Rao (1985) found that long grain types gave significantly lower HRY than either medium or short grain types. They discussed that since milling involves the abrading of kernels against kernels, it is likely that the longer or thinner kernels would tend to break more easily than shorter or fatter kernels,
- Are earlier maturing so that harvest can take place before the other late varieties,
- Fill uniformly so as to have higher grain density and less chalkiness, and
- Are softer or more palatable than others etc.

2.7.2 Climate

There are two main seasons in Cambodia: Wet or rainy and dry. The following climate information reported by Nesbitt (1997) can be very important for consideration when handling the rice crop after harvest:

2.7.2.1 Rainfall

Most of the rice-growing areas receive rainfall of between 1,250 and 1,750 mm annually and mostly in the wet season. The long-term distribution pattern measured in the country's capital city is presented in Figure 2.20.

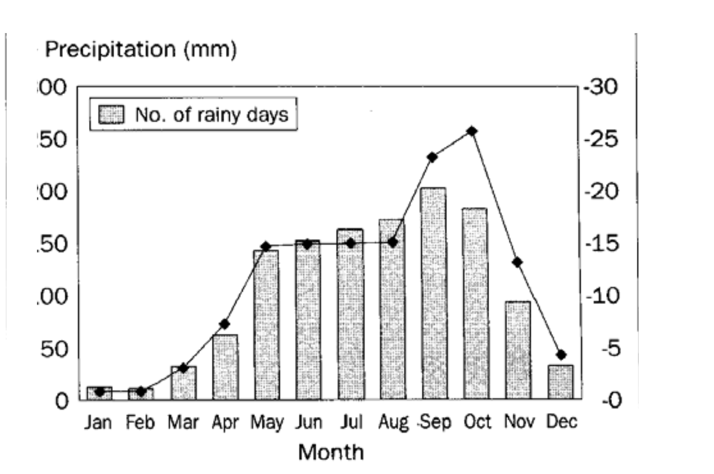


Fig 2.20: Monthly rainfall and number of rainy days in Phnom Penh, Cambodia
(Source: Nesbitt, 1997)

The dry season which usually lasts for five months (From the middle of November to April of the following year) allows rice crops to be conveniently harvested, processed and dried under the sun.

2.7.2.2 Temperature

As can be seen in Fig 2.21, during the dry season, the ambient air temperature can reach 36°C. It usually cools off by approximately 10°C in the evening but remains warm and humid. The temperatures are coolest in October through to January.

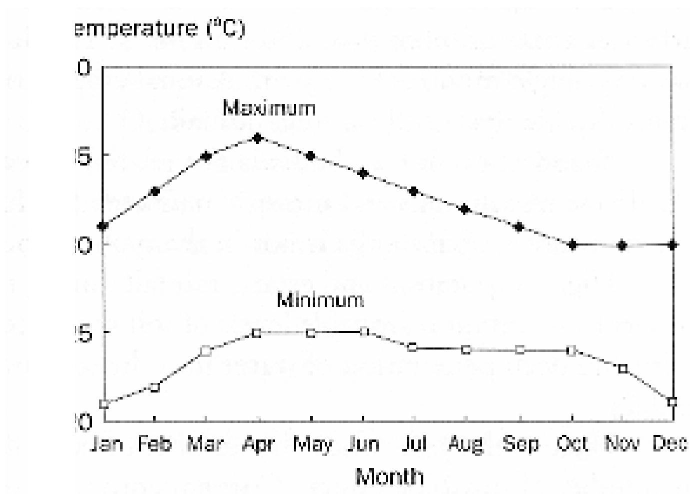


Fig 2.21: Monthly maximum and minimum temperatures in Phnom Penh, Cambodia
(Source: Nesbitt, 1997)

2.7.2.3 Humidity

The RH in Cambodia fluctuates between 60 and 80% throughout the year (Fig 2.22). Although the maximum daily humidity recordings remain reasonably constant, the difference between these and minimum humidity levels decreases considerably when rainfall is at its peak in September and October.

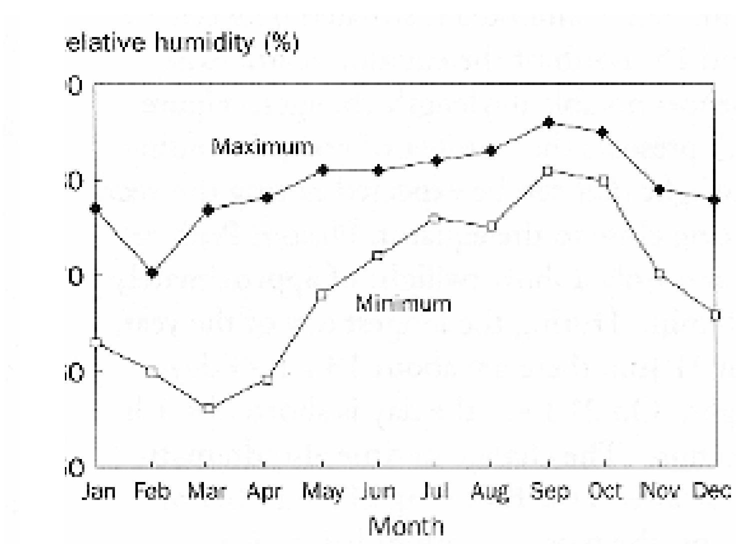


Fig 2.22: Relative humidity of the ambient air in Phnom Penh, Cambodia
(Source: Nesbitt, 1997)

2.7.2.4 Daylength

Although Cambodia is situated close to the Equator (between 10 and 15° north), it still experiences remarkable daylength changes. Fig 2.23 presents the number of hours including twilight that can be expected during the year. The longest days of the year of approximately 13 hours happen around June and July.

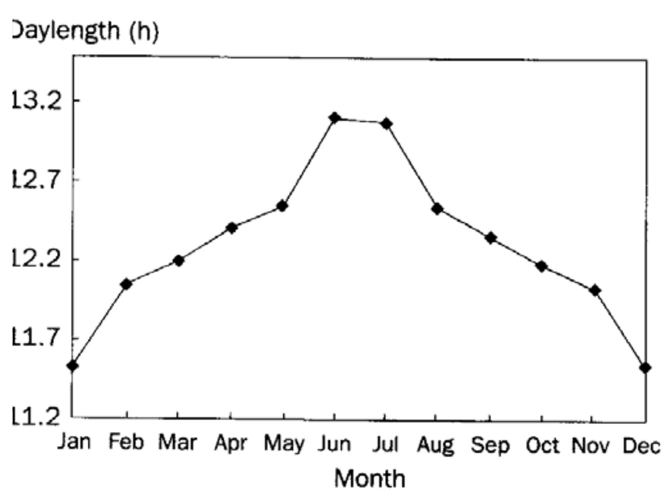


Fig 2.23: Monthly daylength means in Phnom Penh, Cambodia
(Source: Nesbitt, 1997)

2.7.2.5 Sunshine hours

Fig 2.24 shows the sunshine hours measured over an 11-year period (from 1984 to 1995). They were highest from December through to February when most of the days were sunny. The sunshine hours decreased as the cloud cover increased in the wet season.

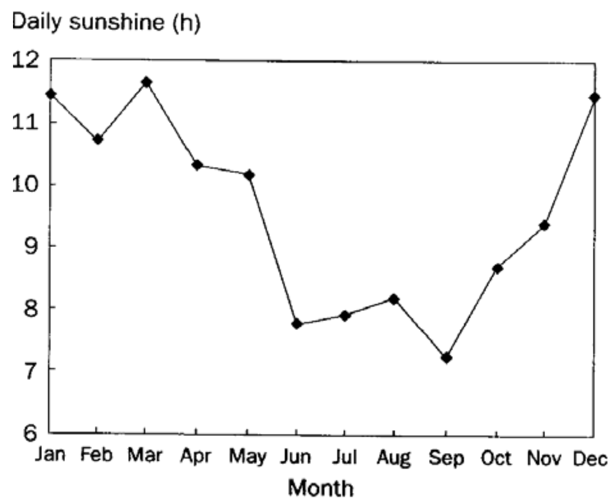


Fig 2.24: Monthly means of daily sunshine hours in Phnom Penh, Cambodia
(Source: Nesbitt, 1997)

2.8 SUMMARY

Rice is different from most other cereal grain as it has an outer husk during harvesting, drying and storage. Rice and oats are the only two cereals with compound starch granules with little or no matrix protein in the endosperm. Most stress cracks are propagated along the edges of the starch granules and tear some starch granules, dividing them into two parts It is hygroscopic in structure and hence reacts with any environment with which it is not in equilibrium. A dry grain surface adsorbs moisture in a humid environment while a wet surface desorbs moisture in a relatively dry environment.

Since rice is consumed mostly in the form of whole grains, increasing the HRY is a universal goal. It is difficult to ascribe the reduction in yield to a single cause. The yield can be affected by the conditions in the field before the grain is harvested and the way the grain is handled after harvest. It is generally believed that the yield is strongly related to internal cracking or fissuring and is especially sensitive to the mode of drying. Drying is usually done to lower the grain MC to a safe level for storage.

Apart from the grain variety and initial MC; temperature, changes of MC, MC difference within the grain kernel and rewetting the grain have been reported to have strong effects on the internal stresses and on the grain quality. Various tempering methods have been performed to dry the grain faster but to still maintain its quality.

Sun drying of the grain is still the most common practice in Asia and other tropical and subtropical countries. It is a complicated and much less controlled process involving the transformation and transfer of heat and moisture influenced by climatic and operator factors. In the system, solar radiation is converted to thermal energy. It involves the transfer of moisture from the centre of each grain kernel to the surface of the grain kernel and from the inside of the bed to the surface of the bed and subsequent evaporation of the moisture.

In the drying system, the moisture-removing capacity of the air can be enough to cause serious damage to the grain. The grain temperature can exceed 50°C. Continuous drying under the sun allows for drying in a short period but causes higher breakage than when the drying is slowed down by tempering between drying steps. Tempering methods in the system can be done by covering or shading the grain bed during the hot times of the day (around midday) and stirring the bed regularly.

Mathematical models have been identified as powerful and useful tools for describing or predicting the MC and temperature distributions inside the grain kernels, within the drying bed and optimising the drying and tempering processes. They have been developed based on the physical and thermal properties of air, water vapour and the grain; the heat and mass transfer between grain and air; the equilibrium state of the grain and ambient air; and the rates of heat and moisture transfer within the grain. The most common methods available to solve the models numerically are explicit finite differences schemes, implicit finite difference schemes, and finite element methods.

Based on all this information, efforts were made in this study to identify the sun drying methods that should be used to dry the grain as fast as possible but to still maintain its quality.

Chapter 3

MATERIALS AND METHODS

3.1 INTRODUCTION

A number of sun drying experiments were conducted in November and December 2003 and 2004 in Cambodia, using four local rice varieties. They were aimed at understanding the conditions of rice grain experienced with sun drying systems and identifying the mechanisms that can influence the dried grain quality. The traditional methods that have been practiced regularly by Cambodian farmers were applied in the experiments with some deliberate modifications, such as tempering the grain during the hottest time of the day. The main purpose of conducting the drying experiments and quality tests in 2003 was to gather experience to help with the design, preparation and application for experiments in 2004.

3.2 OBJECTIVES

The specific objectives of all the experiments and tests were to

1. Monitor the changes of
    a. The ambient air conditions such as the solar intensity, temperature and relative humidity (RH), and
    b. The grain and air conditions within the drying bed such as the temperature, moisture content (MC) and RH during drying;
2. Investigate the effects of the grain varieties and drying methods on
    a. The grain conditions,
    b. The drying time, and
    c. The dried grain quality;
3. Assess the accuracy of different methods for determination of the grain MC,
4. Measure the T_g of the four rice varieties that were used in the experiments, and
5. Generate a state or phase diagram for mapping the conditions of the grain during the drying process so that the effects of the grain state conditions during drying on the drying performance and the dried grain quality could be explained.

3.3 MATERIALS AND METHODS

3.3.1 Grain sample preparation

3.3.1.1 The rice varieties

Rice samples of four varieties (Phka Knhey, CAR11, Masary and IR66), grown on farms in Kandal Stung District, Kandal Province of Cambodia by rice seed growers contracted with an Australian Project named "Agriculture Quality Improvement Project" (AQIP), were targeted to make sure that the samples were of pure varieties. All the varieties (Fig 3.1) are for rainfed lowland conditions with some differences described in Table 3.1.

Fig 3.1: The rice grain of four varieties used

Table 3.1: Characteristics of the rice grain used in the experiments

Description	Pka Knhey	CAR11	Masary	IR66
Photoperiod[a]	Sensitive	Sensitive	Not sensitive	Not sensitive
Maturity[a]	Nov. 5 – 11 (flowering date)	Nov. 5 – 11 (flowering date)	110 – 120 days after planting	105 – 115 days after planting
Yield[a], t/ha	2 – 3.5	2.5 – 4.5	3 - 5	4 – 6.5
Kernel length[b] mm	6.85 ± 0.25	7.87 ± 0.25	5.51 ± 0.30	6.57 ± 0.26
Kernel width[b], mm	1.98 ± 0.07	2.25 ± 0.12	2.17 ± 0.10	1.97 ± 0.16
Kernel thickness[b], mm	1.64 ± 0.06	1.93 ± 0.07	1.56 ± 0.07	1.65 ± 0.10
Shape[c]	Slender	Slender	Medium	Slender
Amylose content[d], %	24.8	25.3	29.2	29.6
Gel consistency[a], mm	Not available	98	Not available	72.0
Gelatinisation temperature[d], °C	76.7	66.7	77.3	77.3
Aroma[a]	Scented / Soft texture	None	None	None

<u>Notes:</u> [a] *VRCC (1999)*
[b] *Brown rice measured by digital calliper (0.01- 150 mm, Mitutoyo, DIGMATIC, Japan) at room temperature*
[c] *Classified according to Rickman (2001)*
[d] *Measured in Queensland, Australia by Melisa Fitzgerald in February, 2004.*

Some knowledge of how different rice varieties perform is in Section 2.7.1. Moreover, grain with bigger kernels would normally have higher porosity in the bed and grain with darker colours would absorb more heat that is radiated by the sun.

3.3.1.2 Harvesting and handling

The crop was manually harvested when its MC was around 22% (ranged from 18 to 26%). To maintain the MC and to minimise mechanical damage to the grain, the cut sheaves or bundles were immediately transported into shade. The grain was then removed from the bundles by trampling as shown in Fig 3.2. The threshed grain was cleaned by winnowing to remove the light materials such as broken stems, chaff and unfilled grains before it was subjected to a moisture equilibration process.

Fig 3.2: Trampling to remove the grain

3.3.1.3 Establishment of initial moisture content

Since the freshly harvested grain of the four varieties was not at the same MC level as required for the designed drying experiments (22%), it was immediately subjected to re-wetting and slow-drying procedures. Some water was added by spraying to raise the MC of IR66 grain from about 18 to about 22%.

This rewetting method has been used to rewet grain samples by many previous workers (Siebenmorgen and Jindal, 1986 and Fan *et al*., 2000b) and was believed not to cause significant crack damage to the grain since the initial MC was a lot higher than the critical MC of around 16%.

On the other hand, the grains of the other three varieties were spread in a thin layer under a shed for about 5 hours to reduce the harvest MC of about 23 to about 22%.

Morita and Singh, (1979) claimed that slow drying using the ambient air would not reduce the grain quality. They dried rice samples using a mechanical dryer at room temperature for about a half to two days to obtain the samples with desired MCs.

After shaking and mixing thoroughly, the grain samples were sealed in double-layer IRRI super bags (made of special plastic for completely airtight storage), placed in a 50kg polypropylene bag and left in a 5^{o}C cold store for at least 12 days. The bags were turned and shaken periodically to establish uniform moisture distribution within the grain kernels and throughout the grain mass. Morita and Singh (1979) and Steffe and Singh (1980) also placed their rice samples of 25 and 31% MC in a plastic bag and held them at 5^{o}C until needed.

The required amount of rough rice was removed from the cold storage one day prior to each of the drying experiments and kept sealed overnight in the bags at room temperature. This step was done to bring the samples into thermal equilibrium with the room temperature and prevent any condensation on the rough rice when it is placed for drying (Steffe and Singh, 1980; Jindal and Siebenmorgen, 1987; Wongwises and Thongprasert, 2000; Chen and Wu, 2001; Sun *et al*., 2002; Shei and Chen, 2002).

3.3.2 Experimental designs and measurements

Altogether there were seven drying experiments conducted in this study. Four of them were conducted in 2003 (coded with 03 at the end) and another three (coded with 04) conducted in 2004.

3.3.2.1 Experiment One/03 - Effect of the bed depth

This experiment was designed as a Complete-Randomized-Design and was conducted from December 2-5, 2003 with three replications using the CAR11 variety. On those days, the sun rose at about 6 am and set at about 5:30 pm and the sky was clear. For each treatment, a grain sample of about 22% initial MC of 5 kg was spread on a tarpaulin and exposed to the sun in 2, 4 or 6 cm layers (labelled as D1, D2 or D3, respectively, Fig 3.3).

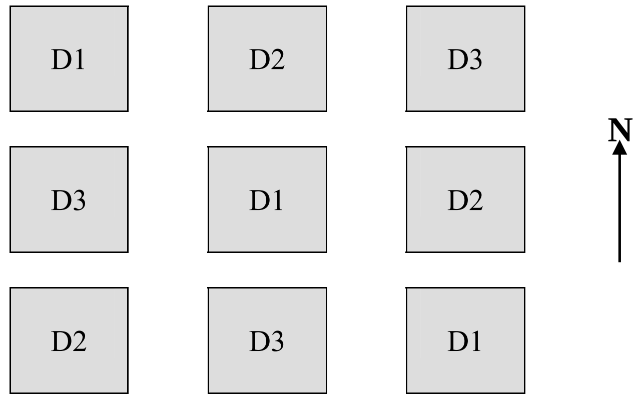


Fig 3.3: Arrangement of the grain samples for drying in Experiment One/03

The drying of all the samples was started at the same time, about 8 am, and continued until 5 pm or until the samples reached the targeted MC of about 14%. No stirring was applied to the samples. The grain MCs were measured on side every one hour by a moisture meter (Wile 55 digital, which uses capacitive measurement principle that uses a high frequency electric circuit and a compressed sample). The meter was pre-calibrated against the oven method (for 24 h at 130^{o}C) in accordance with ASAE (1983). The same method has been used previously by many workers such as Jindal and Siebenmorgen (1987), Sarwa and Kunze (1989), Perdon (1999), Perdon *et al*. (2000), Manski *et al*. (2002), Sun *et al*. (2002), Cnossen *et al*. (2003).

Some of the samples that did not reach the targeted MC within one day were gathered, sealed in a double layered plastic bags overnight and were subjected to further drying on the next day. When the target MC was detected, the drying of the sample was terminated and the dried grain was immediately gathered, sealed and stored at ambient conditions until undergoing qualitative testing.

During the drying runs, the grain MC, temperature at the bed surface and the wind speed were measured at hourly intervals using the moisture meter, a non-contact (infrared) thermometer (DIGICON, DP-88) and a wind speed indicator (Turbo Meter, Davis Instruments, USA), respectively. The temperatures of the ambient air, the air immediately above the bed surface, at three layers within the bed (designated as bottom, middle and top) and the drying floor were detected by electronic sensors called I-buttons (DS1994L, Maxim/Dallas, California, USA). The buttons were set to record the temperatures every 5 min. At the same interval, the RH of the air in the three layers was detected using Tinytag and Tinytalk data loggers (Gemini data Logger, UK, Ltd), while the RH of the ambient air and the air immediately above the bed were detected using a Hobo H6 data logger (Onset Computer Corporation, USA). The placements of all the sensors or data loggers are illustrated in Fig 3.4 and Fig 3.5. Except for the tinyTag/Tinytalk, the sensors were removed from the bed immediately before stirring and placed back immediately after stirring.

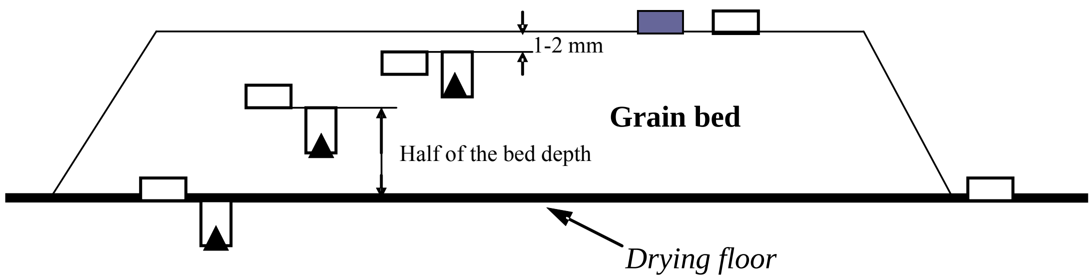


Fig 3.4: Positions of the electronic sensors

Note: TinyTag/ Tinytalk Hobo I-button

Fig 3.5: Positions of the TinyTag/ Tinytalk relative humidity sensors

The solar intensity (the incident energy per unit area of a surface) could not be measured at the site of the experiment. The only solarimeter or pyanometer (MS 601) that was available in Cambodia at that time was positioned in a weather station about 230 km away.

3.3.2.2 Experiment Two/03 - Effect of tempering

This experiment was also a Complete Randomized Design. It was conducted at the same time as Experiment One/03 using the grain samples of the same variety (CAR11). For each treatment, a grain sample of the same initial MC of 5 kg was spread on a tarpaulin, 4 cm in depth, and exposed to the sun from about 8 am to 5 pm until reaching the targeted MC with one of the following three tempering treatments:

1. No stirring and no covering (T1),
2. Stirring every an hour (T2), and
3. Stirring every hour plus covering from 12 to 2 pm (T3).

The arrangement of the treatments is shown in Fig 3.6.

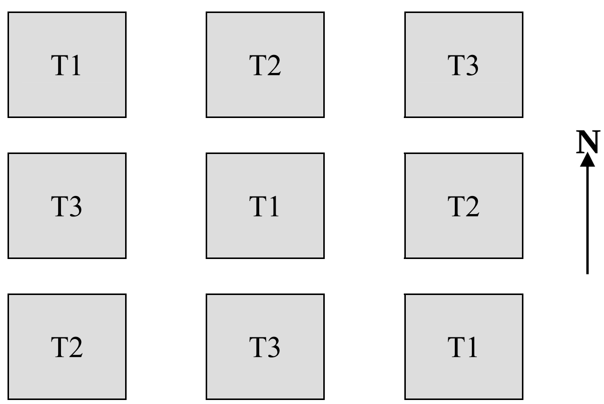


Fig 3.6: Arrangement of the grain samples for drying in Experiment Two/03

The same procedures as applied in Experiment One/03 were also applied in this experiment to measure the wind speed, MC, temperatures and RH as well as to handle and test the quality of the dried samples.

3.3.2.3 Experiment Three/03 - Effect of tempering, variety and drying day

This experiment aimed to verify the effects of the stirring and covering methods, as found in Experiment Two/03, on the rice grains of different varieties and also to determine the effects of different drying days. This experiment, which was designed as a Randomized Complete Block with three replications, was conducted on December 12 to 15, 2003 using the four rice varieties. Different starting days were assigned as the blocks within which treatments were tested using replications (see Fig 3.7).

Day One		**Day Two**		**Day Three**	
V4T3	V2T2	V1T2	V4T1	V2T3	V3T1
V4T1	V3T3	V4T3	V4T2	V4T2	V2T2
V2T3	V2T2	V1T1	V1T2	V3T1	V3T2
V3T2	V2T1	V2T1	V3T3	V3T3	V3T3
V3T2	V4T2	V1T3	V3T1	V2T1	V4T2
V2T2	V3T1	V2T2	V2T3	V4T3	V4T1
V3T1	V3T3	V3T2	V1T2	V4T2	V3T2

Fig 3.7: Arrangement of the grain samples for drying in Experiment Three/03

Note: V1, V2, V3 and V4 are Pka Knhey, CAR11, Masary and IR66 rice varieties, respectively. T1, T2 and T3 have already been described in Experiment One/03.

The 5 kg samples were spread to dry on the tarpaulin with a 3-cm depth. All the monitoring, handling and testing procedures, as applied in the previous two experiments, were used.

3.3.2.4 Experiment Four/03 - Effect of the solar intensity and ambient air

The objectives of this experiment were to measure solar intensity and ambient air temperature and determine their effects on the temperature and humidity within the drying bed. This experiment was conducted at a weather station in Sihaknouk Ville, a Cambodian town located by the sea, about 230 km southwest of the country's capital city, where a solarimeter (MS 601) was available. Grain from the four varieties was used.

Each grain sample of 5 kg was spread 3 cm in depth on a concrete pad, and exposed to the sun for two days (December 20 and 21, 2003) from about 9 am to 5 pm with no stirring and no covering. Overnight, the samples were gathered and handled in the same way as the previous experiments.

The temperature and RH of the ambient air and of the three layers within the gain beds were monitored at 5-min intervals using the same sensors and probes. Due to the thin depth of the drying bed and the impossibility of digging into the drying floor, the tinytag/talks sensors were placed horizontally in the grain bed.

3.3.2.5 Experiment One/04 - MC determination methods

The aim of this experiment was to assess the accuracy of two different MC measurement methods, namely a nylon-bag and direct sampling, for determination of the grain MC. The methods are described in the 2nd paragraph below. In this experiment, which was designed as a Completely Randomized Design, two stirring methods (none and stirring every an hour) were applied to samples of CAR11 during drying. There were two replicates. The fresh samples were spread to dry on open ground at a site in Kandal Province on a tarpaulin with a 2cm depth and exposed to the sun from around 8 am to 4 pm on December 10 and 11, 2004.

To avoid disturbing the grain bed with all the installed probes, the change in the grain MC was measured for one replication while the change in the temperature and RH of the air within the bed was monitored in the other. The initial grain MC was measured using the same moisture meter.

The actual MC of the grain dried in Replicate 1 was determined at one hour intervals. In the first MC measurement method, about 10g of rice grain was placed in a small bag made of nylon net. The bags were placed horizontally at three heights in the bed (top, middle and bottom) (see Fig 3.8). Every hour, the bags were withdrawn for weighing, and the actual grain MC for every layer and the whole bed was determined, based on the grain initial MC and the weight reduction of the samples in the bags. Two types of nylon net were used as it was observed that the first one could not prevent the grain kernels from leakage by piercing through it. In the second MC measurement method, the grain was sampled from each of the designed bed layers or after thorough mixing and was subjected to measurement by the moisture meter.

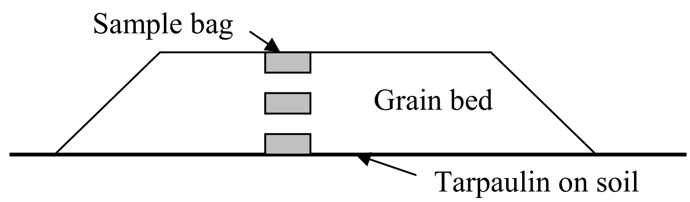


Fig 3.8: Placement of the sample bags in the grain bed for moisture content determination

The temperature and RH of the air in four layers of the drying bed (namely the surface, top, middle and bottom which correspond to about 0, 5, 10 and 15 mm from the surface of the 2-cm bed and about 0, 8, 15 and 23 mm from the surface of the 3-cm bed) were fully monitored at 5-min intervals during the experiment for the two grain samples dried in Replicate 2. U type thermistors (Grant Instruments Ltd, Cambridge, UK) and Hycal square semi conductor sensors (HIH-3602-A, Honeywell, Canada) were used for the temperature and RH measurements, respectively. Frames or supports were made to hold all the sensors firmly at the pre-designed layers. The outputs were recorded by a Squirrel 1200 series datalogger. The placements of the sensors are illustrated in Fig 3.9 and shown in Fig 3.10.

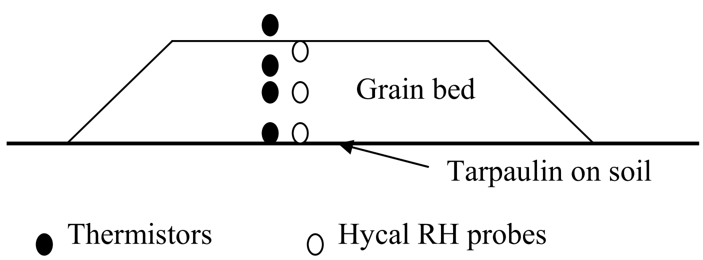


Fig 3.9: Placement of the temperature and humidity sensors in the grain bed

The solar intensity, ambient air temperature and RH were also measured at 5-min intervals by a solarimeter or pyranometer (Li-200SB), an I-button and a Tinytag RH sensor, respectively. The I-buttons and Tinytag sensors were used to verify the temperature and RH data measured by the thermisters and Hycal sensors. The sensor of the solarimeter was exposed horizontally to the sun. The meter was calibrated by comparing its measured data with a set of data measured by three other calibrated meters operated by the Met Service Calibration Laboratory in Paraparaumu, New Zealand.

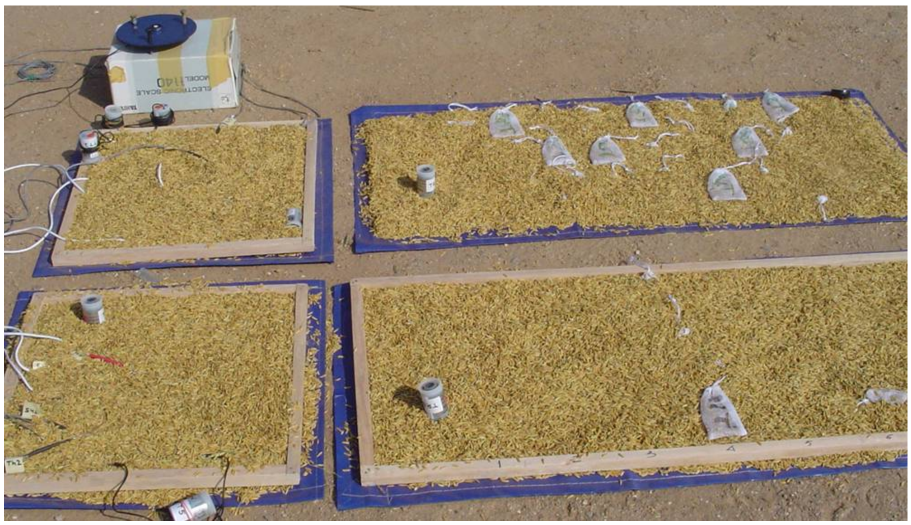


Fig 3.10: Placements of the sensors and the bags in Experiment One/04

In addition, the temperature of the grain at the surface of the bed, the temperature of the drying pads and the wind speed were measured and recorded every one hour using the non-contact thermometer and the wind speed indicator.

Drying was stopped when the grain reached 14% MC. The dried grain samples were then sealed in two-layer plastic bags and stored at ambient conditions until they were subjected to quality tests.

3.3.2.6 Experiment Two/04 - Effect of bed depth and tempering

This experiment was designed as a full factorial experiment. The variables were bed depth, stirring method and covering methods as the main factors. It was conducted at the same location on December 11 and 12, 2004. Both days were clear and sunny. Samples of CAR11 variety were dried with two levels of bed depth (2 and 3 cm), two levels of stirring method (none and every an hour) and four methods of covering (none, direct covering (using a tarpaulin), shading (using a tarpaulin spread about 1.5 m above the bed) and covering combined with shading from 11 am to 2 pm). In addition, two samples (2 varieties) were dried with about 3 mm bed depth under shade with stirring 3 to 4 times per day as control samples. This method of drying has been reported to give the best grain quality. It uses, however, quite a lot of space for only a small amount of grain. The combinations of all the applied treatments are listed in Table 3.2.

The drying was undertaken from 8 am to 4 pm. Each drying sample was spread as a bed on a tarpaulin that was spread on a polystyrene slab of 4 cm thick (see Fig 3.11). This combination of the drying pad was used to eliminate the heat and moisture transfer between the drying grain and the ground and to facilitate the regular (once for every one hour) weighing during the drying to determine the MC reduction. The weight reduction and the initial MC that was measured before drying by the moisture meter were used to calculate the average bed MC during the drying.

Table 3.2: The applied treatments for Experiment Two/04

Sample #	Depth, cm	Stirring	Covering
1	2	No stirring	None
2	2	No stirring	Direct covering
3	2	No stirring	Shading
4	2	No stirring	Shading and covering
5	2	Stirring	None
6	2	Stirring	Direct covering
7	2	Stirring	Shading
8	2	Stirring	Shading and covering
9	3	No stirring	None
10	3	No stirring	Direct covering
11	3	No stirring	Shading
12	3	No stirring	Shading and covering
13	3	Stirring	None
14	3	Stirring	Direct covering
15	3	Stirring	Shading
16	3	Stirring	Shading and covering
Control	0.3	Stirring	Under shade all the time

Fig 3.11: The samples being dried in Experiment Two/04
Note: This was set for photo taking only. The actual drying was done on soil.

Stirring was not applied to the grains that were placed under cover or shade. Due to a limitation on the number of sensors, only the temperature and RH of the grain and air in two drying samples were extensively monitored. The drying was stopped for any of the samples that reached a MC of about 14%. The same monitoring and drying procedures, as well as the quality tests and statistical analysis as applied in Experiment One/04, were applied to these dried samples.

Based on the observations made in this experiment, only two tempering methods (namely none and covering combined with shading from 11 am to 2 pm) were selected to be applied in the next experiment. They were observed to provide the most extreme effects on the drying time or the drying rate and perhaps on the dried grain quality.

3.3.2.7 Experiment Three/04 - Effect of drying pad, variety, bed depth, tempering and drying day

This experiment was designed as a full factorial with four main factors. Rice samples of two varieties (Pka Knhey and CAR11) were dried on four drying pads assigned as blocks (tarpaulin, nylon net, nylon net on husk layer and mat) with two bed depths (2 and 3 cm), stirred by two stirring methods (none and stirring every an hour) and covered by two covering methods (none and covering combined with shading) around noon time. The experiment was conducted from December 18 to 25, 2004.

Based on the number and levels of the design factors, there were all together 64 samples that needed to be dried in this experiment. Due to the limitation of the research materials and the monitoring capability, only 16 samples were selected to dry at one time. This introduced another factor into the design, called drying day. The days were then designated as a co-variate and were randomly selected. The grain and air temperature and air RH in and above the bed were intensively monitored in only two of the samples in each set of 16. All the combinations of the applied treatments that were started to dry on the different days are listed in Table 3.3.

Table 3.3: The applied treatments for Experiment Three/04

No	Sample number	Pad	Variety	Depth, *cm*	Stirring	Covering
Starting Day One						
1	1	Tarpaulin	Pka Knhey	2	No stirring	Covering and shading
2	4	Tarpaulin	CAR11	3	No stirring	Covering and shading
3	9	Tarpaulin	Pka Knhey	2	No stirring	None
4	12	Tarpaulin	CAR11	3	No stirring	None
5	18	Net on soil	CAR11	2	No stirring	Covering and shading
6	22	Net on soil	CAR11	2	Stirring	Covering and shading
7	25	Net on soil	Pka Knhey	2	No stirring	None
8	32	Net on soil	CAR11	3	Stirring	None
9	34	Net on husk	CAR11	2	No stirring	Covering and shading
10	38	Net on husk	CAR11	2	Stirring	Covering and shading
11	40	Net on husk	CAR11	3	Stirring	Covering and shading
12	47	Net on husk	Pka Knhey	3	Stirring	None
13	51	Mat	Pka Knhey	3	No stirring	Covering and shading
14	53	Mat	Pka Knhey	2	Stirring	Covering and shading
15	56	Mat	CAR11	3	Stirring	Covering and shading
16	64	Mat	CAR11	3	Stirring	None
Starting Day Two						
17	5	Tarpaulin	Pka Knhey	2	Stirring	Covering and shading
18	7	Tarpaulin	Pka Knhey	3	Stirring	Covering and shading
19	11	Tarpaulin	Pka Knhey	3	No stirring	None
20	15	Tarpaulin	Pka Knhey	3	Stirring	None
21	17	Net on soil	Pka Knhey	2	No stirring	Covering and shading
22	23	Net on soil	Pka Knhey	3	Stirring	Covering and shading
23	27	Net on soil	Pka Knhey	3	No stirring	None
24	30	Net on soil	CAR11	2	Stirring	None
25	37	Net on husk	Pka Knhey	2	Stirring	Covering and shading
26	42	Net on husk	CAR11	2	No stirring	None
27	43	Net on husk	Pka Knhey	3	No stirring	None
28	48	Net on husk	CAR11	3	Stirring	None
29	50	Mat	CAR11	2	No stirring	Covering and shading
30	52	Mat	CAR11	3	No stirring	Covering and shading
31	60	Mat	CAR11	3	No stirring	None
32	63	Mat	Pka Knhey	3	Stirring	None

Table 3.3: The applied treatments for Experiment Three/04 (Continued)

No	Sample number	Pad	Variety	Depth, *cm*	Stirring	Covering
Starting Day Three						
33	2	Tarpaulin	CAR11	2	No stirring	Covering and shading
34	6	Tarpaulin	CAR11	2	Stirring	Covering and shading
35	14	Tarpaulin	CAR11	2	Stirring	None
36	16	Tarpaulin	CAR11	3	Stirring	None
37	20	Net on soil	CAR11	3	No stirring	Covering and shading
38	24	Net on soil	CAR11	3	Stirring	Covering and shading
39	28	Net on soil	CAR11	3	No stirring	None
40	31	Net on soil	Pka Knhey	3	Stirring	None
41	35	Net on husk	Pka Knhey	3	No stirring	Covering and shading
42	41	Net on husk	Pka Knhey	2	No stirring	None
43	45	Net on husk	Pka Knhey	2	Stirring	None
44	46	Net on husk	CAR11	2	Stirring	None
45	55	Mat	Pka Knhey	3	Stirring	Covering and shading
46	57	Mat	Pka Knhey	2	No stirring	None
47	59	Mat	Pka Knhey	3	No stirring	None
48	61	Mat	Pka Knhey	2	Stirring	None
Starting Day Four						
49	3	Tarpaulin	Pka Knhey	3	No stirring	Covering and shading
50	8	Tarpaulin	CAR11	3	Stirring	Covering and shading
51	10	Tarpaulin	CAR11	2	No stirring	None
52	13	Tarpaulin	Pka Knhey	2	Stirring	None
53	19	Net on soil	Pka Knhey	3	No stirring	Covering and shading
54	21	Net on soil	Pka Knhey	2	Stirring	Covering and shading
55	26	Net on soil	CAR11	2	No stirring	None
56	29	Net on soil	Pka Knhey	2	Stirring	None
57	33	Net on husk	Pka Knhey	2	No stirring	Covering and shading
58	36	Net on husk	CAR11	3	No stirring	Covering and shading
59	39	Net on husk	Pka Knhey	3	Stirring	Covering and shading
60	44	Net on husk	CAR11	3	No stirring	None
61	49	Mat	Pka Knhey	2	No stirring	Covering and shading
62	54	Mat	CAR11	2	Stirring	Covering and shading
63	58	Mat	CAR11	2	No stirring	None
64	62	Mat	CAR11	2	Stirring	None

The nylon net used (Fig 3.12) was of a regular type of net or screen used for protecting food from flies. The net has been recently used widely by the farmers in the Southeast Asian region to dry agricultural products. The husk used was obtained from a local rice mill and was very dry (with the density of about 120 kg/m^3). During drying, it was spread as a layer of about 7 cm. The mat used in the experiment (Fig 3.14) was made of sugar palm leaves. This kind of mat has been used for a very long time by Cambodian farmers.

Fig 3.12: The grain samples being dried on nylon net spread on husk and on the mat spread directly on soil

Monitoring the grain MC was done using the same moisture meter. During the drying, the MC was measured as the average and in three layers (bottom, middle and top) of the drying bed. All the other monitoring, drying, testing and analysing procedures were the same as the ones applied in Experiment One/04 and Two/04.

3.3.3 Grain quality analysis

3.3.3.1 Three-point bending test

About 5 months after drying, the dried samples were taken out of the 4^{o}C store and left open in a room with ambient air for 3 days to equilibrate their temperature and MC to the same level (approx. 13%). Ten kernels were randomly selected from each of the dried samples and were peeled by hand to obtain brown rice for the test. The test was performed based on the following facts, theories and previous findings:

Zhang *et al*. (2003a) stated that mechanical properties of rice kernels are crucial in understanding the fissuring problem. The mechanical properties of rice kernels investigated and reported include the tensile strength (Kunze and Choudbury, 1972; Arora *et al*., 1973), compressive strength (Prasad and Gupta, 1973; Goodman and Rao, 1985) and bending strength (Chattopadhyay *et al*., 1979; Nguyen and Kunze, 1984; Bamrungwong *et al*., 1988; Lu and Siebenmorgen, 1995).

Little information is available regarding the mechanical properties of the fissured rice kernels and the comparison of the mechanical properties between the sound and the fissured rice kernels. Likewise, little information is available on how mechanical properties and physical characteristics of individual kernels are related to the HRY (Lu and Siebenmorgen, 1995).

One of the most used parameters associated with three-point bending tests is peak bending force. Nguyen and Kunze (1984) reported that the average breaking force was greatly correlated to the percentage of fissured kernels. However, the study by Lu and Siebenmorgen (1995) confirmed that the peak bending force would be affected by the dimension of rice kernels.

Compressive strength is not a good indicator, while tensile strength and bending strength are two good indicators of the HRY. However, a tensile test is hard to carry out for rice kernels, since it requires a complicated preparation of the specimen due to the irregular shape of the kernels. In contrast, bending tests are simple and maximum bending force has been proven to hold a good correlation with the yield (Lu and Siebenmorgen, 1995). In this study, bending strength, which is a material-dependent property, was therefore used instead of peak bending force.

Three point bending tests were performed in a rupture mode using a TA.XT2 Texture Analyser (Texture Technologies Corp., Scarsdale, NY) and a cell for holding the grain (Fig 3.13). Each time, the machine crosshead was set to move downward toward the grain at a speed of 0.1 mm/s until the rice kernel broke. That speed, which is the lowest possible for the analyser, was intentionally set to minimise the stored elastic energy remaining when fracture was complete (Nguyen and Kunze, 1984). The rupture test distance was set for 1 mm.

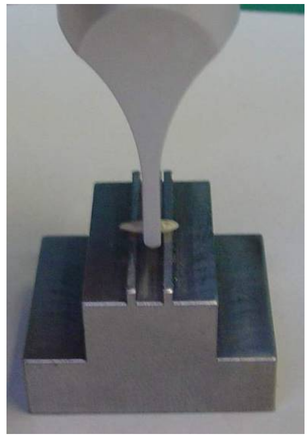


Fig 3.13: Three-point bending cell *(Made by the ITE workshop)*

The beam span of a cell to hold the grain kernel during the test was set at 4 mm, which was the largest possible span for the kernels of the 4 varieties with the longest and shortest lengths of 7.9 and 5.5 mm respectively. Nguyen and Kunze (1984), Lu and Siebenmorgen (1995), Tan *et al*. (2002), Zhang *et al*. (2005) and Yang *et al*. (2005) performed similar tests on grains using the Instron universal machine and the TA.XT2 Texture Analyser. In their tests, Nguyen and Kunze (1984), Zhang *et al*. (2005) and Yang *et al*. (2005) placed each paddy kernel on a cell with a beam span of 4 mm, and the machine crosshead moved toward the grain at a speed of 5, 0.5 and 0.5 mm/min, respectively.

From the bending force-deformation curve that was produced by the machine, the peak bending force was obtained and bending strength (also known as flexural strength) was calculated as

$$\chi = \frac{F_{pbend}.L_b.r}{4\Psi} \qquad \dots (3.1)$$

The cross section area perpendicular to the longitudinal axis of a rice kernel was assumed to be an ellipse and the moment of inertia was calculated as

$$\psi = 0.049.c_{bk}.d_{bk}^3 \qquad \dots \quad (3.2)$$

3.3.3.2 Mechanical impact test

A breakage tester (Fig 3.14) that was designed and constructed by the Crop and Food Research Ltd., based on the principle of Stein breakage tester, was used to determine the breakage susceptibility of dried grain. The tester consists of a cylindrical cup (the test chamber into which a steel impeller fits with a small clearance between the bottom and sides), a small electric motor, a stop-watch system and an electric fan. When testing, the impeller (driven by the electric motor at 1320 rpm) rotates and throws sampled grain against the walls of the test chamber. The stop-watch system cuts the power supply from the tester at the end of a predetermined set time and the fan blows air to cool the motor in order to keep the tester at a constant temperature for a long testing period.

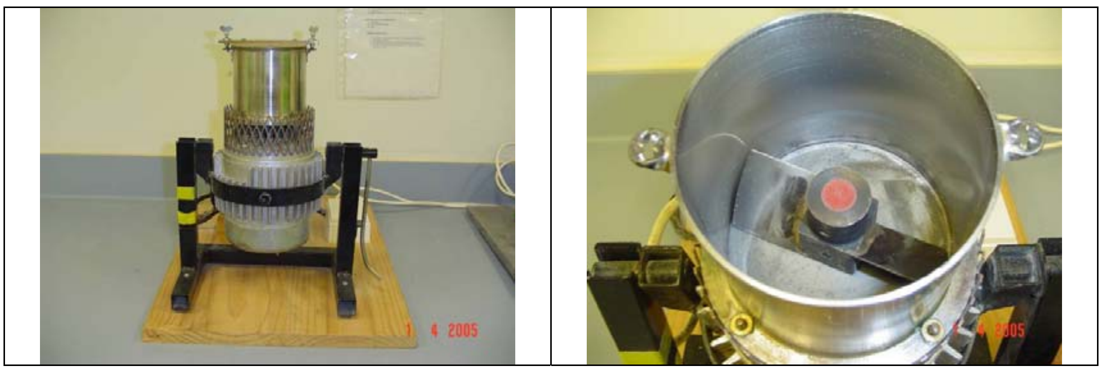


***Fig 3.14: The breakage tester** (Developed by the Crop and Food Research, Ltd.)*

Due to small differences in methods between the Stein breakage test described in the literature (Gunasekaran *et al*. 1985; Fortes and Okos, 1980) and the tests used in this work, this test was designated the mechanical impact test (MI test). Hardacre *et al*. (1997) used the test to measure the susceptibility of maize grain to mechanical damage or breakage, as a result of weakening of the internal structure due to thermal or other stresses.

Prior to the test performed for the 2003 samples, the dried paddy samples were removed from 4^{o}C storage and left for one week in a conditioning room at 18^{o}C and 56.5% RH. Based on the isotherm formulae developed by Teter (1987), the samples were believed to have reached the equilibrium MC of 12%. The MCs were checked by the oven test method (for 24 hours at 130^{o}C). The samples were then de-husked using a hand tool developed by the Crop and Food Research (Fig 3.15) to obtain brown rice and was divided using a grain divider (Model H-3985, Humboldt MFG.Co, Norridge, IL, USA). The divisions were carried out repeatedly until a 20g working sample size was reached.

Fig 3.15: Grain dehusking tool *(developed by the Crop and Food Research, Ltd.)*

The test was carried out with 3 replications. Each time, a 20g sample was placed and impacted in the test cylinder for 1 min and then manually sieved using sieves of 1.4-mm (Retsch, Germany) and 1.68-mm (Endelotts Ltd., London, England) aperture to separate the fine or small particles and broken kernels from large particles and whole kernels.

The breakage susceptibility (BS) was determined as follows

$$BS = \frac{W_{bd} - W_{rem}}{W_{bd}} \times 100 \ \% \qquad \ldots (3.3)$$

Similar methods have been used for testing maize grain by many researchers (Thompson and Foster, 1963; Fortes and Okos, 1980; Miller *et al*., 1981; Hardacre *et al*., 1997; Meas, 1999; Weller *et al*., 1990).

Since it was observed that obtaining the brown rice by the dehusking (grinding) method was problematic for the 2003 samples, brown rice was obtained from the 2004 samples by milling using a small-scale dehusker which is a part of a rice milling machine (the detail of the machine is described in Section 3.3.3.6).

In each dehusking process, that was undertaken for the 2004 samples, a paddy sample of 100 g was put into the dehusker with the same process and adjustments. The resulting brown rice samples were then sealed in double layer plastic bags and left in cold storage at $4^{o}C$ for about 2 months. Three weeks before the MI test, these samples were taken out of the bags and exposed to the same equilibrating process as applied in 2003.

Before the impact test, that was undertaken for the 2004 samples, unhulled paddy kernels were manually removed from the brown rice. Each time, a 50 g sample of the brown rice was placed in the tester cylinder and impacted for 1 minute. The impacted material was then graded using the following three methods:

1. Manual sieving with a 1.7-mm (Endelotts Ltd., London, England) aperture to separate the fine or small particles and broken kernels from large particles
2. Machine grading using an indented cylinder separator (LA-T, Westrup, Slagelge, Denmark). The grading process was carried out with the coarse materials that remained on top of the above sieve. For the CAR11 and Pka Knhey varieties, cylinders with the indentations of 5.5 and 4.50 mm diameters were used with the fine-material collector set at grades 7 and 4.25, respectively and
3. Manual grading to confirm the results of the 2 separation processes. This was done by selecting the rice kernels that were longer than ¾ of the whole kernels from each of the impacted samples.

After the separation or grading processes, the HRY was determined using:

$$HRY_{MI} = \frac{W_{3/4}}{W_{bMI}} \frac{W_{bd}}{W_{pi}} \times 100 \qquad \text{… (3.4)}$$

3.3.3.3 Milling test

After observing that the quality tests performed with the 2003 samples did not represent the quality of the grain samples, a milling test was performed with the 2004 samples, following the principles described by Bhashyam *et al*. (1975), Steffe and Singh (1980), Reid *et al*. (1998), Perdon (1999), Abud-Archila *et al*. (2000), Bautista *et al*. (2000), Zhang *et al*. (2003a), Patindol *et al*. (2003), Wongpornchai *et al*. (2004); and Zhang *et al*. (2005). After a thorough re-clean by a small cleaner as shown in Fig 3.16, two replicate samples were milled about two weeks after the drying experiment. A small milling machine consisting of a rubber-roller husker, a friction whitener and an indented cylinder separator (Fig 3.17) was used. The machine was designed and produced in Thailand and has been used widely by Thai and Cambodian rice millers to test the milling quality of paddy rice.

Fig 3.16: The cleaning machine

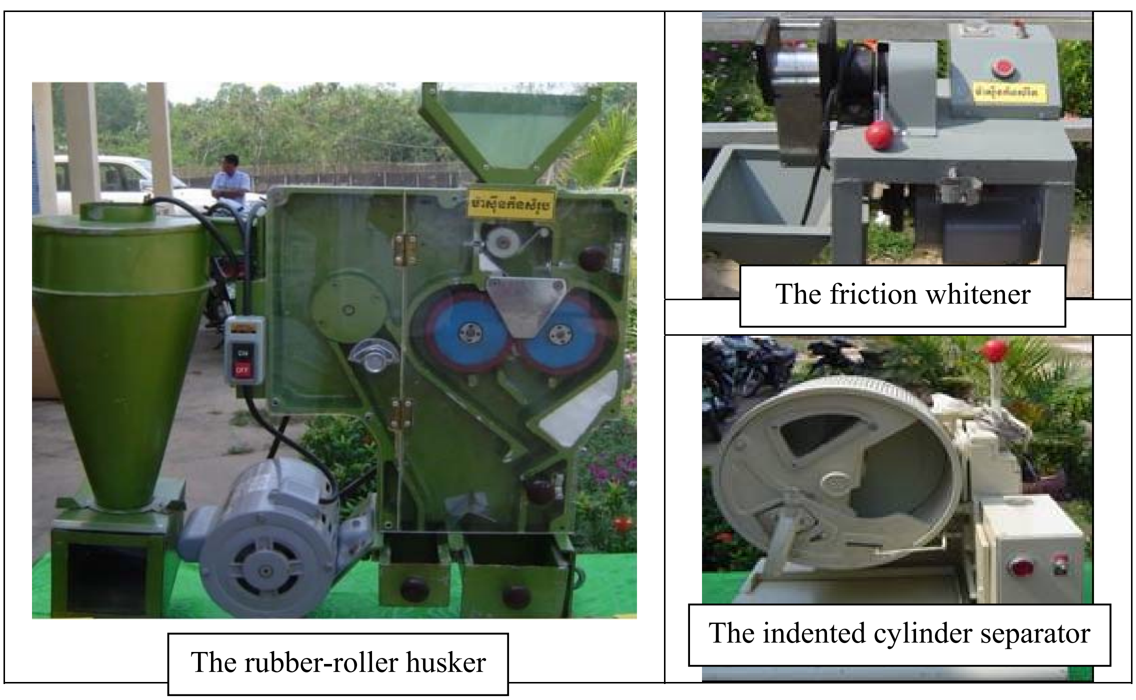


Fig 3.17: The milling machine

For each milling run, the dehusking process was repeated twice to minimise the amount of paddy remaining in the brown rice. To minimise the damage to the bran layer covering the rice and the brown rice kernels, the faces of the two rubber rollers on the husker were set to gently touch when dehusking Pka Knhey and then separated to be 0.3 mm apart from each other for CAR11 samples. The resulting brown rice sample was then weighed before being milled for 35 seconds in the whitener to get an acceptable level of whiteness. The milled rice was later weighed before being graded in the indented cylinder to separate the sound or whole kernels and the kernels that were longer than ¾ of the whole kernels, from the broken ones. Dummy grain samples were used in the test to verify the consistency of the machine performance. It was found that the dehusking and whitening processes were relatively constant.

The results from the test were used to determine the head yield:

$$HRY_{MILL} = \frac{W_{3/4}}{W_{pi}} \times 100 \qquad \text{… (3.5)}$$

3.3.4 Statistical analysis

All the data obtained from 2003 and 2004 experiments were subjected to an analysis of variance using SAS for Windows, v. 8.02 (SAS Institute, Cary, NC) and Minitab (release 14) to detect any significant contribution of the applied treatments on the drying performance and dried grain quality examined. Significantly different means were identified by an ANOVA table and a t-pair-wise comparison test (at a significance level of $\alpha = 0.05$).

3.3.5 Determination of the glass transition temperature

3.3.5.1 Equilibrating the grain to different MC levels

Eight MC levels of about 7, 9, 13, 16, 20, 25, 30 and 35% (wb) were targeted for the rice samples to be used in the tests to determine the glass transition temperature (T_g). Fresh paddy samples of about 16% MC (16.3, 17.1, 17.1, and 15.9% for V1, V2, V3 and V4, respectively) were placed in different storage conditions and/or mixed with calculated amounts of water.

To obtain samples with approx. 7, 9 and 13%, the grain was put in flat plastic plates, spread in a thin layer and exposed to the air in the three cold stores at the Institute of Technology and Engineering (ITE), nominally at 4, 30 and 37^{o}C, respectively (Table 3.4). The grain was shaken and stirred 2 to 3 times daily for 8 days before being put in sealed bottles and placed in the 4^{o}C cold store for another five days.

Table 3.4: Storage conditions and the corresponding MC_e of paddy

Storage	4^{o}C	30^{o}C	37^{o}C
Average Temperature[a], ^{o}C	7.2	31.0	36.9
Average RH[b], %	59.3	40.2	24.6
MC_e of paddy rice[c]	13.1	9.5	7.5
MC_e of paddy rice obtained[d]	13.7	8.7	6.8

Notes: [a] *Measured by the I-button for 28 hours,*
[b] *Measured by Tinytag for 28 hours,*
[c] *Calculated using the Modified-Chung-Pfost Equation*
[d] *Determined by the oven test.*

To obtain further samples with MCs of 20, 25 and 30%, the 16% MC grain was mixed with calculated amounts of water based on equation 3.1.

After thorough mixing, these samples were put in sealed bottles and left in the 4^{o}C store for approximately 8 days. During that period, the bottles were shaken two to three times daily to ensure the MC uniformity within the samples. The targeted higher MCs of 35% could not be achieved due to the existence of free water in the sealed containers.

3.3.5.2 Drop test

The drop tester (model HI – I), that was designed by Kim (2000) to use with maize grain for determining the grain breakage (see Fig 3.18), was modified to suit the rice kernels. Before the test, optimum drop height and weight that produced the most recognisable numbers of broken particles were determined.

Fig 3.18: The drop tester

Before the test, the grain samples with the different moisture levels were placed in sealed bottles and placed in an oven that was preset for 40, 60, 80 or 100^{o}C for about 10 min to obtain the samples with the designed MC and temperature. The base-plates of the tester were also heated at the same time in the oven. Each time, an Aluminium bar of 47 g was dropped from heights of 5 and 10 cm onto a rice kernel that was placed on one of the preheated base-plates and the number of broken particles were counted. Individual kernels were randomly sampled in 10 replications from each grain lot for the test. For the temperatures below these, the test was performed in the ITE storage rooms at 30 and 37^{o}C.

3.3.5.3 The compression test

The compression test was trialled using the combination of a heating unit and the Food Texture Analyser (model TA-XT2, Stable Micro Systems, Godalming, England) (see Fig 3.19) to determine the T_g. Five replications were applied for each of the samples. In each test, one of the MC-equilibrated brown rice kernels was placed in a hole 8-mm diameter and 5mm deep in a copper block that was programmed to be heated by the unit from about 10 to 100^{o}C at the rate of 5^{o}C/min. Heat Transfer Compound (HTC10S, Berkshire, England), was applied slightly at the bottom of the block. After the hole was filled with Aluminum dioxide (AlO_2) powder (to prevent moisture evaporation from the kernel), an 8-mm diameter probe was lowered and 5 Newtons force was applied to hold the powder with the grain kernel firmly.

Fig 3.19: The combination of a heating unit and the Food Texture Analyzer

For each test run, a relationship between the test time and the displacement of the probe was plotted by the analyser (Fig 3.20). The temperature of the block (and of the grain kernel) could be specified on the plot at any moment by reading the display of the unit or based on the temperature at the start and the heating rate. For instance, as the initial temperature was 14^{o}C, the heating rate was 4^{o}C/min, the first and second transitions took place at about 8 and 11 min which correspond to 54 and 60^{o}C, respectively.

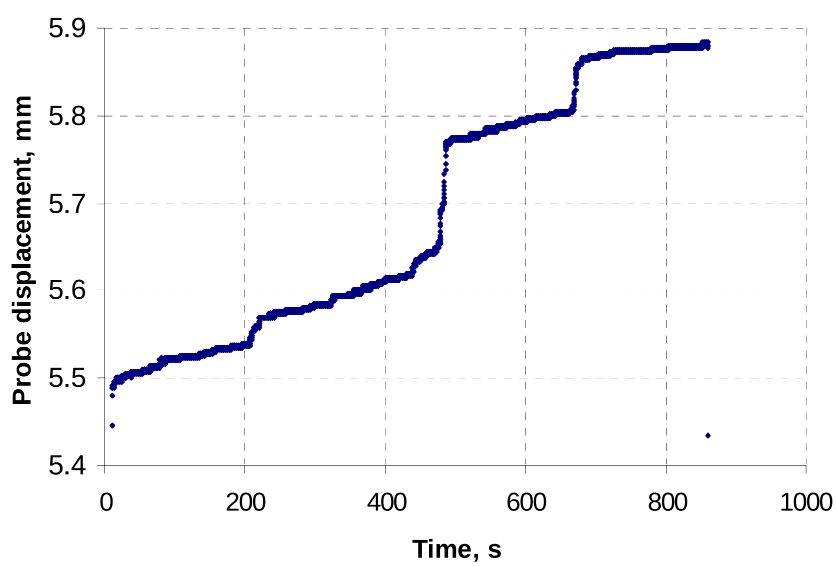


Fig 3.20: A typical plot produced by the combined system during a test

3.3.5.4 Differential Scanning Calorimetry (DSC)

Triplicate DSC tests were performed with the grain samples. A cooler connected to the DSC (shown in Fig 3.21) was set to -45^{o}C. Nitrogen was blown through the DSC chamber at a rate of 20 ml/min. The machine was calibrated with indium (Onset temperature of 156.60^{o}C and latent heat of 28.45 J/g) following the manufacturer's instruction and set to equilibrate within the heat flow of ±0.001 mW. In each test, a sample of about 10 mg, obtained by hand peeling and coarsely grinding in a mortar, was placed in a pre-weighed aluminium pan (Perkin-Elmer, Kit No. 0219 - 0062) and sealed to ensure there was no mass loss during heating (Mohapatra and Bal, 2003). A sealed empty pan of the same type was used as a reference. The sample was placed in the sample holder of the calorimeter, set to be held at -20 ^{o}C for 5 min before it was heated to 90 ^{o}C at a rate of 10^{o}C/min. Then, it was held isothermally at that temperature for 5 min before it was cooled quickly (20^{o}C/min) to the initial temperature (-20^{o}C). Finally, the sample was heated at the same rate to the same temperature.

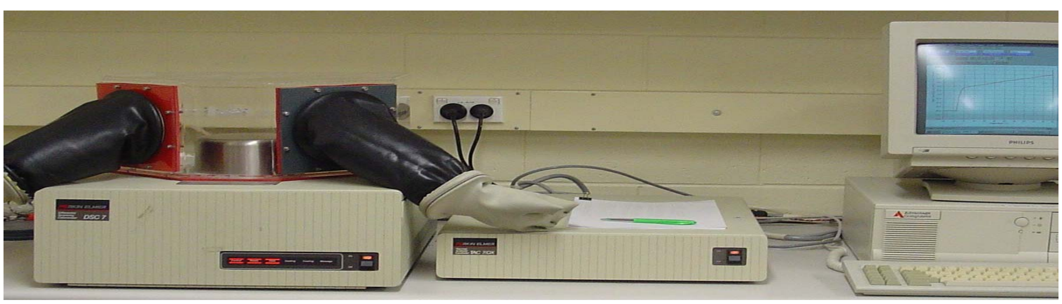


Fig 3.21: The Differential Scanning Calorimeter

The DSC heat flow rate was plotted against the sample temperature (see Fig 3.22) and transitions were observed in most of the graphs. Standardised method(s) for determination or calculation of the T_g that are available were followed (Help topic of the machine software, DPSc, 2003; Foster, 2002). Three temperatures, namely onset, midpoint and endset, have been used and reported. Foster (2002) reported the use of the onset temperature as the T_g while mentioning the others in publication. According to the help topic of the DSC software, the onset value is calculated by finding the intersection of the extrapolated tangent at the first limit and the extrapolated tangent at the inflection point. The end value is calculated by finding the intersection of the extrapolated tangent at the second limit and the extrapolated tangent at the inflection point. In this test, due to some irregularities in the shapes of the transitions, the mid point was taken as the grain T_g based on the method described by DPSc (2003) (see Fig 3.23).

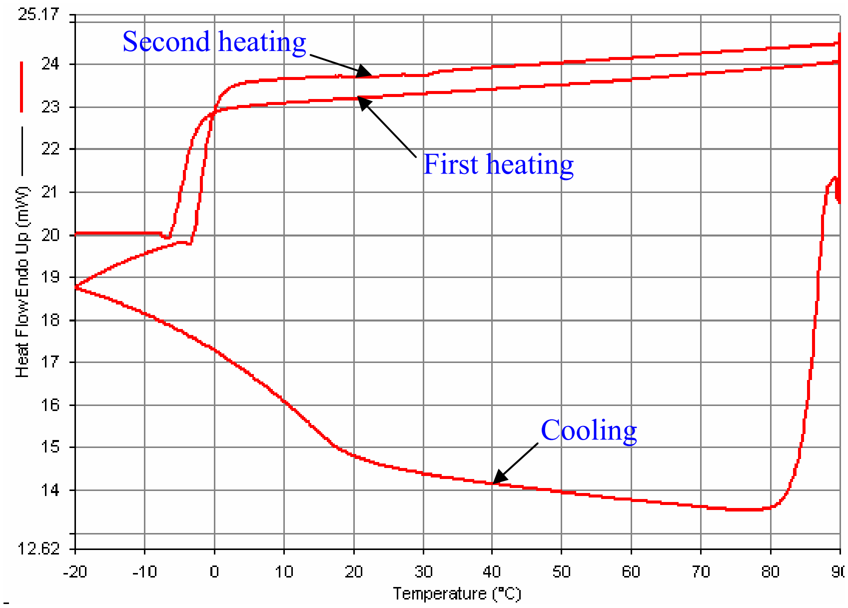


Fig 3.22: A typical result produced by the DSC *(Variety One at 25% MC, replication 1)*
Note: The transition can be observed in the 2nd heating run at about 30°C.

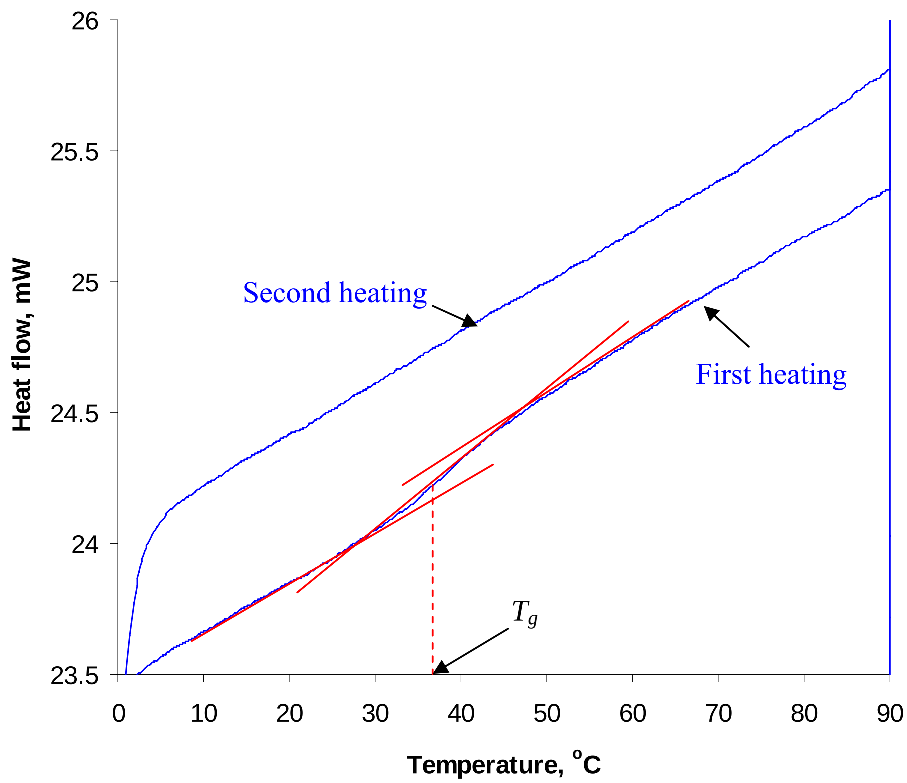


Fig 3.23: Determination of the T_g following the method described by DPSc (1997b)

Chapter 4

RESULTS OF THE EXPERIMENTS AND TESTS

Apart from the changes in the moisture content (MC), temperature and relative humidity (RH) that were monitored for modelling purposes, the following are the results, discussions and conclusions on the effect of all the applied treatments on the drying time and the dried grain quality. The results from the tests to measure T_g determining tests and the rice state diagrams are also presented along with discussion and conclusions. Unless otherwise indicated, all values in tables in this chapter are the means of all the 2 to 3 replications. The results are discussed in Chapter 8.

4.1 EXPERIMENT ONE/03 - EFFECT OF BED DEPTH

This experiment investigated the effect of bed depth on the drying time and the dried grain quality. The raw data obtained and the results of the statistical analysis are listed in Appendix B1 and in A2.1 to A2.8 of Appendix A2, respectively.

4.1.1 Effect of bed depth on the drying time

Drying depth was found to have a significant effect on the mean drying time (Table 4.1). As expected, the thinner the drying depth the faster the drying time. When the grain was dried in 2 cm beds, the drying took about 14 hours which was about 5 and 7 hours shorter than the drying times of the grain with 4 and 6 cm bed depths, respectively. The difference between the drying times of grain dried at 4 and 6 cm, however, was not statistically significant at 5% level.

Table 4.1: Effect of the bed depth on the drying time and the grain quality

Depth	2 cm	4 cm	6 cm
Drying time, h	13.83^{b}	18.83^{a}	20.50^{a}
Bending strength, Pa	0.045^{a}	0.043^{a}	0.031^{b}
BS (1.4 mm), %	3.65^{a}	3.48^{a}	3.81^{a}
BS (1.68 mm), %	11.93^{a}	12.58^{a}	12.36^{a}

<u>Note:</u> *Means for individual variable with the same letter are not significantly different at 5% level.*

Since the drying with 4 and 6 cm bed depths was found to take such a long time, the maximum bed depth for the 2004 experiments was chosen to be 3 cm.

4.1.2 Effect of bed depth on the dried grain quality

Table 4.1 shows that the depth had significant effect on the bending strength of the dried kernels. In general, the thinner the bed, the stronger the grain. No consistent trend was observed in the Breakage Susceptibility (BS as listed in Table 4.1). From the MI test performed with the dried samples obtained from this experiment, it was concluded to be either not appropriate or not sensitive enough to differentiate the effect of the drying treatments or that none of the treatments had a significant effect on the dried grain quality. The manual dehusking method applied in the test (see Section 3.3.3.2) had an inbuilt error due to inconsistency in the pressure and time needed. It was not possible to prevent small or broken dehusked brown rice from mixing with the bran and husk. Likewise, ten kernels selected from a dried sample for the three-point bending test were not enough to give a good average given the variation between tests.

4.2 EXPERIMENT TWO/03 - EFFECT OF TEMPERING

This experiment investigated the effect of a number of tempering methods on the drying time and the dried grain quality. The raw data obtained are listed in Appendix B2 and the results of the statistical analysis are given in A2.9 to A2.16 of Appendix A2.

4.2.1 Effect of tempering on the drying time

The tempering method had a significant effect on the drying time (Table 4.2). Stirring the 4-cm grain bed every one hour (T2) meant the drying was completed within 13.5 h, which was more than 2 hours faster than the other two tempering methods. However, stirring did not speed up drying when the stirred grain was covered for two hours (T3).

Table 4.2: Effect of the tempering methods on the drying time and the grain quality

Tempering methods	**No stirring (T1)**	**Stirring (T2)**	**Stirring and Covering (T3)**
Drying time, h	15.50[a]	13.50[b]	15.50[a]
Bending strength, Pa	0.034[a]	0.037[a]	0.039[a]
BS (1.4 mm), %	3.43[a]	3.02[a]	2.97[a]
BS (1.68 mm), %	10.90[a]	10.44[a]	9.88[a]

Note: Means for individual variable with the same letter are not significantly different at 5% level.

4.2.2 Effect of tempering on the grain quality

The tempering methods did not have any statistically significant effect on the grain quality (Table 4.2). The strengths of the kernels were very close to each other so as to make the difference between them too small to be significant. This could be due to the stirring methods having the same effect on the grain property or the test itself was problematic as the number of kernels used was not big enough to represent the grain in each drying lot. The MI test may have the same problem as quoted for Experiment One/03.

4.3 EXPERIMENT THREE/03 - EFFECT OF TEMPERING, VARIETY AND DRYING DAY

This experiment investigated the effect of a number of tempering methods, grain varieties and drying days on the drying time and the dried grain quality. The raw data obtained are given in Appendix B3 and the results of the statistical analysis are given in A2.17 to A2.24 of Appendix A2.

4.3.1 Effect of grain variety on the drying time and the grain quality

Table 4.3 shows IR66 (V4) took the shortest time (10.18 hours) to reach the target MC of 14%. Next were Pka Knhey (V1) and CAR11 (V2) then Masary (V3). However, statistically, the drying times for V1 and V2 or V2 and V3 were not significantly different. There was no significant interaction between variety and tempering method, so the trend in the drying time in Table 4.3 was the same for all the tempering methods (Fig 4.1).

Table 4.3: Effect of the grain variety on the drying time and the grain quality

Variety	Pka Knhey	CAR11	Masary	IR66
Drying time, h	12.20^{b}	12.55^{ab}	13.73^{a}	10.18^{c}
Bending strength, Pa	0.038^{bc}	0.033^{c}	0.059^{a}	0.038^{b}
BS (1.4 mm), %	5.252^{b}	3.905^{c}	6.927^{a}	7.235^{a}
BS (1.6.8 mm), %	20.95^{b}	12.733^{c}	22.525^{b}	28.30^{a}

Note: Means for individual variable with the same letter are not significantly different at 5% level.

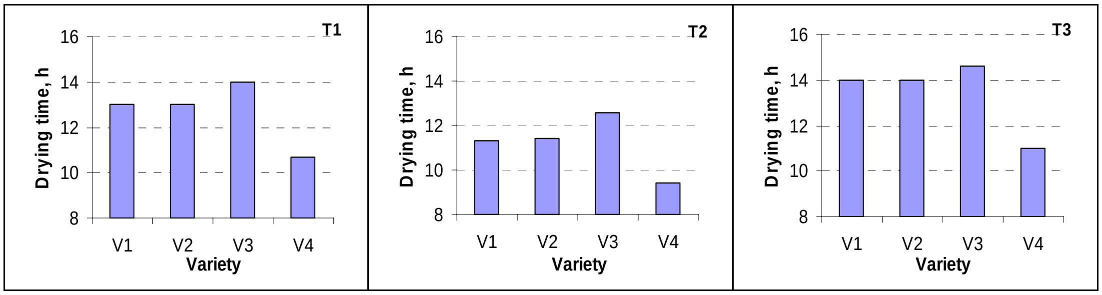


Fig 4.1: Drying times for all the varieties for individual stirring method
(V1:Pka Knhey; V2: CAR11; V3: Masary; V4: IR66)

The grain variety had a significant effect on the grain quality (Table 4.3). The strength and the BS resulting indicated that IR66 was the best in terms of the quality. Next were Masary and Pka Knhey and the worst was CAR11.

4.3.2 Effect of drying day on the drying time and the grain quality

Table 4.4 shows that drying day had no significant effect on the drying time for the varieties used. This result probably reflects insignificant change in climate (e.g. the solar intensity, wind speed) for the three days.

Table 4.4: Effect of the drying day on the drying time and the grain quality

Starting Day	Day 1	Day 2	Day 3
Drying time, h	12.00[a]	12.71[a]	12.21[a]
Bending strength, Pa	0.048[a]	0.042[b]	0.042[b]
BS (1.4 mm), %	6.45[a]	5.71[b]	5.89[ab]
BS (1.68 mm), %	22.52[a]	19.50[b]	21.83[a]

Note: Means for individual variable with the same letter are not significantly different at 5% level. Days 1, 2 and 3 were the starting days on December 12, 13 and 14 of 2003, respectively.

Table 4.4 shows that starting day had a significant effect on the grain quality. The starting Day 1 produced stronger grain than the other two days.

4.3.3 Effect of tempering on the drying time and the grain quality

Similar to what was found in Experiment Two/03, Table 4.5 shows that stirring the grain every hour (T2) had a significant effect on the drying time. With stirring, the target MC was reached about 90 min faster on average than for the other two methods. The results suggest that covering the stirred grain for two hours at noon time slowed the drying down to give the same drying time as exposing the grain continuously with no stirring. The tempering method had a significant effect on the BS but not the grain strength. Stirring and covering the grain produced grain with slightly better quality.

Table 4.5: Effect of tempering on the drying time and the grain quality

Tempering methods	**None (T1)**	**Stirring (T2)**	**Stirring and covering (T3)**
Drying time, h	12.83[a]	11.17[b]	13.50[a]
Bending strength, Pa	0.043[a]	0.042[a]	0.047[a]
BS (1.4 mm), %	6.16[ab]	5.61[b]	6.48[a]
BS (1.68 mm), %	21.51[ab]	20.26[b]	22.60[a]

Note: Means for individual variable with the same letter are not significantly different at 5% level.

4.4 EXPERIMENT FOUR/03 - EFFECT OF SOLAR INTENSITY AND AMBIENT AIR CONDITIONS

The objectives of this experiment were to measure the changes in solar intensity (at a weather station in Sihaknouk Ville, a Cambodian town located by the sea, about 230 km southwest of the country's capital city, where a solarimeter (MS 601) was available) and ambient air temperature and determine their effects on the temperature and humidity within the drying bed. The raw data are given in Appendix B4.

4.4.1 Change in solar intensity

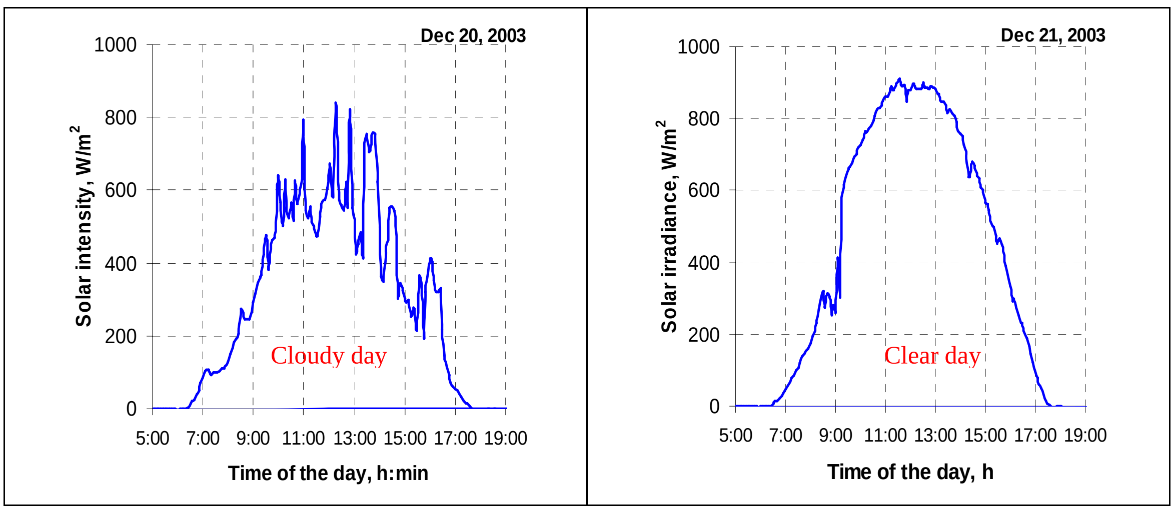


Fig 4.2: Solar intensity measured on site on Dec 20 and 21, 2003

As shown in Fig 4.2, the solar intensity on both days changed similarly according to the time of the day. The intensity was zero at night and was at its maximum values of approximately 820 and 900 W/m^2 at around noon time, for the first and second days, respectively. On the first drying day (December 20, 2003: cloudy day), the cloud cover was greater but was more intermittent than the next day (December 21, 2003: clear day).

4.4.2 Change in the air RH

The RH of the ambient air and the air inside the grain bed was also found to change during the drying time (Fig 4.3). On average, the ambient air on the first drying day had lower RH than on the second day. In contrast, the RH of the air within the grain bed was found to be higher on the first than on the second day. This bad effect was understandable due to the reduction of moisture or water in the grain as the drying proceeded. The lower the moisture the less cooling effect produced by evaporation.

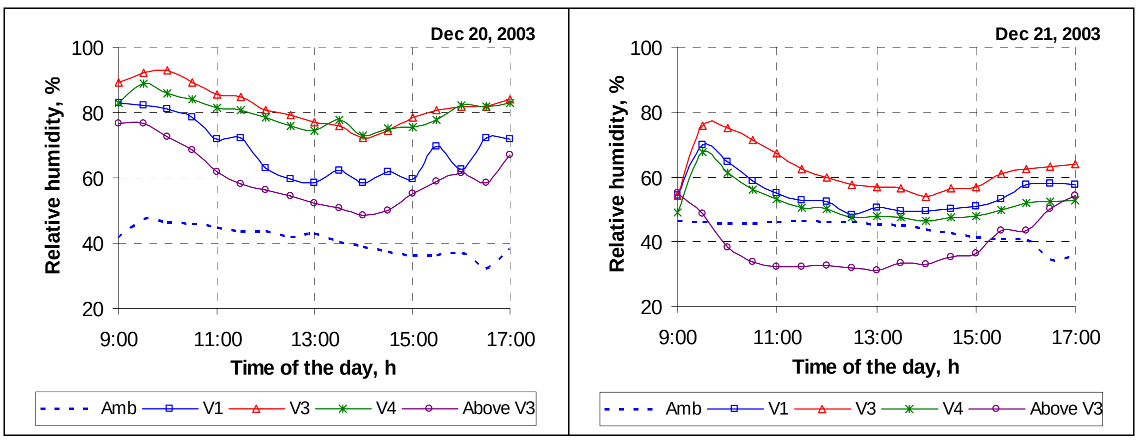


Fig 4.3: RH of the air measured on site on Dec 20 and 21, 2003

The air RH inside all the grain beds was found to be at their highest values in the early morning or late evening and reduced to its lowest value at around 1 to 2 pm.

4.4.3 Change in the temperature

Fig 4.4 shows the measured temperatures for the two days. The temperature of the exposed concrete floor was found to be affected more greatly by the solar intensity rather than the ambient air. From around 9:30 am to 4 pm, the air temperature increased slowly from about 25 to 28^{o}C, while the floor temperature increased and then dropped dramatically consistent with changes in the solar intensity (Fig 4.4). The cloud cover on the first day meant that the floor temperature on the first day was lower and more erratic.

Similar trends were also shown by the temperatures of the three layers within the bed with the bottom of the bed being lower and less affected by the solar intensity.

After those two days of drying, the MC of the grain that was spread in 3 cm bed depths on a concrete pad, and exposed to the sun from about 9 am to 5 pm with no stirring and no covering had dropped from about 22% to 11.6, 12.3, 13.2 and 12.2% for Pka Knhey, CAR11, Masary, and IR66; respectively.

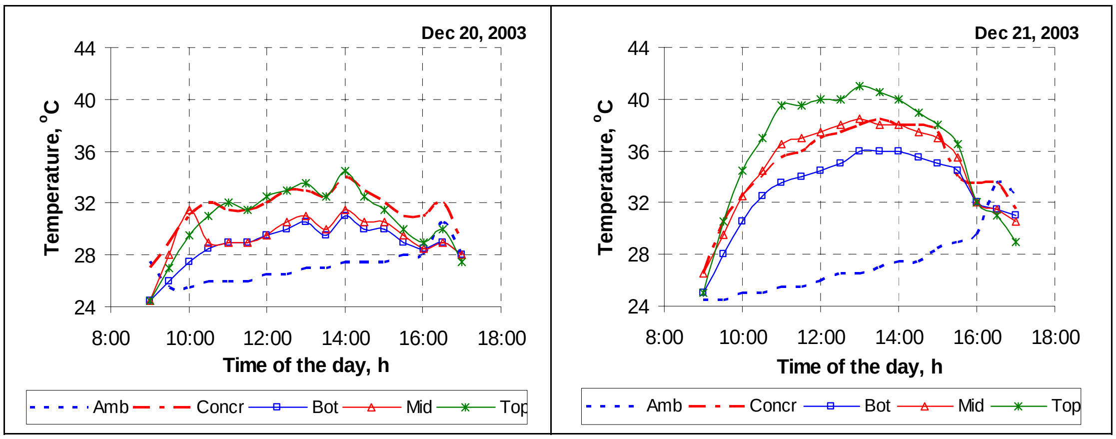


Fig 4.4: Air and grain temperatures measured on site on Dec 20 and 21, 2003

4.5 EXPERIMENT ONE/04 - MC DETERMINATION METHODS

The objectives of this experiment were to assess the accuracy of two different MC measurement methods, namely a nylon-bag and direct sampling methods. The raw data are given in Appendix B5 and results of statistical analysis are given in A2.25 and A2.26 of appendix A2.

As for the 2003 experiments, the changes in the grain temperature, the air temperature and RH that were monitored during the 2004 experiments were only used for the model validation. They are presented and discussed in the model validation section.

Fig 4.5 shows that the moisture meter detected faster moisture reduction than the bag method for both the stirred and non-stirred grain beds. Some restriction of air and moisture movement through the bag could be the reason.

For the stirred bed, the MC detected by the bag that was placed at its bottom was always higher than the MC of the whole bed even after stirring. Obviously, the kernels in the bag did not have a chance to be stirred with the rest of the bed. At around 1 pm, the weight of the grain in the bags dropped dramatically. No identifiable reason was found and it was postulated to be caused by the error of the scale used.

It was observed that there were some grain kernels piercing through the net and it was difficult to decide whether they were from inside or the other way around. Therefore, some weight changes due to loss or gain of grain kernels were likely leading to more erratic weight changes than measured by the moisture meter.

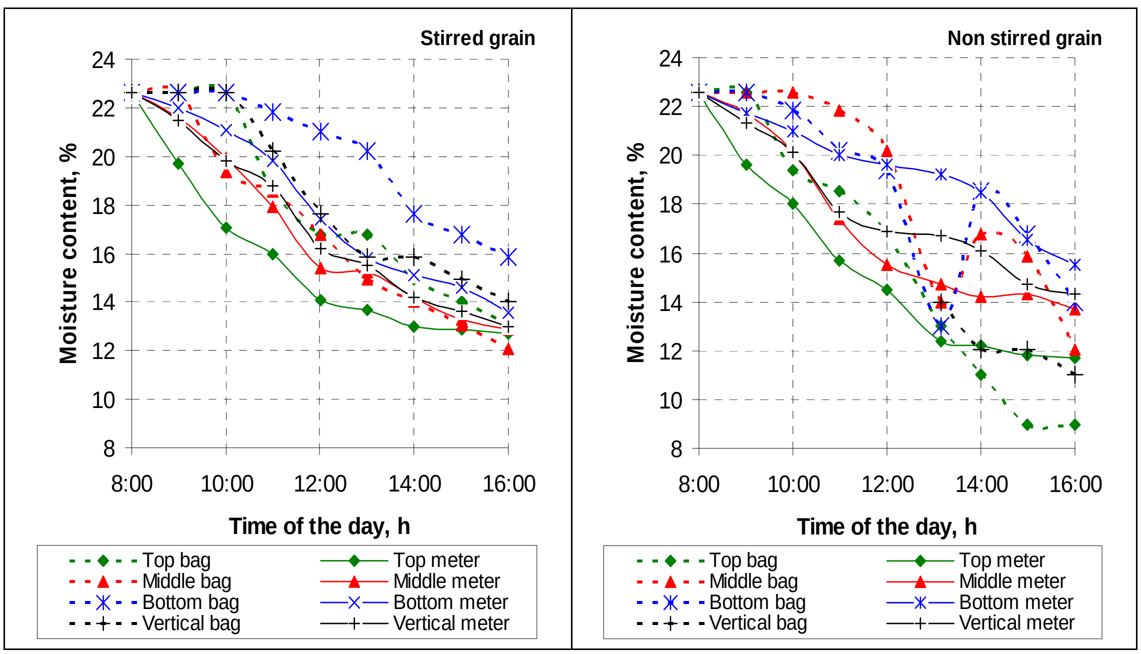


Fig 4.5: The change in the grain MC as detected by the nylon-bag method and measured by the moisture meter

4.5.1 Effect of stirring on the HRY

The mechanical impact (MI) test showed that the HRY was affected significantly ($p = 0.026$) by the stirring method (Table 4.6). No stirring gave a HRY of about 39% and stirring the every one hour increased the HRY by about 7%. This was only 2% lower than the HRY of the control sample that was dried with about 3 mm depth all the time under shade. The milling test result gave similar trends for the effect of the stirring method but the level of the statistical significance was slightly lower.

Table 4.6: Effect of stirring method on the HRY

Stirring methods	HRY_{MI}, %*	HRY_{MILL}, %**
No stirring	38.8^a	43.9^a
Stirring	45.5^b	48.8^b
Control sample	47.7	48.3

** p = 0.026, ** p = 0.066, Means for individual quality test with the same letter are not significantly different.*

4.6 EXPERIMENT TWO/04 - EFFECT OF BED DEPTH AND TEMPERING

Apart from obtaining the data for the model validation, the objective of this experiment was to determine the effect of bed depth and tempering methods on the drying time and HRY. The raw data are given in Appendix B6 and results of statistical analysis are given in A2.27 to A2.29 of Appendix A2.

4.6.1 Effect of bed depth on the drying time

Tables 4.7 shows that the effects of the depth and stirring method on the drying time were significantly different at 5% level (p-values were 0.043 and 0.017, respectively) while the effect of the covering method was also significant but at a slightly higher probability ($p = 0.062$). No interaction effect was significant so it appeared that all three factors acted independently, and the interpretation can be made on the effect of each of the factors (Kuehl, 2000).

Table 4.7: Effect of bed depth, stirring and covering methods on the drying time, h

Bed depth	**2 cm**	09.37[a]
	3 cm	10.92[b]
Stirring method	**No stirring**	11.25[a]
	Stirring	09.03[b]
Covering method	**None**	08.58[a]
	Direct covering	09.95[b]
	Shading	10.25[bc]
	Covering and Shading	11.75[c]

Note: Means for individual variable with the same letter are not significantly different at 5% level.

4.6.2 Effect on the HRY

4.6.2.1 Effect of bed depth on the HRY

The effect of bed depth on the grain quality was not shown to be significant at 5% level ($p = 0.31$) using the MI test. There was, however, an indication showing that drying with the 2-cm depth gave a HRY of about 39% which was 1% higher than drying with a 3-cm depth (Table 4.8). The results obtained from the milling test confirmed this trend at 1% statistical significance ($p = 0.0001$). Compared to the HRY of the control sample, the HRY of the grain dried with 2-cm depth obtained from the MI and the milling tests were about 9 and 4% lower, respectively.

Table 4.8: Effect of bed depth, stirring and covering methods on the HRY

		HRY_{MI}, %	HRY_{MILL}, %
Bed depth	**2 cm**	38.9[a]	44.4[a]
	3 cm	37.8[a]	40.5[b]
Stirring method	**No stirring**	36.8[a]	41.1[a]
	Stirring	39.9[b]	43.8[b]
Covering method	**No covering**	36.1[b]	41.8[b]
	Direct covering	38.8[a]	41.8[b]
	Shading	39.5[a]	42.9[a]
	Covering and shading	39.1[a]	43.2[a]
Control sample		47.7	48.3

Note: Means for individual variable and quality test with the same letter are not significantly different (at 1, 1 and 5% levels for bed depth, stirring and covering, respectively).

4.6.2.2 Effect of stirring on the HRY

Stirring was shown to be a means for increasing the HRY of the dried grain. As can be seen in Table 4.8, when all the bed depths and covering methods were combined, the effect of the stirring method was significant at 1% level both for the MI test ($p = 0.011$) and the milling test ($p = 0.0001$). On average, about a 3% improvement in the HRY was obtained when the grain was stirred every one hour during drying.

4.6.2.3 Effect of covering on the HRY

Different covering methods produced different effects on the grain HRY. The effects were shown to be different at slightly higher than the 5% significant level for the data obtained from the MI ($p = 0.053$) and milling ($p = 0.076$) tests (Table 4.8). Comparison of the effects of all the four covering methods for all the bed depths and stirring methods combined revealed that covering and/or shading the grain during noon time produced similar effects on the HRY which were better (about 3% higher) than exposing it all the time to the sun. The best HRY of all the samples was still far below the HRY of the control sample, which was dried all the time under shade, of about 47%.

4.7 EXPERIMENT THREE/04 - EFFECT OF DRYING PAD, VARIETY, BED DEPTH, TEMPERING AND DRYING DAY

Apart from obtaining the data for the model validation, the objective of this experiment was to determine the effect of drying pad, variety, bed depth, tempering and drying day on the drying time and HRY. The raw data are given in Appendix B7 and results of statistical analysis are given in A2.30 to A2.32 of Appendix A2.

4.7.1 Effect on the drying time

The ANOVA table (A2.30 of Appendix A2) revealed that there was no significant interaction effect between the various factors on the drying time, indicating that the factors acted independently.

Table 4.9: Effect of variety, depth, stirring, covering and pad on the drying time, h

Variety	**Pka Knhey**	15.57[a]
	CAR11	13.93[b]
Bed depth	**2 cm**	12.60[a]
	3 cm	16.90[b]
Stirring method	**No stirring**	16.28[a]
	Stirring	13.22[b]
Covering method	**No covering**	11.40[a]
	Cover and Shade	18.10[b]
Drying pad	**Tarpaulin on soil**	15.50[a]
	Net on soil	15.31[a]
	Mat on soil	14.13[b]
	Net on husk	11.08[c]

Note: Means obtained from each individual variable with the same letter are not significantly different (at 5, 1, 1, 1 and 1% levels for variety, bed depth, stirring, covering and drying pad, respectively).

4.7.1.1 Effect of grain variety on the drying time

When all the treatments were combined, the drying times for the two rice varieties were found to be different at about the 5% significant level ($p = 0.065$). On average, to reach the target MC of 14%, Pka Knhey variety took 15 h and 34 min which was about one and a half hours longer than CAR11 variety (Table 4.9).

4.7.1.2 Effect of bed depth on the drying time

Similar to the results found from Experiments One/03 and Two/04, drying did take a significantly shorter time ($p = 0.0001$) for the thin bed depth compared to the thicker bed (Table 4.9).

4.7.1.3 Effect of stirring on the drying time

On average, when all the varieties and treatments excluding the stirring methods were combined, stirring helped reduce the drying time very significantly ($p = 0.001$). Stirring every one hour during drying caused the grain to reach the target MC three hours faster than when it was not stirred (Table 4.9).

4.7.1.4 Effect of covering on the drying time

Similar to the observation made in Experiment Two/04, covering and shading the grain retarded the drying significantly (p = 0.0001). On average, a covered and shaded sample took about 6 h and 40 min longer to dry than a sample without covering and shading (Table 4.9).

4.7.1.5 Effect of drying pad on the drying time

There were significant differences (p = 0.0001) in drying time found for the grain dried on different pads (Table 4.9). Drying on a tarpaulin and on a nylon net, both spread directly on the soil, took the longest time. Next was the drying on the mat. The shortest time was for drying on the net spread on top of a husk layer.

4.7.2 Effect on the HRY

The HRY from the MI test indicated most of the main factors had a significant effect (A2.31 of Appendix A2). No interaction effect of the factors investigated was significant. The HRY from the milling test (A2.32 of Appendix A2) confirmed that most of the effects were significant but revealed a number of significant interactions between factors.

4.7.2.1 Effect of variety on the HRY

On average, when all the drying treatments except the varieties were combined, the HRY of the two varieties (Table 4.10) were found from the MI test to be significantly different at 1% level (p = 0.0001). CAR11 produced a HRY which was about 4% higher than Pka Knhey variety. The results obtained from the milling test did not show any effect of the two varieties tested. Uncertainty in the results obtained from the milling test could be the result of the grading process. The kernels of the two varieties had very different dimensions and only one indented cylinder was used in the grading process.

Table 4.10: Effect of variety, depth, stirring, covering and pad on the HRY

		HRY_{MI}, %	HRY_{MILL}, %
Variety	**Pka Knhey**	35.7^{a}	40.5^{a}
	CAR11	39.8^{b}	40.9^{a}
Bed depth	**2 cm**	37.6^{a}	40.8^{a}
	3 cm	37.9^{a}	40.5^{a}
Stirring method	**No stirring**	37.0^{a}	41.0^{a}
	Stirring	38.5^{b}	40.4^{a}
Covering method	**No covering**	36.2^{a}	39.4^{a}
	Cover and Shade	39.3^{b}	41.9^{b}
Drying pad	**Tarpaulin on soil**	38.5^{a}	41.4^{a}
	Net on soil	38.8^{a}	41^{ab}
	Mat on soil	37.3^{b}	40.7^{b}
	Net on husk	36.4^{c}	39.6^{c}

Note: Means for individual variable and quality test with the same letter are not significantly different. (at 1, 5, 1, and 1% levels for variety, bed depth, stirring and covering, respectively. For the pad, the means are significantly different at 1 and 10% for the MI and milling HRYs, respectively).

4.7.2.2 Effect of bed depth on the HRY

In contrast to the results found in Experiment Two/04, Table 4.10 shows that the HRY of the grain dried with the two bed depths were not shown to be significantly different at the 5% level (p = 0.523 and 0.437 for the MI and the milling tests, respectively).

As there were so many factors investigated in this experiment, some confounding or random errors were suspected as having some effects on the HRY. Based on the results from the milling test, the bed depth was found to have significant 3-way interaction with the variety and the methods applied.

4.7.2.3 Effect of stirring on the HRY

Data from the MI test revealed that for all the varieties and treatments except the stirring methods combined, stirring the grain every hour during drying had a significant and positive effect on the HRY (p = 0.011) (Table 4.10). It helped increase the HRY by about 2%. The results obtained from the milling test did not show any effect of the two stirring methods tested. Again, the grading process in the milling test was suspected as a source of problems.

4.7.2.4 Effect of covering on the HRY

Covering and shading the grain during the hottest time of the day helped increase the HRY significantly ($p = 0.0001$ both for the MI and the milling tests) (Table 4.10). The increase was 3% on average.

4.7.2.5 Effect of drying pad on the HRY

As for the drying time, the drying pads were also found to have a significant effect on the HRY at the 1% ($p = 0.011$) significance level (Table 4.10). Drying on the tarpaulin and the net spread directly on the ground took the longest time, and gave the highest HRY yields of about 39%. The HRY was reduced by about 2 and 3% for the grain that was dried on the mat and on the same net spread on husk, respectively.

Similar trends were observed for the HRY from the milling test although the differences were only significant at the 10% level.

4.7.2.6 Interaction effect from the milling test

Significant 2- and 3-way interaction effects on the HRY were found from the milling test. They were between

- The depth and cover (significant at 1% level, $p = 0.004$),
- The depth and stirring methods (significant at 5% level, $p = 0.031$),
- The stirring and covering methods (significant at 1% level, $p = 0.008$),
- The depth and stirring with covering methods (significant at 1% level, $p = 0.005$), and
- The depth and stirring with variety on the HRY (significant at 1% level, $p = 0.002$).

According to Kuehl (2000), in the absence of any interactions, all the factors acted independently, and the main effect can be used to interpret the effect of each factor separately. In contrast, in the presence of interactions, the factors did not act independently, and the interpretations should be based on simple effect contrasts.

The significant 3-factor interactions imply that the interactions between the stirring and the depth are not constant over levels of the covering and the variety. Fig 4.6 and 4.7 demonstrate these interaction relationships.

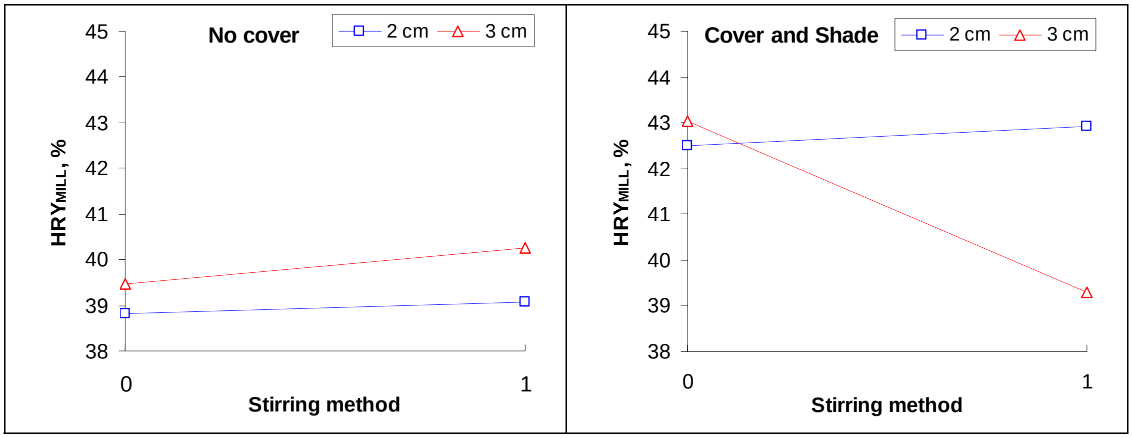


Fig 4.6: Three-factor interaction between depth and stirring with covering on the HRY_{MILL}

Note: Stirring method 0 = No stirring and 1 = Stirring

With 2-cm depth, the stirring treatment had no significant effect and covering in combination with shading helped improve the yield (Fig 4.6). With the 3-cm depth, covering and shading produced the same effect by increasing the HRY for the grain that was not stirred by about 3% but not for the stirred one.

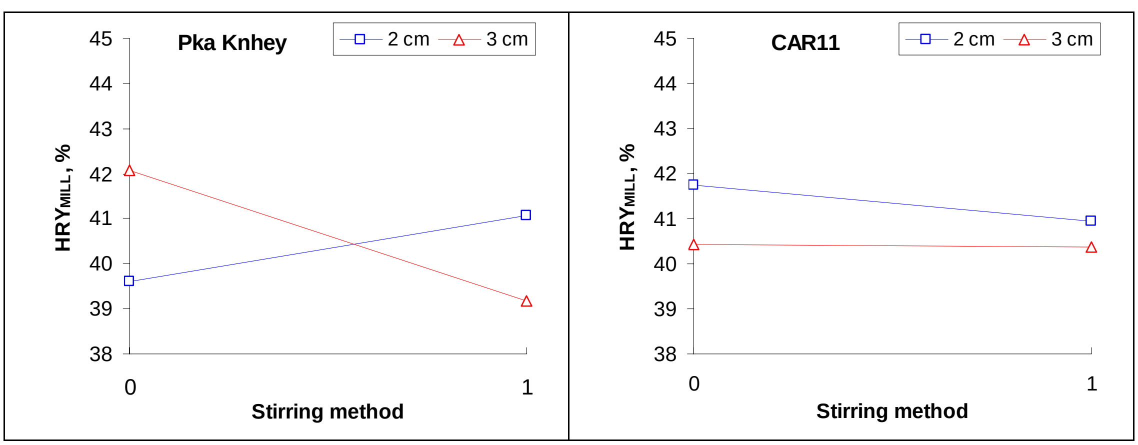


Fig 4.7: Three-factor interaction between depth and stirring with variety on the HRY_{MILL}

Note: Stirring method 0 = No stirring and 1 = Stirring

The results obtained from the milling test indicated that for Pka Knhey variety, stirring helped increase the yield for the grain that was dried with 2-cm depth by about 3% but reduced the yield of grain that was dried with 3-cm depth by about 3% (Fig 4.7).

4.8 THE RICE GRAIN STATE DIAGRAM

The data from the drop test (Appendix B8) revealed no significant difference between the effects of the grain pre-conditioned MC and the number of broken particles. The total number of broken particles was found to vary a lot among the 10 replications. Some general trends, however, were observed. The rice kernels of 10% MC seemed to break the most while the kernels of 15% MC broke the least. The sample of 25% MC was found to break more than the others of 20%.

These findings could not be used to explain the existence and significance of the T_g, but it confirmed that about 15% is the most suitable MC for grain to withstand mechanical stress or impact. In the rice milling industry, 14% MC has been suggested as the most suitable MC for milling (IRRI, 2002d). While the grain of 10% MC was too dry and brittle, the grain with 20 and 25% MC was too wet and soft. Perdon (1999), Perdon *et al*. (2000), Sun *et al*. (2002) reported the linear correlation between the T_g and MC. According to these workers, the lower the MC, the more likely the grain would be in the glassy state and the damage would be greater.

At 40^{o}C, the grain was found to break the most and at 100^{o}C, the grain was found to break the least. At 20^{o}C, the mean number of broken particles was more than at 100^{o}C, but was not significantly different. According to the T_g theory, the higher the temperature, the greater would be the chance for the grain to be in a rubbery state and hence damage is likely to be less.

No noticeable change in the time against displacement graphs was recorded when the compression test was used (Appendix B8). The displacement was almost constant, meaning that nothing changed or the change was not big enough for the sensitivity of the measurement system. It was, therefore, concluded that the combined test could not show clear transition due, perhaps, to the low sensitivity and, mainly, to the difficulty in placing the probe to avoid the resistance from the copper block.

Therefore, only the T_g defined by the DSC test (as given in Appendix B9) were plotted against the corresponding MC to produce the rice state diagrams (Fig 4.8 to 4.12). Following the methods used by Perdon (1999), Perdon *et al*. (2000), and Sun *et al*. (2002), linear, quadratic, exponential, logarithmic and power equations between T_g and MC were tested. The best fit was mostly produced by the quadratic function. However, the quadratic models offered only a very small increase in the R^2 values over the linear function, and therefore, were not considered for the rest of this study. Moreover, many other researchers such as Perdon (1999), Cnossen *et al*. (2001), and Sun *et al*. (2002) have preferred to use the linear relationship for its simplicity.

The linear relationship for each of the varieties and all the varieties combined, respectively, are given in Fig 4.15 to 4.19. The T_g transitions occurred within the range of temperature from about 15 to 62°C with strong correlation (R^2 range from 0.75 to 0.88).

It should be noted that correlation coefficients for T_g against the MC observed in the first heating run were higher than the ones observed in both heating runs.

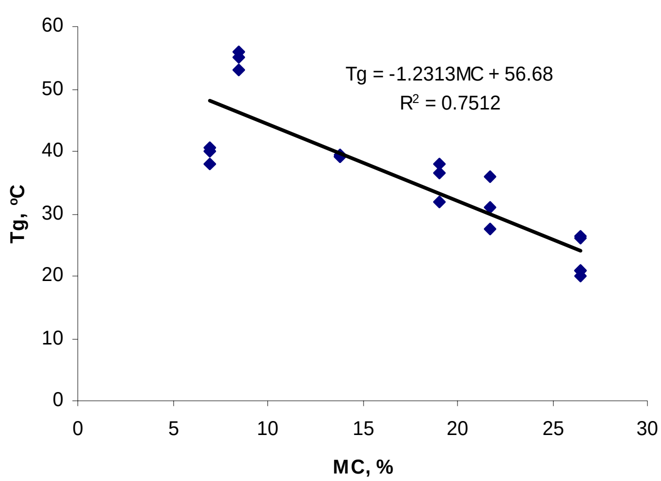


Fig 4.8: State diagram of T_g versus MC for Phka Knhey (V1)

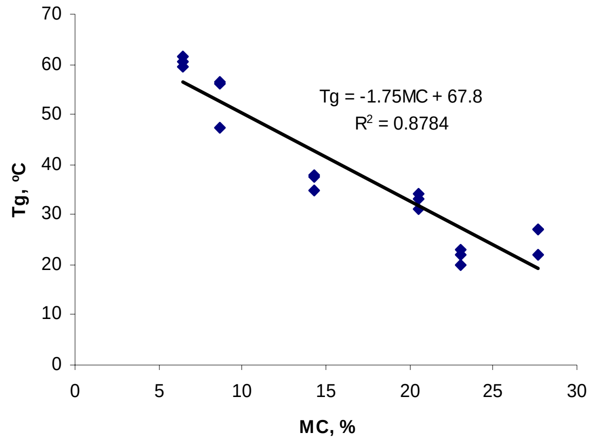


Fig 4.9: State diagram of T_g versus MC for CAR11 (V2)

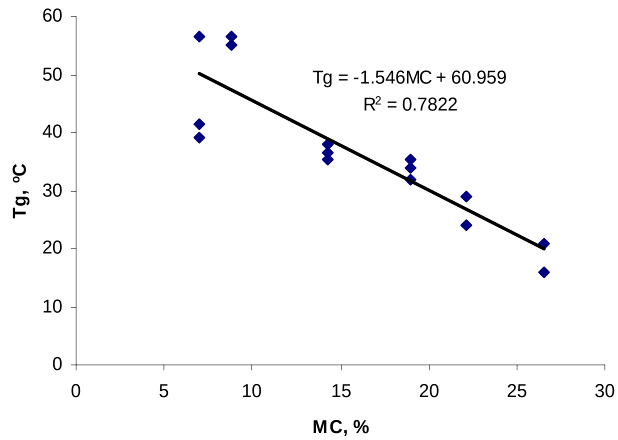


Fig 4.10: State diagram of T_g versus MC for Masary (V3)

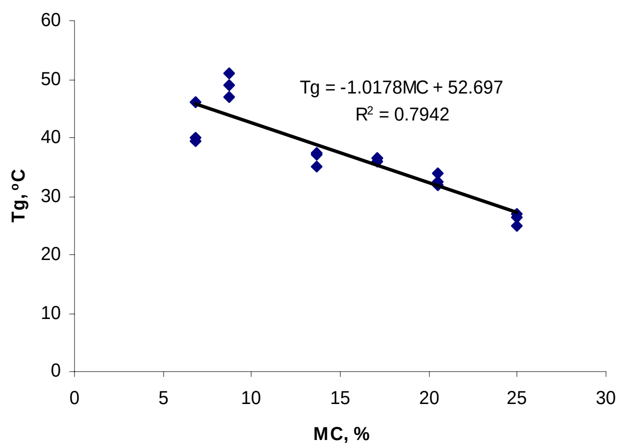


Fig 4.11: State diagram of T_g versus MC for IR66 (V4)

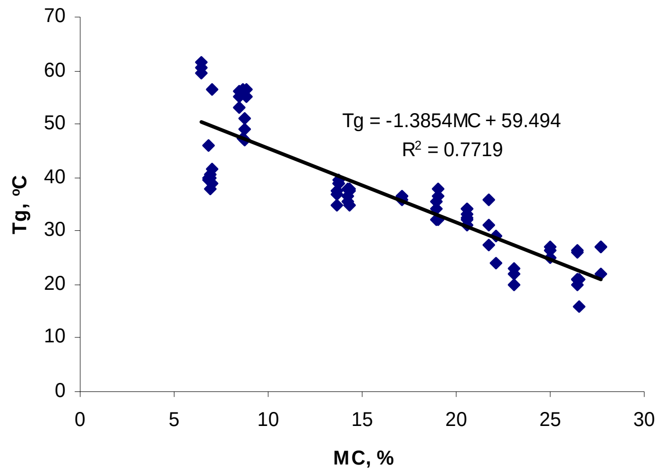


Fig 4.12: State diagram of T_g versus MC for all the 4 varieties

Fig 4.13 shows that these results are similar to those reported by others (Perdon, 1999; Cnossen *et al*., 2001; and Sun *et al*., 2002). Using the thermo-mechanical analysis method, Sun *et al*. (2002) reported the relationship for Drew variety (long grain) as

$$T_g = -1.17\,MC + 59.47 \qquad \ldots (4.2)$$

with $R^2 = 0.57$

When their results were combined with the ones found by Perdon (1999), and Perdon *et al*. (2000) with Bengal (medium grain) and Cypress (long grain), the above authors reported the relationship as

$$T_g = -1.08\,MC + 57.03 \qquad \ldots (4.3)$$

with $R^2 = 0.53$

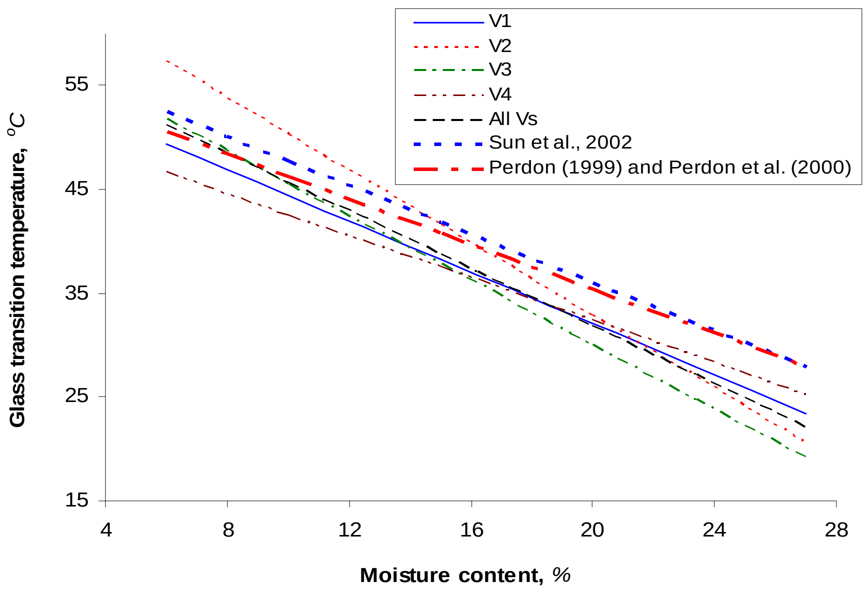


Fig 4.13: State diagram of T_g versus MC of the tested rice varieties compared with correlations reported by Perdon (1999) and Perdon et al. (2000), and Sun et al. (2002)

4.9 SUMMARY

There were seven sun-drying experiments conducted in this study using four local rice varieties. The traditional methods that have been practiced regularly by Cambodian farmers were applied in the experiments with some deliberate modifications. Changes in conditions of the ambient air, grain and air within the drying bed were monitored and effects of the grain varieties and drying methods on the grain conditions, the drying time, and the dried grain quality were investigated. The monitoring process was done for the purpose of modelling as presented and discussed in the model validation section. The results of the experiments are discussed in Chapter 8.

Determination of the grain MC using a nylon bag failed. The air and moisture movement through the bag may have been restricted by the bag and the grain kernels in the bag did not have a chance to be stirred with the rest of the bed.

It took one to three drying days to dry the grain from about 22 to about 14% MC. Apart from the effect of the ambient conditions such as the solar intensity, air temperature and RH and wind speed; the drying depth, tempering method, drying pad and grain variety, were found to have significant effect on the drying time. As expected, the thinner the depth, the faster the drying. Stirring the grain bed every one hour meant the drying was completed faster. However, stirring did not speed up drying when the stirred grain was covered around midday. Drying on the net spread on husk took the shortest time. Next was drying on the mat spread directly on the soil. Drying on a tarpaulin or a net spread directly on the soil took the longest time. When all the varieties were tested in 2003, IR66 took the shortest time to reach the target MC. Next were Pka Knhey and CAR11, then Masary. Statistically, the drying times for the last three varieties were not significantly different. In the 2004 experiment, however, drying of Pka Knhey took significantly longer than drying of CAR11.

The quality tests trialled in 2003 failed to determine the grain quality due mostly to the large experimental errors due to the variations between grains requiring more samples to be tested than was practicable and only the HRYs determined by the MI and milling tests in 2004 could be considered to reliably represent the quality of the grain samples. The tests were, however, not precise as the milling machine used was not standardised as laboratory equipment and the MI tester was developed for testing other grain such as maize.

In general, the bed depth, tempering method, drying pad and grain variety were found to have a significant effect on the HRYs. Drying in a thinner bed on a tarpaulin or net spread directly on the soil, stirring every one hour, not exposing the grain to solar radiation around midday were shown to be beneficial for the grain quality. CAR11 produced higher HRY than Pka Knhey. As there were so many factors investigated in Experiment Three/04, some confounding of effects was experienced.

Among the tests trialled to measure T_g, only the findings from the DSC method could be used to explain the existence and significance of T_g. The temperatures were plotted against the corresponding MC to produce rice state diagrams. For simplicity, linear models were accepted.

These experimental observations could only be used to explain some of the effects on the drying time and the dried grain quality but could not be used to link to the mechanisms of kernel damage as detailed knowledge of the dynamic conditions within the bed were not known. Consequently, a mathematical model for heat and moisture transfer within the bed, as reported in Chapters 5, 6 and 7, was formulated, validated and applied.

Chapter 5

MATHEMATICAL MODEL FORMULATION

5.1 INTRODUCTION

The main goal of rice drying is to maximise the throughput while minimising quality loss. To achieve this goal, mathematical modelling of the drying process has been found to offer an effective tool to better understand the process (Sharma *et al*., 1982; Yang *et al*., 2001; Thielen *et al*., 2001).

Extensive research has been done on mechanical or machine drying of rice. Nevertheless, natural sun-drying of paddy rice will continue to be a widely practised method of drying rice by farmers in developing countries or small operations. There is little quantitative information available on the moisture and temperature gradients inside the drying bed and inside the individual grain kernels for sun drying.

The sun drying system, as described in Section 2.3.4.1 is a complicated and much less controlled process involving the transformation and transfer of heat and moisture influenced by climatic and operator factors. In the system, solar radiation is converted to thermal energy. It involves the transfer of moisture from the centre of each grain kernel to the surface of the grain kernel and from the inside of the bed to the surface of the bed and subsequent evaporation of the moisture. As such it is difficult to understand the interactions between operational variables and to differentiate the different proposed damage mechanisms affecting the HRY and hence to identify the best practise.

The previous chapter aimed to define optimal sun drying condition by experimental design. It was found that the highest HRYs were achieved during trials where the grain was dried with the shallowest bed depth on tarpaulin or mat spread directly on soil with stirring, covering and shading, while the poorest quality was observed when the grain was dried with the highest bed depth on net spread on husk with no stirring, covering and shading. The shortest drying time was found for the grain that was dried in a thin bed on the net spread on husk with stirring but not covering or shading. To a degree it is possible to link these experimental observations to the mechanisms of the kernel damage but detailed knowledge of the dynamic conditions within the bed and the kernels themselves is required to investigate these mechanisms in more detail.

To provide additional detail on the local conditions within the bed for each of the experimental trials presented in Chapter 4, it was decided to develop a mathematical model for heat and moisture transport within the bed. Such a model could be used to better understand the drying process and the interactions between variables and to predict alternative parameters that might be used to correlate with the HRYs that are based directly on the proposed damage mechanisms. In this way, the experimental data analysis carried out in Chapter 4 could be extended to provide more definitive guidelines to optimise traditional sun drying of rice.

5.2 MODEL OBJECTIVES

The model was developed as a simulation tool capable of predicting the patterns of the grain temperature, MC and air RH at different layers of the drying bed as a function of time during sun drying. The predictions could thus be used to

- Understand how farmer operations and the sun drying system affect the drying,
- Predict the drying time, and
- Calculate other parameters in the experimental work that correspond to damage mechanisms, thus enabling more information to be extracted from the experimental design.

It was intended that the model would be applicable to most of the sun drying configurations likely to be used by rice farmers in Cambodia.

5.3 CONCEPTUAL MODEL DEVELOPMENT

5.3.1 Transport processes

The physical situation and modes of transport of heat and moisture included in the model for rice sun drying are illustrated in Fig 5.1. There are four different ways that the rice grain was exposed to the sun which was the only heat source in the system.

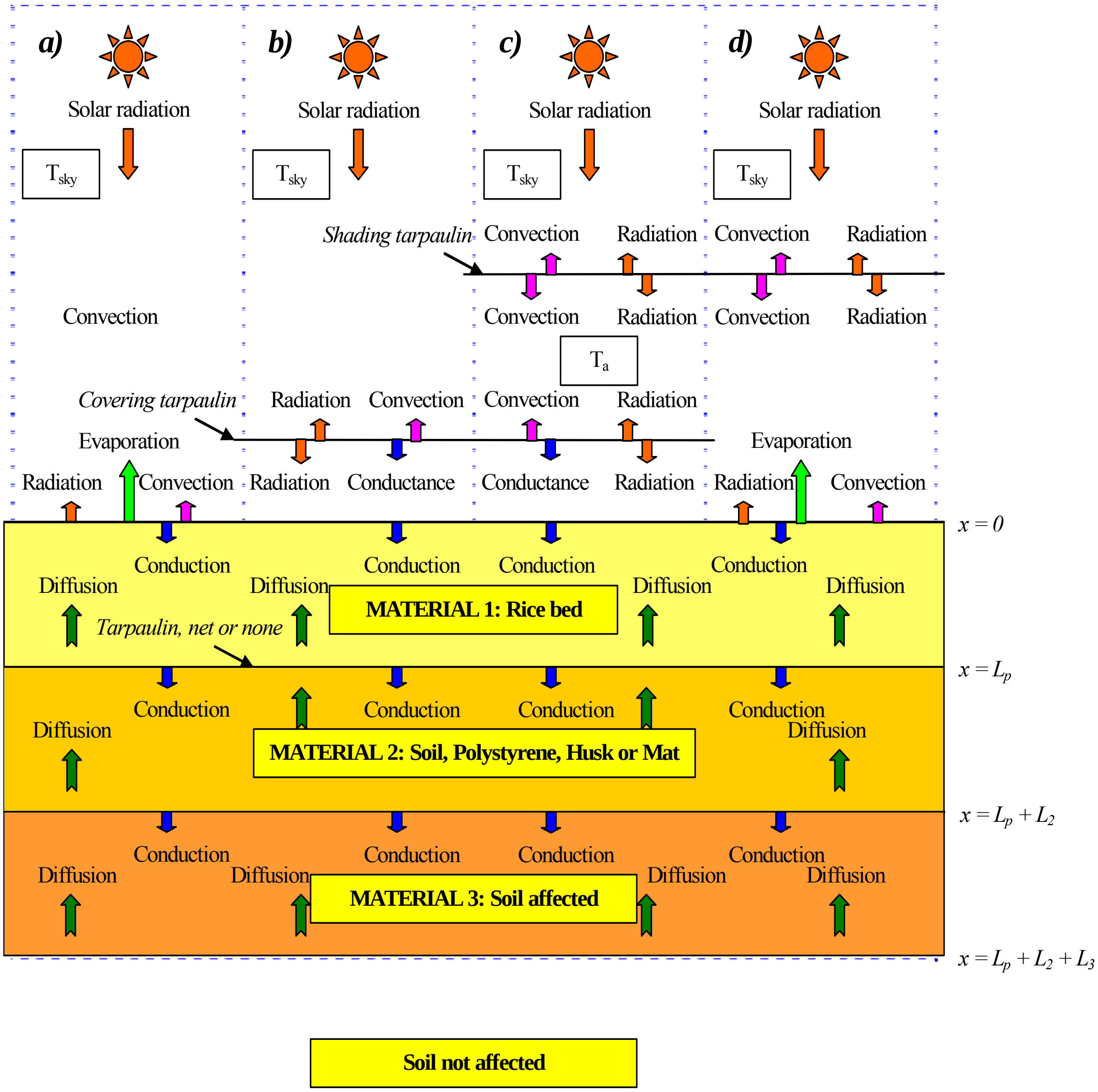


Fig 5.1: Conceptual diagram showing the heat and moisture transfer flows considered in the model

When the grain bed was not shaded or covered (Fig 5.1.a), the solar radiation falling on the bed surface was partly absorbed and partly reflected. The absorbed radiation heated the surface. A part of this heat was utilized to evaporate the moisture from the surface to the surrounding air, while the remaining part was conducted or convected into the interior of the bed or lost through convection to the air and through conduction to the ground or other materials placed below the grain bed. When the rate of gains by radiation exceeds losses by conduction and evaporation, the bed was heated up so as to cause accelerated drying and moisture diffusion. Moisture within the grain kernels was dried out to the air within the bed and diffused out to the bed surface before being carried away by evaporation and convection to the ambient air. In the materials below the rice bed (husk, mat, polystyrene and for soil) moisture was assumed to be in equilibrium between the material and the local air. In the bed, however, drying was considered to be limited by moisture transfer within the kernel, so the bed moisture and the bed air may not be in equilibrium.

When the bed was covered by a water-proof tarpaulin (Fig 5.1 b), the bed was assumed not to lose moisture to the air through evaporation and convection. The surface did not receive the radiation directly from the sun. Instead the tarpaulin was heated by the solar radiation and then lost heat by convection, conduction into the bed and reflected radiation to the sky. Eventually, the tarpaulin acted as the bed surface.

Similar mechanisms of heat and moisture transfer were applied to the grain under both shaded and directly covering (Fig 5.1 c) or shaded only (Fig 5.1 d). The shading tarpaulin received solar radiation and transferred it to the air by convection and to the bed surface or covering tarpaulin by radiation. The only difference was that the heat from the covering tarpaulin or rice bed surface was not radiated to the sky but to the under site of the shading tarpaulin. The heat conduction and moisture drying and diffusion processes within the bed for all the last three drying methods were similar to the ones described for the first.

If the grain was dried on a tarpaulin or mat spread directly on soil, moisture transfer between the bed and the soil was assumed negligible. That was not the case for drying on a net.

The development of the model was based on the following physical basis:

- Temperature and moisture gradients developed across the depth of the bed.
- The solid (rice kernels) and gaseous phases in the bed were considered as continua with interaction over adjacent interfaces
- Moisture diffusivity and thermal conductivity were treated as effective properties of the porous rice bed

- The rate of moisture leaving the bed depended on the vapour pressure difference between the kernel and the surrounding air environment.

5.3.2 Assumptions

The model equations were developed with the following assumptions:

- One-dimensional transfer of heat and moisture vertically through the rice bed. The dimensions of the bed were normally greater than 40 x 40 cm exposed horizontally to the sun. These dimensions are very large compared to the bed depth of 2 and 3 cm, so we can assume that the heat and moisture transfers take place almost entirely in a vertical direction and the bed can be considered as one-dimensional. Bronlund (1997) and Cleland *et al*. (2003) stated that edge effects can generally be neglected if the dimension modelled is less than a quarter of the dimension not modelled. In this case, this ratio was 0.06, so this assumption is reasonable.
- As with any other porous materials, the grain kernels tend to equilibrate their MC with the humidity of the surrounding air. If the MC of the grain was higher than the equilibrium MC, drying will take place; otherwise absorption of moisture will occur. It was assumed that moisture loss from the grain kernels followed a first order kinetic approach to equilibrium and the dynamics of the adsorption process followed the two-compartment thin-layer model with two-term exponential function as has been noted by Chen and Wu (2001).
- No gravitational effects were assumed to be present in the system. This means that there was no flow of free water in the system.
- At any position in the bed, the air and rice were in thermal equilibrium.
- The bulk and true densities, as well as the thermal properties of all the materials exposed to the drying, were assumed to be constant and to not change with either temperature or MC. This is not strictly true, but the level of change was considered small enough to justify this simplifying assumption.

- The temperature at the bottom of material 3 was assumed to be constant (deep soil temperature). This assumption is valid if the soil layer modelled is deep enough.
- No heat and moisture transfer resistance of the nylon net. The nylon net used was very thin and had enough holes so as not to cause any significant obstruction to the heat and moisture transfer through it.
- Negligible moisture diffusion (zero diffusivity) was assumed to occur in polystyrene drying pads.
- Any moisture transfer by air flow within the bed could be approximated by pseudo-diffusion (higher value of diffusivity). During the experiments, wind speed external to the bed was measured to be in the range of 0 to 3 m/s. Side winds on the bed may induce some flow of air within the bed.
- Uniform temperature and MC at the start of drying and at the end of stirring. As it was described in Section 3.3.1, the grain samples were packed in two-layer plastic bags and stored in a cold room for about two weeks to equilibrate the MC. One night prior to the drying, the samples in the sealed bags were removed from the storage and left in ambient air for the temperature to reach ambient conditions and to avoid condensation. The samples, therefore, attained uniform temperature and MC when the drying was started.

  Stirring the grain during drying was done very thoroughly so that it could bring the temperature and MC of all the bed layers to an average value. Stirring was assumed to occur instantaneously. Immediately after stirring, the air within the bed was assumed to have the same RH as the ambient air.
- The grain bed did not completely touch the covering tarpaulin, drying tarpaulin or drying mat, so there was a resistance to heat transfer between them.
- Shading and covering tarpaulins have negligible thermal capacity (immediately reach a steady-state temperature).

5.4 MATHEMATICAL MODEL FORMULATION

5.4.1 Establishment of the basic equations

To account for the simultaneous changes in the material conditions with locations and time, the heat (temperature) and mass (MC and RH) balances were formulated in the form of Partial Differential Equations (PDEs).

5.4.1.1 Heat transfer within the solid materials

Fourier's law for conductive heat transfer in one dimension with an extra term to account for heat transferred by diffusing water vapour (Bronlund, 1997) is given by:

$$\rho_m . c_{pm} \frac{\partial T}{\partial t} = \lambda_m \frac{\partial^2 T}{\partial x^2} - D_{vm.eff} . \varepsilon_m . h_g \frac{\partial^2 C}{\partial x^2} \qquad \ldots \ (5.1)$$

for $0 < x < L_p, (m=1)$

$L_p < x < L_p + L_2, (m=2)$

$L_p + L_2 < x < L_p + L_2 + L_3, (m=3)$ and

$t > 0.$

The physical properties involved in the equation are different for the different materials (i.e. m = 1, 2 or 3) comprising the system. For example, if the drying was performed on a drying pad of husk placed upon the soil then the properties of rice, husk and soil would be used for m = 1, 2 and 3, respectively.

5.4.1.2 Heat transfer at the boundaries

Heat transfer at the surface of the bed

Because the conceptualised model (Fig 5.1) includes a range of different drying operation setups (i.e. uncovered, direct covering, shading) a number of heat and moisture transport terms were included into the boundary condition at the bed surface. A word energy balance describing all the heat transfers at the boundary was written as:

Rate of heat gained from solar radiation if the bed is not shaded nor covered	or	Rate of heat gained from solar radiation if the bed is shaded but not covered	+	Rate of heat gained from shading tarpaulin by radiation if the bed is shaded but not covered	or	Rate of heat gained from covering tarpaulin by radiation if the bed is covered	+	Rate of heat gained by conduction from covering tarpaulin if the bed is covered	+	Rate of heat gained by moisture diffusion from the bed

=	Rate of heat lost by surface radiation to the sky if the bed is not shaded or covered	or	Rate of heat lost by surface radiation to the ambient air if the bed is shaded but not covered	+	Rate of heat lost by moisture evaporation to the ambient air if the bed is not covered	+	Rate of heat lost by convection to air if the bed is not covered	+	Rate of heat lost by conduction to the bulk grain below the surface

The balance was converted into the following mathematical equation

$$
\begin{aligned}
&\left(1 - S_1\right)\left(1 - S_2\right)\beta_p .A_{top} .I + S_1\left(1 - S_2\right)\beta_p .A_{top} .I_{sh} \\
&+ S_1\left(1 - S_2\right)F_{A1} .\in_{tarp} .\in_p .A_{top} .\sigma\left[\left(T_{sh} + 273.15\right)^4 - \left(T_{x=0} + 273.15\right)^4\right] \\
&+ S_2 .F_{A2} .\frac{1}{\left(\frac{1}{\in_{tarp}} + \frac{1}{\in_p}\right) - 1} .A_{top} .\sigma\left[\left(T_{cov} + 273.15\right)^4 - \left(T_{x=0} + 273.15\right)^4\right] \\
&+ S_2 .A .U_{tarp/p}\left(T_{cov} - T_{x=0}\right) - D_{vp.eff} .\varepsilon_p .h_{gin} .A\frac{\partial C}{\partial x} \\
&= \left(1 - S_1\right)\left(1 - S_2\right)\in_p .A_{top} .\sigma\left[\left(T_{x=0} + 273.15\right)^4 - \left(T_{sky} + 273.15\right)^4\right] \\
&+ S_1\left(1 - S_2\right)\in_p .A_{top} .\sigma\left[\left(T_{x=0} + 273.15\right)^4 - \left(T_a + 273.15\right)^4\right] \\
&- \left(1 - S_2\right)k_y .h_{gout} .A\left(C_1 - C_a\right) + \left(1 - S_2\right)h .A_{top}\left(T_{x=0} - T_a\right) - \lambda_p .A\frac{\partial T}{\partial x}
\end{aligned}
$$

… (5.2)

for $x = 0$ and $t > 0$.

The switches S_1 and S_2 correspond to the presence ($S = 1$) or not ($S = 0$) of the shade and direct cover, respectively. As an example, if the grain bed is shaded but not covered ($S_1 = 1$, $S_2 = 0$) then the bed surface does not receive direct solar heat load but indirect radiation load from the bottom of the shading tarpaulin, convective heat transfer from the ambient air, and loses heat by evaporation from the bed surface.

The surface area of the top of the bed may be different to the cross-sectional area of the bed due to the uneven surface. It was estimated by assuming that half the thickness of the paddy kernel (*d*) on the bed surface was exposed to the ambient air or the sun. So

$$A_{top} = a_k.V_{top} = a_k.A.\frac{d_k}{2} \qquad \text{… (5.3)}$$

Heat transfer between the rice bed and material 2 or between materials 2 and 3

The following equation was developed to describe the heat transfer between two of the materials and had to include a heat transfer resistance, especially when another material such as a tarpaulin was used at the interface:

$$\lambda_m \left.\frac{\partial T}{\partial x}\right|_m = \frac{\lambda_{tarp}}{L_{tarp}}\left(T_m - T_{m+1}\right) = \lambda_{m+1}\left.\frac{\partial T}{\partial x}\right|_{m+1} \qquad \text{... (5.4)}$$

for $x = L_p, (m=1)$ or $x = L_p + L_2, (m=2)$ and $t > 0$.

Heat transfer between material 3 and the ground

For this boundary, it was assumed that the temperature was equal to the constant deep ground temperature:

$$T_x = T_{gr} \qquad \text{... (5.5)}$$

for $x = L_p + L_2 + L_3$ and $t > 0$.

5.4.1.3 Heat transfer for the shading tarpaulin

For the shading tarpaulin, a word balance describing the steady-state heat transfer was written as

Rate of heat gained from the solar radiation	=	Rate of heat lost by radiation to the sky	+	Rate of heat lost by radiation to covering tarpaulin if the bed is covered	or	Rate of heat lost by radiation to the bed surface if the bed is not covered	+	Rate of heat lost by convection from the top and bottom to ambient air

And the balance was expressed mathematically as

$$A.\beta_{tarp}.I = \in_{tarp}.A.\sigma\left[\left(T_{sh}+273.15\right)^4-\left(T_{sky}+273.15\right)^4\right]+S_2.F_{A1}.\in_{tarp}.\in_{tarp}.A.\sigma\left[\left(T_{sh}+273.15\right)^4-\left(T_{cov}+273.15\right)^4\right]$$
$$+\left(1-S_2\right)F_{A1}.\in_{tarp}.\in_p.A.\sigma\left[\left(T_{sh}+273.15\right)^4-\left(T_{x=0}+273.15\right)^4\right]+2A.h\left(T_{sh}-T_a\right)$$

… (5.6)

Rearranging Equation (5.6) yielded:

$$T_{sh}=\frac{2h.T_a+\beta_{tarp}.I}{2h}$$
$$-\frac{\in_{tarp}.\sigma\left\{\left[\left(T_{sh}+273.15\right)^4-\left(T_{sky}+273.15\right)^4\right]+S_2.F_{A1}.\in_{tarp}\left[\left(T_{sh}+273.15\right)^4-\left(T_{cov}+273.15\right)^4\right]+F_{A1}\left(1-S_2\right).\in_p\left[\left(T_{sh}+273.15\right)^4-\left(T_{x=0}+273.15\right)^4\right]\right\}}{2h}$$

… (5.7)

This was applied when shading was applied (S_1 = 1) e.g. (11 am ≤ t ≤ 2 pm).

5.4.1.4 Heat transfer for the covering tarpaulin

For the covering tarpaulin, a word balance describing the steady-state heat transfer was written as:

[Rate of heat gained from the solar radiation if it is not shaded] or [Rate of heat gained from the solar radiation if it is shaded] + [Rate of heat gained from shading tarpaulin by radiation if it is shaded]

= [Rate of heat lost by radiation to the sky if it is not shaded] + [Rate of heat lost by radiation to the bed surface] + [Rate of heat lost by convection to ambient air] + [Rate of heat lost by conduction to the bed surface]

And the balance was expressed mathematically as

$$\left(1-S_1\right)A.\beta_{tarp}.I+S_1.A.\beta_{tarp}.I_{sh}+S_1.F_{A1}.\in_{tarp}.\in_{tarp}.A.\sigma\left[\left(T_{sh}+273.15\right)^4-\left(T_{cov}+273.15\right)^4\right]$$
$$=\left(1-S_1\right)\in_{tarp}.A.\sigma\left[\left(T_{cov}+273.15\right)^4-\left(T_{sky}+273.15\right)^4\right]$$
$$+F_{A2}\frac{1}{\left(\frac{1}{\in_{tarp}}+\frac{1}{\in_p}\right)-1}A.\sigma\left[\left(T_{cov}+273.15\right)^4-\left(T_1+273.15\right)^4\right]$$
$$+A.h\left(T_{cov}-T_a\right)+A.U_{tarp/p}\left(T_{cov}-T_{x=0}\right)$$

… (5.8)

The resistance for the heat conducted from the covering tarpaulin to the bed surface is

$$R_{tarp/p}=\frac{1}{U_{tarp/p}}=\frac{L_{tarp}}{\lambda_{tarp}}+\frac{L_a}{\lambda_a}=\frac{\lambda_a.L_{tarp}+\lambda_{tarp}.L_a}{\lambda_{tarp}.\lambda_a}$$

The temperature for the covering tarpaulin could be expressed as

$$T_{cov}=\frac{h.T_a+U_{tarp-p}.T_{x=0}+\beta_{tarp}\left[\left(1-S_1\right).I+S_1.I_{sh}\right]}{h+U_{tarp/p}}$$
$$+\frac{\in_{tarp}.\sigma\left\{S_1.F_{A1}.\in_{tarp}\left[\left(T_{sh}+273.15\right)^4-\left(T_{cov}+273.15\right)^4\right]-\left(1-S_1\right)\left[\left(T_{cov}+273.15\right)^4-\left(T_{sky}+273.15\right)^4\right]\right\}}{h+U_{tarp/p}}$$
$$-\frac{F_{A2}\frac{1}{\left(\frac{1}{\in_{tarp}}+\frac{1}{\in_p}\right)-1}\sigma\left[\left(T_{cov}+273.15\right)^4-\left(T_{x=0}+273.15\right)^4\right]}{h+U_{tarp/p}}$$

… (5.9)

for $x = 0$, $S_2 = 1$ and 11 am $\leq t \leq$ 2 pm.

When there is both shading and covering, Equations (5.7) and (5.9) are solved together iteratively to find T_{sh} and T_{cov}.

5.4.1.5 Moisture transfer in the grain kernels within the grain bed

The rate of moisture transfer in the grain kernels (drying rate) was taken as

$$\frac{\partial MC}{\partial t}=-k\left(MC-MC_e\right)+B \qquad \text{… (5.10)}$$

Determination of this rate expression is given in more detail in Section 6.1.28.

5.4.1.6 Moisture transfer in the air within the grain bed

The moisture transfer in the air within the grain bed was defined using Fick's law for diffusion in one dimension including a term for the rate of moisture transfer between the air space and the drying grain kernels.

$$\frac{\partial C}{\partial t} = D_{vp.eff}\frac{\partial^2 C}{\partial x^2} + \frac{\rho_{bp}}{\varepsilon_p}\left(-\frac{\partial MC}{\partial t}\right) \qquad \ldots (5.11)$$

for $0 < x < L_p$, $(m = 1)$ and $t > 0$.

5.4.1.7 Moisture transfer in the air within materials 2 and 3

The rate of moisture transfer in the air within these materials is defined as

$$\frac{\partial C}{\partial t} = D_{vm.eff}\frac{\partial^2 C}{\partial x^2} \qquad \ldots (5.12)$$

where

$$D_{vm.eff} = \frac{D_{vm}}{1+k''} \quad \text{and} \quad k'' = \frac{\rho_{bm} n_{slope}.522 P_{tot}.\rho_a}{\varepsilon_m.P_{vs}\left(18\,\rho_a + 29\,C\right)^2}$$

for $L_p < x < L_p+L_2$, $(m = 2)$ and for $L_p+L_2 < x < L_p+L_2+L_3$, $(m = 3)$.

Determination of this rate expression is given in more detail in Section 6.1.5.

5.4.1.8 Moisture transfer at the boundaries

<u>Moisture transfer at the surface of the bed</u>

A word balance describing the moisture movement at this bed boundary was written as

Rate of moisture diffusion from the bed	=	Rate of moisture convection out to the ambient air if the bed is not covered	or	Zero if the bed is covered

The mathematical equation was written as

$$D_{vp.eff}.\varepsilon_p.A\frac{\partial C}{\partial x} = (1 - S_2)k_y.A(C_{x=0} - C_a) \qquad \ldots (5.13)$$

for $x = 0$ and $t > 0$.

<u>Moisture transfer in at the bottom of the bed or bottom of material 2</u>

For these boundaries, a word balance describing the moisture diffusion was written as

Rate of moisture diffusion from the material below	=	Rate of moisture diffusion to the material above

If an interface such as tarpaulin is used, a term to account for the additional moisture transfer resistance was included. The mathematical equation is:

$$D_{vm.eff}\left.\frac{\partial C}{\partial x}\right|_m = \frac{1}{R_{MTm/m+1}}(C_m - C_{m+1}) = D_{vm+1.eff}\left.\frac{\partial C}{\partial x}\right|_{m+1} \qquad \ldots (5.14)$$

for $x = L_p$, $(m = 1)$ or $x = L_p + L_2$, $(m = 2)$ and $t > 0$.

Where $R_{MTm/m+1}$ is the resistance for the mass transfer due to the interface.

<u>Moisture transfer at the bottom of material 3</u>

Because no mass transfer is assumed to occur at this boundary:

$$D_{vm.eff}\frac{\partial C}{\partial x} = 0 \qquad \ldots (5.15)$$

for $x = L_p + L_2 + L_3$, $m = 3$ and $t > 0$.

5.4.1.9 The initial conditions

At the start of the drying, the initial temperatures for the grain, husk, mat, polystyrene, tarpaulin and net were assumed to be the same as the temperature of the ambient air at the moment because the plastic bags of grain and all the other materials had been exposed to the air. Therefore, at $t = 0$:

$$T = T_a \qquad \text{… (5.16)}$$

for the grain bed ($0 \leq x \leq L_p$) and for the husk, mat, polystyrene, tarpaulin and net pads ($L_p \leq x \leq L_p + L_2$) if they were used.

The temperature of the ground (T_{gr}) was assumed to be the initial temperature of the soil.

$$T_i = T_{gr} \qquad \text{… (5.17)}$$

for $x > L_p$ if no husk, mat or polystyrene was used as material 2, or
for x > L_p+L_2 if husk, mat or polystyrene was used as material 2.

The initial MC of the grain (MC_i) was measured by the moisture meter, therefore

$$MC = MC_i \qquad \text{… (5.18)}$$

for the grain bed or $0 \leq x \leq L_p$.

The initial water vapour concentration was calculated from the RH of the ambient air (RH_a) at that moment and the saturated vapour pressure at T_i.

$$C = C_i = \frac{0.018 RH_a . P_{vs}(T_i)}{R(T_i + 273.15)} \qquad \text{… (5.19)}$$

for $0 \leq x \leq L_P + L_2 + L_3$.

When the treatment involved the bed being stirred, the simulation was stopped at the point in time when stirring occurred, the temperature and the MC of the grain at the moment were taken to be the averages of all the nodes within the bed, and the simulation was restarted with all the nodes reset to the average values.

$$T = T_{average} = \frac{\int_0^{L_p} T.dx}{L_p} \qquad \ldots (5.20)$$

for $0 \leq x \leq L_P$ at $t = t_{stir}$.

$$MC = MC_{average} = \frac{\int_0^{L_p} MC.dx}{L_p} \qquad \ldots (5.21)$$

for $0 \leq x \leq L_P$ at $t = t_{stir}$.

The water vapour concentration in the air within the bed was determined using Equation (5.35) based on the RH of the ambient air at the time of stirring.

As stirring was done only for the grain bed, the temperature and water concentration for materials 2 and 3 were the same as they were just prior to stirring.

5.5 FINITE DIFFERENCE SOLUTION

After the conceptualisation development and formulation of the mathematical equations describing all the heat and moisture transfer in the sun drying system, the following steps were undertaken to solve the model.

As there were many coupled PDEs describing transport of heat and mass in the model and some of the algebraic equations were nonlinear, it was difficult to solve the problem analytically and thus numerical solutions were developed.

Because changes in the variables were observed not to occur quickly making stability problems less likely, an explicit finite differences scheme, which are one of the most common and easiest methods available to solve the models numerically, was chosen.

5.5.1 The grid

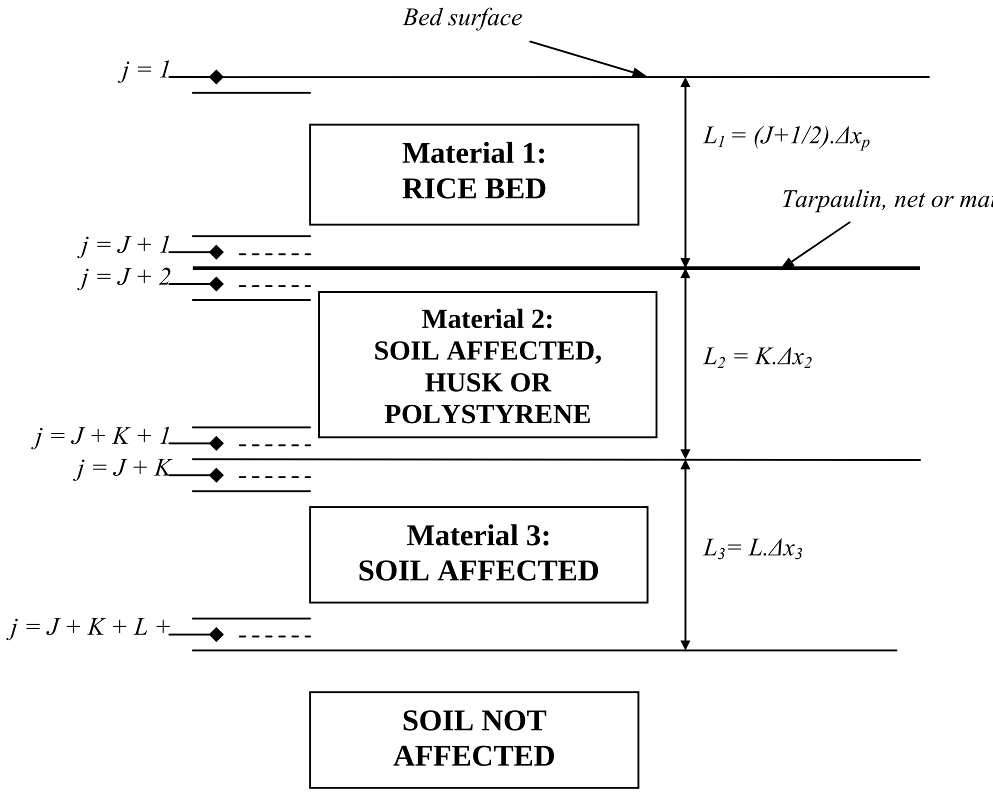


Fig 5.2: The finite difference grid used for all the materials during drying

A finite difference grid for all the materials exposed to the drying with all the nodes designation is shown in Fig 5.2. There are $J + ½$, K, and L space steps of Δx_p or $\Delta x_{m=1}$, Δx_2 and Δx_3 assigned in the rice bed, material 2 and 3 of L_p, L_2 and L_3 depths, respectively. To avoid having a node that contained two materials as well as the complexity caused by placing an interface between the two materials, the bottom node of each exposed material (i.e. $J+1$, $J+K+1$ or $J+K+L+1$) was located half a space step above the bottom of the material. Node 1 ($j = 1$) was located at the very surface of the grain bed with a space step of $\Delta x_p/2$. The top nodes of materials 2 and 3 were located half a space step below the corresponding material boundary.

5.5.2 ODE Equations

The following are the complete sets of the Ordinary Differential Equations ODEs describing the heat and moisture transfer within the sun drying system resulting from the heat and moisture balances over each node. More details of the material and node arrangements with the movements of heat and moisture including the mathematical derivation of the ODEs and other algebraic equations for the whole drying system are described in Appendix A3.

5.5.2.1 For the surface of the grain bed

For $j = 1$, Equation (5.1) subject to the boundary condition given in Equation (5.2) was approximated by

$$\begin{aligned}\frac{\partial Q_1}{\partial t} = & -(1-S_2)h.a_k.A\frac{d_k}{2}T_1 + (1-S_2)h.a_k.A\frac{d_k}{2}T_a - \frac{\lambda_p.A T_1}{\Delta x_p} + \frac{\lambda_p.A.T_2}{\Delta x_p} \\ & + (1-S_1)(1-S_2)\beta.a_k.A\frac{d_k}{2}I + S_1(1-S_2)\beta_p.a_k.A\frac{d_k}{2}I_{sh} \\ & + S_2.F_{A2}.\frac{1}{\left(\frac{1}{\in_{tarp}}+\frac{1}{\in_p}\right)-1}.a_k.A\frac{d_k}{2}\sigma\left[(T_{cov}+273.15)^4-(T_1+273.15)^4\right] \\ & + S_1(1-S_2).F_{A1}.\in_{tarp}.\in_p.a_k.A\frac{d_k}{2}\sigma\left[(T_{sh}+273.15)^4-(T_1+273.15)^4\right] \\ & + S_2.A.U_{tarp/p}(T_{cov}-T_1) + \frac{D_{vp.eff}.\varepsilon_p.A\left(h_{fg}+c_{pv}\frac{T_2+T_1}{2}\right)(C_2-C_1)}{\Delta x_p} \\ & - (1-S_1)(1-S_2)\in_p.a_k.A\frac{d_k}{2}\sigma\left[(T_1+273.15)^4-(T_{sky}+273.15)^4\right] \\ & - S_1(1-S_2)\in_p.a_k.A\frac{d_k}{2}\sigma\left[(T_1+273.15)^4-(T_a+273.15)^4\right] \\ & - (1-S_2)k_y.A\left(h_{fg}+c_{pv}\frac{T_1+T_a}{2}\right)(C_1-C_a)\end{aligned}$$

… (5.22)

where Q_1 is the amount of energy (J) in the node.

The temperature of the top node ($j = 1$) can be calculated from Q_1 using an energy balance given by:

$$T_1 = \frac{2Q_1 - C_1.\varepsilon_p.A.\Delta x_p.h_{fg}}{\left(1-\varepsilon_p\right)\rho_p.A.\Delta x_p.c_{pp} + \left(1-\varepsilon_p\right).\rho_p A.\Delta x_p.cp_w MC_1 + \varepsilon_p.\rho_a.A.\Delta x_p.c_{pa} + \varepsilon_p.A.\Delta x_p.c_{pv}.C_1} \quad \ldots (5.23)$$

The rate of the moisture transfer within the air for the node ($j = 1$) was given by:

$$\frac{\partial C_1}{\partial t} = \frac{2D_{vp.eff}\left(C_2 - C_1\right)}{\Delta x_p^2} + \frac{\rho_{bp}\left[k\left(MC_1 - MC_{e1}\right) - B\right]}{\varepsilon_p} - \frac{\left(1-S_2\right)2k_y\left(C_1 - C_a\right)}{\varepsilon_p.\Delta x_p} \quad \ldots (5.24)$$

The rate of moisture loss from the grain kernels in the top node ($j = 1$) was slightly different from the heat formulation because the kernels were assumed to be dried both to the air voids within the node, and directly into the ambient air.

$$\frac{\partial MC_1}{\partial t} = -k\left(MC_1 - MC_{e1}\right) + B - \frac{\left(1-S_2\right).d\left[k\left(MC_1 - MC_{ea}\right) - B\right]}{\Delta x_m} \quad \ldots (5.25)$$

for $j = 1$ and $t > 0$.

5.5.2.2 For the grain bed, material 2 and material 3

The rate of change of the energy content of nodes within the grain bed ($2 \le j \le J,\ m = 1$) or the other materials ($J+3 \le j \le J+K,\ m = 2$ and $J+K+3 \le j \le J+K+L,\ m = 3$) were approximated by

$$\frac{\partial Q_j}{\partial t} = \frac{\lambda_m.A\left(T_{j-1} - 2T_j + T_{j+1}\right)}{\Delta x_m} + \frac{D_{vm.eff}.\varepsilon_m.A\left(h_{fg} + c_{pv}\frac{T_{j+1}+T_j}{2}\right)\left(C_{j+1} - C_j\right)}{\Delta x_m} - \ldots$$
$$- \frac{D_{vm.eff}.\varepsilon_m.A\left(h_{fg} + c_{pv}\frac{T_j+T_{j-1}}{2}\right)\left(C_{j+1} - C_j\right)}{\Delta x_m}$$

(5.26)

The temperature was calculated using

$$T_j = \frac{Q_j - C_j.\varepsilon_m.A.\Delta x_m.h_{fg}}{\left(1-\varepsilon_m\right)\rho_m.A.\Delta x_m.c_{pm} + \left(1-\varepsilon_m\right).\rho_m A.\Delta x_m.c_{pw} MC_j + \varepsilon_m.\rho_a.A.\Delta x_m.c_{pa} + \varepsilon_m.A.\Delta x_m.c_{pv}.C_j}$$

… (5.27)

The moisture balances for the air associated with the nodes within the grain bed ($2 \le j \le J$) were given by

$$\frac{\partial C_j}{\partial t} = \frac{D_{vp.eff}\left(C_{j-1} - 2C_j + C_{j+1}\right)}{\Delta x_p^2} + \frac{\rho_{bp}\left[k\left(MC_j - MC_{ej}\right) - B\right]}{\varepsilon_p} \quad \text{… (5.28)}$$

The moisture balances for the air associated with the nodes within material 2 ($J+3 \leq j \leq J+K$, $m = 2$) and material 3 ($J+K+3 \leq j \leq J+K+L$, $m = 3$) were given by

$$\frac{\partial C_j}{\partial t} = \frac{D_{vm.eff}\left(C_{j-1} - 2C_j + C_{j+1}\right)}{\Delta x_m^2} \quad \text{… (5.29)}$$

5.5.2.3 For the rate of MC change within the grain bed

The rate of moisture drying out from a grain kernel for a node within the bed ($2 \leq j \leq J$) is given by

$$\frac{\partial MC_j}{\partial t} = -k\left(MC_j - MC_{ej}\right) + B \quad \text{… (5.30)}$$

5.5.2.4 For the bottom of the bed and bottom of material 2

The rate of change of the energy content of the nodes at $j = J+1$, $(m = 1)$ and $j = J+K+1$, $(m = 2)$ was given by

$$\frac{\partial Q_j}{\partial t} = \frac{\lambda_m.A\left(T_{j-1} - T_j\right)}{\Delta x_m}$$

$$+ \frac{2.\varepsilon_m.\varepsilon_{m+1}.D_{vm.eff}.D_{vm+1.eff}.A\left(C_{j+1} - C_j\right)\left(h_{fg} + c_{pv}\frac{T_{j+1} + T_j}{2}\right)}{\Delta x_m.\varepsilon_{m+1}.D_{vm+1.eff} + \Delta x_{m+1}.\varepsilon_m.D_{vm.eff} + 2.R_{MTm/m+1}.\varepsilon_m.\varepsilon_{m+1}.D_{vm.eff}.D_{vm+1.eff}}$$

$$- \frac{2\lambda_m.\lambda_{m+1}A\left(T_j - T_{j+1}\right)}{\lambda_{m+1}.\Delta x_m + \lambda_m.\Delta x_{m+1} + 2.\lambda_m.\lambda_{m+1}.R_{m/m+1}} - \frac{D_{vm.eff}.\varepsilon_m.A\left(C_j - C_{j-1}\right)\left(h_{fg} + c_{pv}\frac{T_j + T_{j-1}}{2}\right)}{\Delta x_m}$$

... (5.31)

Each term for heat transfer between nodes either side of the interface between materials includes effective properties calculated as heat/moisture transfer resistances in series. Full details of how this was done are given in Appendix A3.

The moisture balance for the air associated with the nodes was given by

$$\frac{\partial C_j}{\partial t} = \frac{2\,\varepsilon_{m+1}.D_{vm.eff}D_{vm+1.eff}\left(C_{j+1} - C_j\right)}{\Delta x_m\left(\varepsilon_{m+1}.D_{vm+1.eff}.\Delta x_m + \varepsilon_m.D_{vm.eff}.\Delta x_{m+1} + 2\,R_{MTm/m+1}\varepsilon_m.\varepsilon_{m+1}.D_{vm.eff}D_{vm+1.eff}\right)}$$

$$+\frac{\rho_{bm}\left[k\left(MC_j - MC_{ej}\right) - B\right]}{\varepsilon_m} - \frac{D_{vm.eff}\left(C_j - C_{j-1}\right)}{\Delta x_m^2}$$

… (5.32)

5.5.2.5 For the top of material 2 and material 3

The rate of change of the energy content of the nodes at $j = J+2$, $(m = 2)$ and $j = J+K+2$, $(m = 3)$ was given by

$$\frac{\partial Q_j}{\partial t} = \frac{2\,\lambda_{m-1}.\lambda_m A\left(T_{j-1} - T_j\right)}{\lambda_m.\Delta x_{m-1} + \lambda_{m-1}.\Delta x_m + 2.\lambda_{m-1}.\lambda_m.R_{m-1/m}} + \frac{D_{vm.eff}.\varepsilon_m.A\left(C_{j+1} - C_j\right)\left(h_{fg} + c_{pv}\dfrac{T_{j+1} + T_j}{2}\right)}{\Delta x_m}$$

$$-\frac{\lambda_m.A\left(T_j - T_{j+1}\right)}{\Delta x_m} - \frac{2\,\varepsilon_{m-1}.\varepsilon_m.D_{vm-1.eff}.D_{vm.eff}A\left(C_j - C_{j-1}\right)\left(h_{fg} + c_{pv}\dfrac{T_{J+2} + T_{J+1}}{2}\right)}{\Delta x_{m-1}.\varepsilon_m.D_{vm.eff} + \Delta x_m.\varepsilon_{m-1}.D_{vm-1.eff} + 2\,R_{MTm-1/m}.\varepsilon_{m-1}.\varepsilon_m.D_{vm-1.eff}.D_{vm.eff}}$$

… (5.33)

The moisture balance for the nodes was given by

$$\frac{\partial C_j}{\partial t} = \frac{D_{vm.eff}\left(C_{j+1} - C_j\right)}{\Delta x_m^2} + \frac{\rho_{bm}\left[k\left(MC_j - MC_{ej}\right) - B\right]}{\varepsilon_m}$$

$$-\frac{2\,\varepsilon_{m-1}.D_{vm-1.eff}.D_{vm.eff}\left(C_j - C_{j-1}\right)}{\Delta x_m\left(\varepsilon_{m-1}.D_{vm-1.eff}.\Delta x_m + \varepsilon_m.D_{vm.eff}.\Delta x_{m-1} + 2\,R_{MTm-1/m}.\varepsilon_{m-1}.\varepsilon_m.D_{vm-1.eff}.D_{vm.eff}\right)}$$

… (5.34)

5.5.2.6 For the bottom of material 3

at node $j = J+k+L+1$, the temperature

$T = T_{gr}$ ... (5.35)

The moisture balance for the node was given by

$$\frac{\partial C_{J+K+L+1}}{\partial t} = \frac{\rho_{bm}\left[k\left(MC_{J+K+L+1} - MC_{e.J+K+L+1}\right) - B\right]}{\varepsilon_m} - \frac{D_{vm.eff}\left(C_{J+K+L+1} - C_{J+K+L}\right)}{\Delta x_m^2}$$

... (5.36)

5.5.2.7 For the initial conditions

The initial amount of heat contained within the top node ($j = 1$) is given by

$$Q_{1i} = \left(1-\varepsilon_p\right)\rho_p.A\frac{\Delta x_p}{2}c_{pp}.T_{1i} + MC_{1i}\left(1-\varepsilon_p\right)\rho_p.A\frac{\Delta x_p}{2}c_{pw}.T_{1i} + \varepsilon_p.\rho_a.A\frac{\Delta x_p}{2}c_{pa}.T_{1i} + C_{1i}.\varepsilon_p.A\frac{\Delta x_p}{2}c_{pv}.T_{1i} + C_{1i}.\varepsilon_p A\frac{\Delta x_p}{2}h_{fg}$$

… (5.37)

and for all other nodes ($2 \leq j \leq J+K+L+1$) by

$$Q_{ji} = T_{ji}\left[\left(1-\varepsilon_m\right)\rho_m.A.\Delta x_m.c_{pm} + \left(1-\varepsilon_m\right).\rho_m A.\Delta x_m.c_{pw}MC_{ji} + \varepsilon_m.\rho_a.A.\Delta x_m.c_{pa} + \varepsilon_m.A.\Delta x_m.c_{pv}.C_{ji}\right]$$

$$+ C_{ji}.\varepsilon_m.A.\Delta x_m.h_{fg}$$

… (5.38)

5.5.3 Ancillary equations

The model formulation also relies on the following ancillary equations (ASHRAE, 1993):

From the ideal gas law

$$P_v = \frac{C.R\left(T + 273.15\right)}{0.018}$$ … (5.39)

Therefore, $RH = \frac{P_v}{P_{vs}} = \frac{C.R\left(T + 273.15\right)}{0.018P_{vs}\left(T\right)}$ … (5.40)

$$C = \frac{0.018RH_a.P_{vs}\left(T\right)}{R\left(T+273.15\right)} \text{ and} \quad \ldots (5.41)$$

$$P_{vs} = e^{23.4795-\frac{3990.56}{T+233.833}} \quad \ldots (5.42)$$

5.5.4 Numerical solution

The computer Matlab program version 7.1.0.246 (R14) with default value of 0.001 of relative error tolerance and ode 2.3 solver was used to solve the model numerically. The formulated ODEs as described in Section 5.5.2 were transformed to code to solve the model (Appendices A4 and B11).

Before proceeding to the final solutions, the model was checked in order to verify that it can perform with acceptable numerical and analytical errors.

5.5.5 Model checking

The numerical solution was checked after the formulation and solution by comparison to analytical solutions for simplified situations (see the details in Appendix A5). The discretisation of both space and time, by dividing the continua into a series of nodes and time-steps, over which the properties of the material are averaged, is the fundamental principle which forms the finite difference numerical scheme used in this work to solve the coupled heat and moisture transfer equations. In the case that the time-step approaches zero and the number of nodes approaches infinity, the real continua would be more closely modelled. This would, however, increase or extend the simulation time and introduces rounding errors which accumulate in the calculated results. Some trade-off is therefore required so numerical errors are at an acceptable level and simulation times are also sensible.

Based on all of the checks on the number of space steps in the grain bed, magnitude of time step in the solution, depth of the soil affected by the drying, number of space steps within the materials below the grain bed, temperature of the grain at the bottom and middle of the drying bed with the first and third kinds of boundary conditions, temperature of the grain at the surface of the bed under unsteady state condition, moisture concentration in the air at the bottom of the drying bed with first and third kinds of boundary conditions and moisture content of the grain within the bed, it can be declared that there were no significant numerical errors present when the number of space steps in the grain bed was 24 or more, the number of space steps within each material below the grain bed was 12 or more, the thickness of soil affected by the drying was 20 cm or more, and the default value of 0.001 of relative error tolerance in the Matlab ODE solver was selected. As a result of these checks, these values were used for all future simulations.

When compared with existing analytical solutions for simplified scenarios of the overall model the predicted heat and moisture transfer through the slab were shown to give accurate predictions. All of these checks indicated that the implementation of the formulated models was performed with no apparent error.

5.6 SUMMARY

A mathematical model describing the heat and moisture transfer within a sun drying system of rice had been conceptualised and mathematically formulated. Matlab code was developed to solve the resulting finite difference solutions. A numerical solution was required due to the many coupled PDEs and because some of the algebraic equations were nonlinear. The model was checked for a range of the space steps and by comparison to analytical solutions and was shown to contain no significant numerical error. The next steps in the modelling process were to determine or estimate the best values and uncertainties of the system inputs before the model could be validated against the experimental data.

Chapter 6

MODEL VALIDATION

6.1 DETERMINATIONS OF THE SYSTEM INPUTS AND CONSEQUENTIAL VARIABLES

There were many input parameters and consequential value variables required in the mathematical model. They were determined and selected for use based on the measurements made or information found in the literature, as described in the following sections. Tables 6.7 and 6.8 summarise all the parameters and variables.

6.1.1 Specific surface area of the paddy kernel, a_k [m^2/m^3]

The specific surface area of the paddy kernel was the ratio of the kernel surface area to its bulk volume. The surface and volume were calculated using the equations reported by Mohsenin (1986), based on the assumptions that the kernel shape is ellipsoid with its length as the major axis and the average of its width and thickness as the minor axis, and that the bulk and true densities remained constant during the drying period (see the detail of the calculation in Section A6.3 of Appendix A6).

The specific surface areas of the grain used of 1,000 ± 200 and 1,100 ± 240 m^2/m^3 were calculated from the average length and thickness measurements for CAR11 and Pka Knhey varieties, respectively (Appendix A6). Kunze and Wratten (1985) and Brooker *et al*. (1992) reported values of 1039 to 1132 m^2/m^3 for the specific surface area of medium paddy grain showing the results calculated here are reasonable.

6.1.2 Surface area of the drying bed and cross-sectional area of other materials, *A* [m^2]

Since the profiles of the heat, temperature and moisture were predicted within the thickness of the bed and the thickness is very small compared to the area, the drying bed was assumed to be an infinite slab and the model was formulated in one-dimension. So a cross-sectional area was arbitrarily taken to be 1 m^2 even though the actual drying bed was 0.16 m^2.

6.1.3 Specific heat capacity of air, husk, mat, grain, polystyrene, soil, water vapour and water, c_p [J/kg.^{o}C]

Incropera and DeWitt, (1996) as well as Lienhard and Lienhard (2005) reported a range of 1007 to 1008 J/kg.^{o}C for specific heat of air (c_{pa}) over the temperature range of 25 and 55^{o}C. Brooker *et al* (1992) reported a value of almost the same of 1007 J/kg.^{o}C. The air specific heat capacity was taken as 1007 J/kg.^{o}C.

Because the husk had been left in the ambient air for quite a long time since the grain was milled, its moisture content (MC) could be assumed to be equilibrated with the air humidity. Based on the husk isotherm used (Equation 6.33) as will be discussed later), for the average relative humidity (RH) of the ambient air of about 60%, the MC of the husk would be around 10%.

Based on measurements of the husk bulk density of 120 kg/m^3 and assuming that the true density was 705 kg/m^3 (Houston, 1972), the husk was estimated to be 83% air.

The specific heat of the husk (c_{ph}) was 1870 ± 187 J/kg.^{o}C. It was estimated based on the Equations given by Urbicain and Lozano (1997):

$$c_{ph} = \sum_{i=1}^{n} c_{pi}.w_i = c_{pa}.w_a + c_{pw}.w_w + c_{pcarb}.w_{carb} \qquad \text{… (6.1)}$$

Due to the similarity of the materials used to make the mat to that of paper, the specific heat of paper of 1340 ± 134 J/kg.^{o}C was chosen to apply for the mat (Incropera and DeWitt, 1996).

Based on the equations reported, the grain type and the way the parameter was used in the model formulation (Equation A3.9 of Appendix A3), a specific heat capacity of the grain defined on a dry-matter basis of 1115 ± 75 J/kg.^{o}C was used. This corresponds to the grain of zero MC.

A value of the specific heat of polystyrene *(c_{ppol})* of 1210 J/kg.^{o}C was used in the model, based on the information reported by Incropera and DeWitt (1996).

Incropera and DeWitt (1996) and Çengel (1997) reported a value of specific heat of soil *(c_{ps})* of 1840 J/kg.^{o}C while Çengel (2003) reported two values of 1900 and 2200 J/kg.^{o}C for dry and wet soils, respectively. As the soil used in the experiment was dry, the specific heat was taken as 1870 ± 30 J/kg.^{o}C.

Brooker *et al*. (1992) reported the specific heat of water vapour *(c_{pv})* as 1876 J/kg.^{o}C while Incropera and DeWitt (1996) reported a range of 1868 to 1911 J/kg.^{o}C for the temperature ranging from 22 to 57^{o}C as incurred in this study. Therefore, 1875 J/kg.^{o}C was used.

According to Incropera and DeWitt (1996) and Lienhard and Lienhard (2005), the specific heat of water *(c_{pw})* can change slightly under different temperatures. For the range of the temperatures that occurred in our drying of around 22 to 57^{o}C, these workers reported the specific heat from 4181 to 4185 J/kg.^{o}C. Again, as the range is very small (about 0.01% change), an average value of 4183 J/kg.^{o}C was used.

6.1.4 Thickness of the paddy kernel, d_k [mm]

From a measurement undertaken in this study, in which thickness of the paddy kernel was measured for 10 kernels, the values were observed to increase with the MC. The detail of the measurement, relevant calculations and the resultant data are described in Appendix A6. For the range of MC, the thicknesses of CAR11 and Pka Knhey paddy kernels of 2.12 ± 0.16 and 1.96 ± 0.18 mm, respectively, were used.

These values and ranges were consistent to values found from the literature. Kunze and Wratten (1985) reported the changes of the thicknesses of some paddy kernels as a function of MC. For MC ranging from 12 to 18%, the thickness was found to range from 1.96 to 2.01 mm and 1.9 to 1.98 for medium and long (Bluebonnet variety) kernels respectively. For other long grain (Starbonnet variety), the thickness was changed from 1.58 to 1.69 mm when the MC was changed from 5 to 19%.

6.1.5 Diffusivity of moisture in the air within the exposed materials, D_{vm} [m^2/s]

Diffusivity of moisture in the air (m^2/s) is affected by its temperature (Shah *et al.*, 1984). In still air, it was estimated using the following correlation:

$$D_{va} = 1.7255 \times 10^{-7}(T + 273.15) - 2.552 \times 10^{-5} \qquad \ldots (6.2)$$

In the presence of grain kernels within the bed, the diffusivity (D_{vp}) could be less because of the reduced area available for the transfer of the vapour and the effects of constrictivity and tortuosity in the media, but could be more because of the wind effects.

Initially, the assumption was made to neglect any bulk air flow through the bed; the diffusion was not as fast as in the open air due to the tortuosity and constrictivity of the diffusion path, and all the transfer processes were assumed to happen vertically. It was then observed that the predicted average MC of the bed was a lot higher than the measured data while the temperatures matched quite well. Of the two parameters that influenced the moisture transfer the most (the convective moisture transfer coefficient and the moisture diffusivity), the diffusivity was found to have an observable effect. Increasing the coefficient by 20 to 30% had an almost undetectable effect on the predicted average MCs, implying that it was out by a large amount.

The only reason why the diffusion coefficient could be increased significantly was if bulk air movement occurred in the bed. The wind speed measured during the experiments was found to vary during the day and from day to day in the range of 0 to 3 m/s. From simple hydrodynamics, a side wind must build up a small but positive pressure against the side of the bed which will induce a flow of bulk air through the bed.

To see if the effect of bulk air movement occurred in the bed could explain the observed difference in MC between the predicted and measured data, an order of magnitude calculation was conducted to estimate the likely velocities and hence distances that air might be moving within the bed, induced by the wind.

From the relationship between the pressure increase and the air current within the bed (Kunii and Levenspiel, 1991);

$$\frac{\Delta P}{L_{wp}} = 150 \frac{\left(1-\varepsilon_p\right)^2}{\varepsilon_p^3} \frac{\mu.u_o}{\left(\phi_s.D_k\right)^2} \qquad \ldots (6.3)$$

where

Diameter of the grain kernel (D_k), length of the kernel (L_k) and air viscosity (μ) were chosen to be 2.3 mm, 7 mm and 1.80 10^{-5} Pa.s, respectively and

The equivalent diameter $\phi_s.D_k = \sqrt{\dfrac{2\pi\dfrac{D_k^2}{4} + \pi.D_k.L_k}{\pi}}$ … (6.4)

Using $\Delta P = \frac{1}{2}\rho.u_o^2$, the velocities induced in the bulk air within the bed of 0, 4.8, 16.8 and 32.3 mm/s were calculated for the wind speed of 0, 1, 2 and 3 m/s, respectively, for a path of 400 mm through the bed. Since 400 mm is the longest possible path through the bed, actual velocities will be higher.

As an approximation, the diffusion coefficient was used to calculate an equivalent velocity for moisture in the bed. It was found to be 7.6 mm/s in still air. Looking at the relative magnitudes of these velocities, it could be seen that when the wind was blowing, diffusivities from 2 to 5 times larger would be needed to account for the effect of the wind.

To define the patterns of the pressure drop and air currents within the three dimensional bed would be a very complicated process due to many factors, such as the surface, shape and arrangement of the grain kernels within the bed as well as the angle of the bed side and the fluctuation in the wind speed. This was beyond the limits of the simple model developed here and it was decided to look at the effect of increasing the diffusion co-efficient by an average factor of 1.5 to account for the effect of the tortuosity and constrictivity of the diffusion path and the wind on the drying rate.

Based on the assumptions described in Section 5.3.2 of Chapter 5 and to account for the effects of tortuosity and constrictivity (Bronlund, 1997), as well as the effect of wind speed on moisture movement, the effective diffusivity of moisture in the air within the grain bed (D_{vp}) was taken as the diffusivity for still air multiplied by a factor of 1.5 ± 0.5.

For materials 2 and 3; an effective diffusivity which included the equilibrium absorption of the particles was required.

A general moisture balance in the air is given by

$$\frac{\partial C}{\partial t} = D_{vm} \frac{\partial^2 C}{\partial x^2} - \frac{\rho_{bm}}{\varepsilon_m} \frac{\partial MC}{\partial t} \qquad \dots (6.5)$$

Rather than having the drying rate of the particles following some dynamic rate (as within the grain kernels), within these materials equilibrium with the air was assumed.

The moisture sorption isotherms for soil, husk and mat are complex but over most of the range of interest they are relatively linear (see more detail in Section 6.1.29). Assuming a linear isotherm, relatively between MC_e and air *RH*

$$MC_e = n_{slope}.a_w + E \qquad \dots (6.6)$$

where the water activity (a_w) is defined as

$$a_w = \frac{RH}{100} = \frac{P_v}{P_{vs}} \qquad \dots (6.7)$$

The water vapour pressure, according to ASHRAE (1993), is expressed as

$$P_v = \frac{29\, H.P_{tot}}{18 + 29\, H} \qquad \dots (6.8)$$

Humidity ratio can be written in terms of water vapour concentration using

$$H = \frac{C}{\rho_a} \qquad \dots (6.9)$$

Substituting Equation (6.8) in (6.7) yields

$$P_v = \frac{29\,C.P_{tot}}{\rho_a\left(18 + \frac{29\,C}{\rho_a}\right)} = \frac{29C.P_{tot}}{18\rho_a + 29\,C} \quad \ldots (6.10)$$

Using equations (6.6), (6.7) and (6.10) yields

$$MC_e = \frac{n_{slope}.29\,C.P_{tot}}{P_{vs}\left(18\,\rho_a + 29\,C\right)} + F \quad \ldots (6.11)$$

Differentiating and simplifying equation (6.11) yields

$$\frac{\partial MC_e}{\partial C} = \frac{522.n_{slope}.P_{tot}.\rho_a}{P_{vs}\left(18\,\rho_a + 29\,C\right)^2} \quad \ldots (6.12)$$

As $\frac{\partial MC_e}{\partial t} = \frac{\partial MC}{\partial C} \cdot \frac{\partial C}{\partial t}$

$$\Rightarrow \frac{\partial MC_e}{\partial t} = \frac{n_{slope}.522.P_{tot}.\rho_a}{P_{vs}\left(18\,\rho_a + 29\,C\right)^2}\frac{\partial C}{\partial t} \quad \ldots (6.13)$$

Substituting equation (6.13) in equation (6.5):

$$\frac{\partial C}{dt} = D_{vm}\frac{\partial^2 C}{\partial x_m^2} - \frac{\rho_{bm}}{\varepsilon_m}\frac{n_{slope}.522.P_{tot}.\rho_a}{P_{vs}\left(18\,\rho_a + 29\,C\right)^2} \cdot \frac{\partial C}{\partial t}$$

$$= \frac{D_{vm}}{1 + \frac{\rho_{bm}}{\varepsilon_m}\frac{n_{slope}.522.P_{tot}.\rho_a}{P_{vs}\left(18\,\rho_a + 29\,C\right)^2}}\frac{\partial^2 C}{\partial x_m^2} \quad \ldots (6.14)$$

If $k'' = \frac{\rho_{bm} n_{slope}.522 P_{tot}.\rho_a}{\varepsilon_m.P_{vs}\left(18\,\rho_a + 29\,C\right)^2}$

The rate of moisture diffusion in the air was overall defined as

$$\frac{\partial C}{\partial t} = D_{vm.eff}\frac{\partial^2 C}{\partial x^2} \quad \ldots (6.15)$$

where

The effective diffusivity in the materials $D_{vm.eff} = \dfrac{D_{vm}}{1+k''}$

for $L_p < x < L_p+L_2, (m = 2)$ and for $L_p+L_2 < x < L_p+L_2+L_3, (m = 3)$.

Therefore, the effective diffusivity in these materials is dependent on the isotherm slope (n_{slope}), porosity (ε) and bulk density (ρ_b) of the material, saturated water vapour pressure (P_{sat}) and moisture concentration (C).

The diffusivity was set to zero for the polystyrene (D_{vpol}) as the structure or property of the material does not allow moisture or air to move through it.

6.1.6 Geometric and emissivity correction factors for energy radiated between parallel surfaces

The net heat radiated between parallel surfaces, according to Kern (1950), is

$$q = F_{A1}.F_e.A.\sigma\left(T_{sh}^4 - T_{cov}^4\right) \qquad \ldots (6.16)$$

for shading and covering tarpaulins, where the geometric factor F_{A1} = 0.63. This was defined based on the geometric considerations where the ratio of the side length of the shading tarpaulin and distance from the bed is 3 (4.5 × 4.5 m tarpaulin 1.5 m over the bed) and the emissivity correction factor $F_e = \in_{tarp} . \in_{tarp}$

$$q = F_{A1}.F_e.A.\sigma\left(T_{sh}^4 - T_1^4\right) \qquad \ldots (6.17)$$

for shading tarpaulin and bed surface, where F_{A1} = 0.63 and $F_e = \in_{tarp} . \in_p$

$$q = F_{A2}.F_e.A.\sigma\left(T_{cov}^4 - T_{x=0}^4\right) \qquad \ldots (6.18)$$

for covering tarpaulin and bed surface, where F_{A2} = 1 and $F_e = \dfrac{1}{\left(\dfrac{1}{\in_{tarp}} + \dfrac{1}{\in_p}\right) - 1}$

6.1.7 Convective heat transfer coefficient, *h* [W/m^2.^{o}C]

Convective heat transfer coefficient is an important parameter in a drying simulation since it influences the temperature difference between the air and the crop. The coefficient is related to the rate of air movement and depends on the degree of exposure of a surface to air flow and the amount of turbulence (Cleland *et al*., 2005). Anwar and Tiwari (2001) and Togrul (2003) reported the value of 0.25 to 26 W/m^2.^{o}C for a number of crops and stated that the large variation was due to different porosity (different air movement), MC, shape and size of the crop. According to Fellows (2000), the heat transfer coefficient changes for different wind speeds (6 and 30 W/m^2.^{o}C for the wind speed of 0 to 3 m/s).

Cleland *et al*. (2005) stated that for natural convection (less than 0.4 m/s wind speed) over a planar surface, the coefficient is typically 3 to 10 W/m^2.^{o}C. For the air movement or wind speed greater than 0.4 m/s over the surface, the coefficient can be predicted approximately using:

$$h = 7.3\, v_a^{0.8} \quad \ldots (6.19)$$

To account for the sensitivity of the wind meter (the propeller was observed to hardly move when the wind speed was lower than 1 m/s) and the roughness of the grain bed, the coefficient was firstly determined by using Equations 6.19 for the wind speed greater than 1 m/s. For the wind speed lower than that, a coefficient of 7.3 was chosen. Fig 6.1 shows the wind speed measured during the 2004 experiments.

All the values were increased by a factor of 2 (Table 6.1). This was based on the results of a number of attempts to use the model. Without the correction, the model was found to predict the air and grain conditions very poorly. The logical basis is that the grain kernels can not be arranged perfectly or smoothly at the bed surface leading to some increase in surface area (A_{top} = 1.11 A for CAR11 and A_{top} = 1.08 A for Pka Knhey). The bed surface roughness will also affect the heat convection due to an increase in the amount of turbulence etc.

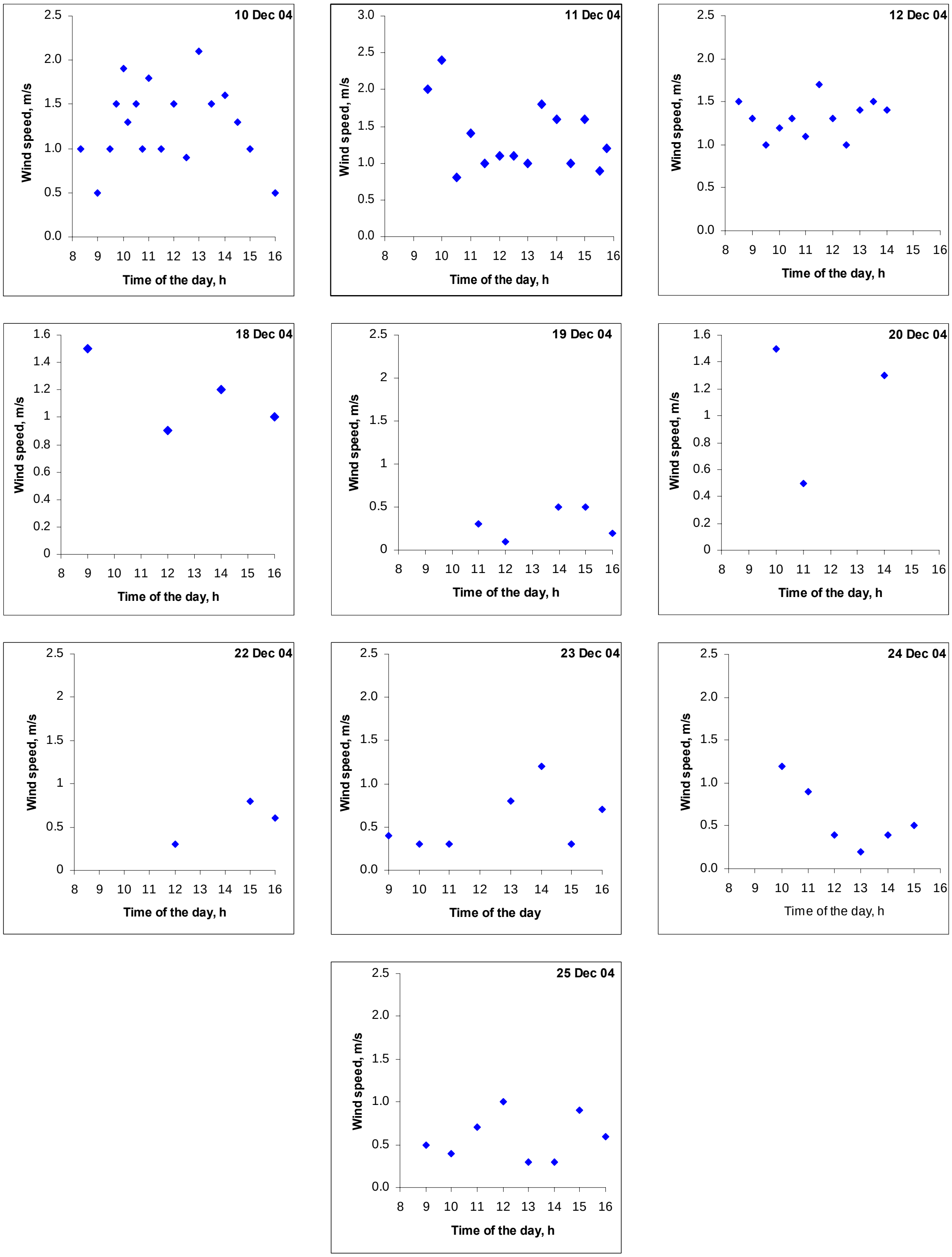


Fig 6.1: Wind speed measured during the 2004 experiments

Table 6.1: The measured wind speed and corresponding convective heat transfer coefficient used in the model

Date	v_a, *m/s*	**h**, $W/m^2.^oC$
10/12/04	1.3	18.0
11/12/04	1.35	18.6
12/12/04	1.3	18.0
18/12/04	1.2	16.9
19/12/04	0.32	14.6
20/12/04	1.1	15.8
22/12/04	0.57	14.6
23/12/04	0.57	14.6
24/12/04	0.6	14.6
25/12/04	0.59	14.6

Note: The heat transfer coefficient was calculated as $h = 14.6$ for $v_a < 1$ m/s and

$h = 14.6\, v_a^{0.8}$ for $v_a > 1$ m/s

6.1.8 Latent heat of evaporation, h_{fg} [J/kg]

Jain and Tiwari (2004) reported the latent heat of evaporation of water of 2260 kJ/kg while other workers claimed a change in the value for paddy grain under the effects of its MC and temperature. Brooker *et al*. (1992) suggested an exponential equation between the h_{fg}, the grain temperature (T) and MC (dry basis):

$$h_{fg} = 1000\,(2502.2 - 2.39\,T)\,(1 + 2.0692\,e^{-21.739.MC_{db}}) \quad \ldots (6.20)$$

Applying this equation with the temperature and MC ranges observed in the drying experiments, the heat of evaporation of water from paddy kernels was found to range from about 2453 to 2589 kJ/kg. For a similar range of temperature, according to Incropera and DeWitt (1996) and Lienhard and Lienhard (2005), h_{fg} would range from about 2343 to 2500 kJ/kg. Therefore, a latent heat of evaporation of 2424.5, ± 164.5 kJ/kg was used.

6.1.9 Solar intensity, I [W/m^2]

The solar intensity was measured at the drying site at 5 minute intervals for the whole drying time by a solarimeter or pyranometer (Li-200SB) that was exposed horizontally to the sun. The meter was calibrated by comparing with three other calibrated meters operated by the Met Service Calibration Laboratory in Paraparaumu, New Zealand.

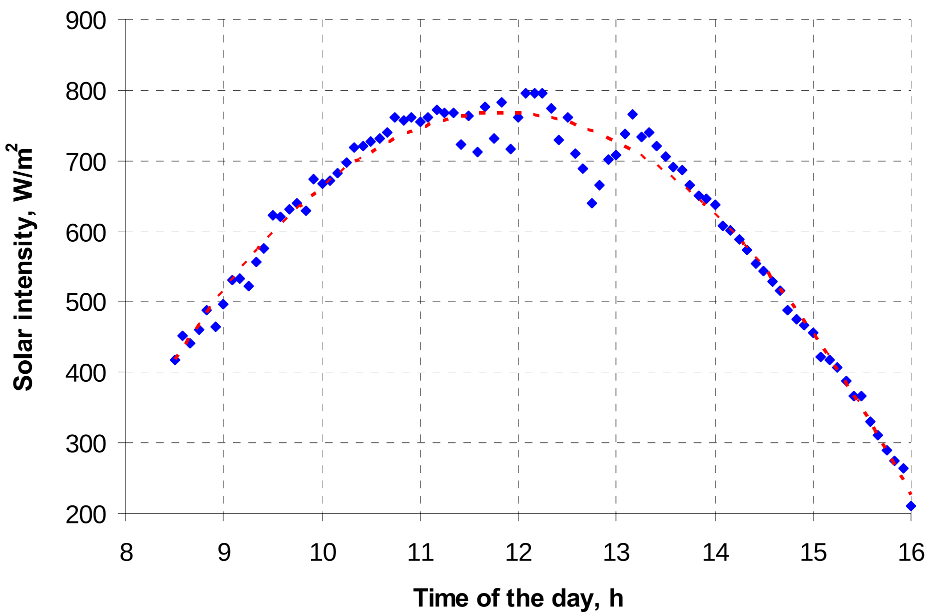


Fig 6.2: The measured and curve-fitted solar intensity for December 10, 2004

Fig 6.2 shows the intensity for one drying day (December 10, 2004) as it fluctuated throughout the drying time. The data were fitted by a polynomial line (dash) expressed as

$$I = -2.42 \times 10^{-6}\ t^2 + 2.06 \times 10^{-1}\ t - 3632.83 \qquad \ldots (6.21)$$

with the correlation coefficient R^2 of 0.97, where the time (t) of the day is expressed in seconds. In addition to R^2, Root Mean Square Error (RMSE) was also used to determine the quality of fit (Toğrul and Pehlivan, 2002).

Due to the variation in the intensity caused by the movement of clouds as shown by the Fig 6.2, values of the intensity had a RMSE of 24 W/m^2 about the fitted line. This level of variation was used in the sensitivity analysis.

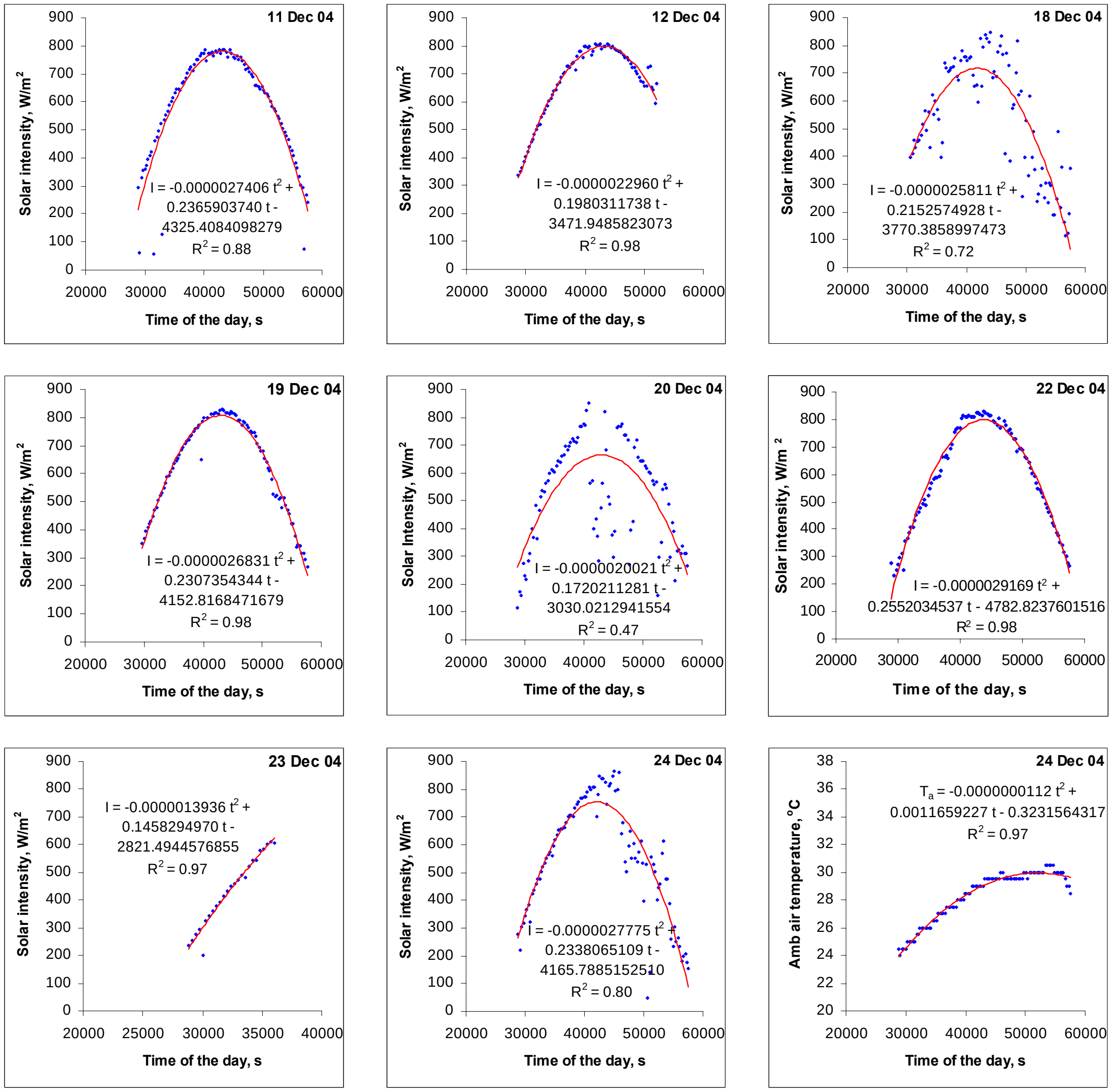


Fig 6.3: Solar intensity measured during the 2004 experiments

<u>Note</u>: For December 18 and 20, the raw data of I was used instead of the equations

The same approach was used to determine the intensity during the other drying days (see Fig 6.3) and the results are summarised in Table 6.2. For the days in which the intensity was more variable, the raw data was directly used using a table search instead of the fitted equation. This lead to significant increases in computation time, so use of the fitted equation was preferred.

Table 6.2: Solar intensity vs day time (s) as measured during the experiments

Date	I, W/m^2	R^2	± RMSE*
10/12/04	-2.42E-06 t^2 + 2.06E-01 t - 3.63E+03	0.97	24.30
11/12/04	-2.74E-06 t^2 + 2.37E-01 t - 4.33E+03	0.89	62.39
12/12/04	-2.30E-06 t^2 + 1.98E-01 t - 3.47E+03	0.98	17.07
18/12/04	-2.58E-06 t^2 + 2.15E-01 t - 3.77E+03	0.72	108.28
19/12/04	-2.68E-06 t^2 + 2.31E-01 t - 4.15E+03	0.98	17.79
20/12/04	Raw data via table search		
22/12/04	-2.92E-06 t^2 + 2.55E-01 t - 4.78E+03	0.98	27.62
23/12/04	-1.39E-06 t^2 + 1.46E-01 t - 2.82E+03	0.97	10.05
24/12/04	Raw data via table search		
25/12/04	- 2.49E-06 t^2 + 2.16E-01 t - 3.95E+03	0.98	25.22

*Note: *Root Mean Square Error.*

A test to detect the relative change in solar intensity in shade under a tarpaulin or under a direct cover was undertaken in New Zealand with clear sky conditions. Placing the solarimeter sensor in the shade under the tarpaulin caused the intensity to drop to about 5% of the value found under direct sunlight and covering it caused the measured solar intensity to drop to zero. For that reason, a value for the solar intensity under the shade (I_{sh}) of 5% of the value found under direct sunlight was applied.

6.1.10 Convective moisture transfer coefficient, k_y [m/s]

The mass transfer coefficient was related to the heat transfer coefficient by the Lewis relationship which is expressed as (Foust *et al.*, 1980):

$$Le = \frac{h}{k_g . c_{pa}} \approx 1 \qquad \text{… (6.22)}$$

The convective moisture transfer coefficient was expressed as

$$k_y = \frac{k_g}{\rho_a} = \frac{h}{Le . c_{pa} . \rho_a} \qquad \text{… (6.23)}$$

A 5% variation of the value of the Lewis number was assumed so *Le* was taken as 1 ± 0.05.

6.1.11 Thickness of the air gap between the grain and the covering tarpaulin or the drying pad below, L_a [m]

The thickness of the air gap between the surface of the bed and the covering tarpaulin was taken to range from 0.8 to 1.2 mm. The same gap was taken between the bottom of the bed and the drying tarpaulin or the mat.

6.1.12 Depth or thickness of the materials, L_m [mm]

During the experiments, the depth of the drying beds was controlled by using wooden frames with 20 and 30-mm heights. Before drying, the grain samples were poured into the frames that were placed on the appropriate drying pad and a level was used to smooth the bed surfaces. Due to the grain size, the roughness of the bed surface and the effect of MC reduction, bed depths of 20 ± 2 and 30 ± 2 mm were used.

The depths or thicknesses of the husk, mat polystyrene and tarpaulin were measured to be 70 ± 5, 2 ± 0.5, 40 ± 2 and 0.6 ± 0.1 mm respectively.

6.1.13 Initial moisture content, MC_i [decimal, db]

The results of four replicates measurement for each day were used. The initial MC of the grain was found to vary from 21.0 to 22.6% wet basis (or 0.266 to 0.292 dry basis).

Because the assumption was made that the particles in materials 2 and 3 (soil, husk, polystyrene and mat) were always in equilibrium with the surrounding air, the ODEs for the rate of moisture transfer were not needed. Therefore, initial MCs these materials were not required.

6.1.14 Ambient air relative humidity, RH_a [%]

RH of the ambient air was also measured at 5-minute intervals for the whole drying time by the Tinytag RH sensor placed under shade. Fig 6.4 shows the RH measured on December 10, 2004. A curve-fitting the data (dash) was used (R^2 = 0.95), as for the solar intensity, the *RH* was defined as

$$RH_a = 2.56 \times 10^{-8}\ t^2 - 0.002.92 \times 10^{-3}\ t + 134.51 \qquad \ldots (6.24)$$

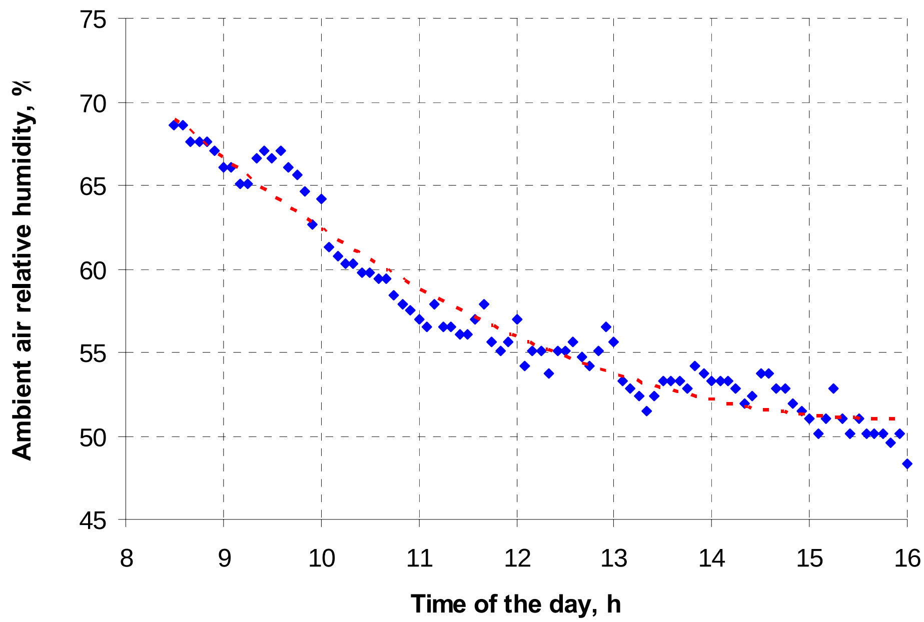


Fig 6.4: The ambient air relative humidity measured on December 10, 2004

The same approach was used to determine the RH during the other drying days (see Fig 6.5) and fitted equations for the *RH* with corresponding R^2 and RMSE for the various days are listed in Table 6.3.

Table 6.3: Relative humidity of the ambient air vs day time (s) as measured during the experiments

Date	RH_a**, %**	R^2	**± RMSE**
10/12/04	2.56E-08 t^2 - 2.92E-03 t + 1.35E+02	0.95	1.23
11/12/04	3.47E-08 t^2 - 3.65E-03 t + 1.53E+02	0.97	1.01
12/12/04	-3.62E-08 t^2 + 2.78E-03 t + 2.23E+00	0.77	1.17
18/12/04	9.5E-12 t^3 1.24E-06 t^2 + 5.21E-02 t - 6.55E+02	0.91	2.77
19/12/04	2.06E-08 t^2 - 2.80E-03 t + 1.34E+02	0.93	2.20
20/12/04	Raw data via table search		
22/12/04	3.96E-08 t^2 - 4.81E-03 t + 1.86E+02	0.93	3.31
23/12/04	-3.39E-08 t^2 - 2.81E-04 t + 1.19E+02	0.97	1.00
24/12/04	6.94E-08 t^2 - 7.35E-03 t + 2.38E+02	0.96	2.54
25/12/04	1.44E-08 t^2 - 1.95E-03 t + 1.11E+02	0.90	2.04

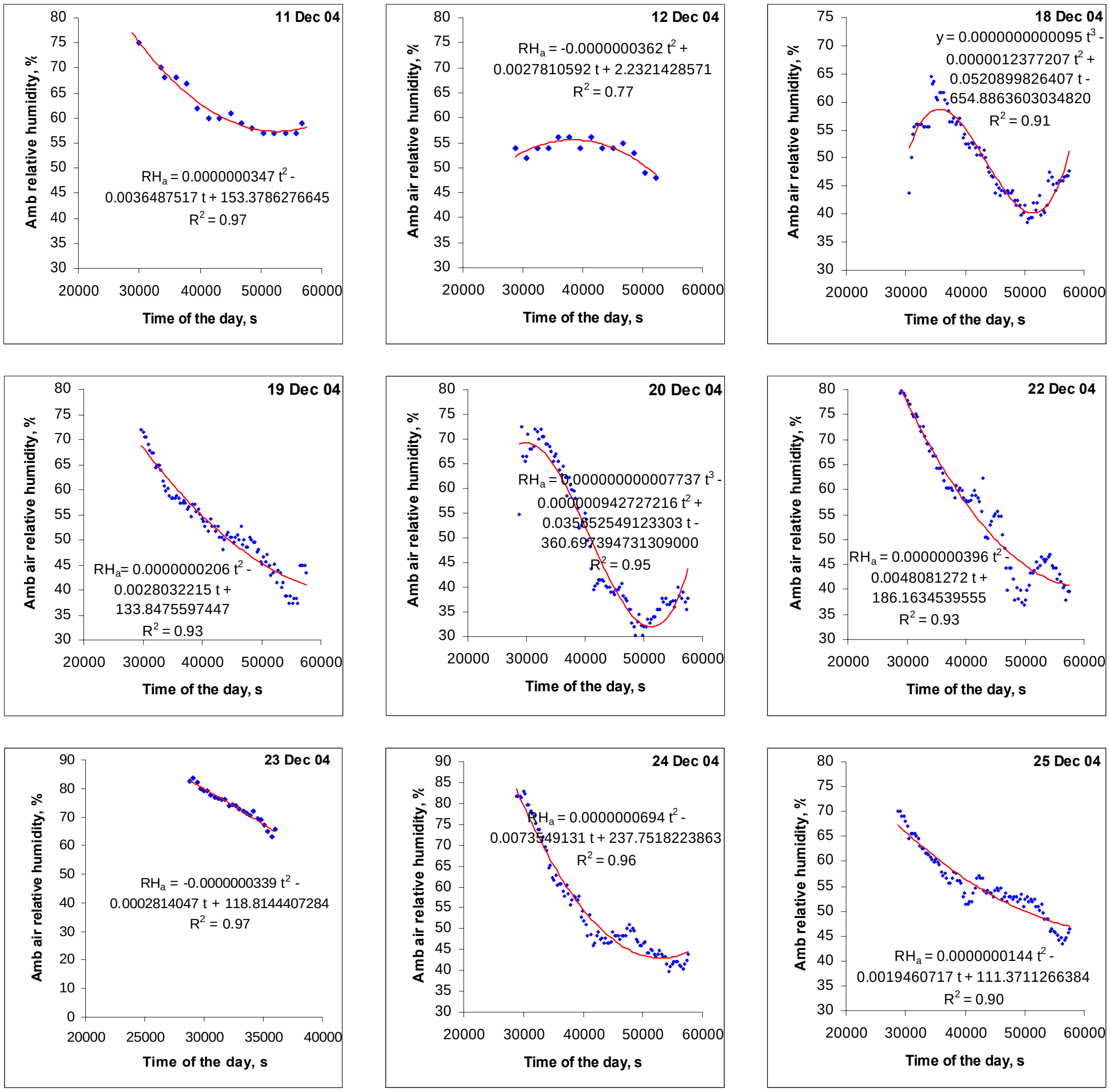


Fig 6.5: RH of the ambient air measured during the 2004 experiments

6.1.15 Resistance to moisture transfer through material, $R_{MTm/m+1}$ [s/m]

As it was assumed that no moisture transfer occurred through the tarpaulin so the resistance to the moisture transfer through this material was set to infinity. For other materials, the resistance was set to zero. The zero value was used for the mat because it was observed to be wet during the drying which suggests that the mat material could let moisture pass through it quite easily.

6.1.16 Resistance to heat conduction, $R_{tarp/p}$ and $R_{m/m+1}$ [m^2.^{o}C/W]

The resistance of the covering tarpaulin to the grain bed or from the grain bed to the drying pads represented the combined effect of the sheet material and the air layer between the material and the bed.

6.1.17 Initial RH of the air within the materials, RH_i [decimal]

The initial RH of the air within the grain bed was determined from the rice moisture isotherm (Equation 6.32) assuming that the air and the grain were in equilibrium.

6.1.18 Ambient air temperature, T_a [^{o}C]

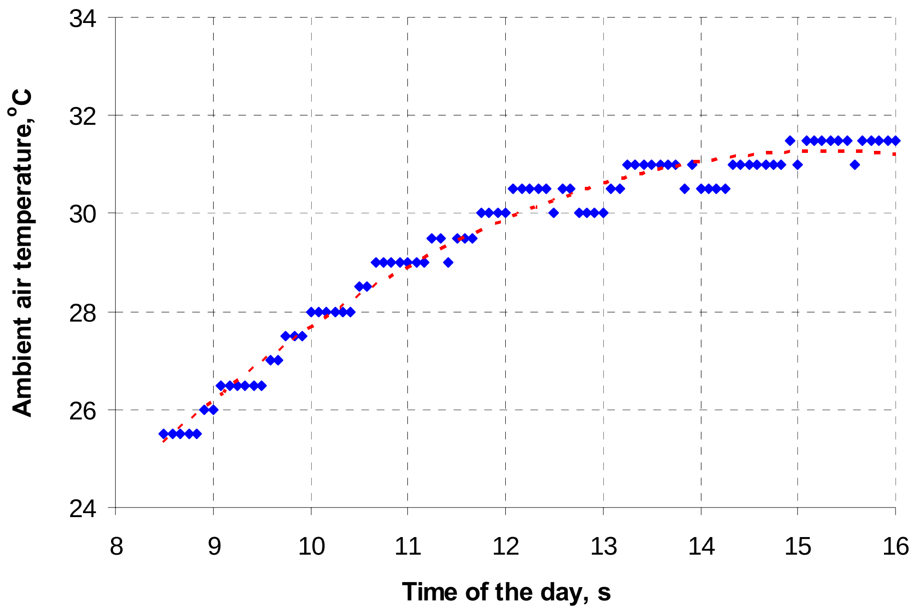


Fig 6.6: The temperature of the ambient air measured on December 10, 2004

The ambient air temperature was measured at 5 minute intervals for the whole drying time by an I-button placed under shade. The measured data were fitted by (dash) (Fig 6.6) (R^2 = 0.98)

$$T_a = -1.00 \times 10^{-8}\ t^2 + 0.001.10^{-3} \times t + 1.07 \qquad \dots (6.25)$$

As shown by Fig 6.6, there was some scattering for the temperature measured which could be caused by the sensitivity of the I-button used (0.5°C resolution). Using a similar approach to that for solar intensity and RH of the ambient air (Fig 6.7), the fitted equations for the ambient air temperature with corresponding R^2 and RMSE are listed in Table 6.4.

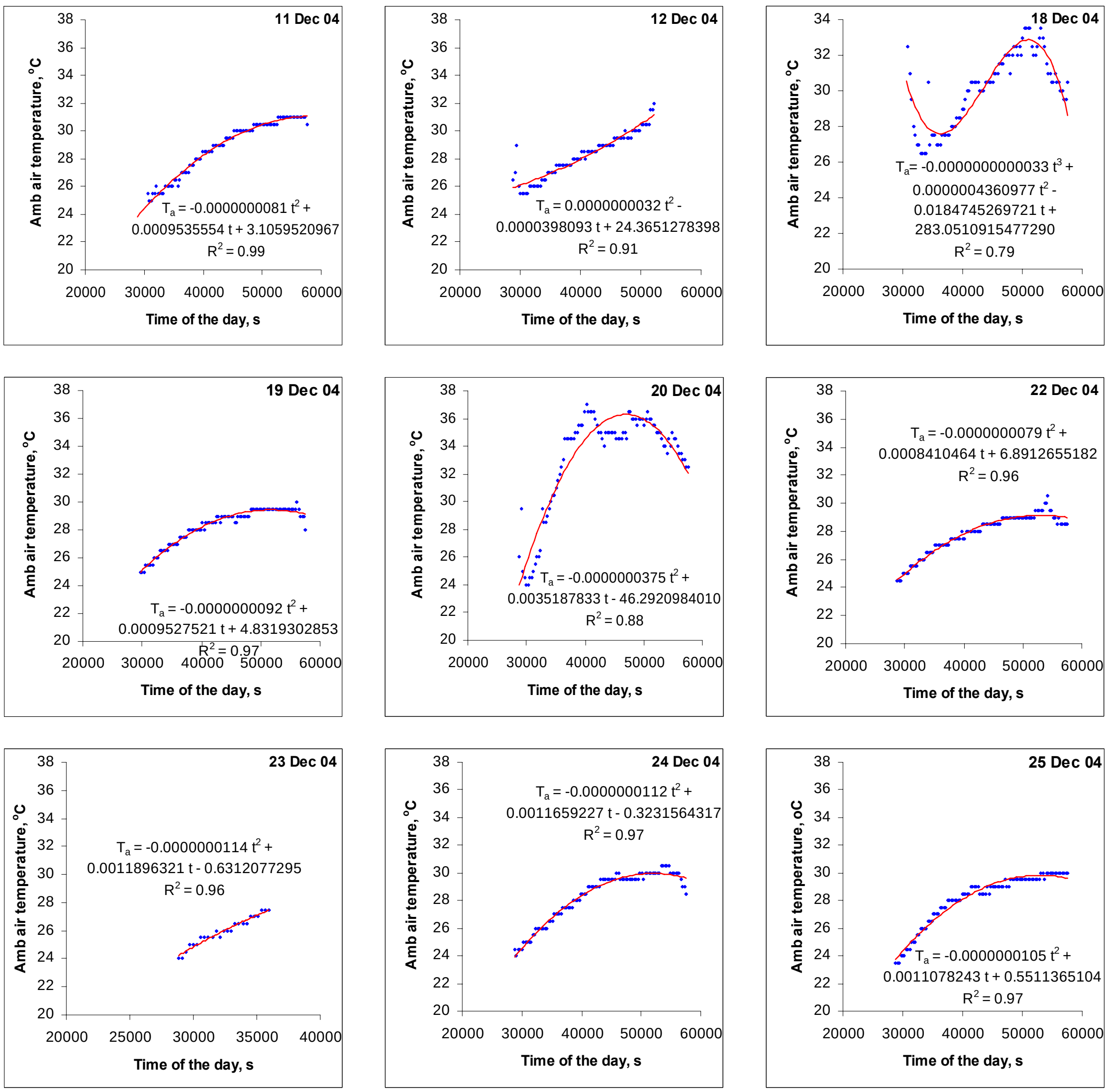


Fig 6.7: Temperature of the ambient air measured during the 2004 experiments

Table 6.4: Temperature of the ambient air vs day time (s) as measured during the experiments

Date	T_a**, %**	R^2	**± RMSE**
10/12/04	-1.00E-08 t^2 + 1.10E-03 t + 1.07E+00	0.98	0.28
11/12/04	-8.10E-09 t^2 + 9.54E-04 t + 3.11E+00	0.99	0.24
12/12/04	3.20E-09 t^2 - 3.98E-05 t + 2.44E+01	0.91	0.50
18/12/04	-3.30E-12 t^3 + 4.36E-07 t^2 - 1.85E-02 t + 2.83E+02	0.79	3.73
19/12/04	-9.20E-09 t^2 + 9.53E-04 t + 4.83E+00	0.97	0.23
20/12/04	Raw data via table search		
22/12/04	-7.90E-09 t^2 + 8.41E-04 t + 6.89E+00	0.96	0.30
23/12/04	-1.14E-08 t^2 + 1.17E-03 t - 6.31E-01	0.96	0.21
24/12/04	-1.12E-08 t^2 + 1.17E-03 t - 3.23E-01	0.97	0.29
25/12/04	-1.05E-08 t^2 + 1.11E-03 t + 5.51E-01	0.97	0.32

6.1.19 Temperature of the ground, T_{gr} [^{o}C]

The temperature of the ground or the soil (below j = J + K + L + 1) was assumed to stay constant at 25^{o}C for the whole time. The temperature was taken as the average temperature of the ambient air for the month that was reported by Nesbitt (1997) (see Fig 2.7.22 of Chapter 2).

6.1.20 Initial temperature of the grain, T_i [^{o}C]

Initial temperature of the grain samples were recorded at the start of the drying by the I-buttons (Table 6.5):

Table 6.5: Initial temperature of the grain samples measured on the drying days

Date	T_i**, ^{o}C**	**Date**	T_o**, ^{o}C**
December 10, 2004	25	December 22, 2004	24
December 11, 2004	23	December 23, 2004	27
December 18, 2004	26	December 24, 2004	24
December 19, 2004	28	December 25, 2004	24
December 20, 2004	24	December 26, 2004	24
December 21, 2004	24		

6.1.21 Temperature of the sky, T_{sky} [°C]

Incropera and DeWitt (1996) reported the sky temperature to vary depending on atmospheric conditions. It ranges from a low of -43°C under a cold, clear sky to a high of approximately 12°C under warm, cloudy conditions.
Rauch (2003) presented a relationship for determination of the sky temperature during the day:

$$T_{sky} = 0.0552\,(T_a + 273.15)^{1.5} - 273.15 \qquad \text{… (6.26)}$$

Based on this relationship, for the daily minimum and maximum temperatures of 20 and 31.5°C as incurred during the experiments, respectively, the sky temperature was found to vary from 3.9 to 21°C during the days of experiments.

Alternatively, Amos (1995) suggested a procedure to calculate the sky temperature. Using this method, an average sky temperature of 12.6°C was calculated, which is close to the average value found from Rauch (2003) method. A sky temperature of 12.6 ± 7.4°C was used.

6.1.22 Thermal conductivity of air, polystyrene, soil and tarpaulin, λ [W/m.°C]

A thermal conductivity of air (λ_a) of 0.0263 W/m.°C was used (Incropera and DeWitt, 1996).

The same workers reported different values for thermal conductivity of polystyrene (λ_{pol}) (0.027 and 0.04 W/m.°C for extruded and model beads, respectively, at 25°C). Fellows (2000) reported the value for foam polystyrene as 0.036 W/m.°C at 0 °C while Lienhard and Lienhard (2005) reported the value for expanded polystyrene as 0.035 W/m.°C at 4 to 55°C. As extruded foam was the type of the material used, a thermal conductivity of 0.027 to 0.036 or 0.0315 ± 0.0045 W/m.°C was used.

A thermal conductivity of the soil (λ_s) between 0.52 ± 0.05 W/m.°C was used based on the soil characteristics and the value reported by Incropera and DeWitt (1996), Çengel (1997) and Garg and Kumar (2000). The chosen range is consistent with that reported by Evett (1999) for silt loam soil (consisting of a friable mixture of varying proportions of clay, silt, and sand): 0.4 and 1.0 W/m.^{o}C for dry and wet respectively.

For the tarpaulin, a thermal conductivity (λ_{tarp}) of polyethylene of 0.42 ± 0.05 W/m.^{o}C (Cleland and Valentas, 1997) was used.

6.1.23 Effective thermal conductivity of the husk, mat and grain [W/m.^{o}C]

Houston (1972) gave husk effective thermal conductivity value in the range 0.0359 to 0.0864 W/m.^{o}C that varied with bed depth. A value of 0.07 ± 0.01 W/m.^{o}C was used. It is noted that this is twice the value of about 0.036 W/m.^{o}C reported by Juliano (1985) and value calculated using the method given by Urbicain and Lozano (1997) and Levy (1981).

Due to the similarity of the materials, a thermal conductivity value of solid cardboard of 0.06 ± 0.01 W/m.^{o}C (Cleland and Valentas, 1997) was used for the mat.

Based on the information described in Section 2.2.1.4 of Chapter 2, an effective thermal conductivity of 0.125 ± 0.045 W/m.^{o}C was used for the grain.

6.1.24 Absorptivity (β) and emissivity ($\in$) of radiation of the grain bed and tarpaulin

The absorptivity, absorptance or absorption coefficient of radiation is expressed as a fraction of the solar energy incident on the grain bed or tarpaulin surface which has been absorbed by the surface. According to physical laws for black and grey bodies, a material has the same absorptivity and emissivity (or emittance) for a given wavelength (Mills, 1995; Shivakumar, 1996; and Fellows, 2000).

The absorptivity and emissivity are relative absorptive and emissive power of the grain compared to that of an ideal blackbody. In other words, they are a fraction of solar radiation absorbed and emitted compared to the amount emitted if the body were a blackbody. By definition, a blackbody is an ideal surface that has absorptivity and emissivity of 1 (Mills, 1995). Brewster (1992) and Çengel (2003) described a blackbody's surface as a perfect absorber and perfect emitter; it absorbs any and all radiation incident upon it and reflects none.

Brewster (1992), Mills (1995), Shivakumar (1996), Fellows (2000) and Çengel (2003) list the coefficients for a number of materials, including soil (0.93 to 0.96), vegetation (0.92 to 0.96), asphalt (0.88 to 0.93), concrete (0.88 to 0.94) and human skin (0.95). Jain and Tiwari (2003) suggest a value of 0.9 for emissivity but 0.65, 0.8, 0.8, 0.7, 0.8 and 0.65 for absorptivity of green chillies, green peas, white gram, onion flakes, potato slices and cauliflower, respectively. According to ETI (2006), the absorptivity and emissivity of tarpaulin (polypropylene) is 0.97. Based on all of these, the two coefficients of radiation of 0.85 ± 0.05 and 0.97 ± 0.02 were selected for the bed and tarpaulin surfaces, respectively.

6.1.25 True density of husk, mat, grain, polystyrene and soil, ρ [kg/m^3]

Houston (1972) reported that rice husk has a density (ρ_h) of about 735 kg/m^3 while Juliano (1985) reported a density of 670 to 740 kg /m^3. The density of the husk was taken as 705 ± 35 kg/m^3.

Due to lack of measuring equipment, it was not possible to measure the mat density in Cambodia. The density (ρ_{mat}) was then assumed to be 950 ± 95 kg/m^3 as for sole leather or paper (Incropera and DeWitt, 1996).

As reported in Section A6.5 of Appendix A6, the densities of the grain (ρ_p) for CAR11 and Pka Knhey varieties were taken to be 1145 ± 95 and 1135 ± 85 kg/m^3, respectively.

As it was assumed that there was no moisture diffusion in the polystyrene, the material can be assumed to have zero porosity without affecting model predictions. Therefore, its density (ρ_{pol}) of 22 ± 1 kg/m^3 that was measured during the experiments was taken to be the same as its bulk density (ρ_{bpol}).

Iwata *et al*. (1995) reported the volume fraction of solids of different soils in Japan as ranging from 20 to 49% with the rest being water and air. Based on this information, the bulk density of the soil used and the soil characteristic observed during the trials, a density of the soil particles (ρ_s) of 3250 ± 250 kg/m^3 was used.

6.1.26 Bulk density of rice husk, mat, grain, polystyrene and soil, ρ_b [kg/m^3]

The measured bulk density of the husk (ρ_{bh}) of 120 ± 10 kg/m^3 was used. The measurement was made by weighing the husk of known volume. The bulk density value was found to agree very well with the range of 100 to 160 kg/m^3 as reported by Juliano (1985). Houston (1972) reported the density of husk to be about 100 kg/m^3.

Due to the same problem as described in 6.1.25, the mat bulk density (ρ_{bmat}) was assumed be 690 ± 69 kg/m^3 as for cardboard (Incropera and DeWitt, 1996).

The bulk density of paddy rice is, according to ASAE (2004d) and ASAE (2005d), approximately 579 kg/m^3. For the grain used, the bulk density (ρ_{bp}) was found from a standard test (see the detail in A6.5 of Appendix A6) to be 548 ± 23 to 580 ± 23 and 568 ± 12 to 622 ± 24 kg/m^3 for CAR11 and Pka Knhey varieties with MC from about 14 to 27%, respectively. When shaking or tapping was applied, the bulk density was found to increase to 593 ± 28 to 615 ± 13 and 610 ± 16 to 642 ± 13 kg/m^3, respectively. To cover the ranges found, the bulk density of the two varieties were taken as 576 ± 54 and 600 ± 45 kg/m^3, respectively.

A bulk density of the soil (ρ_{bs}) of 1800 kg/m^3 was measured on site. However, to avoid under or over-estimation, due to the change in the soil compactness as caused by the sampling disruption, the soil density was taken to range from 1,750 to 1,850 or 1800 ± 50 kg/m^3. Incropera and DeWitt (1996), Çengel (1997) and Garg and Kumar (2000) reported the density of similar soil to be around 2050 kg/m^3. Lienhard and Lienhard (2005) and Çengel (2003) reported the density range of 1500 to 1930 kg/m^3, depending on the soil types, its wetness and compactness.

6.1.27 Porosity of the materials, ε_m

Porosity is the ratio or percentage of the air space or air void to the material bulk volume. For rice grain, it was reported to range from 0.48 to 0.58 (Kunze and Wratten, 1985; Brooker *et al*., 1992; Chakraverty and Singh, 2001, ASAE, 2004d; and ASAE 2005d). The property has also been reported to change according to the grain type and MC. (Wratten *et al*., 1969).

The porosity was calculated for all the materials using

$$\varepsilon = 1 - \frac{\rho_b}{\rho} + eps \qquad \text{… (6.27)}$$

where a very small value of *eps* (2.2204×10^{-16}) was used to avoid having a zero porosity for mathematical reasons in the case of polystyrene.

6.1.28 Coefficients for the drying rate

The rate of moisture transfer in the grain kernels (drying rate, $\frac{\partial MC}{\partial t}$) was determined as a linear function of the difference between current *M*C and MC_e

$$MR = \frac{MC - MC_e}{MC_i - MC_e} \qquad \text{… (6.28)}$$

The approach developed by Chen and Wu (2001) was adopted. It is a two-compartment thin-layer model with two-term exponential function. This corresponds to drying with no constant drying rate period.

The finding agrees very well with what was reported by Trim and Robinson (1994). According to the author, when a single layer of grain is exposed to drying, the moisture content falls rapidly at first but as the grain loses moisture the rate of drying slows and, in general, the drying rate decreases with moisture content, increases with an increase in air temperature or decreases with an increase in air humidity.

Moreover, Brooker *et al*. (1992) claimed that cereal grain kernels, when drying as single particles under constant external conditions, dry entirely within the falling-rate period; while some biological products exhibit a constant-rate moisture loss during the initial drying period followed by a falling-rate drying phase. About this kind of relationship, these authors also claimed that it is often used in the grain drying analysis by assuming that the rate of moisture loss of a grain kernel surrounded by air is proportional to the difference between the kernel moisture and its equilibrium moisture content.

The fitting as shown in Fig 6.8 yielded

$$MR = \frac{MC - MC_e}{MC_i - MC_e} = a_1.e^{-k_1.t} + a_2.e^{-k_2.t} \quad \ldots (6.29)$$

where,

a_1 = 15.02E-02; a_2 = 84.98E-02; k_1 = 49.39E-04; k_2 = 11.50E-05 for CAR11

a_1 = 14.49E-02; a_2 = 85.26E-02; k_1 = 50.76E-04; k_2 = 12.90E-05 for Pka Knhey variety and R^2 = 0.999 for both varieties.

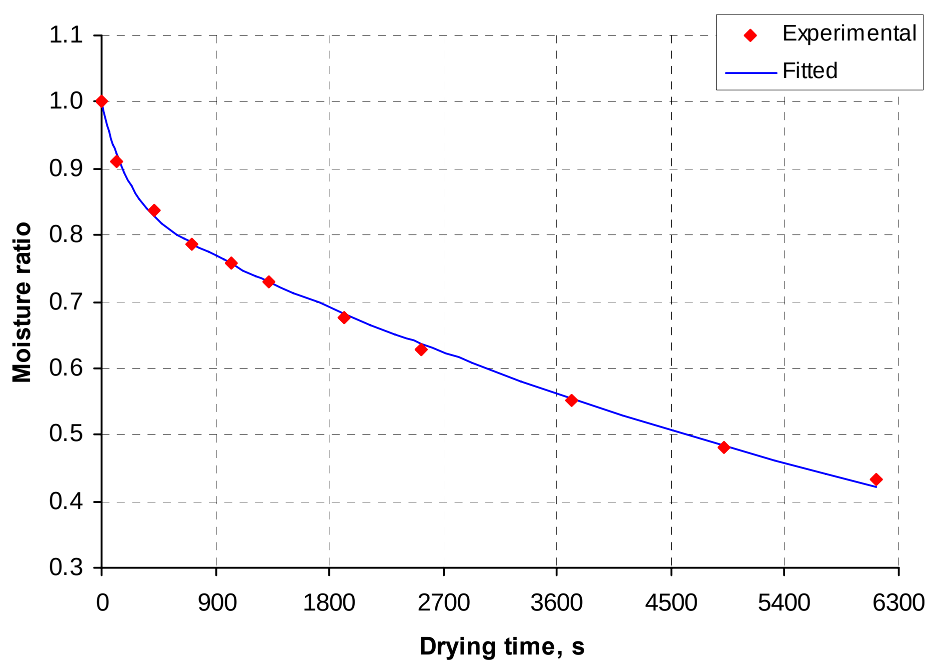


Fig 6.8: Change in the moisture ratio of CAR11 variety during the drying time

<u>Note</u>: The grain of about 24% MC was dried in a thin layer using a flat bed dryer (Taylor and Andrews Ltd., Palmerston North, New Zealand) at a constant air temperature of 51°C. The inlet air temperature was 22°C and the air velocity was 3 m/s.

Therefore,

$$MC = MC_e + \left(MC_i - MC_e\right).\left(a_1.e^{-k_1.t} + a_2.e^{-k_2.t}\right)$$

A differential form of the model is required because drying conditions change with the time. So

$$\frac{\partial MC}{\partial t} = \left(MC_i - MC_e\right)\left(-k_1.a_1.e^{-k_1.t} - k_2.b_2.e^{-k_2.t}\right) \qquad \ldots (6.30)$$

Plotting $\frac{\partial MC}{\partial t} = \left(MC_i - MC_e\right)\left(-k_1.a_1.e^{-k_1.t} - k_2.b_2.e^{-k_2.t}\right)$ versus *(MC - MC$_e$)* (Fig 6.9) and performing a regression analysis, the drying rate is

$$\frac{\partial MC}{\partial t} = -\,k\left(MC - MC_e\right) + B \qquad \ldots (6.31)$$

where,

$$\frac{\partial MC}{\partial t} = -\,12.15 \times 10^{-05}\left(MC - MC_e\right) + 97 \times 10^{-08}$$

with R^2 = 0.999 for CAR11 variety and moisture content difference of 0.12 to 0.22 db.

$$\frac{\partial MC}{\partial t} = -\,35.68 \times 10^{-4}\left(MC - MC_e\right) + 76.62 \times 10^{-5}$$

with R^2 = 0.984 for CAR11 variety and moisture content difference of 0.22 to 0.28 db..

$$\frac{\partial MC}{\partial t} = -\,13.78 \times 10^{-5}\left(MC - MC_e\right) + 12.20 \times 10^{-7}$$

with R^2 = 0.999 for Pka Knhey variety and moisture content difference of 0.11 to 0.22 db.

$$\frac{\partial MC}{\partial t} = -\,38.60 \times 10^{-4}\left(MC - MC_e\right) + 81.07 \times 10^{-5}$$

with R^2 = 0.999 for Pka Knhey variety and moisture content difference of 0.22 to 0.27 db.

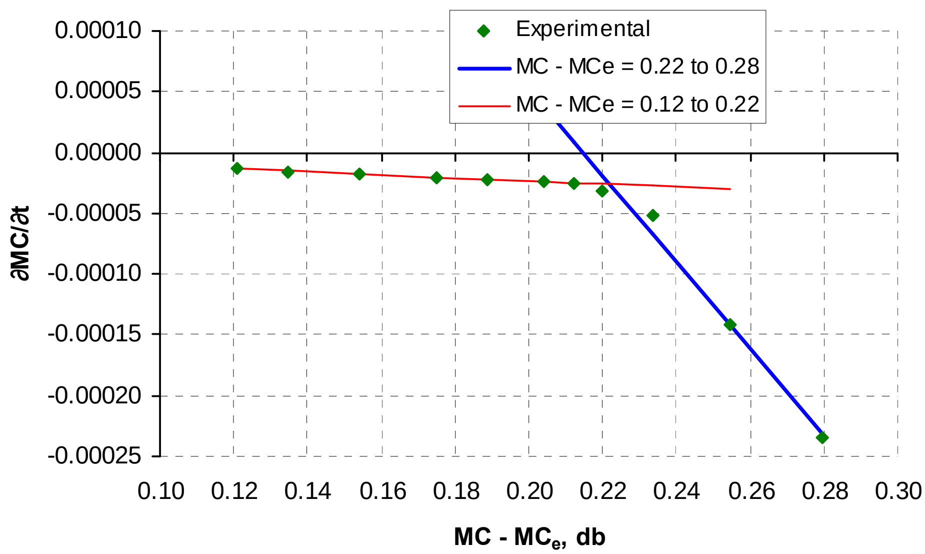


Fig 6.9: Fitting the $\frac{\partial MC}{\partial t}$ ***vs MC – MC$_e$ for CAR11 variety***

Therefore, the trend of $\frac{\partial MC}{\partial t}$ is not constant but changes with time and difference in the grain moisture contents ($MC - MC_e$). It follows two different slopes (k) and two intersects (B) above and below a MC difference of about 22% db.

6.1.29 Moisture isotherms for the exposed materials

To determine the MC_e of the grain, husk, mat and soil during drying, isotherm equations were identified and used.

The isotherm equations for paddy grain that have been reported in the literature were found to make the MC asymptotic when the RH approaches 100%. This caused mathematical solution problems and, therefore, the modified-Chung-Pfost isotherm equation, using the MCs of paddy (ASAE, 2001; ASAE, 2003c; ASAE, 2004c; ASAE, 2005c), equilibrated in the air of different RH as reported by Brooker *et al*. (1992) was used.

To supplement the reported set of data that did not include the grain MC for the 100% RH, a test was performed using the paddy samples. In the test, after soaking in water for five hours, all the free water surrounding the sample kernels was removed by wiping with paper tissues before they were subjected to the oven test (130^{o}C for 24 hours) to determine their MCs. When studying the change in the RH of the air at the bottom of the bed during the drying experiment, the grain kernels were exposed to the air with saturated water vapour for about five hours after the drying was started. From that test, the highest MCs of 33.87 and 35.84 for the Pka Knhey and CAR11 rice varieties, respectively, were found. These results compared quite well with the MCs of many other grains in the air at 100% RH that were published by Brooker *et al* (1992).

Using Excel, fitting the data set with the equation by shifting the water activity 0.0063 to the right (offset of the RH = -0.0063) resulted in the following isotherm equation:

$$MC_{ep} = 0.308782 - 0.051337 \ln [-(T + 35.586) \ln (a_w - 0.00631436)] \quad \ldots (6.32)$$

The equation was compared against the fitted data and Fig 6.10 shows that a good fit was achieved.

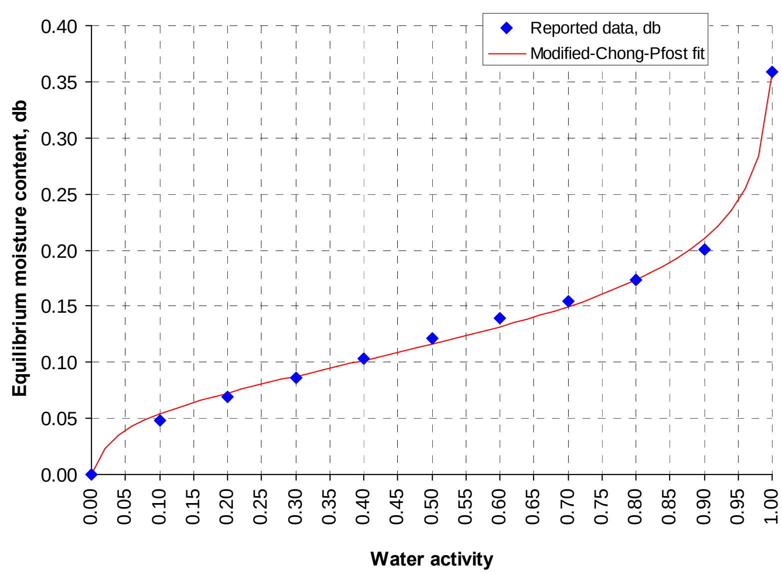


Fig 6.10: Comparison of the equilibrium MC predicted by the developed isotherm equation against equilibrium MC reported by ASAE, 2001; ASAE, 2003c; ASAE, 2004c; ASAE, 2005c

According to Houston (1972), the MC of husk of mixed rice varieties as shown in Table 6.6 falls consistently below those for milled, brown, or paddy rice. The differences of several percent are undoubtedly due to the absence of any quantity of starch or sugars in husk, which have relatively high equilibrium values, and to the presence of considerable silica.

Table 6.6: Equilibrium MC of rice husk (Source: Houston, 1972)

RH, %	10	20	30	40	50	60	70	80	90
MC_{eh}, % wb.	3.7	5.4	6.8	7.9	9.1	10.1	10.8	11.6	14

While assuming that there was equilibrium between the solid husk and the air phase at any point in the bed, and the isotherm for the husk was linear with a slope n_{slope}, plotting the data in the table (as shown in Fig 6.11) in combination with the use of the isotherm developed for the experimental paddy and performing regression technique yielded Equation (6.33) which describes the moisture isotherm for the husk. Bureau *et al.* (2002) claimed that many sorbents exhibit linear isotherms at low concentrations.

$$MC_{eh} = n_{slope}.a_w + F = 0.1404\ a_w + 0.0278 \qquad \ldots (6.33)$$

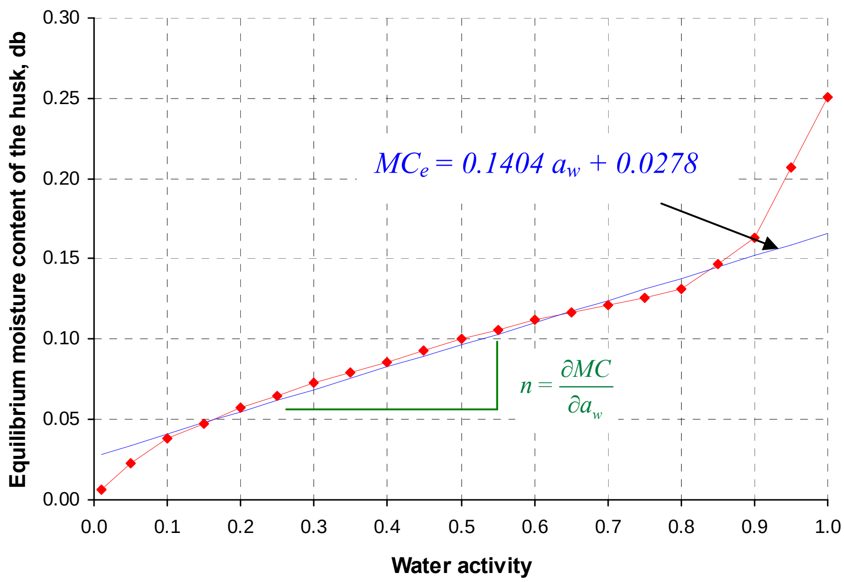


Fig 6.11: Assumed linear moisture isotherm for the husk

For the mat used, due to the complexity in the determination and the unavailability of the information in the literature, the isotherm for the husk was used.

For polystyrene, the slope of infinity was taken due to the fact that there is no movement of air or moisture within this material.

The slope of 0.413 was defined for the application with the soil using an isotherm reported by Orchiston (1954) for Montmorillonite clay soil.

Table 6.7: Summary of the values and ranges of the system inputs used

Symbol	Description	Value taken	Reference
a_k [m^2/m^3]	Specific surface area of CAR11	1000 ± 200	Mohsenin (1986)
a_k [m^2/m^3]	Specific surface area of Pka Knhey	1100 ± 240	Mohsenin (1986)
A [m^2]	Flat surface area of the bed	1	Assumption
c_{pa} [J/kg.^{o}C]	Specific heat of air	1007	Brooker *et al* (1992), Incropera and DeWitt, (1996) and Lienhard and Lienhard (2005)
c_{ph} [J/kg.^{o}C]	Specific heat of the husk	1870 ± 187	Urbicain and Lozano (1997)
c_{pmat} [J/kg.^{o}C]	Specific heat of the mat	1340 ± 134	Incropera and DeWitt, (1996)
c_{pp} [J/kg.^{o}C]	Specific heat of the grain dry matter	1115 ± 75	Own estimation
c_{ppol} [J/kg.^{o}C]	Specific heat of the polystyrene	1210	Incropera and DeWitt, (1996)
c_{ps}, [J/kg.^{o}C]	Specific heat of the soil	1870 ± 30	Incropera and DeWitt (1996), Çengel (1997), Çengel (2003)
c_{pv} [J/kg.^{o}C]	Specific heat of water vapour	1875	Brooker *et al*. (1992), Incropera and DeWitt (1996)
c_{pw} [J/kg.^{o}C]	Specific heat of water	4183	Incropera and DeWitt (1996), Lienhard and Lienhard (2005)
d_k [mm]	Thickness of CAR11 kernel	2.12 ± 0.16	Own measurement
d_k [mm]	Thickness of Pka Knhey kernel	1.96 ± 0.18	Own measurement
h [W/m^2.^{o}C]	Convective heat transfer coefficient	Dependent on wind speed	Table 6.1
h_{fg} [kJ/kg]	Latent heat of evaporation	2424.5 ± 164.5	Brooker *et al*. (1992), Incropera and DeWitt (1996), Jain and Tiwari (2004), Lienhard and Lienhard (2005)
I [W/m^2]	Solar intensity	Dependent on cloud movement	Table 6.2
L_a [mm]	Thickness of the air gap above and below the bed	1 ± 0.2	Assumption
L_h [mm]	Thickness of the husk	70 ± 5	Own measurement
L_{mat} [mm]	Thickness of the mat	2 ± 0.5	Own measurement
L_p [mm]	Depth or thickness of the grain bed	20 ± 2 and 30 ± 2	Own measurement
L_{pol} [mm]	Thickness of polystyrene	40 ± 2	Own measurement
L_{tarp} [mm]	Thickness of the tarpaulin	0.6 ± 0.1	Own measurement
MC_{ip} [dry basis]	Initial moisture content of the grain	0.266 to 0.292	Own measurement
MC_{im} [dry basis]	Initial moisture content of materials 2 and 3	0	Assumption
$R_{MTm/m+1}$ [s/m]	Resistance to moisture transfer through tarpaulin	∞	Assumption
$R_{MTm/m+1}$ [s/m]	Resistance to moisture transfer through nylon net and mat	0	Assumption
RH_a [%]	Ambient air relative humidity	Fluctuated	Table 6.3
T_a [^{o}C]	Ambient air temperature	Fluctuated	Table 6.4

Table 6.7: Summary of the values and ranges of the system inputs used (Continued)

Symbol	Description	Value taken	Reference
T_{gr} [°C]	Temperature of the ground	25	Nesbitt (1997)
T_{sky} [°C]	Temperature of the sky	12.6 ± 7.4	Amos (1995) and Rauch (2003)
λ_a [W/m.°C]	Thermal conductivity of the air	0.0263	Incropera and DeWitt (1996)
λ_p [W/m.°C]	Effective thermal conductivity of paddy	0.125 ± 0.045	Chakraverty and Singh (2001)
λ_{pol} [W/m.°C]	Thermal conductivity of the polystyrene	0.0315 ± 0.0045	Incropera and DeWitt (1996), Fellows (2000), Lienhard and Lienhard (2005)
λ_s [W/m.°C.]	Effective thermal conductivity of soil	0.52 ± 0.05	Incropera and DeWitt (1996), Çengel (1997), Garg and Kumar (2000)
λ_{tarp} [W/m.°C.]	Thermal conductivity of the tarpaulin	0.42 ± 0.05	Cleland and Valaentas (1997)
λ_h [W/m.°C]	Effective thermal conductivity of the husk	0.07 ± 0.01	Urbicain and Lozano (1997)
λ_{mat} [W/m.°C]	Effective thermal conductivity of mat	0.06 ± 0.01	Cleland and Valentas (1997)
β_p and ϵ_p [dec]	Absorptivity and emissivity of paddy	0.85 ± 0.05	Brewster (1992), Mills (1995), Shivakumar (1996), Fellows (2000), Çengel (2003)
$\beta_{tarp}$and ϵ_{tarp} [dec]	Absorptivity and emissivity of tarpaulin	0.97 ± 0.02	ETI (2006)
ρ_a [kg/m^3]	Density of drying air	1.12	Brooker *et al*. (1992)
ρ_h [kg/m^3]	Density of husk particles	705 ± 35	Houston (1972), Juliano (1985)
ρ_{mat} [kg/m^3]	Density of mat material	950 ± 95	Incropera and DeWitt (1996)
ρ_p [kg/m^3]	Density of CAR11	1145 ± 95	Own measurement
	Density of Pka Knhey	1135 ± 85	Own measurement
ρ_{pol} [kg/m^3]	Density of polystyrene	22 ± 1	Own measurement
ρ_s [kg/m^3]	Density of soil particles	3250 ± 250	Iwata *et al*. (1995)
ρ_{bh} [kg/m^3]	Bulk density of husk	120 ± 10	Own measurement
ρ_{bmat} [kg/m^3]	Bulk density of mat	690 ± 69	Incropera and DeWitt (1996)
ρ_{bp} [kg/m^3]	Bulk density of CAR11 grain	576 ± 54	Own measurement
ρ_{bp} [kg/m^3]	Bulk density of Pka Knhey grain	600 ± 45	Own measurement
ρ_{bpol} [kg/m^3]	Bulk density of polystyrene	22 ± 1	Own measurement
ρ_{bs} [kg/m^3]	Bulk density of soil	1800 ± 50	Own measurement

Table 6.8: Summary of the consequential value variables used

Symbol	Description	Value taken	Reference
D_{va} [m/s]	Moisture diffusivity in still air	$1.7255 \times 10^{-7}(T + 273.15) - 2.552 \times 10^{-5}$	Shah *et al.* (1984)
D_{vp} [m/s]	Effective moisture diffusivity in the grain bed	$1.5 \pm 0.5 * D_{va}$	Assumption
$D_{vm.eff}$ [m/s]	Moisture diffusivity in the soil or other materials	$\dfrac{D_{vp}}{1+\dfrac{\rho_{bm} n_{slope} .522 P_T .\rho_a}{\varepsilon_m .P_{sat}\left(18\,\rho_a + 29\,C\right)^2}}$	Assumption
k and B [1/s]	Drying constant for CAR11	k = 0.00012148 and B = 0 for $MC - MC_e < 0.22$ db k = 0.00356761 and B = 0.00076619 for $MC - MC_e > 0.22$ db	Own definition
k and B [1/s]	Drying constant for Pka Knhey	k = 0.00013779 and B = 0.00000122 for $MC - MC_e < 0.22$ db k = 0.00385975 and B = 0.00081067 for $MC - MC_e > 0.22$ db	Own definition
k_y, [m/s]	Convective moisture transfer coefficient	$\dfrac{h}{(1 \pm 0.05).c_{pa}.\rho_{pa}}$	Foust *et al.*, 1980
MC_{eh} and MC_{emat} [dec, db]	Moisture isotherm for husk and mat	$0.1404\, a_w + 0.0278$	Houston (1972)
MC_{ep} [dec, db]	Moisture isotherm for paddy	$30.8782 - 5.1337 \ln [-(T + 35.586) \ln (a_w - 0.00631436)]$	Own definition
MC_{epol} [dec, db]	Moisture isotherm for polystyrene	∞	Assumption
MC_{es} [dec, db]	Moisture isotherm for soil	$0.1413\, a_w$	Orchiston (1954)

6.2 MODEL VALIDATION

The model was validated by testing its predictions against the experimental data for the 12 trials that were extensively monitored. This was done to identify the reliability of the model prediction and to find out the reasons for lack of fit between the predicted and experimental data. Lack of fit found in this study can be attributed to (Bahnasawy and Shenana, 2004)

- Inappropriate formulation of the model or the formulated model has some weakness,
- Uncertainty in the values of the system inputs, or
- Uncertainty in the experimental data.

6.2.1 Sensitivity analysis

A sensitivity analysis was carried out for Treatments 9 (Pka Khney dried on tarpaulin in 2 cm bed depth with no stirring and no covering), 47 (Pka Khney dried on net spread on husk in 3 cm bed depth with stirring and no covering) and 64 (CAR11 dried on mat in 3 cm bed depth with stirring and no covering) of Experiment Three/04 to identify the sensitivity of the model for the ranges of the system inputs identified in Section 6.1.

Data in Table A7.1, A7.2 and A7.3 of Appendix A7 indicate the differences in the measured temperature, MC and water activity that were calculated from the numerical solution at close to midday (11:55) and near to the end of the first drying day (15:55) for nodes 1, 7, 13, 19 and 25 when the system input variables were varied between the highest and lowest values.

The system inputs that had the most significant effects on the model predictions or the model sensitivity (over 1^{o}C, 1% db and 0.01 for the temperature, MC and water activity, respectively) at 11:55 and 15:55 are summarised in Table 6.9 and Table 6.10. The key findings were

- At 11:55, the predicted temperature was particularly sensitive to the specific surface area of the grain kernel (a), solar intensity (I), ambient air temperature (T_a), sky temperature (T_{sky}), absorptivity (β_p) and emissivity (ϵ_p) of the paddy grain. At 15:55, the temperature was sensitive to the specific surface area, ambient air and sky temperature and effective thermal conductivity (λ_p) of the grain.
- At 11:55, the predicted MC was particularly sensitive to the moisture diffusivity (D_v), solar intensity, thickness of the grain bed (L_p) and bulk density (ρ_{bp}) of the grain. At 15:55, the MC was sensitive to the moisture diffusivity, solar intensity, thickness of the grain bed, RH and temperature of the ambient air, sky temperature, absorptivity and emissivity, thermal conductivity, true and bulk density of the grain;
- At 11:55, the predicted water activity was particularly sensitive to the specific surface area, moisture diffusivity, solar intensity, thickness of the grain bed, RH of the ambient air, sky temperature, absorptivity, emissivity, thermal

conductivity and bulk density of the grain. At 15:55, the water activity was significantly sensitive to the specific surface area, moisture diffusivity, solar intensity, thickness of the grain bed, RH and temperature of the ambient air, sky temperature, absorptivity, emissivity, thermal conductivity, true and bulk densities of the grain.

Table 6.9: Summary of the effects the system inputs have on the model predictions at 11:55

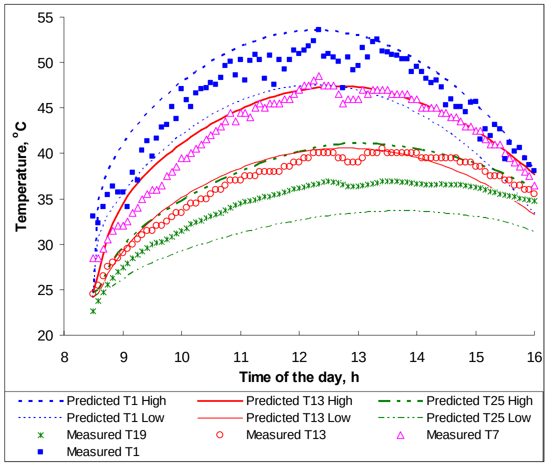
Temperature, ^oC		Moisture content, % db		Water activity, dec	
Highest*	**Lowest**	**Highest**	**Lowest**	**Highest**	**Lowest**
a high	a low	D_v low	D_v high	a low	a high
I high	I low	I low	I high	D_v low	D_v high
T_a high	T_a low	L_p high	L_p low	I low	I high
T_{sky} high	T_{sky} low	ρ_{bp} high	ρ_{bp} low	L_p high	L_p low
β_p & $\in_p$ high	β_p & $\in_p$ low			RH_a high	RH_a low
				T_{sky} low	T_{sky} high
				β_p & $\in_p$ low	β_p & $\in_p$ high
				λ_p high	λ_p low
				ρ_{bp} high	ρ_{bp} low

Note: **The temperature would be predicted the highest for the combination of a high, I high, T_a high, T_{sky} high, β_p and $\in_p$ high.*

Table 6.10: Summary of the effects the system inputs have on the model predictions at 15:55

Temperature, ^oC		Moisture content, % db		Water activity, dec	
Highest	**Lowest**	**Highest**	**Lowest**	**Highest**	**Lowest**
I high	I low	D_v low	D_v high	a low	a high
T_a high	T_a low	I low	I high	D_v low	D_v high
T_{sky} high	T_{sky} low	L_p high	L_p low	I low	I high
λ_p high	λ_p low	RH_a high	RH_a low	L_p high	L_p low
		T_a high	T_a low	RH_a high	RH_a low
		T_{sky} low	T_{sky} high	T_a high	T_a low
		β_p & $\in_p$ low	β_p & $\in_p$ high	T_{sky} low	T_{sky} high
		λ_p low	λ_p high	β_p & $\in_p$ low	β_p & $\in_p$ high
		ρ_p low	ρ_p high	λ_p low	λ_p high
		ρ_{bp} high	ρ_{bp} low	ρ_p low	ρ_p high
				ρ_{bp} high	ρ_{bp} low

Combining all the system inputs that were found to have a positive (increasing) and negative (decreasing) effects on the predicted variables, as listed in Table 6.9 and Table 6.10 resulted in prediction bands (Fig 6.12 to Fig 6.14). Generally, the measured data lay inside the bands suggesting lack of fit can be explained by the uncertainty in the values of the system inputs (Bronlund and Davey, 2003). This means that to improve the fit, better values for the inputs must be applied.



Note: Predicted High or Low means the highest or the lowest prediction caused by combining all the corresponding system inputs

Fig 6.12: Prediction bands for the temperatures at the bed surface, middle and bottom and the measured data of Experiment One/04

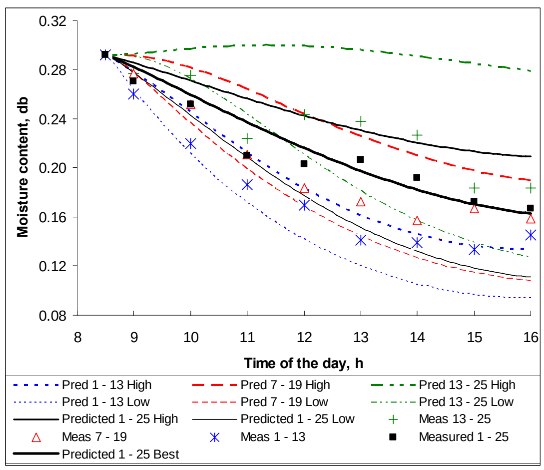


Fig 6.13: Prediction bands for the moisture contents at different layers of the bed and the measured data of Experiment One/04

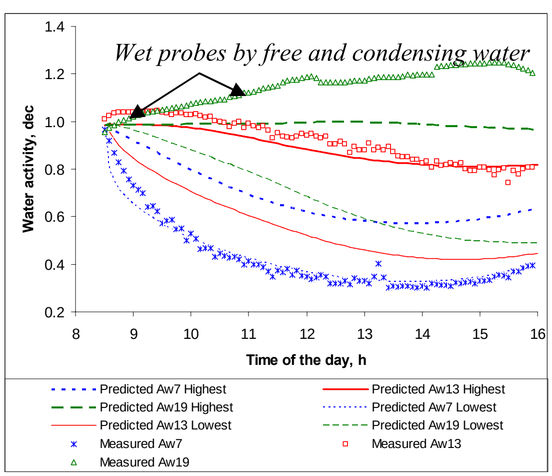


Fig 6.14: Prediction bands for the water activities at different layers of the bed and the measured data of Experiment One/04

6.2.2 Comparison of the predictions with measured data

6.2.2.1 Drying time

To indicate the usefulness of the model in predicting the drying time required to bring the grain to the target moisture content (MC) of 14%, the drying times predicted by the model using the best estimates of the system input parameters were compared with the drying times measured in Experiment Three/04 (Fig 6.15 to Fig 6.16). The figures were plotted for individual groups of the drying conditions to show clearly whether the model performed well for all the drying combinations or not. The comparison revealed that, on average, the model under-predicted the drying times by about 40 min.

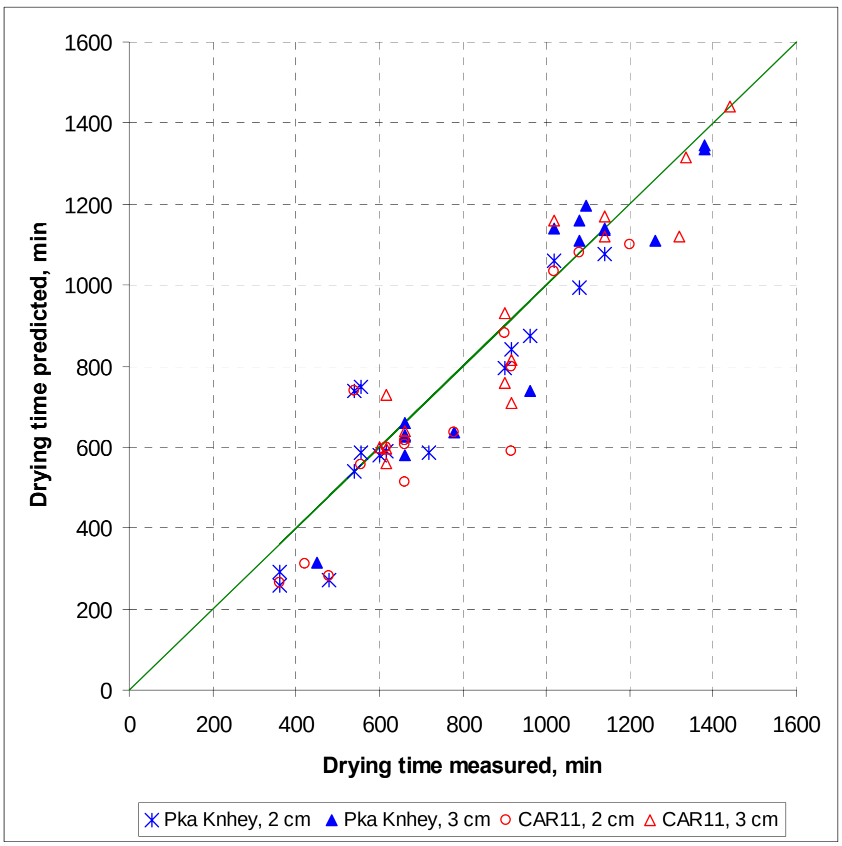


Fig 6.15: Comparison of the measured and predicted drying times (Variety and depth)

Fig 6.15 indicates the overall trend for all the varieties used. The model predicted the drying time for all the varieties and bed depths equally well. An average of 800 min (13 h and 23 min) was predicted for the grain of Pka Knhey variety which was about 20 min longer than for the other variety, CAR11. Drying with 2-cm bed depth was predicted to take 670 min (or 11 h and 10 min) on average which was 50 min shorter than the 3-cm depth bed. These trends were consistent with the measured drying times.

Fig 6.16 shows the same data, but plotted with stirring and covering treatments indicated. The beds that were stirred and exposed to the sun for the whole time were predicted to reach the target MC in the shortest time (455 min or 7 h and 35 min). Next were the beds that were not stirred and not covered (776 min or 11 h and 17 min) and stirred and covered (882 min or 14 h and 42 min). The longest time was predicted for the beds that were not stirred but covered (1063 min or 17 h and 43 min). All of these indicate that stirring helped shorten the drying while covering and shading prolonged the drying time.

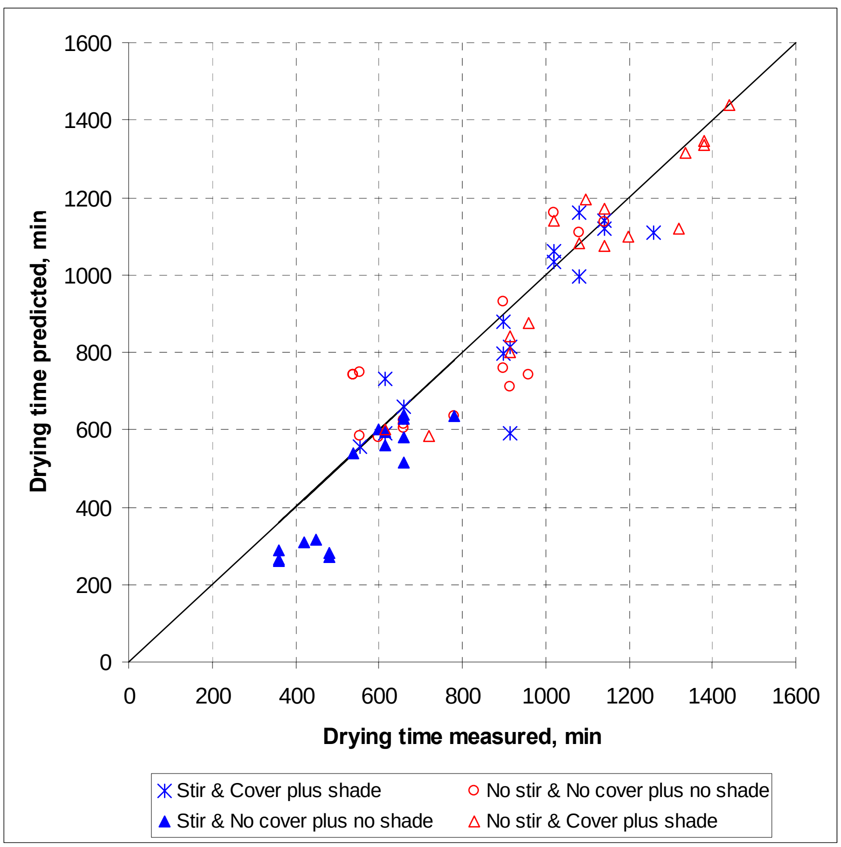


Fig 6.16: Comparison of the measured and predicted drying times (Stirring and Covering methods)

While the drying time was different for each stirring, shading and covering treatment, the predictions were similarly accurate for all, suggesting that the model was equally accurate irrespective of the heat and mass transfer mechanisms.

Fig 6.17 plots the same data but with the pad treatment differences identified. Table 6.11 gives the average drying time for each pad. Overall, the model predictions of drying time were consistent with measured data for all except the trials with a polystyrene pad.

The drying on the tarpaulin spread on polystyrene gave the shortest drying time (502 min or 8 h and 22 min) and had the largest difference between predicted and measured (predictions too short). The under-prediction of the drying time was due to the over prediction of the temperature. As discussed in Section 6.2.2.2, poor predictions for polystyrene were investigated but no obvious reason was identified.

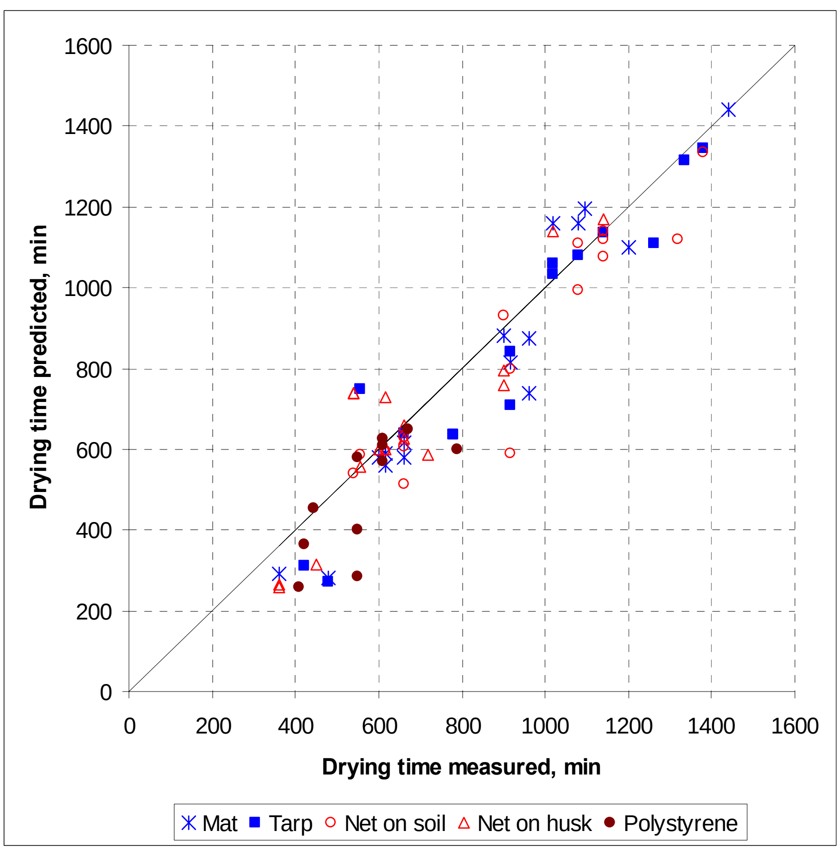


Fig 6.17: Comparison of the measured and predicted drying times (Drying pads)

Table 6.11: Average measured and predicted drying times for individual drying pads, min

	Net on husk	Mat on soil	Net on soil	Tarpaulin on soil	Tarpaulin on polystyrene
Measured	665	848	919	930	602
Predicted	659	804	855	858	502

For the grain and air conditions within the drying bed, twelve trials were checked to the extent that they could be used for model validation. Fig 6.18 to 6.65 compare the model predictions with the measured temperatures, MCs and water activities for the grain dried in the 2004 trials that were intensively monitored.

6.2.2.2 Temperature

On the whole, the predicted temperatures for different layers of the bed as a function of time are in reasonable agreement with the experimental observations. In most cases, the lack of fit that can be explained by:

1. Uncertainties in the values of the system inputs used (as described in Section 6.1) and
2. Particular uncertainties in the experimental data. Some probes in the lower layers of the bed might have become wet from the free or condensing water within the bed or they might have accidentally been misplaced from the intended position. Moreover, possible air movement within the bed could also create evaporative cooling effects on the probes. Such uncertainties in the experimental data are evident by the differences in the temperatures of up to 4^{o}C that were measured by different kinds of temperature probes (thermisters, I-buttons and the non-contact thermometer) normally placed in the same position in the bed.

For the case of drying on the polystyrene slabs (Fig 6.20), the temperatures were significantly over predicted and could not be explained by the sensitivity analysis or data uncertainty. While the quality of the locally made polystyrene was doubtful, no logical reason for this over prediction could be identified.

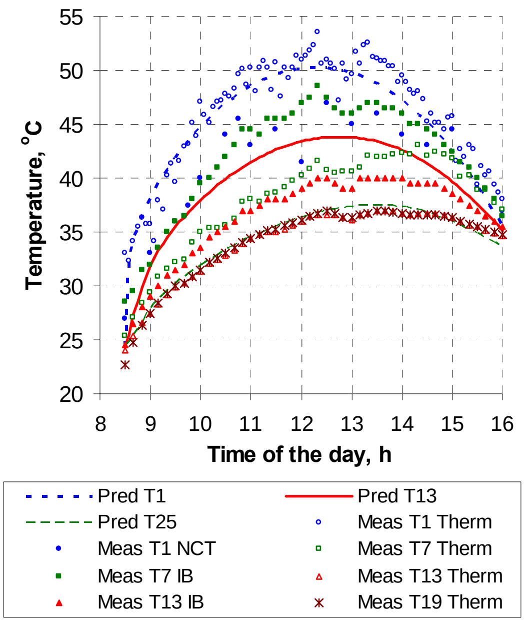


Fig 6.18: Comparison of the predicted and measured temperatures for Rep 1 of Experiment One/04

CAR11, 2 cm, tarpaulin spread on soil, no stirring, no covering, Day One (Dec 10, 2004)

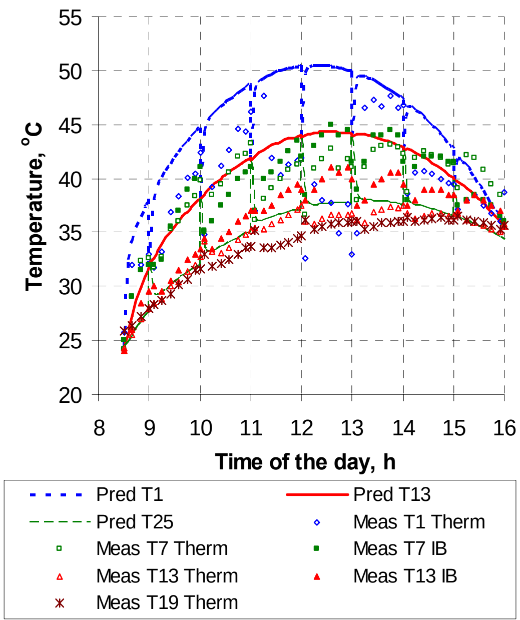


Fig 6.19: Comparison of the predicted and measured temperatures for Rep 2 of Experiment One/04

CAR11, 2 cm, tarpaulin spread on soil, stirring, no covering, Day One (Dec 10, 2004)

<u>Notes:</u> Pred: Predicted; Meas: Measured; T1, T7, T13, T19 and T25: Temperatures at nodes 1 (the bed surface), 7, 13 (middle of the bed), 19 and 25 (bottom of the bed), respectively.

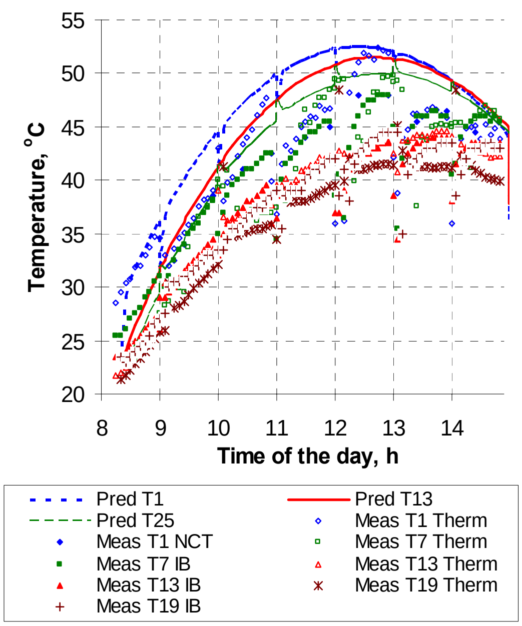


Fig 6.20: Comparison of the predicted and measured temperatures for treatment 5 of Experiment Two/04

CAR11, 2 cm, tarpaulin spread on polystyrene, stirring, no covering, Day One (Dec 11, 2004)

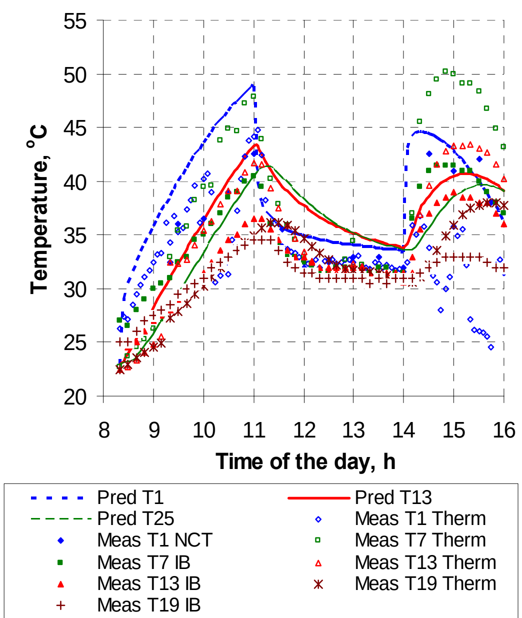


Fig 6.21: Comparison of the predicted and measured temperatures for treatment 12 of Experiment Two/04

CAR11, 3 cm, tarpaulin spread on polystyrene, no stirring, covering plus shading, Day One (Dec 11, 2004)

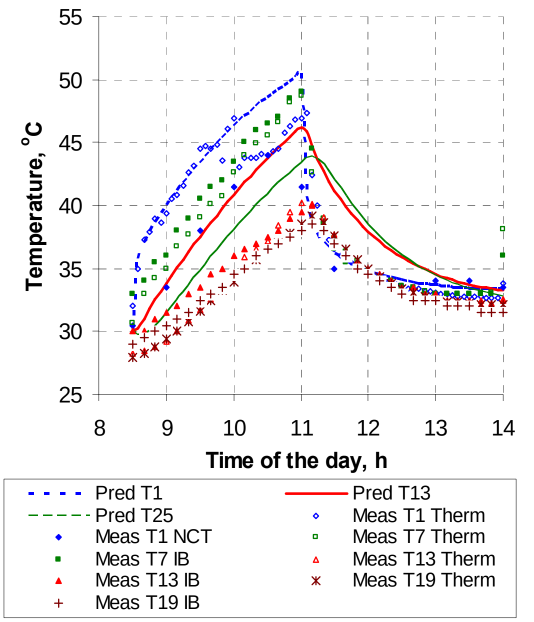


Fig 6.22: Comparison of the predicted and measured temperatures for treatment 12 of Experiment Two/04

CAR11, 3 cm, tarpaulin spread on polystyrene, no stirring, covering plus shading, Day Two (Dec 12, 2004)

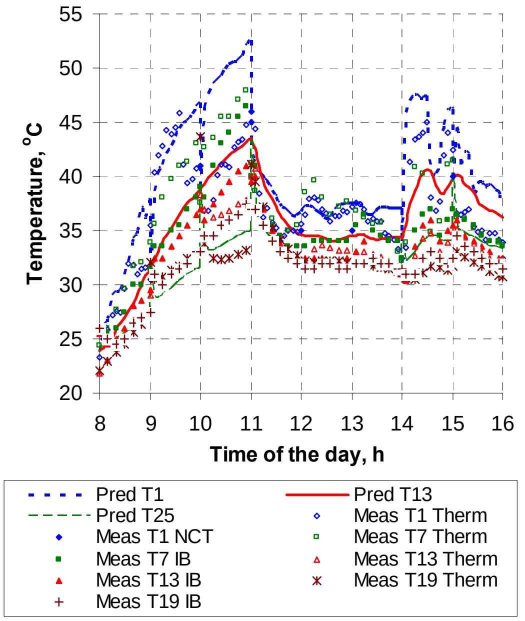


Fig 6.23: Comparison of the predicted and measured temperatures for treatment 5 of Experiment Three/04

Pka Knhey, 2 cm, tarpaulin spread on soil, stirring, covering plus shading, Day One (Dec 20, 2004)

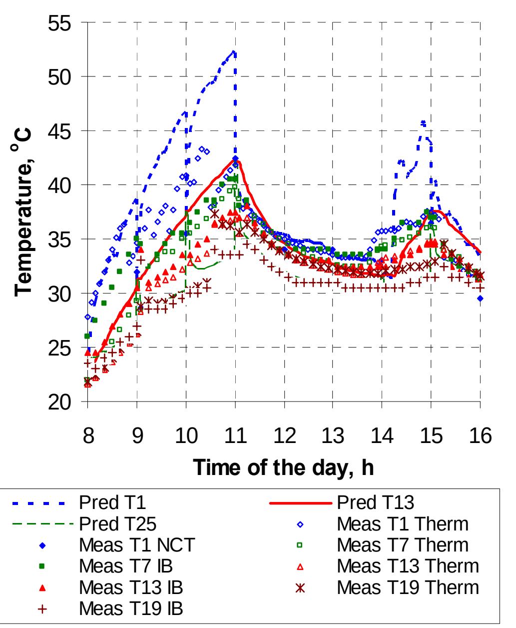


Fig 6.24: Comparison of the predicted and measured temperatures for treatment 8 of Experiment Three/04

CAR11, 3 cm, tarpaulin spread on soil, stirring, covering plus shading, Day One (Dec 24, 2004)

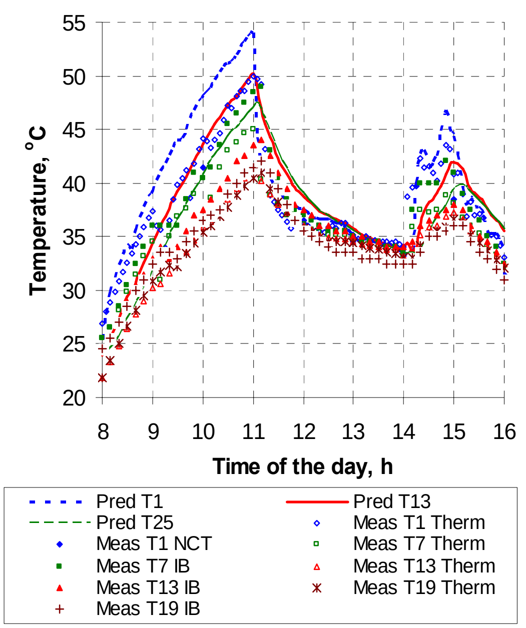


Fig 6.25: Comparison of the predicted and measured temperatures for treatment 33 of Experiment Three/04

Pka Knhey, 2-cm, net spread on husk, no stirring, covering plus shading, Day One (Dec 24, 2004).

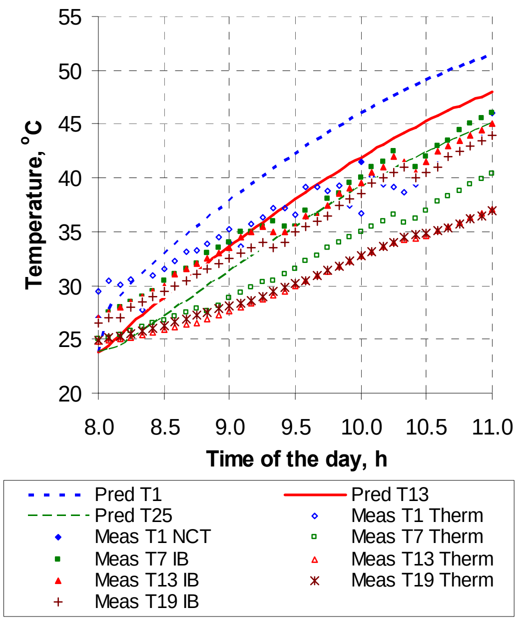


Fig 6.26: Comparison of the predicted and measured temperatures for treatment 33 of Experiment Three/04

Pka Knhey, 2 cm, net spread on husk, no stirring, covering plus shading, Day Two (Dec 25, 2004)

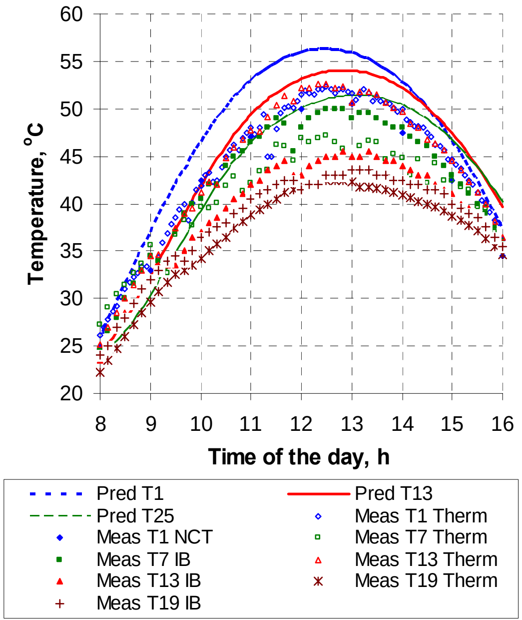


Fig 6.27: Comparison of the predicted and measured temperatures for treatment 41 of Experiment Three/04

Pka Knhey, 2 cm, net spread on husk, no stirring, no covering, Day One (Dec 22, 2004)

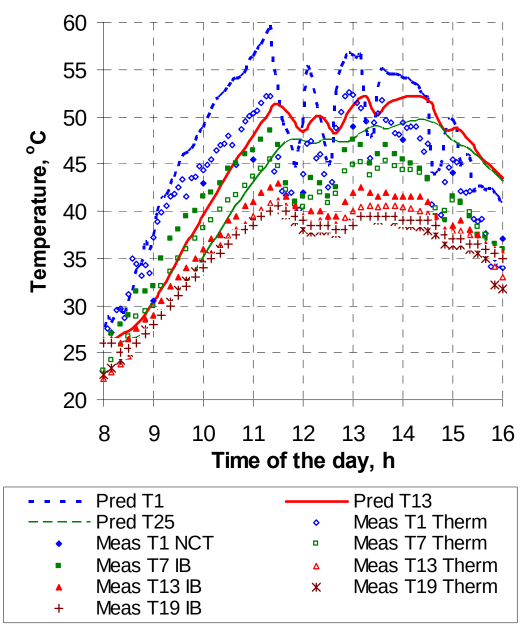


Fig 6.28: Comparison of the predicted and measured temperatures for treatment 43 of Experiment Three/04

Pka Knhey, 3 cm, net spread on husk, no stirring, no covering, Day One (Dec 20, 2004)

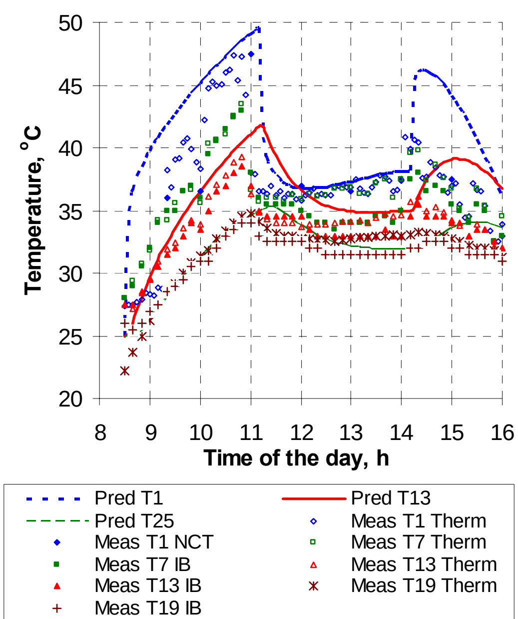


Fig 6.29: Comparison of the predicted and measured temperatures for treatment 51 of Experiment Three/04

Pka Knhey, 3 cm, mat spread on soil, no stirring, covering plus shading, Day One (Dec 18, 2004)

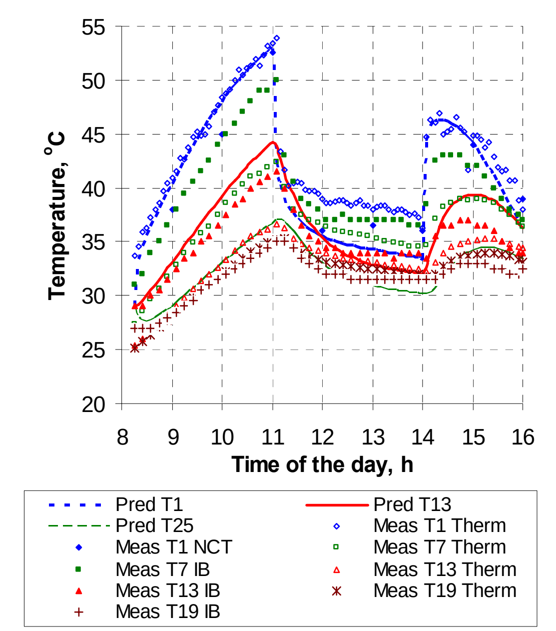


Fig 6.30: Comparison of the predicted and measured temperatures for treatment 51 of Experiment Three/04

Pka Knhey, 3 cm, mat spread on soil, no stirring, covering plus shading, Day Two (Dec 19, 2004)

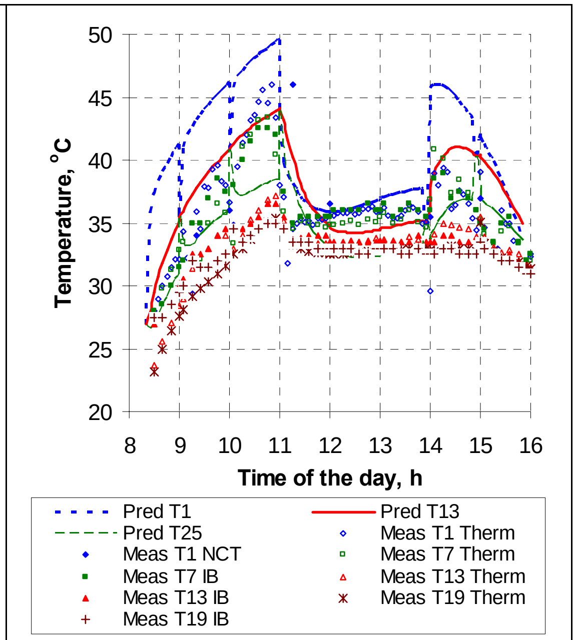


Fig 6.31: Comparison of the predicted and measured temperatures for treatment 53 of Experiment Three/04

Pka Knhey, 2 cm, mat spread on soil, stirring, covering plus shading, Day One (Dec 18, 2004)

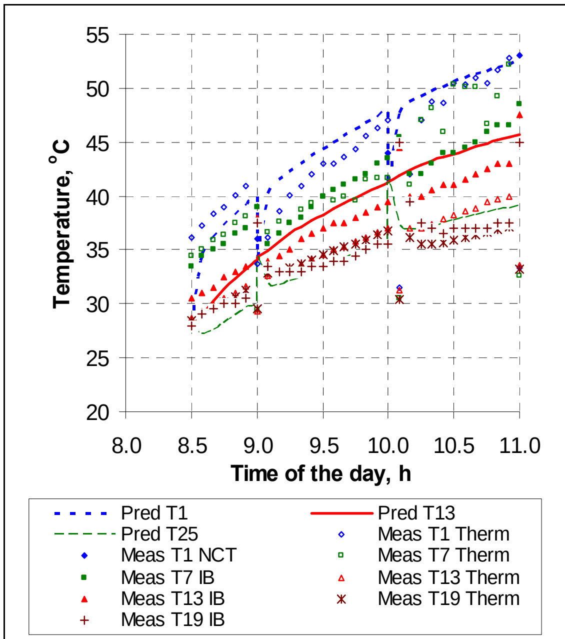


Fig 6.32: Comparison of the predicted and measured temperatures for treatment 53 of Experiment Three/04

Pka Knhey, 2 cm, mat spread on soil, stirring, covering plus shading, Day Two (Dec 19, 2004)

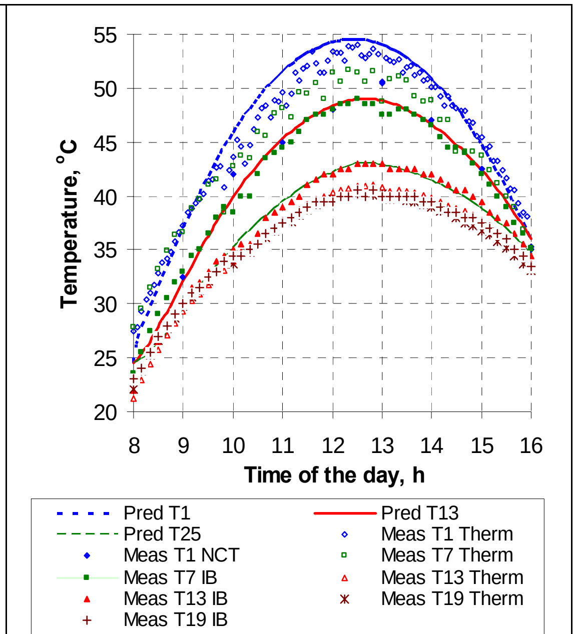


Fig 6.33: Comparison of the predicted and measured temperatures for treatment 57 of Experiment Three/04

Pka Knhey, 2 cm, mat spread on soil, no stirring, no covering, Day One (Dec 22, 2004)

6.2.2.3 Moisture content

Fig 6.34 to 6.49 show a comparison of the predicted with the measured MCs for the grain dried in replication 2 of Experiment One/04 and in treatment 33 of Experiment Three/04. The MCs measured were considered particularly uncertain due to the indirect method of the moisture meter employed and the difficulty in getting appropriate samples from different parts of the bed. Therefore, rather than comparing the MC at each location in the bed, predictions for the average MC of the bed are shown.

The measured MCs scatter around the model prediction. Again, uncertainty in the system input values and experimental measurement explain most of the lack of fit. Irregular changes in the MCs measured during the experiments confirm that significant uncertainties in the measurement existed. With the moisture meter used, about 200 g of the grain sample was needed for every moisture determination. For that reason, even when extreme attention was paid in the sampling process, the reading from the meter could easily fail to accurately represent the MC of the grain at the exact position intended. Moreover, error of ±1% MC was observed to happen with the meter.

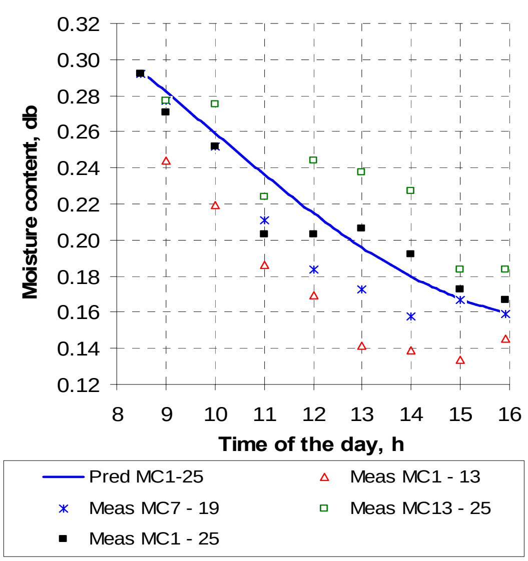


Fig 6.34: Comparison of the predicted and measured MCs for Rep 1 of Experiment One/04

CAR11, 2 cm, tarpaulin spread on soil, no stirring, no covering, Day One (Dec 10, 2004)

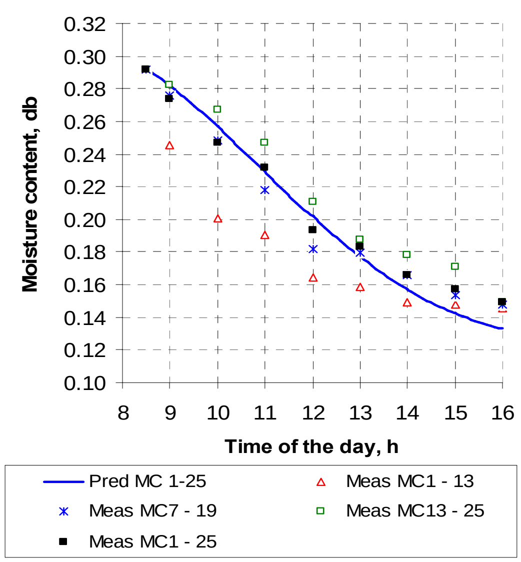


Fig 6.35: Comparison of the predicted and measured MCs for Rep 2 of Experiment One/04

CAR11, 2 cm, tarpaulin spread on soil, stirring, no covering, Day One (Dec 10, 2004)

<u>Notes:</u> Pred: Predicted; Meas: Measured; MC1-13, MC7-19, MC13-25, MC1-25: Moisture contents at nodes 1 to 13 (upper half of the bed), 7 to 19 (middle portion of the bed), 13 to 25 (lower half of the bed, and 1 to 25 (whole bed), respectively

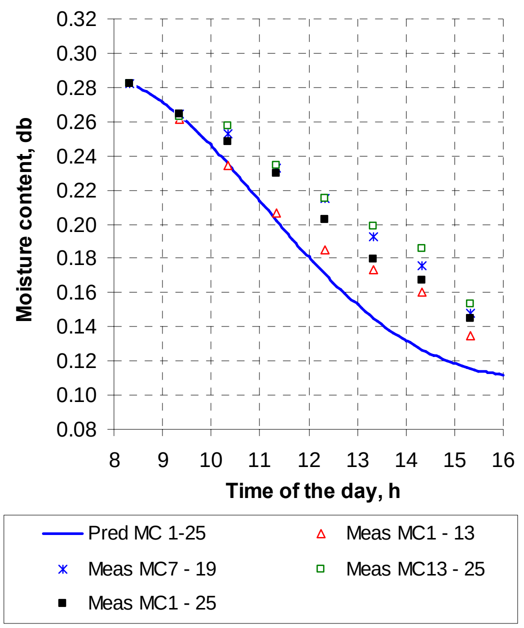


Fig 6.36: Comparison of the predicted and measured MCs for treatment 5 of Experiment Two/04

CAR11, 2 cm, tarpaulin spread on polystyrene, stirring, no covering, Day One (Dec 11, 2004)

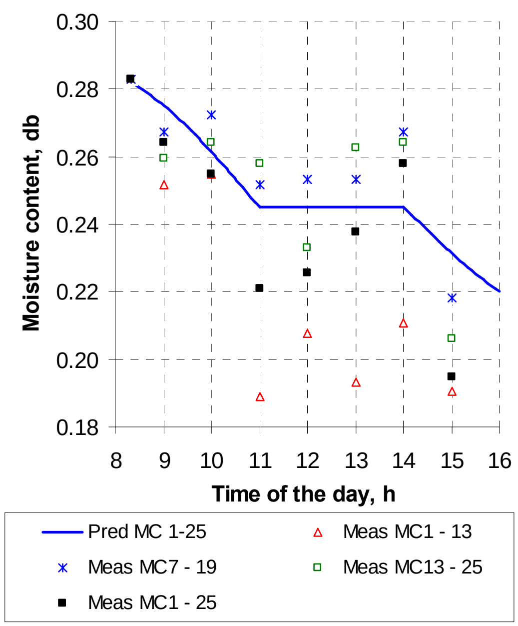


Fig 6.37: Comparison of the predicted and measured MCs for treatment 12 of Experiment Two/04

CAR11, 3 cm, tarpaulin spread on polystyrene, no stirring, covering plus shading, Day One (Dec 11, 2004)

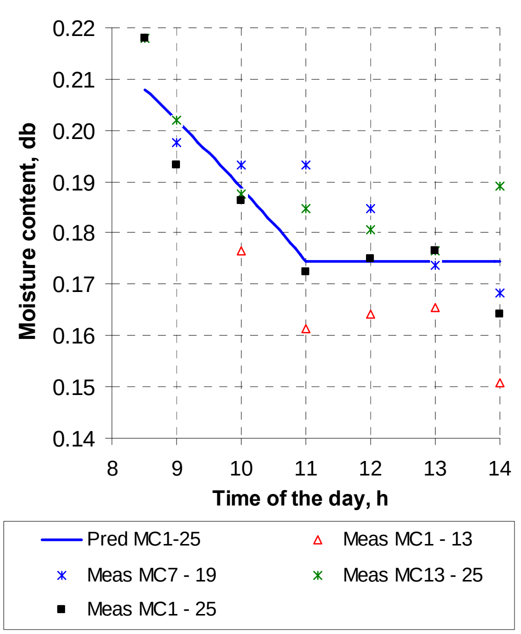


Fig 6.38: Comparison of the predicted and measured MCs for treatment 12 of Experiment Two/04

CAR11, 3 cm, tarpaulin spread on polystyrene, no stirring, covering plus shading, Day Two (Dec 12, 2004)

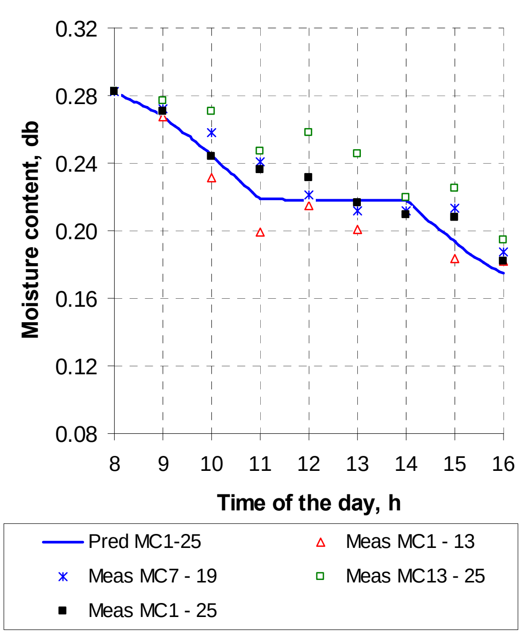


Fig 6.39: Comparison of the predicted and measured MCs for treatment 5 of Experiment Three/04

Pka Knhey, 2 cm, tarpaulin spread on soil, stirring, covering plus shading, Day One (Dec 20, 2004)

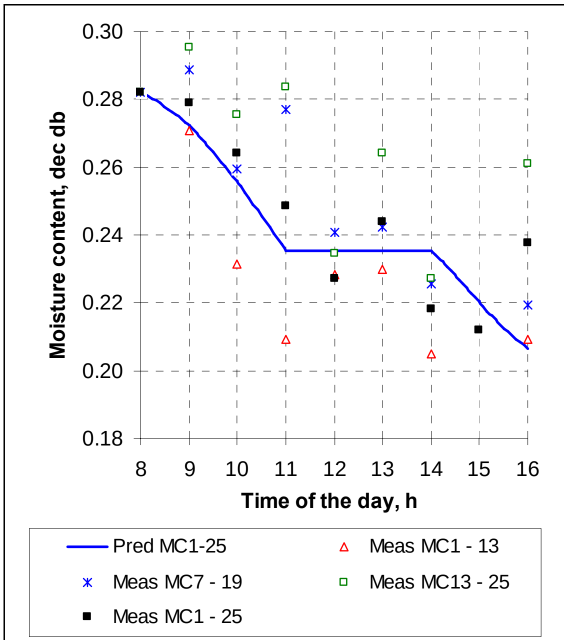


Fig 6.40: Comparison of the predicted and measured MCs for treatment 8 of Experiment Three/04

CAR11, 3 cm, tarpaulin spread on soil, stirring, covering plus shading, Day One (Dec 24, 2004)

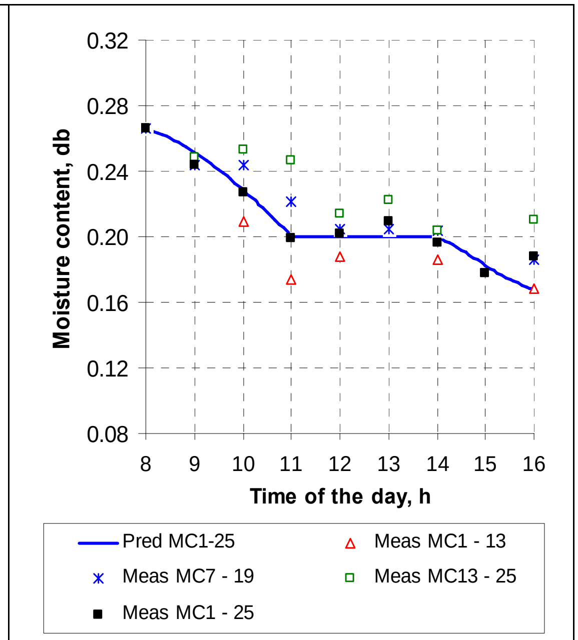


Fig 6.41: Comparison of the predicted and measured MCs for treatment 33 of Experiment Three/04

Pka Knhey, 2-cm, net spread on husk, no stirring, covering plus shading, Day One (Dec 24, 2004)

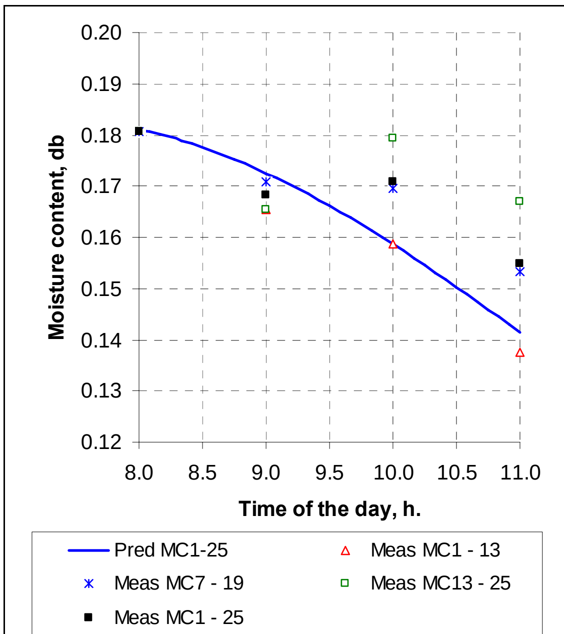


Fig 6.42: Comparison of the predicted and measured MCs for treatment 33 of Experiment Three/04

Pka Knhey, 2 cm, net spread on husk, no stirring, covering plus shading, Day Two (Dec 25, 2004)

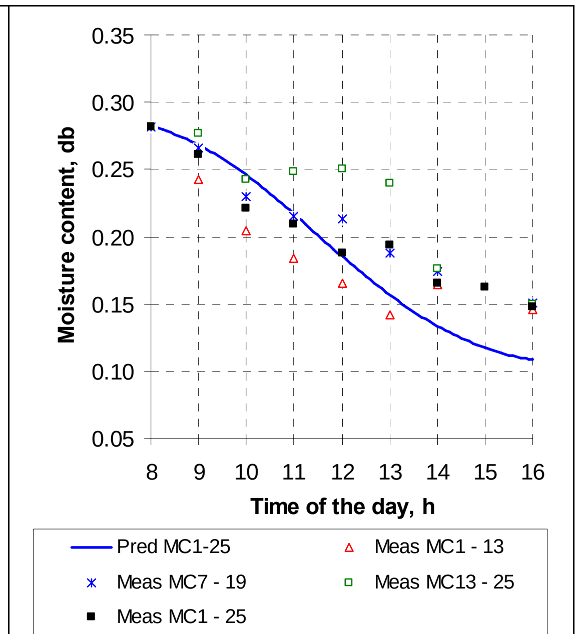


Fig 6.43: Comparison of the predicted and measured MCs for treatment 41 of Experiment Three/04

Pka Knhey, 2 cm, net spread on husk, no stirring, no covering, Day One (Dec 22, 2004)

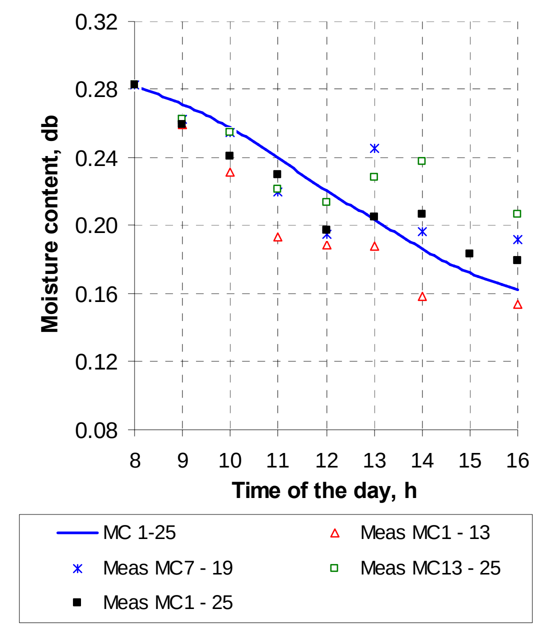


Fig 6.44: Comparison of the predicted and measured MCs for treatment 43 of Experiment Three/04

Pka Knhey, 3 cm, net spread on husk, no stirring, no covering, Day One (Dec 20, 2004)

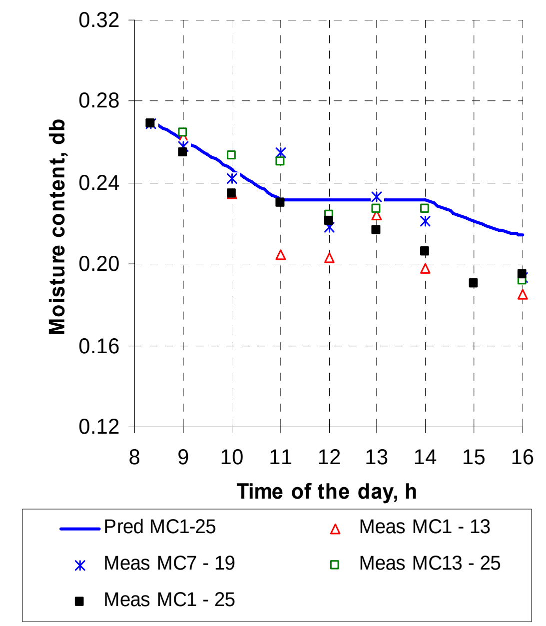


Fig 6.45: Comparison of the predicted and measured MCs for treatment 51 of Experiment Three/04

Pka Knhey, 3 cm, mat spread on soil, no stirring, covering plus shading, Day One (Dec 18, 2004)

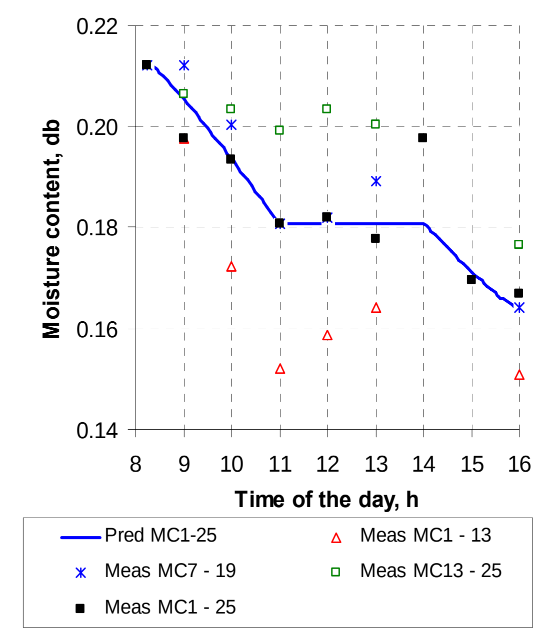


Fig 6.46: Comparison of the predicted and measured MCs for treatment 51 of Experiment Three/04

Pka Knhey, 3 cm, mat spread on soil, no stirring, covering plus shading, Day Two (Dec 19, 2004)

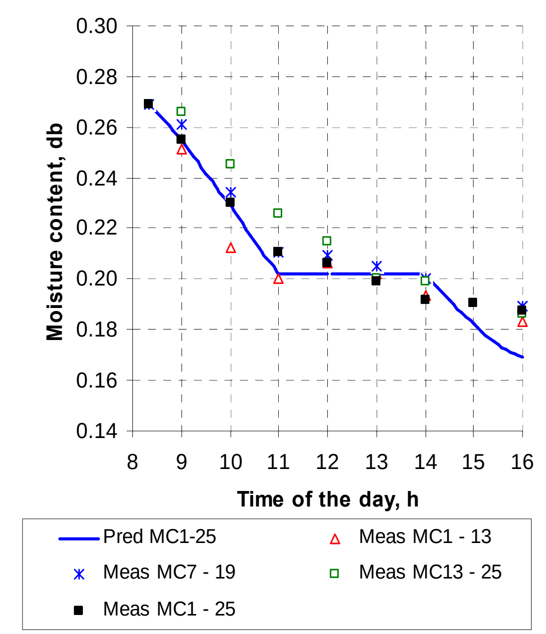


Fig 6.47: Comparison of the predicted and measured MCs for treatment 53 of Experiment Three/04

Pka Knhey, 2 cm, mat spread on soil, stirring, covering plus shading, Day One (Dec 18, 2004)

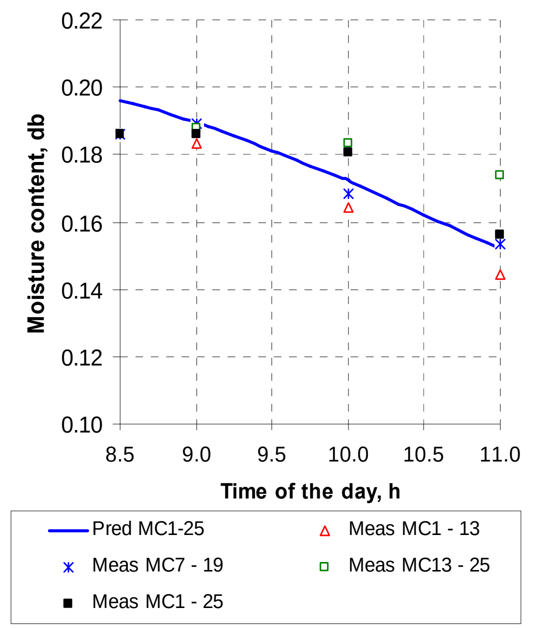


Fig 6.48: Comparison of the predicted and measured MCs for treatment 53 of Experiment Three/04

Pka Knhey, 2 cm, mat spread on soil, stirring, covering plus shading, Day Two (Dec 19, 2004)

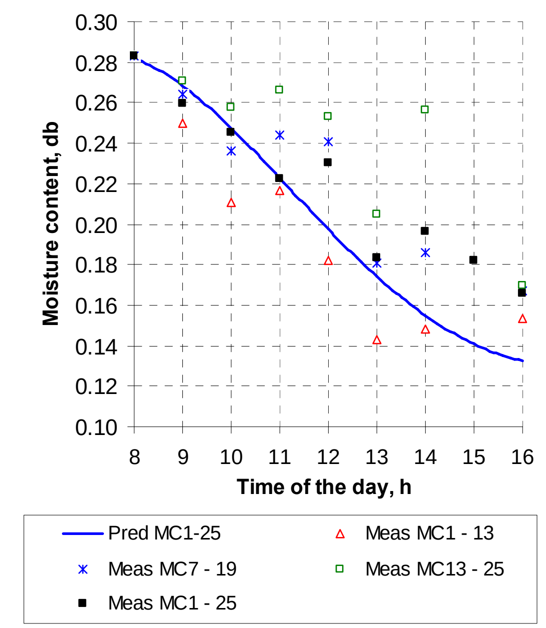


Fig 6.49: Comparison of the predicted and measured MCs for treatment 57 of Experiment Three/04

Pka Knhey, 2 cm, mat spread on soil, no stirring, no covering, Day One (Dec 22, 2004)

6.2.2.4 Water activity

The water activities predicted by the model were consistently lower than measured. Apart from the uncertainties in the values of the system inputs, there were significant uncertainties in the measured RH data especially for the middle and bottom layers. The water activities measured for these two layers were in some cases higher than 1 (the maximum value for the parameter). A possible reason is that the Hycal probes became wet by the free and condensing water within the bed, thereby affecting their calibration. Despite these problems with measurement, the model has not predicted the experimental water activities consistently. More work is needed to investigate why the model and experiments do not agree.

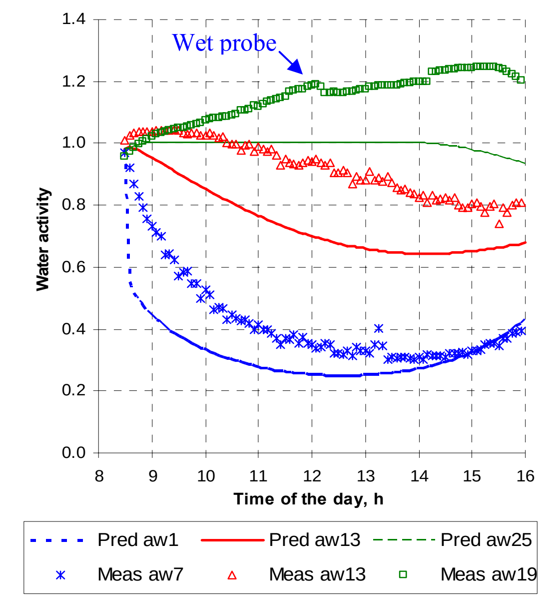


Fig 6.50: Comparison of the predicted and measured water activities for Rep 1 of Experiment One/04

CAR11, 2 cm, tarpaulin spread on soil, no stirring, no covering, Day One (Dec 10, 2004)

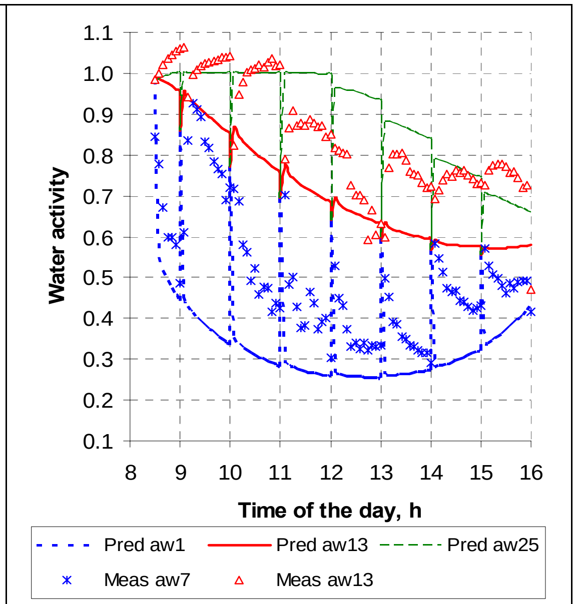


Fig 6.51: Comparison of the predicted and measured water activities for Rep 2 of Experiment One/04

CAR11, 2 cm, tarpaulin spread on soil, stirring, no covering, Day One (Dec 10, 2004)

<u>Notes:</u> Pred: Predicted; Meas: Measured; Aw1, Aw7, Aw13, Aw19, and Aw25: Water activities at nodes 1, 7, 13, 19 and 25, respectively

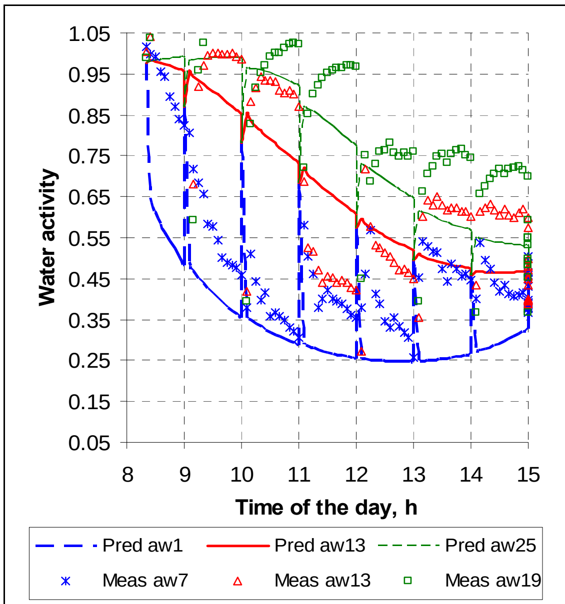


Fig 6.52: Comparison of the predicted and measured water activities for treatment 5 of Experiment Two/04

CAR11, 2 cm, tarpaulin spread on polystyrene, stirring, no covering, Day One (Dec 11, 2004)

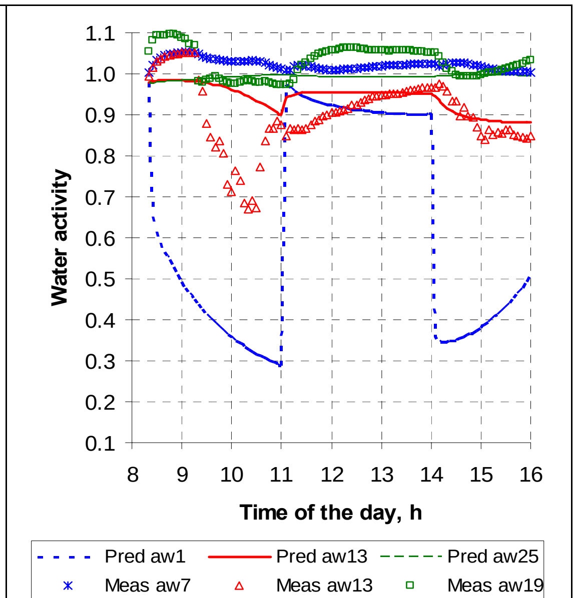


Fig 6.53: Comparison of the predicted and measured water activities for treatment 12 of Experiment Two/04

CAR11, 3 cm, tarpaulin spread on polystyrene, no stirring, covering plus shading, Day One (Dec 11, 2004)

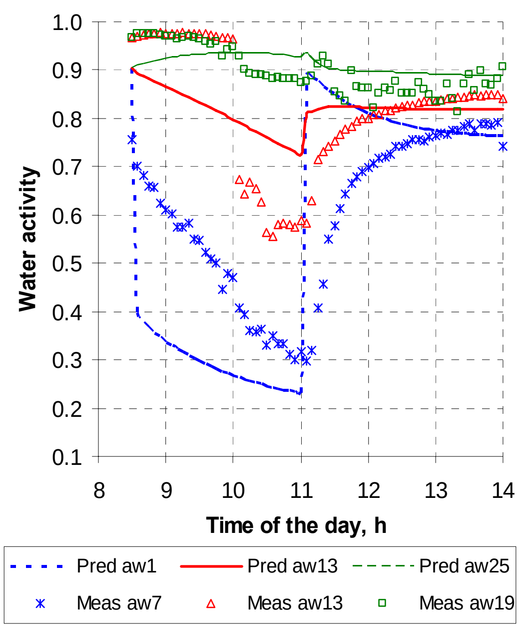


Fig 6.54: Comparison of the predicted and measured water activities for treatment 12 of Experiment Two/04
CAR11, 3 cm, tarpaulin spread on polystyrene, no stirring, covering plus shading, Day Two (Dec 12, 2004)

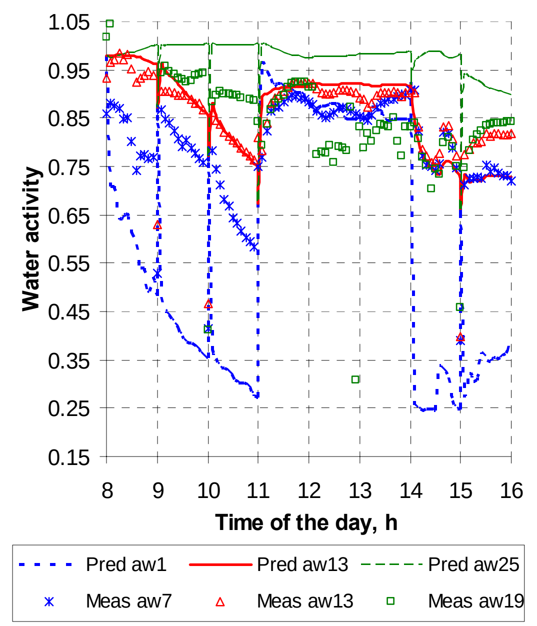


Fig 6.55: Comparison of the predicted and measured water activities for treatment 5 of Experiment Three/04
Pka Knhey, 2 cm, tarpaulin spread on soil, stirring, covering plus shading, Day One (Dec 20, 2004)

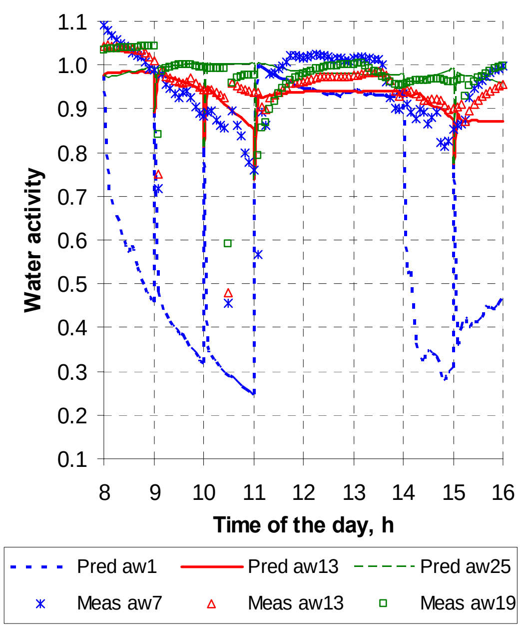


Fig 6.56: Comparison of the predicted and measured water activities for treatment 8 of Experiment Three/04
CAR11, 3 cm, tarpaulin spread on soil, stirring, covering plus shading, Day One (Dec 24, 2004)

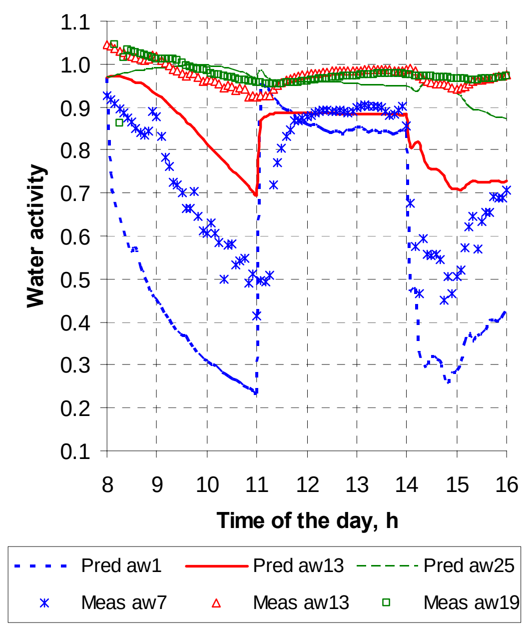


Fig 6.57: Comparison of the predicted and measured water activities for treatment 33 of Experiment Three/04
Pka Knhey, 2-cm, net spread on husk, no stirring, covering plus shading, Day One (Dec 24, 2004)

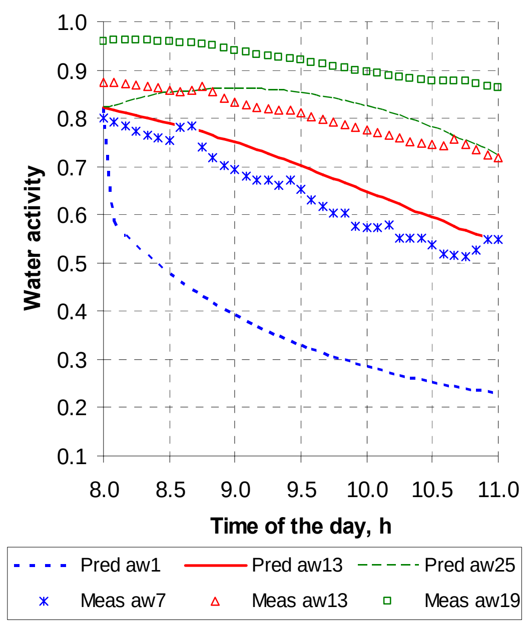


Fig 6.58: Comparison of the predicted and measured water activities for treatment 33 of Experiment Three/04

Pka Knhey, 2 cm, net spread on husk, no stirring, covering plus shading, Day Two (Dec 25, 2004)

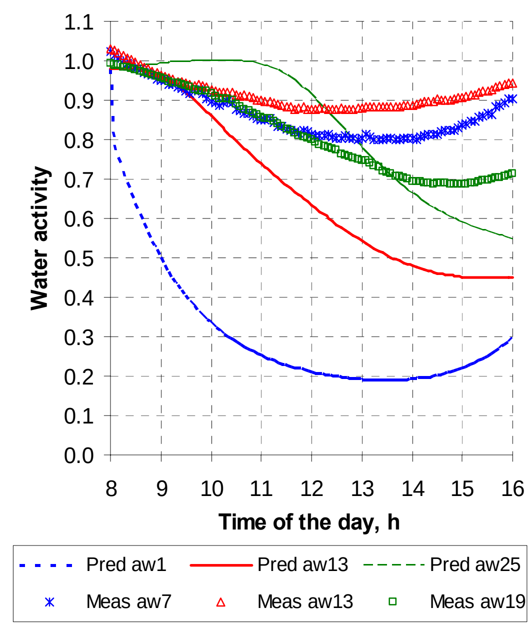


Fig 6.59: Comparison of the predicted and measured water activities for treatment 41 of Experiment Three/04

Pka Knhey, 2 cm, net spread on husk, no stirring, no covering, Day One (Dec 22, 2004)

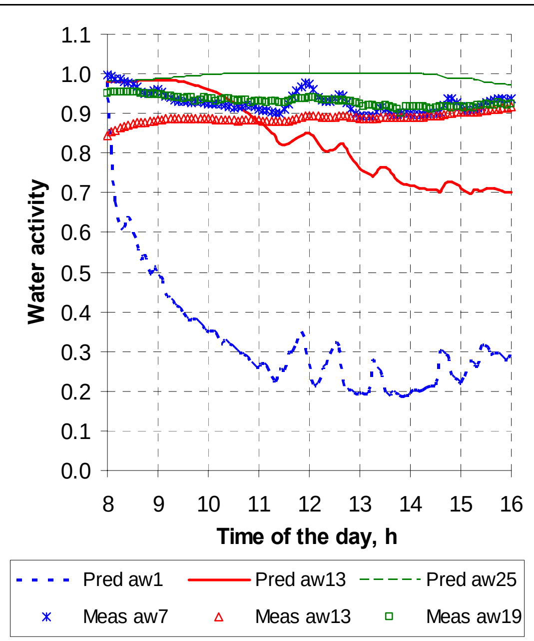


Fig 6.60: Comparison of the predicted and measured water activities for treatment 43 of Experiment Three/04

Pka Knhey, 3 cm, net spread on husk, no stirring, no covering, Day One (Dec 20, 2004)

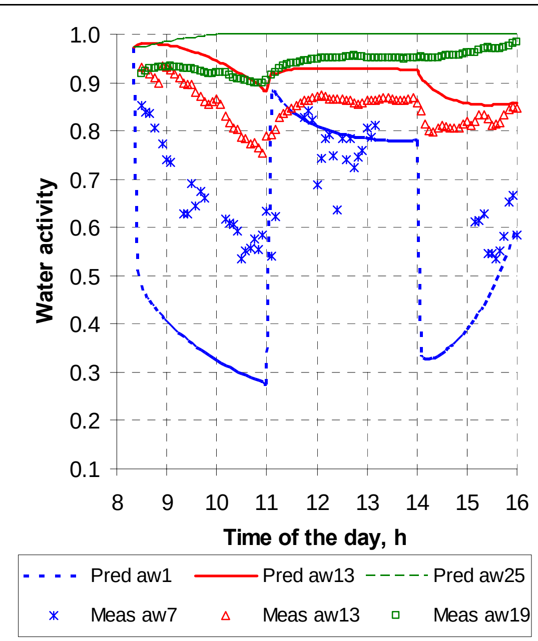


Fig 6.61: Comparison of the predicted and measured water activities for treatment 51 of Experiment Three/04

Pka Knhey, 3 cm, mat spread on soil, no stirring, covering plus shading, Day One (Dec 18, 2004)

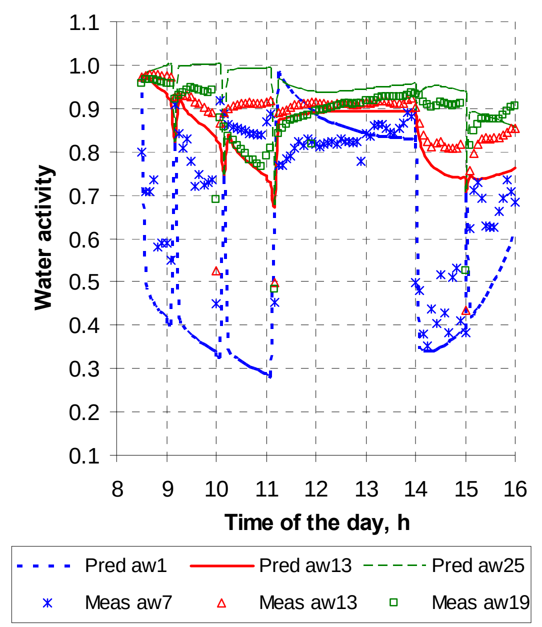


Fig 6.62: Comparison of the predicted and measured water activities for treatment 53 of Experiment Three/04
Pka Knhey, 2 cm, mat spread on soil, stirring, covering plus shading, Day One (Dec 18, 2004).

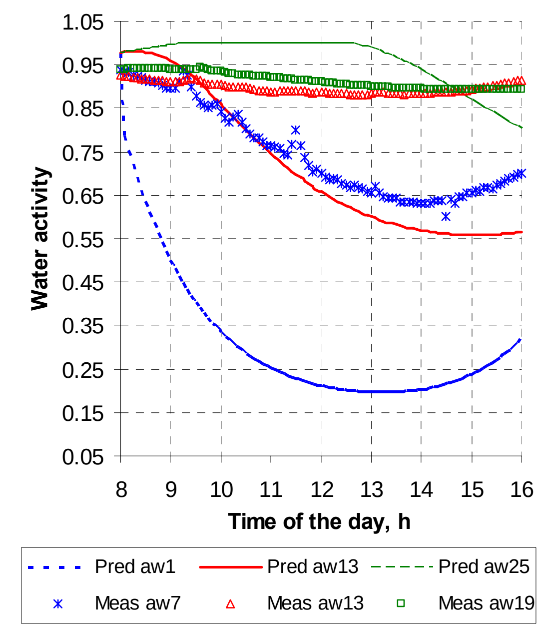


Fig 6.63: Comparison of the predicted and measured water activities for treatment 57 of Experiment Three/04
Pka Knhey, 2 cm, mat spread on soil, no stirring, no covering, Day One (Dec 22, 2004)

6.3 SUMMARY

A heat and moisture transfer model was successfully developed based on heat and moisture balance equations. The model solution was shown to have no significant numerical errors. It provided reliable predictions of the drying time, grain temperature and MC of the air at different layers within the grain bed as a function of time during sun drying for the ranges of the ambient conditions and most of the drying parameters or conditions considered in the experiments. The model has, however, not predicted the experimental water activities consistently.

Some lack of fit was evident from the comparisons between the model predictions and the experimental data, especially for the experiments carried out on polystyrene pads. Uncertainties in the values of the system inputs selected and in the experimental data explained the lack of fit for the other drying treatments. The model predicted drying times about 40 min shorter than were measured. This is thought to be due to approximate estimation of the effect of wind on the effective diffusion coefficient and heat transfer coefficient.

Chapter 7

MODEL APPLICATION

After showing that the model could predict the grain and air conditions during drying as well as the drying time, the predicted conditions for Experiment Three/04 were used to see if some of the bed parameters during drying, especially those that could not be measured directly, were related to the head rice yield (HRY). The Experiment Two/04 trials, where all the treatments were dried on the tarpaulin spread on polystyrene, were omitted from the analysis due to the over-prediction of temperature and under prediction of drying time.

7.1 METHODOLOGY

7.1.1 Parameter identifications

Based on the information and theories about possible mechanisms of grain fissure development and breakage available in the literature, a number of parameters were identified and calculated from the simulations. These mechanisms and the related parameters are given below. Table 7.1 summarises all the mechanisms and parameters.

7.1.1.1 Grain temperature

Many workers such as Nguyen *et al*. (1995), Zaman and Bala (1989), Li *et al*. (1999), Abud-Archila *et al*. (2000), Davidson *et al*. (2000), Fan *et al*. (2000b), Wongwises and Thongprasert (2000), Yang *et al*. (2002), Patindol *et al*. (2003) and Tirawanichakul *et al*. (2004) reported the strong effects of temperature on grain quality and recommended not to dry rice and maize grain with the air temperature of over 40^{o}C. In the sun drying system, moisture-removing capacity of the air can be very large and can cause serious damage to the grain (Imoudu and Olufayo, 2000). Internal stresses due to combined MC and temperature gradients could happen in the grain kernel to cause breakage. Based on this information, the following parameters were calculated to be used as variables that might be linked to the HRY:

- Maximum temperature at the bed surface, *Max* T_1, during the whole drying time

- Maximum average temperature of the rice bed, *MAT*, during the whole drying time. A weighted average for nodes 1 to 25 was used due to the thickness of node 1 being only half of the rest of nodes within the bed:

$$MAT = \frac{0.5\,T_1 + \sum_{j=2}^{j=25} T_j}{24.5} \qquad \text{… (7.1)}$$

- Maximum difference between the grain temperature at the bed surface and the bottom for the run, *MDT*:

$$MDT = maximum\ of\ (T_1 - T_{25}) \qquad \text{… (7.2)}$$

- Difference between the grain temperatures at the bed surface and the bottom, DT_{bulk}, when the bed was bulked or mixed together at the end of the day:

$$DT_{bulk} = T_{1\,bulk} - T_{25\,bulk} \qquad \text{… (7.3)}$$

7.1.1.2 Drying rate

According to Bhashyam *et al*. (1975), Aguerre *et al*. (1986), Ekstrom *et al*. (1966) and Imoudu and Olufayo (2000); rapid drying is a cause for the fissuring of rice grain. High temperature (40-45^{o}C) and low *RH* (less than 45%) of the ambient air were found to increase the drying rate and to cause high levels of breakage in the grain. They explained that when the water is removed so fast, large moisture gradients develop and cause physical stress for the grain. Therefore, the following parameters were calculated:

- Average drying rate, *ADR*. The drying rate (*DR*) was calculated for each 5-min period as:

$$DR_t = (MC_{av\,t} - MC_{av\,t+300}) / 300 \qquad \text{… (7.4)}$$

  and the *ADR* was the average of the drying rates calculated over the whole drying time.

- Maximum drying rate during drying, *MDR*. It was the maximum value of the 5-min drying rates calculated.

7.1.1.3 Grain critical MC

Siebenmorgen and Jindal (1986) reported that a number of studies indicated that the MC of around 16% is the critical level for the grain HRY. The concept was that if grain with lower MC than the critical MC was exposed to environments with high RH or is mixed with other grain with higher MC than the critical MC, it will adsorb moisture, become rewetted and hence cracks are formed (Hellevang, 2004). The following parameters were calculated based on the possible effects of the critical MC and moisture re-adsorption on the grain fissuring and HRY reductions.

- Product of the maximum difference between the MC at the bed boundaries and critical MC (16% wb or 19% db) when the bed was bulked together at the end of the day, $BBMC_{crit}$:

  $$BBMC_{crit} = (MC_1 - MC_{crit})*(MC_{25} - MC_{crit}) \quad \ldots (7.5)$$

  A higher negative value of $BBMC_{crit}$ corresponds to a greater gradient in the MC over the bed and could be the worst case for the HRY when the bed was bulked or mixed together. If the two nodes are either above or below the critical point, the value was positive and was set to zero, because mixing the grains that are all above or all below the critical MC has been reported to not cause any deterioration of the HRY.

- Maximum difference between the MC at different bed layers and the critical MC, $BLMC_{crit}$, when the bed was bulked. This parameter was calculated as

  $$BLMC_{crit} = \frac{1}{\left|\sum_{j=1}^{j=25}\left(MC_j - MC_{crit}\right)\right|} \quad \ldots (7.6)$$

- Maximum fraction of the bed versus the critical MC, $BFRMC_{crit}$, when the bed was bulked. Multiplication of the number of nodes with the MCs above the critical MC by the number of nodes with the MCs below the critical MC was the value of this fraction:

$$BFRMC_{crit} = Number\ of\ nodes\ with\ MC > MC_{crit} \times Number\ of\ nodes\ with\ MC < MC_{crit} \quad \ldots (7.7)$$

The notes as applied for $BBMC_{crit}$ are also applied for $BLMC_{crit}$ and $BFRMC_{crit}$.

7.1.1.4 Grain rewetting

Many workers have reported that the grain quality was affected by the changes in MC and moisture gradient differences both within the grain bed and within the individual kernels (Kunze and Hall, 1965; Kunze and Hall, 1967; Beeny and Ngin, 1970; Srinivas *et al*., 1977; Kunze, 1977; Srinivas *et al*., 1978; Kunze, 1979; Steffe *et al*., 1979; Sharma and Kunze, 1982; Sharma *et al*., 1982; Nguyen *et al*., 1995; Nguyen and Kunze, 1984; Aguerre *et al*., 1986; Banaszek and Siebenmorgen, 1990; Zhang and Litchfield, 1991; Soponronnarit, 1995; Lan and Kunze, 1996b; Sarker *et al*., 1996; Bonazzi *et al*., 1997; Shei and Chen, 1998; Li *et al*., 1999; Soponronnarit *et al*., 1999; Abud-Archila *et al*., 2000; Bautista *et al*., 2000; Perdon *et al*., 2000; Cnossen and Siebenmorgen, 2000; Chen and Wu, 2000; Fan *et al*., 2000b; Cihan and Ece, 2001; Yang *et al*., 2001; Cnossen *et al*., 2001; Kunze, 2001; Shei and Chen, 2002; Jia *et al*., 2002a; Jia *et al*., 2002b; Cnossen *et al*., 2002; Yang *et al*., 2002; Siebenmorgen, 2003; Cnossen *et al*., 2003). The following parameters were calculated to characterise MC gradients and the potential for rewetting:

- Maximum difference between the MC at the bed boundaries for the whole drying time, $REWET_{bb}$. For each drying day, the parameter was calculated as

$$REWET_{bb} = Average\ of\ (MC_{25} - MC_{1}) \qquad ... \qquad (7.8)$$

- Maximum difference between the MC at the bed boundaries when the bed was bulked at the end of the drying day(s), $REWET_{bb\ bulk}$:

$$REWET_{bb\,bulk} = MC_{25} - MC_{1}\ at\ the\ end\ of\ a\ drying\ day \qquad \ldots\ (7.9)$$

7.1.1.5 Stress within the grain kernels

Based also on the facts that are stated in Sections (iii) and (iv) above, the following parameters were calculated:

- Gradient between kernel average and surface MCs calculated when the drying rate was the highest, $STRESS_{max\ DR}$:

$$STRESS_{maxDR} = \frac{\sum_{j=1}^{j=25} MC_j \text{ - } MC_{ej}}{25} \quad \text{… (7.10)}$$

The equilibrium MC (MC_{ej}) at the kernels' surface was defined from the water activity at each layer at that point of time using the grain moisture isotherm

- Gradient between kernel average and surface MCs when the bed was bulked, $STRESS_{bulk}$. Equation 7.10 was also applied to determine this parameter. The difference was that the MCs were determined when the grain was bulked at the end of each drying day and the end of drying.

7.1.1.6 Glass transition

A number of workers such as Cnossen and Siebenmorgen (2000), Cnossen *et al*. (2001), Cnossen *et al*. (2002) hypothesised that the HRY should not be affected if rice is dried below the T_g line (lower than the glass transition temperature). If the grain is dried above the T_g line sufficiently long enough with no precaution, a state transition of the starch can cause fissuring in the kernels and consequent HRY reduction. Therefore, the following parameters were calculated:

- Maximum magnitude of phase change, TT_g among the drying days was determined as

$$TT_g = \frac{\sum_{j=1}^{j=25} \sum_{t=0}^{t=t_{end}} \left(T_{jt} - T_{gjt}\right)}{25 \times t_{end}} \quad \text{… (7.11)}$$

where the T_{git} was calculated for every bed layer at every point of time during the whole day using the T_g equations reported in Section 4.8 with the corresponding temperature and *MC*:

$T_g = -1.23\ MC + 56.7$ for Pka Knhey and

$T_g = -1.75\ MC + 67.8$ for CAR11

This parameter was applied, based on the fact that if the grain is dried above the T_g line, the state transition would cause fissuring in the kernels and consequent HRY reduction, if tempering was not done long enough at that temperature.

7.1.2 Effect on HRY

To identify potential relationships between the proposed parameters (independent or predictor variables) and the HRY (dependent or criterion variable), backward elimination regression analysis was performed for each grain variety separately. Results of the analysis were expected to help select parameters that are truly good predictors of HRY from those that appear to have an effect due to random chance, and therefore to identify which mechanisms were best at characterising the loss in HRY.

Table 7.1: Proposed mechanisms and parameters that could affect the HRYs with the ranges of their maximum values predicted by the model for Experiment Three/04

Mechanisms					
Temperature	**Drying rate**	**Critical MC**	**Rewetting**	**Stress**	**Glass transition**
$Max\ T_1$ (50.25 to 58.51)	ADR (0.002 to 0.04)	$BBMC_{crit}$ (-146.49 to14.25)	$REWET_{bb}$ (0.03 to 0.21)	$STRESS_{maxDR}$ (0.03 to 0.08)	TT_g (-0.46 to 9.46)
MAT (41.32 to 54.74)	MDR (0.02 to 0.06)	$BLMC_{crit}$ (0.005 to 0.04)	$REWET_{bb\ bulk}$ (0.02 to 2.40)	$STRESS_{bulk}$ (0.007 to 0.05)	
MDT (7.16 to 19.49)		$BFRMC_{crit}$ (0 to 250)			
DT_{bulk} -6.5 to 18.84)					

<u>Note:</u> *Details of the calculations of the proposed parameters are in Appendix B14.*

To eliminate the variables that were strongly correlated, a correlation matrix was constructed using Statistica software (99 Edition by StatSoft Inc). The relationship between all the proposed parameters was defined (see details in Appendix A8). Among the parameters identified in Table 7.2, the following pairs were shown to be closely correlated (a correlation coefficient of bigger than 0.9 or a coefficient of determination, R^2, of 0.81 which means that 81% of the variation in one variable was explained by variation in the other variable):

- MDR and $STRESS_{max\ DR}$ both for Pka Knhey and CAR11 varieties and

- $REWET_{bb}$ and $REWET_{bb\ bulk}$ for Pka Knhey variety only.

Therefore, in the regression analysis only one of the pairs of parameters was used.

The backward elimination was performed, based on the method reported by Dallal (2004). According to this worker, the method has an advantage over forward selection, because:

- It is possible for a set of variables to have considerable predictive capability even though any subset of them does not,
- It starts with everything in the model, so their joint predictive capability will be seen,
- Forward selection can fail to identify variables. As the variables don't predict well individually, they will never get to enter the model to have their joint behaviour noticed; only the results obtained from the backward method were considered.

It started with all of the parameters (predictors), except the ones that were eliminated in (i), in the model. The parameter that was least significant (that is, the one with the largest p value) was removed and the model refitted. Each subsequent step removed the least significant variable in the model until all remaining variables had individual p values of smaller than 0.05.

7.2 RESULTS OF THE MULTIPLE REGRESSION ANALYSIS

As there was more than one independent variable, the regression equation or line resulting from the analysis could not be visualized in two-dimensional space. Table 7.2 summarises the parameters that were found to have some contributing effects on the HRYs with corresponding R^2 values, while the details of all the results obtained from the regression analysis are in Appendix A8. The R^2 values indicate the degree to which the parameters (or predictors or independent variables) are related to the yields (dependent variable).

Table 7.2: Parameters that were shown to have some effects in combination on the HRYs

	Milling HRY	**MI HRY**
Pka Knhey	*ADR, Max T1, MAT,* DT_{bulk}, $BBMC_{crit}$, $BLMC_{crit}$, $STRESS_{maxDR}$ *and* $STRESS_{bulk}$ (R^2 = 0 .0.4329)	*Max T1, MAT, MDT,* DT_{bulk}, $REWET_{bb}$, $STRESS_{bulk}$ *and* TT_g (R^2 = 0.771)
CAR11	*MDR, MDT,* DT_{bulk}, $BLMC_{crit}$, $REWET_{bb}$, $REWETT_{bb}$ *bulk and* TT_g (R^2= 0.489)	*Max* T_1, $BLMC_{crit}$, $BFRMC_{crit}$, $REWET_{bb}$ *and* TT_g (R^2= 0.620)

For the two grain varieties and the two methods for determination of the HRYs, the significant relationships obtained by the regression analysis were:

$$HRY_{MILL} \text{ for Pka Knhey} = -217.816\ ADR - 1.302\ Max\ T_1 + 0.623\ MAT + 0.352\ DT_{bulk} - 0.116\ BBMC_{crit} - 130.039\ BLMC_{crit} + 231.517\ STRESS_{ma\ DR} - 147.113\ STRESS_{bulk} + 75.186 \quad \ldots (7.12)$$

$$HRY_{MI} \text{ for Pka Knhey} = -1.905\ Max\ T_1 + 1.382\ MAT + 0.589\ MDT + 0.161\ DT_{bulk} - 22.892\ REWET_{bb} - 138.016\ STRESS_{bulk} - 1.042\ TT_g + 72.680 \quad \ldots (7.13)$$

$$HRY_{MILL} \text{ for CAR11} = -318.459\ MDR - 1.116\ MDT + 0.165\ DT_{bulk} - 107.063\ BLMC_{crit} - 22.422\ REWET_{bb} + 1.760\ REWET_{bb\ bulk} - 1.243\ TT_g + 75.640 \quad \ldots (7.14)$$

$$HRY_{MI} \text{ for CAR11} = -0.438\ Max\ T_1 - 137.222\ BLMC_{crit} + 0.030\ BFRMC_{crit} - 27.660\ REWET_{bb} - 0.277\ TT_g + 66.451 \quad \ldots (7.15)$$

Because the values of the corresponding coefficients of determination of lower than 0.5 which means that less than 50% of the yield can be accounted for, the models describing the milling HRYs for both varieties will not be discussed further.

Therefore, only Equations 7.13 and 7.15 were considered to be indicative of likely mechanisms affecting HRY. The regression coefficients (or B coefficients) shown in these equations are not normalised so their values are not comparable between variables because they depend on the units of measurement or ranges of the respective variables. Thus, to compare the relative contribution of each independent variable in the prediction of the dependent variable, the magnitudes of beta coefficients were used. These mean that the HRY obtained from the MI test of

- Pka Knhey variety was affected the most by the decrease in the maximum average temperature, *MAT*. The next most influential mechanisms in rank were the increase in maximum temperature of the bed surface, *Max T1*, the increases in the phase change magnitude, TT_g, the decrease in the maximum difference between the grain temperatures at the bed boundaries, *MDT*, the increase in the maximum disparity between the MC at the bed boundaries when the bed was bulked at the end of the drying day, $REWET_{bb}$, the increase in the stress when the grain bed was bulked at the end of the drying day, $STRESS_{bulk}$ and the decrease in the difference between the grain temperatures at the bed surface and bottom, DT_{bulk} (see Table A8.6 of Appendix A8).
- CAR11 variety was affected the most by the decrease in the maximum fraction of the bed versus the critical MC when the bed was bulked, $BFRMC_{crit}$. Next in rank were the increase in $REWET_{bb}$, the increase in the disparity between the MCs of individual bed layers and the critical MC when the bed was bulked, $BLMC_{crit}$, the increase in $Max\ T_1$ and the increase in TT_g (see Table A8.8 of Appendix A8).

As it was observed that the magnitudes of the beta coefficient changed within a small range (from 0.3 to 1.5) and due to all the uncertainties involved in the quality test, it could only be assumed that the mechanisms corresponding to the parameters appearing in the final regression equations had some contributing effects on the grain quality.

7.3 SUMMARY

In summary, the model was shown to be very useful in predicting the drying time required to bring the grain to the target MC as well as predicting the grain and air conditions within the bed for the whole drying time. A number of parameters that were relevant to the mechanisms of the grain fissure development and breakage available in the literature were identified and calculated from the simulations. The mechanisms that have been identified as having an impact on the HRY are the grain temperature, critical MC, rewetting, stress within individual kernels and the phase change in regard with the T_g.

Chapter 8

DISCUSSION AND CONCLUSIONS

8.1 GENERAL ASPECTS OF SUN DRYING

Sun drying of rice grain and other agricultural products has always been of great importance for the preservation of food, as mechanical dryers have not yet been established to the desired extent, due to socio-cultural, technical and financial reasons. Sun drying offers the simplest and lowest energy cost drying and is commonly practised where reliable solar radiation is available. It usually takes 1 to 3 days to dry rice after threshing, depending on the solar intensity, ambient air temperature and relative humidity (RH), wind velocity, the grains' initial moisture content (MC) and variety, depth of drying bed, the type of drying pad and the intensity of stirring. It has been estimated that on average eight man hours is required to dry one ton of rice grain and large-scale production can limit the use of the method due to lack of ability to control the drying process which in turn can produce paddy with lower milling quality than other drying methods.

In ideal and efficient drying situations, the grain should be dried uniformly and quickly, and its end-use quality should not be badly affected. It has been reported that controlled sun drying may result in a head yield comparable or even better than some artificial or mechanical drying (Bakker-Arkema and Salleh, 1985; Teter, 1987; Zaman and Bala, 1989; Garg and Kumar, 2000; Imoudu and Olufayo, 2000).

8.1.1 Ambient air conditions

There is only limited means of adjusting the drying air conditions in the system and the only heat source for the system is the solar radiation or intensity. Similar to the ambient air, the intensity can fluctuate from day to day and from time to time. It is zero at night and is at its maximum value around midday. It is affected strongly by the movement and intensity of cloud.

The grain temperature was found to be more greatly affected by the solar intensity than the ambient air temperature. On the other hand, the solar intensity also affects the ambient air temperature and RH, thus influencing its drying potential. Wind speed or velocity is another important factor that is indirectly related to solar radiation in a particular location.

8.1.2 Drying time

Apart from the differences between drying days due to solar radiation and ambient air conditions, the grain varieties used and the bed depths, stirring, tempering and drying pads were found to have significant effects on the drying time. For mechanical drying, increasing the air temperature and flow rate is used to increase the rate of drying. The fastest sun drying could be achieved when

i. The bed was less compacted. Porosity within the grain bed played an important role in the drying rate as it affects the movement of moisture out of the bed. The smaller the grain kernels, as in the case of Masary variety, the higher the bulk density, and the more tightly they can be arranged resulting in smaller porosity. With the lower porosity, the moisture diffusivity, both from the internal to the surface parts of the grain kernels and from within the bed to the bed surface, is reduced due to less exposure of the kernel surfaces to the air, higher constrictivity and tortuosity (repeated twists, bends, or turns) within the bed and less convective movement of the air.

ii. The bed was thinner. With a thinner bed, the grain kernels had more chance to be exposed to the sun, ambient air and wind as the heat sources. Moreover, there was less resistance for the moisture to move through the bed. From their experience, farmers have realised this effect and in practice they tend to dry their grain as thin as the drying materials and/or available area allow.

iii. The bed was stirred but not shaded or covered. Stirring the grain bed was shown to give more chance for the grain kernels to be exposed uniformly to the sun. Stirring brings up the wet grain kernels from the lower or bottom parts of the bed. When the wet kernels are exposed to the drying sources, evaporation of moisture from the bed surface can happen faster than just allowing it to diffuse by itself up through the bed. Covering the grain bed, on the other hand, stops or reduces both the effect of heating caused by the solar radiation and evaporation. Covering the bed at midday prevents the grain from being exposed to the solar radiation and from evaporating its moisture to the ambient air, thus causing the drying to slow or stop during that period.

iv. Drying on a porous pad. Some of the drying pads were porous which allow some air and moisture movement through and out of the bed, respectively. When spread directly on the ground, the waterproof tarpaulin and the nylon net do not provide a space for the air to circulate between the grain bed and the ground. The mat and to a much larger extent, the husk, give a region under the grain through which air can permeate which aids in the circulation of air through the grain which, in turn, aids drying. Moreover, with non-porous pads, moisture accumulates at the lower and bottom layers of the bed. The mat, even when it was also spread directly on the ground and the husk base, allow this moisture to move out of the bed. When the nylon net was spread on top of the husk layer, the husk gave the rice at the bottom a good supply of dry air. Therefore, the drying time for this type of pad was found to be the shortest. The reasons were evidenced by the highest temperatures (maximum temperature at the surface of the bed and average bed temperature) and the highest drying rate that were defined from the model predictions for the pad.

Different chemical and structural properties of the grain varieties might also have some influences on the drying time or drying rate but were considered to be outside the scope of this study.

8.1.3 The grain quality

Only the HRYs determined by the MI and milling tests in 2004 could be considered to reliably represent the quality of the grain samples. The tests were, however, not precise as the milling machine used was not standardised as laboratory equipment and the MI tester has been in principle developed for testing other grain such as maize. Even so, efforts were made to perform the tests as appropriately as possible and among the equipment available in Cambodia and New Zealand at the time of study, the two testers were considered to be the most suitable for the rice grain. The other quality tests failed to determine the grain quality.

Based on the results obtained from the MI and milling tests performed in 2004, most of the design parameters and the ambient conditions were also found to have significant effects on the HRYs. Less damage to the dried grain and/or higher HRY was found when

i. The bed was stirred. Stirring the paddy during drying was not only important for increasing the rate of drying, but also for maintaining good milling quality. Results obtained from all the experiments conducted in 2003 and 2004 indicated that stirring the same grain dried with the same depth and on the same drying pad every one hour helped increase the yields. Bala and Woods (1994) also found that stirring, turning or mixing the grain bed regularly caused the grain to dry more uniformly, to avoid over-drying and also to give a tempering effect.

ii. The bed was shaded. Different covering methods produced different effects on the grain HRY. The HRY increased by about 3% when the grain was shaded. Shading the grain with or without covering during the hottest time of the day gave a tempering effect which helped to reduce MC gradients within the bed and within individual kernels that might induce fissuring. Under the shade, the grain was maintained in a more even environment so that the moisture inside the grain kernels could equalise between the centre and surface of the kernel at a nearly constant temperature. During shading, diffusion phenomena predominate and the average temperature and MC of the kernel remain nearly constant. Bhashyam *et al*. (1975) found that continuous drying of the grain under the sun gave the shortest drying time but caused higher breakage than when the drying was slowed down by tempering between drying steps. When the grain temperature was mild (25 – 32^{o}C), the tempering steps were not essential.

iii. Drying slowly on pads with less air circulation. Rapid drying was found to cause fissuring in the dried grain. The yields were found to be inversely related to the drying times. The drying pads were found to have very significantly different effects on the yields. The pad that took the shortest drying time (the net spread on husk) was shown to give the worst damage to the dried grain and the pad that took the longest time (the tarpaulin or the net spread directly on the ground) provided the dried grain with the highest quality. From the model predictions (Appendix B13), it was revealed that drying on the net spread on husk made the smallest difference between the grain temperatures at the bed surface and the bottom (DT_{bulk}) and created less rewetting problem but had the highest temperatures (both for the surface and average of the bed), drying rate, maximum difference between the MC at the bed boundaries and critical MC when the bed was bulked ($BBMC_{crit}$), stress within the grain kernels (both at maximum drying rate and when the bed was bulked) and the magnitude of phase change (TT_g).

iv. The bed was thin. In Experiment Two/04, drying the grain of CAR11 variety with 2 cm depth on a tarpaulin spread on a polystyrene slab provided the dried rice with a HRY of about 44%, while drying the same grain on the same drying pad with a 1 cm thicker bed caused the HRY to decrease by about 4%. However, there were competing effects. In contrast to these results, the MI and milling yields of the grain dried within the 2 cm bed in Experiment Three/04 were not shown to be significantly different from the other grain dried within the 3 cm bed.. As discussed earlier, drying the grain with a thick bed results in less uniform drying. The MC difference between the grain kernels at different bed layers is larger and stirring or bulking the beds might cause greater rewetting problems than for shallower beds or the same depth without stirring. For the thinner bed depth, a greater proportion of the grain is exposed directly to the sun and air giving quicker and more uniform drying, but also smaller MC differences, and thus less risk of grain damage by the rewetting process.

The HRYs of the varieties tested were significantly different. That could be caused by the different intrinsic characteristics (physically and chemically) of the different varieties and hence different resistance to breakage. Therefore, optimum drying conditions are likely to differ from one cultivar to another.

Except for the DSC, other methods trialled to determine the T_g of rice kernels used in the study failed. The T_g values found from the DSC method were, however, scattered but generally decreased with increasing MC. They compared quite well with the published T_g value for rice. The variability was probably due to the sample heterogeneity rather than the method. Some regions of a kernel may be more amorphous and less crystalline than others.

8.2 DRYING MODELS AND CONCEPTUAL FRAMEWORK FOR MAINTAINING RICE QUALITY

Heat and moisture transfer phenomena during sun drying of rice were successfully simulated using thermal and moisture-transport properties of all the materials and systems involved. The dependent variables (the temperatures, MC and water activities of the grain at different layers of the beds) predicted by the model fitted the experimental data within the system input and experimental uncertainties. However, this level of fit required some adjustments and modifications to the values of the system inputs.

The model was shown to be very useful in predicting the grain and air conditions within the bed for the whole drying time, as well as predicting the drying time required to bring the grain to the target MC. Overall, the model predicted drying times to be about 40 min shorter than were measured.

The grain conditions within the bed predicted by the model for the whole drying time were used to relate drying parameters to the HRYs. Based on the various theories about the mechanisms of grain fissures and breakage available in the literature, a number of parameters were derived to characterise these mechanisms and the model was used to estimate these parameters. These parameters were then regressed against HRY to determine which mechanisms contributed to HRY.

The relationship of mechanistic parameters and milling HRYs was weak. The multiple regression analysis of the MI HRY for both grain varieties revealed that the stress, rewetting, critical MC maximum temperature and the magnitude of phase change all had significant effect on the yield. Therefore re-absorption of moisture or rewetting after drying appeared to be the most likely mechanisms leading to fissure formation. Thus, drying the grain in a shallower bed, stirring regularly, and covering or shading the bed at midday are the best options to improve the HRY. This result is consistent with the earlier statistical analysis.

This finding agrees with other workers such as Siebenmorgen and Jindal (1986) and Hellevang (2004). They claimed that the main cause of excessive fissuring of the kernels with subsequent low head yields is allowing too large a moisture variation to be created following mixing or bulking the dry kernels with the wet where some are below and some are above the critical MC of about 16%. This is most likely to occur when the grain bed is thick and is inadequately stirred. The grain kernels at the surface or the higher parts of the bed became very dry while the other kernels deep in the bed remain quite wet.

However, the relationship between the proposed mechanistic parameters and the HRYs was not strong. The weak correlation was suspected to be caused by uncertainties in the experimental data and in some material properties defined for the model application. For instance, the physical and thermal properties of the soil, husk, mat, tarpaulin and net used in the experiments were not measured and had to be taken from published literature. Also, the uncertainty in the measurements of air relative humidity, grain temperature, MC and HRYs during the experiments were large for the following reasons:

- Fluctuation in cloud movement as well as the ambient air conditions from hour to hour and from day to day
- Non-uniformity in ripeness and MC of the grain before drying. Even after all the grain samples were rewetted and/or preconditioned to attain the same MC, differences in the initial MCs as determined by the moisture meter at the start of drying of around 2% were still observed. The apparent differences in MC might be due to the different locations of the kernels on the panicles and in the field or might be due to inaccuracy of the moisture meter itself. Hellevang (2004) and others stated that a grain MC variation among kernels after drying can exist if there was a MC variation before drying. For example, if the kernels vary in moisture between 20 and 30% before drying, the variation may be between 12 and 18% after drying. Moreover, moisture meters are normally calibrated for mature grain with normal characteristics. Variations in grain maturity, growing conditions and bulk density can affect the accuracy of the meter. The fact that the samples contained kernels with different sizes has added further uncertainty in the measurements.
- The sensitivity and accuracy of the sensors, measuring devices/equipment and the quality tests. For instance, moisture condensation or penetration into some probes could happen easily, especially for the probes placed in the lower parts

of the bed. Imprecise placements of the probes or sensors at the desired position within the drying bed and disturbance of the bed due to stirring, covering, and shading could also contribute to increased uncertainty.

- Sampling methods to get representative samples used in the quality tests. Lower parts of the bed were sometimes affected by moisture condensation. When a bed sample was taken, the measured MC would be likely sensitive to the amount of the kernels taken from the bottom of the bed. Wadsworth *et al*. (1982); Wadsworth and Hayes (1991); and Sun and Siebenmorgen (1993) reported that at time of harvest and milling, the thickness of individual grain kernels within a lot varies widely and the variation has a strong impact in the milling test and the milling yield.

Moreover, the model was found not to be able to predict the grain and air conditions when the grain was dried on polystyrene. The temperature of the grain and reduction of MC were over-predicted for this treatment and the uncertainty of the predicted temperatures within the bed was not large enough to cover the experimental data.

Based on all the observations, the following methods are recommended as providing the drying with optimum outcomes in terms of HRY, drying time and simplicity:

- <u>Stirring the bed</u>. Stirring the bed every one hour during drying was important both for reducing the drying time and increasing the HRY. It made the drying 2 to 3 h faster and provided the dried grain with a HRY from 2 to 7% higher than not stirring at al.
- <u>Drying with a thin bed</u>. Drying the grain with a thin bed (2 cm depth) was important both for reducing the drying time and increasing the HRY. It made the drying 2 to 4 h faster and provided the grain with a HRY 1 to 4% higher than drying with a thicker bed (3 cm). However, the main constraint can be the size of the drying floor and the drying pad available.
- <u>Covering or shading the bed</u>. Covering or shading the bed for several hours around midday was important for reducing the maximum bed temperature (especially good for seed), and for increasing the HRY. Any of the two methods could increase the drying time by about 1.5 h but provided the grain with the HRY of about 2 to 3% higher than exposing the bed for the whole time to the sun. Covering the grain bed is the simplest method but requires additional pad.

Providing the bed with shade can also require another pad and more effort. Moving the bed to a shade (under tree or house) can be another option to avoid using another pad. Covering the bed under shade should be avoided as the HRY can be the same but caused the drying time to be 1.5 to 5 h longer when compared to the direct covering or shading method.

- Drying on pad with low air circulation. Tarpaulin or net spread directly on the ground was found to be the best drying pad for the HRY. Drying on any of the two pads took about 4.5 hours longer but provided the grain with the HRY of about 2% higher than drying on the net spread on husk. Drying on mat could reduce the time by about 1.2 h but the yield was nearly as bad as drying on the net spread on husk (about 1% higher).

8.3 CONCLUSIONS

In summary, some key scientific principles about sun drying of rice have been identified and investigated in the study. Grain producers or handlers can follow the principles to achieve higher benefits from this most practicable and economical method of drying.

Unlike the mechanical drying systems within which the drying air temperature and flow rate can be adjusted, the time required in the sun drying system was found to depend very much on the climatic conditions. The higher the solar intensity, wind speed and ambient air and sky temperatures, and the lower the RH of the ambient air, the shorter was the drying time. Practical methods that can be applied to help reduce time in the sun drying system were found to be

- Less compaction of the bed to enable more air movement between the grain kernels
- Drying on a thin bed to provide greater chance for the grain kernels to expose to the heat sources
- Stirring the grain bed regularly to enable fast and uniform drying
- No covering or shading the bed and
- Using a pad which allows some air and moisture movement below the grain bed.

Among all the methods tested in this study, only the DSC method could determine T_g of the rice used in this study. The measured T_g values were found to have lots of variation but there was a general trend of decreased T_g with increasing MC. The values compared quite well with others for rice from published data.

The quality tests other than the MI and milling tests performed in 2004 were unsuccessful in determining the grain quality. Different rice varieties showed different resistances to damage under similar drying conditions.

To obtain dried grain with higher quality from the sun drying system, the following methods were found to be helpful:

- Spreading the grain to dry in a thin bed
- Drying the grain slowly on the pads with less air circulation below the bed (e.g. drying on a waterproof tarpaulin or net spread directly on the ground).
- Stirring the grain bed regularly to achieve uniform MC, avoid over-drying, give a tempering effect and reduce variation in the MC within the bed that can cause rewetting and subsequent cracking of drier grain kernels. Avoid mixing dry grain (MC less than 16 %) with moist grain (MCs greater than 16%). Once the rice kernel is dried to a level below the critical MC, any rewetting may cause excessive fissuring and head rice yield reductions, and
- Shading with or without covering the bed during midday or when the solar intensity was high to reduce the severity of the solar intensity.

To optimise the drying process or to obtain the best trade-off between the HRY and the drying time, one should dry the grain in a thin bed on tarpaulin or nylon net spread directly on the ground with stirring every one hour and covering or shading for several hours around midday.

The formulated model was experimentally validated and shown to be a very good mechanistic tool with advantages of simplicity and practical accuracy in the design and management of the sun drying system. It predicted the drying time required for drying and the temperature, water activity and MC within the bed during the whole drying time. Uncertainty in the system input data and experimental methods accounted for most of the difference between predicted and measured data.

Model predictions were used to identify the mechanisms that cause the loss in HRY. Among all the mechanisms proposed, the stress within the grain kernels, rewetting the grain bed when bulked, critical MC, the grain temperature and magnitude of phase change were found to be the best predictors of the yields.

8.4 FURTHER RESEARCH

This study has provided advancement in the level of knowledge on the sun drying of rice.

In order to gain more knowledge in optimising the drying process, the following areas for further research are recommended:

- To conduct more experiments with a limited number of drying factors to avoid having high interaction levels. Also, all the treatments should be undertaken simultaneously to avoid differences due to uncontrolled variables such as the climate.
- To use wider ranges of variables so that their effects on the grain quality will be more obvious.
- To devise and use better measuring probes, instruments and equipment as well as standardising test methods.
- To try solving the model using other set of Matlab's ODE solvers.
- To reduce the model inaccuracies by exploring and, if necessary, including other mechanisms. For instance:
    - Modelling the changes in the air and the grain properties as functions of the actual temperature and MC during drying.
    - Modelling the heat and moisture transport term due to air expansion and contraction with changing temperature as when a node of fixed volume is heated, the air density would decrease and the air would flow out of the fixed volume and carry heat and moisture with it.

    - Modelling the coefficients for thin-layer drying constants as a function of the grain initial MC, actual temperature and humidity.
    - Modelling air flow within the bed induced by the wind.
    - Modelling the heat transfer coefficient and the moisture diffusivity within the bed and all the exposed materials as affected by the air flow.
- To develop and solve a stress-strain model using finite elements methods to predict the temperature and moisture gradients within individual kernels and their impact on fissure formation and reduction in HRY.

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Appendix A1

NOMENCLATURE

Latin symbols

a_k	Specific surface area of paddy kernels (surface/ bulk volume)	m^2/m^3
A	Flat surface area of drying bed	m^2
a_{sph}	Major semi- axis of ellipse of rotation	mm
A_{top}	Top surface area of drying bed	m^2
a_w	water activity ($_{meas}$ and $_{pred}$ for measured and predicted, respectively)	-
B	The second coefficient for drying constant	1/s
Bi	Biot number	-
b_{sph}	Minor semi-axis of ellipse of rotation	mm
C	Moisture concentration in air	kg/m^3 of air
C_a	Moisture concentration in the ambient air	kg/m^3 of air
c_{bk}	Width of brown rice kernel	mm
c_k	Width of paddy kernel	mm
c_p	Specific heat capacity ($_{a,\ carb,\ h,\ m,\ mat,\ p,\ pd,\ pol,\ s,\ v,}$ *and* $_w$ for ambient air, carbohydrate, husk, a material, mat, paddy, paddy dry matter, polystyrene, soil, water vapour and water, respectively)	$J/kg.^oC$
d_{bk}	Thickness of brown rice kernel	mm
d_k	Thickness of paddy kernel	mm
D_k	Diameter of paddy kernel	mm
D_v	Diffusivity of water vapour ($_{a,\ m}$ and $_p$ in open air, exposed material and in grain bed, respectively)	m^2/s
$D_{vm.eff}$	Effective diffusivity of the water vapour in the materials 2 and 3	m^2/s
E	Constant for Equations 2.10, 2.13, 2.14 and 6.4	-
e_{sph}	Eccentricity	mm
F	Constant for Equation 2.10, 2.13, 2.14 and 6.31	-
F_{A1}	Configuration or geometric factor between shading tarpaulin and covering tarpaulin or between shading tarpaulin and grain bed	-
F_{A2}	Configuration or geometric factor between covering tarpaulin and grain bed	-

F_e	Emissivity correction factor	-
F_{pbend}	Peak bending force	N
G	Constant for Equation 2.10 and 2.14	-
h	Convective heat transfer coefficient	$W/m^2.^oC$
H	Humidity ratio	-
h_{fg}	Latent heat of evaporation (from fluid to gas)	J/kg
h_g	Enthalpy or heat of evaporation	J/kg
h_{gin}	Enthalpy or heat for evaporating moisture into a node	J/kg
h_{gout}	Enthalpy or heat for evaporating moisture out from a node	J/kg
HRY	Head rice yield	%
HRY_{MI}	Head rice yield from MI test	%
HRY_{MILL}	Head rice yield from milling test	%
I	Solar intensity	W/m^2
J	Number of space steps in the grain bed	-
k	The first coefficient for drying constant	1/s
K	Number of space steps in material 2	-
k_g	Mass transfer coefficient in humidity units	$kg/m^2.s$
k_y	Convective moisture transfer coefficient	m/s
L	Number of space steps in material 3	-
L_a	Thickness of air layer below covering tarpaulin	mm
L_b	Beam span used for bending test	m
Le	Lewis relationship	-
L_k	Length of the paddy kernel	mm
L_m	Thickness or depth of a material	mm
L_p	Depth of the grain bed	mm
L_s	Depth of soil affected by drying	mm
M	Constant for Equation 2.14	-
m'	Ratio of rice and soil depths to the rice depth	-
MC	Moisture content ($_{db}$, $_e$, $_i$, $_{wb}$, $_{meas}$, and $_{pred}$ for dry basis, equilibrium, initial, wet basis, measured and predicted, respectively)	% or decimal
MR	Moisture ratio	-
n_{slope}	Slope of moisture isotherm	-
P_v	Water vapour pressure	Pa

P_{vs}	Saturated water vapour pressure	Pa
P_{tot}	Total pressure	Pa
q	Rate of heat	W
Q	Heat	J
R	Ideal gas constant, 8.3145	J/mol K
R'	Thickness of an infinite slab	mm
r	Distance from the neutral axis to the outer layer of brown rice kernel	m
r_k	Radius of paddy kernel	m
$R_{m/m+1}$	Resistance for heat conducted from an exposed material to other exposed material below	$m^2.^oC/W$
$R_{MTm/m+1}$	Resistance for mass transfer from an exposed material to other exposed material below	$m^2.^oC/W$
$R_{tarp/p}$	Resistance for heat conducted from covering tarpaulin to paddy bed	$m^2.^oC/W$
RH	Relative humidity	% or decimal
RH	Relative humidity ($_a$ and $_i$, for the ambient air and initial, respectively)	% or decimal
S	Switches ($_1$ and $_2$ for shading and covering, respectively)	-
t	time ($_{stir}$ for stirring)	s
T	Temperature ($_{a,\ cov,\ cryst,\ g,\ gr,\ h,\ i,\ m,\ mat,\ meas,\ melt,\ p,\ pol,\ pred,\ s,\ sh,\ sky}$ and $_{stir}$ for ambient air, covering tarpaulin, crystallisation, glass transition, ground, husk, initial, a material, mat, measured, melting, paddy, polystyrene, predicted, soil, shading tarpaulin, sky and stirring, respectively)	^oC
u_o	Air current through the bed	mm/s
$U_{m/m+1}$	Reciprocal of $R_{m/m+1}$	$W/m^2.^oC$
$U_{tarp/p}$	Reciprocal of $R_{tarp/p}$	$W/m^2.^oC$
V	Volume	mm^3 or m^3
v_a	Wind speed	m/s
V_{sph}	Volume of spheroid object	mm^3 or m^3
W_a	Weight of air in the grain	g
W_{carb}	Weight of carbohydrate in the grain	g
$W_{3/4}$	Weight of white rice longer than ¾ of whole kernels	g

W_{bd}	Weight of brown rice obtained from dehusking paddy	g
W_{bMI}	Weight of brown rice sample assigned for MI test	g
W_{pi}	Initial weight of paddy sample	g
W_{rem}	Weight of brown rice remaining on sieve	g
W_w	Weight of water in the grain	g
x	Spatial coordinate	m

Greek Symbols

ΔP	Pressure drop	g/cm^2
Δx	Spatial step ($_2$, $_3$, $_m$ and $_p$ for material 2, material 3, a material and the grain bed, respectively)	m
ρ	True density ($_a$, $_h$, $_m$, $_{mat}$, $_p$, $_{pol}$ and $_s$ for ambient air, husk, a material, mat, paddy, polystyrene and soil, respectively)	kg/m^3
ρ_b	Bulk density ($_a$, $_h$, $_m$, $_{mat}$, $_p$, $_{pol}$ and $_s$ for ambient air, husk, a material, mat, paddy, polystyrene and soil, respectively)	kg/m^3
λ_a	Thermal conductivity of the air	$W/m.^oC$
λ	Effective thermal conductivity ($_h$, $_m$, $_{mat}$, $_p$, $_{po}$, $_s$ and $_{tarp}$ for husk, material, mat, paddy, polystyrene, soil and tarpaulin, respectively)	$W/m.^oC$
α	Thermal diffusivity	m^2/s
σ	Stefan-Boltzmann constant, 5.669×10^{-8}	$W/m^2.K^4$
ε	Porosity of air in a bulk material ($_h$, $_m$, $_{mat}$, $_p$, $_{pol}$ and $_s$ for the husk, a material, mat, paddy, polystyrene and soil, respectively)	-
$\in$	Emissivity of a surface (*tarp* and *p* for the tarpaulin and grain bed, respectively)	-
θ	Absolute temperature	K
β	Absorptivity of a surface (*tarp* and *p* for the tarpaulin and grain bed, respectively)	-
μ	Air viscosity	Pa.s
$\phi_s.d_k$	Equivalent grain diameter	cm
ϕ'	Volume fraction of water in solid material	-
ψ	Moment of inertia	m^4
χ	Bending strength	Pa

Abbreviations

ADR	Average drying rate
ANOVA	Analysis of Variance
ASAE	American Society of Agricultural Engineers
ASHRAE	American Society of Heating, Refrigeration and Air-conditioning Engineers
$BBMC_{crit}$	Maximum difference between the moisture content at the bed boundaries and critical moisture content when the bed was bulked,:
$BFRMC_{crit}$	Maximum fraction of the bed versus the critical moisture content, when the bed was bulked.
$BLMC_{crit}$	Maximum disparity between the moisture content at different bed layers and the critical moisture content, when the bed was bulked.
BS	Breakage susceptibility
CAR	Cambodian Rice
DMA	Differential mechanical analyses
DPSc	Department of Polymer Science University of Southern Mississippi, USA
DSC	Differential scanning calorimetry
DT_{bulk}	Difference between the grain temperatures at the bed surface and bottom when the bed was bulked or mixed together
eps	A very small value of $2.2204\ 10^{-16}$
IR	International Rice
IRRI	International Rice Research Institute, Los Banos, Philippines
ISO	Organization for Standardization
ITE	Institute of Technology and Engineering, Massey University
MAT	Maximum average temperature of nodes 1 to 25
Max T1	Maximum temperature at the bed surface
MDR	Maximum drying rate during drying
MDT	Maximum difference between the grain temperatures at the bed surface and bottom for the run
MI	Mechanical impact (test)
ODE	Ordinary differential equation
PDE	Partial differential equation
Rel Tol	Relative tolerance

$REWET_{bb}$ Maximum difference between the moisture content at the bed boundaries for the whole drying time

$REWET_{bb\ bulk}$ Maximum difference between the moisture content at the bed boundaries when the bed was bulked at the end of the drying day(s)

RMSE Root Mean Square Error

$STRESS_{bulk}$ Gradient between kernel average and surface moisture contents when the bed was bulked

$STRESS_{max\ DR}$ Gradient between kernel average and surface moisture contents during drying when the drying rate was the highest,:

TMA Thermomechanical analysis

TT_g Maximum magnitude of phase change

VRCC Varietal Recommendation Committee of Cambodia.

Appendix A2

STATISTICAL ANALYSIS OF THE EXPERIMENTAL DATA

A2.1 ANOVA table for drying time of Experiment One/03

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	85.77777778	21.44444444	6.23	0.0522
Error	4	13.77777778	3.44444444		
Corrected Total	8	99.55555556			

R-Square	Coeff Var	Root MSE	time Mean
0.861607	10.47228	1.855921	17.72222

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Replication	2	13.55555556	6.77777778	1.97	0.2541
Depth	2	72.22222222	36.11111111	10.48	0.0257

A2.2 t-test for drying time of Experiment One/03

t Grouping	Mean	N	Replication
A	19.167	3	R3
A			
A	17.833	3	R1
A			
A	16.167	3	R2

t Grouping	Mean	N	Depth
A	20.500	3	D3
A			
A	18.833	3	D2
B	13.833	3	D1

A2.3 ANOVA table for bending strength of Experiment One/03

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	0.00170216	0.00028369	4.68	0.0012
Error	38	0.00230464	0.00006065		
Corrected Total	44	0.00400680			

R-Square	Coeff Var	Root MSE	Str Mean
0.424818	19.57143	0.007788	0.039791

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Depth	2	0.00159822	0.00079911	13.18	<.0001
Rep	4	0.00010394	0.00002599	0.43	0.7871

A2.4 t-test for bending strength of Experiment One/03

t Grouping	Mean	N	Depth
A	0.044974	15	1
A			
A	0.042956	15	2
B	0.031444	15	3

t Grouping	Mean	N	Bending test rep
A	0.041832	9	2
A			
A	0.041029	9	1
A			
A	0.039617	9	4
A			
A	0.038945	9	3
A			
A	0.037532	9	5

A2.5 ANOVA table for breakage susceptibility (1.4 mm) of Experiment One/03

Dependent Variable: BS14

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	0.98104761	0.19620952	0.69	0.6437
Error	12	3.43607267	0.28633939		
Corrected Total	17	4.41712028			

R-Square	Coeff Var	Root MSE	BS14 Mean
0.222101	14.67901	0.535107	3.645389

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Depth	2	0.33777744	0.16888872	0.59	0.5697
Dryrep	2	0.09586344	0.04793172	0.17	0.8478
Testrep	1	0.54740672	0.54740672	1.91	0.1920

A2.6 t-test for breakage susceptibility (1.4 mm) of Experiment One/03

t Grouping	Mean	N	Depth
A	3.8115	6	3
A			
A	3.6487	6	1
A			
A	3.4760	6	2

t Grouping	Mean	N	Drying Rep
A	3.7310	6	1
A			
A	3.6525	6	3
A			
A	3.5527	6	2

t Grouping	Mean	N	Test Rep
A	3.8198	9	2
A			
A	3.4710	9	1

A2.7 ANOVA table for breakage susceptibility (1.68 mm) of Experiment One/03

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	7.48895294	1.49779059	2.65	0.0775
Error	12	6.78717000	0.56559750		
Corrected Total	17	14.27612294			

R-Square	Coeff Var	Root MSE	BS168 Mean
0.524579	6.120325	0.752062	12.28794

Source	DF	Type III SS	Mean Square	F Value	Pr > F

Depth	2	1.32070711	0.66035356	1.17	0.3441
Dryrep	2	4.67928311	2.33964156	4.14	0.0430
Testrep	1	1.48896272	1.48896272	2.63	0.1307

A2.8 t-test for breakage susceptibility (1.68 mm) of Experiment One/03

t Grouping	Mean	N	Depth
A	12.5805	6	2
A			
A	12.3558	6	3
A			
A	11.9275	6	1

t Grouping		Mean	N	Drying rep
	A	12.7768	6	1
	A			
B	A	12.5025	6	2
B				
B		11.5845	6	3

t Grouping	Mean	N	Test Rep
A	12.5756	9	2
A			
A	12.0003	9	1

A2.9 ANOVA table for drying time of Experiment Two/03

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	4	8.66666667	2.16666667	6.50	0.0486
Error	4	1.33333333	0.33333333		
Corrected Total	8	10.00000000			

R-Square	Coeff Var	Root MSE	Drytime Mean
0.866667	3.892249	0.577350	14.83333

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Day	2	0.66666667	0.33333333	1.00	0.4444
Treatment	2	8.00000000	4.00000000	12.00	0.0204

A2.10 t-test for drying time of Experiment Two/03

t Grouping	Mean	N	Treat
A	15.5000	3	T1
A			
A	15.5000	3	T3
B	13.5000	3	T2

Duncan Grouping	Mean	N	Treat
A	15.5000	3	T1
A			
A	15.5000	3	T3
B	13.5000	3	T2

A2.11 ANOVA table for bending strength of Experiment Two/03

Dependent Variable: Str

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	6	0.00032512	0.00005419	0.76	0.6030
Error	38	0.00269652	0.00007096		
Corrected Total	44	0.00302164			

R-Square	Coeff Var	Root MSE	Str Mean
0.107597	23.06043	0.008424	0.036529

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Tempering	2	0.00017794	0.00008897	1.25	0.2970
Bending test Rep	4	0.00014718	0.00003680	0.52	0.7226

A2.12 t-test for bending strength of Experiment Two/03

t Grouping	Mean	N	Tempering
A	0.038762	15	3
A			
A	0.036893	15	2
A			
A	0.033933	15	1

t Grouping	Mean	N	Bending test Rep
A	0.039036	9	4
A			
A	0.037713	9	3
A			
A	0.036553	9	1
A			
A	0.035614	9	5
A			
A	0.033731	9	2

A2.13 ANOVA table for breakage susceptibility (1.4 mm) of Experiment Two/03

Dependent Variable: BS14

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	1.44990956	0.28998191	1.27	0.3371
Error	12	2.73342089	0.22778507		
Corrected Total	17	4.18333044			

R-Square	Coeff Var	Root MSE	BS14 Mean
0.346592	15.20232	0.477268	3.139444

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Stir	2	0.78795678	0.39397839	1.73	0.2188
Dryrep	2	0.50627078	0.25313539	1.11	0.3608
Testrep	1	0.15568200	0.15568200	0.68	0.4245

A2.14 t-test for breakage susceptibility (1.4 mm) of Experiment Two/03

t Grouping	Mean	N	Tempering
A	3.4337	6	1
A			
A	3.0195	6	2
A			
A	2.9652	6	3

t Grouping	Mean	N	Drying Rep
A	3.3620	6	3
A			
A	3.0992	6	1
A			
A	2.9572	6	2

t Grouping	Mean	N	Test Rep
A	3.2324	9	2
A			
A	3.0464	9	1

A2.15 ANOVA table for breakage susceptibility (1.68 mm) of Experiment Two/03

Dependent Variable: BS168

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	5	5.78306411	1.15661282	1.96	0.1573
Error	12	7.07587433	0.58965619		
Corrected Total	17	12.85893844			

R-Square	Coeff Var	Root MSE	BS168 Mean
0.449731	7.377496	0.767891	10.40856

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Stir	2	3.13140044	1.56570022	2.66	0.1110
Dryrep	2	1.49545011	0.74772506	1.27	0.3165
Testrep	1	1.15621356	1.15621356	1.96	0.1867

A2.16 t-test for breakage susceptibility (1.68 mm) of Experiment Two/03

t Grouping		Mean	N	Tempering
	A	10.9037	6	1
	A			
B	A	10.4387	6	2
B				
B		9.8833	6	3

t Grouping	Mean	N	Drying Rep
A	10.7875	6	1
A			
A	10.3492	6	2
A			
A	10.0890	6	3

t Grouping	Mean	N	Test Rep
A	10.6620	9	2
A			
A	10.1551	9	1

A2.17 ANOVA table for drying time of Experiment Three/03

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	7	123.7678571	17.6811224	11.30	<.0001
Error	34	53.2083333	1.5649510		
Corrected Total	41	176.9761905			

R-Square	Coeff Var	Root MSE	drytime Mean
0.699348	10.16270	1.250980	12.30952

Source	DF	Type III SS	Mean Square	F Value	Pr > F
Day	2	8.13122242	4.06561121	2.60	0.0891
Variety	3	76.19642857	25.39880952	16.23	<.0001
Stir	2	32.11854839	16.05927419	10.26	0.0003

A2.18 t-test for drying time of Experiment Three/03

t Grouping		Mean	N	Variety
	A	13.7333	15	V3
	A			
B	A	12.5455	11	V2
B				
B		12.2000	5	V1
	C	10.1818	11	V4

t Grouping	Mean	N	Tempering
A	13.5000	12	T3
A			
A	12.8333	12	T1
B	11.1667	18	T2

t Grouping	Mean	N	Day
A	12.7143	14	D2
A			
A	12.2143	14	D3
A			
A	12.0000	14	D1

A2.19 ANOVA table for bending strength of Experiment Three/03

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	11	0.02699613	0.00245419	21.88	<.0001
Error	193	0.02164701	0.00011216		
Corrected Total	204	0.04864314			

R-Square	Coeff Var	Root MSE	Strength Mean
0.554983	24.17125	0.010591	0.043815

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Var	3	0.02437952	0.00812651	72.45	<.0001
Stir	2	0.00034452	0.00017226	1.54	0.2179
DryDay	2	0.00208691	0.00104345	9.30	0.0001
TestRep	4	0.00018517	0.00004629	0.41	0.7993

A2.20 t-test for bending strength of Experiment Three/03

t Grouping		Mean	N	Variety
	A	0.058752	70	3
	B	0.038028	55	4
	B			
C	B	0.037632	25	1
C				
C		0.033401	55	2

t Grouping	Mean	N	Tempering
A	0.047194	60	3
B	0.042533	55	1
B			
B	0.042345	90	2

t Grouping	Mean	N	Drying Day
A	0.047585	65	1
B	0.042399	70	2
B			
B	0.041729	70	3

t Grouping	Mean	N	Bending Test Rep
A	0.045571	41	1
A			
A	0.043960	41	4
A			
A	0.043415	41	3
A			
A	0.043316	41	2
A			
A	0.042813	41	5

A2.21 ANOVA table for breakage susceptibility (1.4 mm) of Experiment Three/03

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	200.1928591	25.0241074	22.58	<.0001
Error	75	83.1198276	1.1082644		
Corrected Total	83	283.3126867			

R-Square	Coeff Var	Root MSE	BS14 Mean
0.706615	17.49709	1.052741	6.016667

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Var	3	161.5148747	53.8382916	48.58	<.0001
Stir	2	5.6068949	2.8034475	2.53	0.0865
Dryrep	2	31.7804973	15.8902486	14.34	<.0001
Testrep	1	1.2905922	1.2905922	1.16	0.2840

A2.22 t-test for breakage susceptibility (1.4 mm) of Experiment Three/03

t Grouping	Mean	N	Variety
A	7.2351	22	4
A			
A	6.9269	30	3
B	5.2520	10	1
C	3.9045	22	2

t Grouping		Mean	N	Tempering
	A	6.4789	24	3
	A			
B	A	6.1640	24	1
B				
B		5.6103	36	2

t Grouping		Mean	N	Drying Rep
	A	6.4484	28	1
	A			
B	A	5.8894	28	3
B				
B		5.7122	28	2

t Grouping	Mean	N	Test Rep
A	6.1406	42	1
A			
A	5.8927	42	2

A2.23 ANOVA table for breakage susceptibility (1.68 mm) of Experiment Three/03

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	8	3240.963290	405.120411	42.26	<.0001
Error	75	718.956164	9.586082		
Corrected Total	83	3959.919454			

R-Square	Coeff Var	Root MSE	BS168 Mean
0.818442	14.54601	3.096140	21.28514

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Var	3	2739.051581	913.017194	95.24	<.0001
Stir	2	53.936578	26.968289	2.81	0.0664
Dryrep	2	447.144704	223.572352	23.32	<.0001
Testrep	1	0.830427	0.830427	0.09	0.7693

A2.24 t-test for breakage susceptibility (1.68 mm) of Experiment Three/03

t Grouping	Mean	N	Variety
A	28.300	22	4
B	22.525	30	3
B			
B	20.949	10	1
C	12.733	22	2

t Grouping		Mean	N	Tempering
	A	22.5988	24	3
	A			
B	A	21.5065	24	1
B				
B		20.2618	36	2

t Grouping	Mean	N	Drying Rep
A	22.5186	28	1
A			
A	21.8337	28	3
B	19.5032	28	2

t Grouping	Mean	N	Test Rep
A	21.3846	42	2
A			
A	21.1857	42	1

A2.25 ANOVA table for MI HRY of Experiment One/04

One-way ANOVA: HRY, % of paddy versus Stirring

```
Source    DF     SS    MS     F      P
Stirring   1   89.8  89.8  8.57  0.026
Error      6   62.9  10.5
Total      7  152.7

S = 3.237   R-Sq = 58.83%   R-Sq(adj) = 51.97%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  ---+---------+---------+---------+------
-1     4  38.770  4.300  (---------*---------)
 1     4  45.472  1.572                  (---------*---------)
                         ---+---------+---------+---------+------
                         36.0      40.0      44.0      48.0
Pooled StDev = 3.237

Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of Stirring

Individual confidence level = 95.00%
```

A2.26 ANOVA table for milling HRY of Experiment One/04

One-way ANOVA: HRY versus Stirring

```
Source    DF      SS     MS     F      P
Stirring   1   47.39  47.39  5.03  0.066
Error      6   56.53   9.42
Total      7  103.91

S = 3.069   R-Sq = 45.60%   R-Sq(adj) = 36.53%

                         Individual 95% CIs For Mean Based on
                         Pooled StDev
Level  N    Mean  StDev  -----+---------+---------+---------+----
-1     4  43.918  3.581  (---------*----------)
 1     4  48.785  2.454               (---------*----------)
                         -----+---------+---------+---------+----
                           42.0      45.5      49.0      52.5

Pooled StDev = 3.069

Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of Stirring

Individual confidence level = 95.00%

Stirring = -1 subtracted from:

Stirring   Lower  Center   Upper  ---+---------+---------+---------+------
 1        -0.443   4.867  10.178              (-----------*-----------)
                                  ---+---------+---------+---------+------
                                  -4.0       0.0       4.0       8.0
```

A2.27 ANOVA table for drying time of Experiment Two/04

General Linear Model: Time versus Depth, Stirring, Covering

Factor	Type	Levels	Values
Depth	fixed	2	-1, 1
Stirring	fixed	2	-1, 1
Covering	fixed	4	1, 2, 3, 4

Analysis of Variance for Time, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Depth	1	34225	34225	34225	11.38	0.043
Stirring	1	70225	70225	70225	23.34	0.017
Covering	3	71025	71025	23675	7.87	0.062
Depth*Stirring	1	3025	3025	3025	1.01	0.390
Depth*Covering	3	13225	13225	4408	1.47	0.381
Stirring*Covering	3	19425	19425	6475	2.15	0.273
Error	3	9025	9025	3008		
Total	15	220175				

S = 54.8483   R-Sq = 95.90%   R-Sq(adj) = 79.50%

Least Squares Means for Time

Depth		Mean	SE Mean
-1		562.5	19.39
1		655.0	19.39
Stirring			
-1		675.0	19.39
1		542.5	19.39
Covering			
1		517.5	27.42
2		597.5	27.42
3		615.0	27.42
4		705.0	27.42
Depth*Stirring			
-1	-1	615.0	27.42
-1	1	510.0	27.42
1	-1	735.0	27.42
1	1	575.0	27.42
Depth*Covering			
-1	1	485.0	38.78
-1	2	505.0	38.78
-1	3	600.0	38.78
-1	4	660.0	38.78
1	1	550.0	38.78
1	2	690.0	38.78
1	3	630.0	38.78
1	4	750.0	38.78

Stirring*Covering			
-1	1	630.0	38.78
-1	2	660.0	38.78
-1	3	630.0	38.78
-1	4	780.0	38.78
1	1	405.0	38.78
1	2	535.0	38.78
1	3	600.0	38.78
1	4	630.0	38.78

A2.28 ANOVA table for MI HRY of Experiment Two/04

General Linear Model: HRY, % of paddy versus Depth, Stir

Factor	Type	Levels	Values
Depth	fixed	2	-1, 1
Stir	fixed	2	-1, 1

Analysis of Variance for HRY, % of paddy, using Adjusted SS for Tests (Cover as covariate)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cover	1	18.792	18.792	18.792	4.68	0.053
Depth	1	4.555	4.555	4.555	1.13	0.310
Stir	1	37.727	37.727	37.727	9.39	0.011
Depth*Stir	1	0.324	0.324	0.324	0.08	0.782
Error	11	44.180	44.180	4.016		
Total	15	105.578				

S = 2.00409   R-Sq = 58.15%   R-Sq(adj) = 42.94%

Term	Coef	SE Coef	T	P
Constant	35.928	1.227	29.28	0.000
Cover	0.9693	0.4481	2.16	0.053

Means for Covariates

Covariate	Mean	StDev
Cover	2.500	1.155

Least Squares Means for HRY, % of paddy

Level	Mean	StDev
1	36.074	3.591
2	38.762	1.876
3	39.516	2.352
4	39.054	

Depth		Mean	SE Mean
-1		38.88	0.7086
1		37.82	0.7086
Stir			
-1		36.82	0.7086
1		39.89	0.7086
Depth*Stir			
-1	-1	37.49	1.0020
-1	1	40.28	1.0020
1	-1	36.14	1.0020
1	1	39.50	1.0020

A2.29 ANOVA table for milling HRY of Experiment Two/04

General Linear Model: HRY versus Depth, Stir

Factor	Type	Levels	Values
Depth	fixed	2	-1, 1
Stir	fixed	2	-1, 1

Analysis of Variance for HRY, using Adjusted SS for Tests (Cover as covariate)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Cover	1	11.342	11.342	11.342	3.41	0.076
Depth	1	124.031	124.031	124.031	37.33	0.000
Stir	1	59.951	59.951	59.951	18.04	0.000
Depth*Stir	1	10.351	10.351	10.351	3.12	0.089
Error	27	89.713	89.713	3.323		
Total	31	295.389				

S = 1.82283   R-Sq = 69.63%   R-Sq(adj) = 65.13%

Term	Coef	SE Coef	T	P
Constant	41.0875	0.7893	52.06	0.000
Cover	0.5325	0.2882	1.85	0.076

Unusual Observations for HRY

Obs	HRY	Fit	SE Fit	Residual	St Resid

3	48.0000	43.8538	0.6604	4.1463	2.44 R

R denotes an observation with a large standardized residual.

Means for Covariates

Covariate	Mean	StDev
Cover	2.500	1.136

Least Squares Means for HRY

Level	N	Mean	StDev
1	8	41.825	2.404
2	8	41.750	1.847
3	8	42.875	4.347
4	8	43.225	3.495

Depth		Mean	SE Mean
-1		44.39	0.4557
1		40.45	0.4557
Stir			
-1		41.05	0.4557
1		43.79	0.4557
Depth*Stir			
-1	-1	43.59	0.6445
-1	1	45.19	0.6445
1	-1	38.51	0.6445
1	1	42.39	0.6445

A2.30 ANOVA table for drying time of Experiment Three/04

Factor	Type	Levels	Values
Blocks	fixed	4	1, 2, 3, 4
Variety	fixed	2	-1, 1
Depth	fixed	2	-1, 1
Stir	fixed	2	-1, 1
Cover	fixed	2	-1, 1

Analysis of Variance for Time, h, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Blocks	3	362.87	362.88	120.96	10.27	0.000
Variety	1	42.25	42.25	42.25	3.59	0.065
Depth	1	297.56	297.56	297.56	25.25	0.000
Stir	1	150.06	150.06	150.06	12.74	0.001
Cover	1	715.56	715.56	715.56	60.73	0.000
Variety*Depth	1	18.06	18.06	18.06	1.53	0.222
Variety*Stir	1	3.06	3.06	3.06	0.26	0.613
Variety*Cover	1	2.25	2.25	2.25	0.19	0.664
Depth*Stir	1	22.56	22.56	22.56	1.91	0.173
Depth*Cover	1	6.25	6.25	6.25	0.53	0.470
Stir*Cover	1	22.56	22.56	22.56	1.91	0.173
Variety*Depth*Stir	1	0.06	0.06	0.06	0.01	0.942
Variety*Depth*Cover	1	27.56	27.56	27.56	2.34	0.133
Variety*Stir*Cover	1	42.25	42.25	42.25	3.59	0.065
Depth*Stir*Cover	1	3.06	3.06	3.06	0.26	0.613
Error	46	542.00	542.00	11.78		
Total	63	2258.00				

S = 3.43258   R-Sq = 76.00%   R-Sq(adj) = 67.13%

Unusual Observations for Time, h

Obs	Time, h	Fit	SE Fit	Residual	St Resid
7	29.0000	22.8125	1.8204	6.1875	2.13 R
17	27.0000	19.0000	1.8204	8.0000	2.75 R
39	11.0000	17.0625	1.8204	-6.0625	-2.08 R
53	10.5000	16.8750	1.8204	-6.3750	-2.19 R

```
R denotes an observation with a large standardized residual.
Least Squares Means for Time, h

Variety                Mean  SE Mean
-1                   15.563   0.6068
 1                   13.938   0.6068
Depth
-1                   12.594   0.6068
 1                   16.906   0.6068
Stir
-1                   16.281   0.6068
 1                   13.219   0.6068
Cover
-1                   18.094   0.6068
 1                   11.406   0.6068
Variety*Depth
-1      -1           12.875   0.8581
-1       1           18.250   0.8581
 1      -1           12.313   0.8581
 1       1           15.563   0.8581
Variety*Stir
-1      -1           16.875   0.8581
-1       1           14.250   0.8581
 1      -1           15.688   0.8581
 1       1           12.188   0.8581
Variety*Cover
-1      -1           19.094   0.8581
-1       1           12.031   0.8581
 1      -1           17.094   0.8581
 1       1           10.781   0.8581
Depth*Stir
-1    -1             13.531   0.8581
-1     1             11.656   0.8581
 1    -1             19.031   0.8581
 1     1             14.781   0.8581
Depth*Cover
-1    -1             16.250   0.8581
-1     1              8.938   0.8581
 1    -1             19.938   0.8581
 1     1             13.875   0.8581
Stir*Cover
-1   -1              19.031   0.8581
-1    1              13.531   0.8581
 1   -1              17.156   0.8581
 1    1               9.281   0.8581
Variety*Depth*Stir
-1      -1    -1     13.563   1.2136
-1      -1     1     12.188   1.2136
-1       1    -1     20.188   1.2136
-1       1     1     16.313   1.2136
 1      -1    -1     13.500   1.2136
 1      -1     1     11.125   1.2136
 1       1    -1     17.875   1.2136
 1       1     1     13.250   1.2136
Variety*Depth*Cover
-1      -1    -1     17.375   1.2136
-1      -1     1      8.375   1.2136
-1       1    -1     20.813   1.2136
-1       1     1     15.688   1.2136
 1      -1    -1     15.125   1.2136
 1      -1     1      9.500   1.2136
 1       1    -1     19.063   1.2136
 1       1     1     12.062   1.2136
Variety*Stir*Cover
-1      -1   -1      19.000   1.2136
-1      -1    1      14.750   1.2136
-1       1   -1      19.188   1.2136
-1       1    1       9.313   1.2136
```

1	-1	-1	19.063	1.2136
1	-1	1	12.313	1.2136
1	1	-1	15.125	1.2136
1	1	1	9.250	1.2136
Depth*Stir*Cover				
-1	-1	-1	16.813	1.2136
-1	-1	1	10.250	1.2136
-1	1	-1	15.688	1.2136
-1	1	1	7.625	1.2136
1	-1	-1	21.250	1.2136
1	-1	1	16.813	1.2136
1	1	-1	18.625	1.2136
1	1	1	10.937	1.2136

A2.31 ANOVA table for MI HRY of Experiment Three/04

General Linear Model: HRY, % of paddy versus Blocks, Variety, ...

Factor	Type	Levels	Values
Blocks	fixed	4	1, 2, 3, 4
Variety	fixed	2	-1, 1
Depth	fixed	2	-1, 1
Stir	fixed	2	-1, 1
Cover	fixed	2	-1, 1

Analysis of Variance for HRY, % of paddy, using Adjusted SS for Tests (Pad as block and start day as covariate)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Start Day	1	9.548	2.793	2.793	0.60	0.442
Blocks	3	57.697	57.697	19.232	4.14	0.011
Variety	1	268.497	268.828	268.828	57.91	0.000
Depth	1	1.884	1.922	1.922	0.41	0.523
Stir	1	32.883	32.870	32.870	7.08	0.011
Cover	1	160.173	159.010	159.010	34.25	0.000
Variety*Depth	1	0.000	0.001	0.001	0.00	0.990
Variety*Stir	1	15.368	15.609	15.609	3.36	0.073
Variety*Cover	1	0.323	0.380	0.380	0.08	0.776
Depth*Stir	1	0.726	0.625	0.625	0.13	0.715
Depth*Cover	1	1.346	0.891	0.891	0.19	0.663
Stir*Cover	1	13.688	13.828	13.828	2.98	0.091
Variety*Depth*Stir	1	0.615	0.585	0.585	0.13	0.724
Variety*Depth*Cover	1	4.264	4.394	4.394	0.95	0.336
Variety*Stir*Cover	1	4.340	4.393	4.393	0.95	0.336
Depth*Stir*Cover	1	0.429	0.429	0.429	0.09	0.762
Error	45	208.901	208.901	4.642		
Total	63	780.683				

S = 2.15459   R-Sq = 73.24%   R-Sq(adj) = 62.54%

Term	Coef	SE Coef	T	P
Constant	38.2847	0.7273	52.64	0.000
Start Day	-0.2096	0.2702	-0.78	0.442

Unusual Observations for HRY, % of paddy

Obs	HRY, % of paddy	Fit	SE Fit	Residual	St Resid
13	39.7610	35.7284	1.1563	4.0326	2.22 R
16	34.3520	39.3057	1.2042	-4.9537	-2.77 R
45	29.3440	33.8754	1.1464	-4.5314	-2.48 R
46	33.3720	37.3343	1.1434	-3.9623	-2.17 R

R denotes an observation with a large standardized residual.

Means for Covariates

Covariate	Mean	StDev
Start Day	2.500	1.127

Least Squares Means for HRY, % of paddy

Level	N	Mean	StDev	
1	16	38.486	2.964	Tarp
2	16	38.810	2.795	Net
3	16	36.423	3.953	Net on husk

```
4      16  37.324  3.996      Mat

Variety               Mean  SE Mean
-1                   35.71   0.3813
 1                   39.81   0.3813
Depth
-1                   37.59   0.3824
 1                   37.94   0.3824
Stir
-1                   37.04   0.3810
 1                   38.48   0.3810
Cover
-1                   36.18   0.3813
 1                   39.34   0.3813
Variety*Depth
-1       -1          35.53   0.5397
-1        1          35.89   0.5386
 1       -1          39.64   0.5397
 1        1          39.99   0.5429
Variety*Stir
-1       -1          34.49   0.5386
-1        1          36.92   0.5397
 1       -1          39.59   0.5389
 1        1          40.04   0.5410
Variety*Cover
-1       -1          34.05   0.5389
-1        1          37.36   0.5410
 1       -1          38.31   0.5410
 1        1          41.32   0.5452
Depth*Stir
-1     -1            36.97   0.5386
-1      1            38.20   0.5429
 1     -1            37.12   0.5389
 1      1            38.75   0.5452
Depth*Cover
-1     -1            35.88   0.5553
-1      1            39.29   0.5429
 1     -1            36.48   0.5481
 1      1            39.39   0.5397
Stir*Cover
-1   -1              35.00   0.5389
-1    1              39.09   0.5386
 1   -1              37.36   0.5389
 1    1              39.59   0.5397
Variety*Depth*Stir
-1       -1     -1   34.51   0.7625
-1       -1      1   36.55   0.7685
-1        1     -1   34.48   0.7625
-1        1      1   37.29   0.7625
 1       -1     -1   39.43   0.7625
 1       -1      1   39.86   0.7625
 1        1     -1   39.76   0.7618
 1        1      1   40.21   0.7737
Variety*Depth*Cover
-1       -1     -1   33.48   0.7648
-1       -1      1   37.57   0.7618
-1        1     -1   34.61   0.7685
-1        1      1   37.16   0.7685
 1       -1     -1   38.28   0.7883
 1       -1      1   41.01   0.7737
 1        1     -1   38.35   0.7685
 1        1      1   41.63   0.7625
Variety*Stir*Cover
-1       -1    -1    32.10   0.7685
-1       -1     1    36.89   0.7685
-1        1    -1    36.00   0.7648
-1        1     1    37.84   0.7618
 1       -1    -1    37.90   0.7737
 1       -1     1    41.29   0.7685
 1        1    -1    38.73   0.7625
 1        1     1    41.34   0.7648
Depth*Stir*Cover
-1     -1    -1      34.72   0.7648
-1     -1     1      39.22   0.7648
-1      1    -1      37.05   0.7883
-1      1     1      39.36   0.7648
 1     -1    -1      35.28   0.7625
```

1	-1	1	38.96	0.7648
1	1	-1	37.68	0.7803
1	1	1	39.83	0.7618

A2.32 ANOVA table for milling HRY of Experiment Three/04

General Linear Model: HRY, % versus Blocks, Variety, Depth, Stir, Cover

Factor	Type	Levels	Values
Blocks	fixed	4	1, 2, 3, 4
Variety	fixed	2	-1, 1
Depth	fixed	2	-1, 1
Stir	fixed	2	-1, 1
Cover	fixed	2	-1, 1

Analysis of Variance for HRY, %, using Adjusted SS for Tests (Pad as block and start day as covariate)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Start Day	1	17.889	4.902	4.902	0.94	0.334
Blocks	3	52.653	52.653	17.551	3.38	0.021
Variety	1	4.396	4.782	4.782	0.92	0.340
Depth	1	3.956	3.170	3.170	0.61	0.437
Stir	1	10.653	10.299	10.299	1.98	0.162
Cover	1	200.684	202.339	202.339	38.92	0.000
Variety*Depth	1	12.497	11.965	11.965	2.30	0.132
Variety*Stir	1	0.444	0.597	0.597	0.11	0.735
Variety*Cover	1	0.068	0.216	0.216	0.04	0.839
Depth*Stir	1	27.794	24.832	24.832	4.78	0.031
Depth*Cover	1	44.878	44.309	44.309	8.52	0.004
Stir*Cover	1	38.181	38.140	38.140	7.34	0.008
Variety*Depth*Stir	1	52.325	52.180	52.180	10.04	0.002
Variety*Depth*Cover	1	10.397	10.193	10.193	1.96	0.164
Variety*Stir*Cover	1	0.259	0.143	0.143	0.03	0.869
Depth*Stir*Cover	1	42.732	42.732	42.732	8.22	0.005
Error	109	566.691	566.691	5.199		
Total	127	1086.497				

S = 2.28013   R-Sq = 47.84%   R-Sq(adj) = 39.23%

Term	Coef	SE Coef	T	P
Constant	41.1656	0.5443	75.64	0.000
Start Day	-0.1964	0.2022	-0.97	0.334

Unusual Observations for HRY, %

Obs	HRY, %	Fit	SE Fit	Residual	St Resid	
2	48.4000	43.8968	0.8832	4.5032	2.14	R
6	47.4700	43.2174	0.8745	4.2526	2.02	R
24	46.5300	40.4706	0.8634	6.0594	2.87	R
44	41.6700	37.0343	0.8972	4.6357	2.21	R
72	35.6700	40.6486	0.9138	-4.9786	-2.38	R
99	37.4000	42.4101	0.8556	-5.0101	-2.37	R
109	42.8000	37.8131	0.8579	4.9869	2.36	R

R denotes an observation with a large standardized residual.

Means for Covariates

Covariate	Mean	StDev
Start Day	2.500	1.122

Least Squares Means for HRY, %

Pad	Mean	StDev	
1	41.361	3.467	Tarp
2	40.987	2.749	Net
3	39.638	2.065	Net on husk
4	40.713	3.083	Mat

Variety	Mean	SE Mean
-1	40.48	0.2853
1	40.87	0.2853

Depth				
-1			40.83	0.2861
1			40.52	0.2861
Stir				
-1			40.96	0.2851
1			40.39	0.2851
Cover				
-1			39.41	0.2853
1			41.93	0.2853
Variety*Depth				
-1	-1		40.33	0.4039
-1	1		40.63	0.4031
1	-1		41.33	0.4039
1	1		40.40	0.4062
Variety*Stir				
-1	-1		40.83	0.4031
-1	1		40.13	0.4039
1	-1		41.08	0.4033
1	1		40.65	0.4049
Variety*Cover				
-1	-1		39.26	0.4033
-1	1		41.70	0.4049
1	-1		39.57	0.4049
1	1		42.17	0.4080
Depth*Stir				
-1	-1		40.67	0.4031
-1	1		41.00	0.4062
1	-1		41.25	0.4033
1	1		39.79	0.4080
Depth*Cover				
-1	-1		38.96	0.4156
-1	1		42.71	0.4062
1	-1		39.87	0.4101
1	1		41.16	0.4039
Stir*Cover				
-1	-1		39.15	0.4033
-1	1		42.76	0.4031
1	-1		39.68	0.4033
1	1		41.10	0.4039
Variety*Depth*Stir				
-1	-1	-1	39.60	0.5706
-1	-1	1	41.07	0.5751
-1	1	-1	42.07	0.5706
-1	1	1	39.19	0.5706
1	-1	-1	41.74	0.5706
1	-1	1	40.93	0.5706
1	1	-1	40.43	0.5700
1	1	1	40.38	0.5789
Variety*Depth*Cover				
-1	-1	-1	38.22	0.5723
-1	-1	1	42.45	0.5700
-1	1	-1	40.31	0.5751
-1	1	1	40.95	0.5751
1	-1	-1	39.70	0.5899
1	-1	1	42.97	0.5789
1	1	-1	39.44	0.5751
1	1	1	41.37	0.5706
Variety*Stir*Cover				
-1	-1	-1	39.04	0.5751
-1	-1	1	42.63	0.5751
-1	1	-1	39.49	0.5723
-1	1	1	40.77	0.5700
1	-1	-1	39.27	0.5789
1	-1	1	42.90	0.5751
1	1	-1	39.86	0.5706
1	1	1	41.44	0.5723
Depth*Stir*Cover				
-1	-1	-1	38.83	0.5723
-1	-1	1	42.51	0.5723
-1	1	-1	39.08	0.5899
-1	1	1	42.91	0.5723
1	-1	-1	39.48	0.5706
1	-1	1	43.02	0.5723
1	1	-1	40.27	0.5839
1	1	1	39.30	0.5700

Appendix A3

MODEL FORMULATION AS ODEs

This appendix provides the methodology used to derive the formulated equations. The formulation of the ODEs was based on the conceptual models and grids illustrated in Fig 5.1 and 5.2 of Chapter 5.

A3.1 HEAT TRANSFER AT THE SHADING TARPAULIN WHEN SHADING WAS APPLIED

a. Word balance

$$\begin{bmatrix} \text{Rate of heat} \\ \text{received from} \\ \text{the solar} \\ \text{radiation} \end{bmatrix} = \left[\text{Rate of heat lost by radiation to the sky}\right]$$

$$+\left[\begin{pmatrix} \text{Rate of heat lost by radiation to the} \\ \text{covering tarpaulin if the bed is covered} \end{pmatrix} or \begin{pmatrix} \text{Rate of heat lost by radiation} \\ \text{to the bed surface if it is not covered} \end{pmatrix}\right]$$

$$+\left[\text{Rate of heat lost by convection from the top and bottom to the ambient air}\right]$$

b. Mathematical equation

$$\begin{aligned} A.\beta_{tarp}.I = {} & \in_{tarp}.A.\sigma\left[\left(T_{sh}+273.15\right)^4-\left(T_{sky}+273.15\right)^4\right] \\ & + S_2.0.63\in_{tarp}.\in_{tarp}.A.\sigma\left[\left(T_{sh}+273.15\right)^4-\left(T_{cov}+273.15\right)^4\right] \\ & + \left(1-S_2\right)0.63\in_{tarp}.\in_p.A.\sigma\left[\left(T_{sh}+273.15\right)^4-\left(T_1+273.15\right)^4\right] \\ & + 2A.h\left(T_{sh}-T_a\right) \end{aligned} \quad \ldots \text{(A3.1)}$$

<u>Note</u>: S_1 and S_2 =1 when shading and covering was applied, respectively; otherwise S_1 and S_2 = 0.

As described in Section 6.1.6 of Chapter 6, geometric and emissivity correction factors for energy radiated between parallel surfaces are described based on the net heat radiated between parallel surfaces (Kern, 1950).

For shading and covering tarpaulins

$q = F_{A1}.F_e.A.\sigma\left(T_{sh}^4 - T_{cov}^4\right)$ where F_{A1} = 0.63 and $F_e = \in_{tarp} . \in_{tarp}$

For shading tarpaulin and bed surface

$q = F_{A1}.F_e.A.\sigma\left(T_{sh}^4 - T_1^4\right)$ where F_{A1} = 0.63 and $F_e = \in_{tarp} . \in_p$

For covering tarpaulin and bed surface

$q = F_{A2}.F_e.A.\sigma\left(T_{cov}^4 - T_{x=0}^4\right)$ where F_{A2} = 1 and $F_e = \dfrac{1}{\left(\dfrac{1}{\in_{tarp}} + \dfrac{1}{\in_p}\right) - 1}$

Dividing by A, Equation (A3.1) becomes

$$\begin{aligned}
\beta_{tarp}.I =& \in_{tarp} .\sigma\left[\left(T_{sh}+273.15\right)^4 - \left(T_{sky}+273.15\right)^4\right] + S_2.0.63 \in_{tarp} . \in_{tarp} .\sigma\left[\left(T_{sh}+273.15\right)^4 - \left(T_{cov}+273.15\right)^4\right] \\
&+ \left(1-S_2\right)0.63 \in_{tarp} . \in_p .\sigma\left[\left(T_{sh}+273.15\right)^4 - \left(T_1+273.15\right)^4\right] + 2h\left(T_{sh} - T_a\right) \\
=& \in_{tarp} .\sigma\left[\left(T_{sh}+273.15\right)^4 - \left(T_{sky}+273.15\right)^4\right] + S_2.0.63 \in_{tarp} . \in_{tarp} .\sigma\left[\left(T_{sh}+273.15\right)^4 - \left(T_{cov}+273.15\right)^4\right] \\
&+ \left(1-S_2\right)0.63 \in_{tarp} . \in_p .\sigma\left[\left(T_{sh}+273.15\right)^4 - \left(T_1+273.15\right)^4\right] + 2h.T_{sh} - 2h.T_a
\end{aligned}$$

… (A3.2)

From Equation (A3.2),

$$T_{sh} = \frac{2h.T_a + \beta_{tarp}.I - \in_{tarp} .\sigma\left[\left(T_{sh}+273.15\right)^4 - \left(T_{sky}+273.15\right)^4\right] - S_2.0.63 \in_{tarp} . \in_{tarp} .\sigma\left[\left(T_{sh}+273.15\right)^4 - \left(T_{cov}+273.15\right)^4\right]}{2h}$$

$$- \frac{\left(1-S_2\right)0.63 \in_{tarp} . \in_p .\sigma\left[\left(T_{sh}+273.15\right)^4 - ((T_1+273.15)^4\right]}{2h}$$

$$= \frac{2h.T_a + \beta_{tarp}.I}{2h}$$

$$- \frac{\in_{tarp} .\sigma\left\{\left[\left(T_{sh}+273.15\right)^4 - \left(T_{sky}+273.15\right)^4\right] + S_2.0.63 \in_{tarp}\left[\left(T_{sh}+273.15\right)^4 - \left(T_{cov}+273.15\right)^4\right] + 0.63\left(1-S_2\right). \in_p\left[\left(T_{sh}+273.15\right)^4 - ((T_1+273.15)^4\right]\right\}}{2h}$$

… (A3.3)

For the shading tarpaulin level and 11 am $\leq t \leq$ 4 pm.

The units of Equation (A3.3)

$$\left[{}^{o}\mathrm{C}\right] = \frac{\left[\dfrac{\mathrm{J.^oC}}{\mathrm{s.m^2.^oC}} + \dfrac{\mathrm{J}}{\mathrm{s.m^2}} + \dfrac{\mathrm{J.^oC^4}}{\mathrm{s.m^2.^oC^4}}\right]}{\left[\dfrac{\mathrm{J}}{\mathrm{s.m^2.^oC}}\right]} = \frac{\left[\dfrac{\mathrm{J}}{\mathrm{s.m^2}}\right]}{\left[\dfrac{\mathrm{J}}{\mathrm{s.m^2.^oC}}\right]} = \left[{}^{o}\mathrm{C}\right]$$ are correct.

A3.2 HEAT TRANSFER AT THE COVERING TARPAULIN WHEN COVERING WAS APPLIED

a. Word balance

$$\begin{bmatrix} Rate\ of\ \ heat \\ gained\ \ from\ the \\ solar\ radiation\ if \\ it\ is\ not\ shaded \end{bmatrix}$$

$$or\left[\begin{pmatrix} Rate\ of\ \ heat \\ gained\ \ from\ the \\ solar\ radiation \\ if\ \ it\ is\ shaded \end{pmatrix}+\begin{pmatrix} Rate\ of\ \ heat\ gained \\ from\ the\ shading \\ tarpaulin\ radiation\ if \\ it\ is\ shaded \end{pmatrix}\right]=\begin{bmatrix} Rate\ of\ \ heat\ lost\ by\ radiation\ to \\ the\ sky\ if\ \ it\ is\ not\ shaded \end{bmatrix}$$

$$+\begin{bmatrix} Rate\ of\ \ heat\ lost\ by\ radiation \\ to\ the\ bed\ \ surface \end{bmatrix}$$

$$+\begin{bmatrix} Rate\ of\ \ heat\ lost\ by\ convection \\ to\ the\ ambient\ air \end{bmatrix}$$

$$+\begin{bmatrix} Rate\ of\ \ heat\ lost\ by \\ conductance\ to\ the \\ bed\ \ surface \end{bmatrix}$$

b. Mathematical equation

$$\begin{aligned}
&\left(1-S_1\right)A.\beta_{tarp}.I+S_1.A.\beta_{tarp}.I_{sh}+S_1.0.63\in_{tarp}.\in_{tarp}.A.\sigma\left[\left(T_{sh}+273.15\right)^4-\left(T_{cov}+273.15\right)^4\right] \\
&\quad=\left(1-S_1\right)\in_{tarp}.A.\sigma\left[\left(T_{cov}+273.15\right)^4-\left(T_{sky}+273.15\right)^4\right] \\
&\quad+\frac{1}{\left(\frac{1}{\in_{tarp}}+\frac{1}{\in_p}\right)-1}A.\sigma\left[\left(T_{cov}+273.15\right)^4-\left(T_1+273.15\right)^4\right] \\
&\quad+A.h\left(T_{cov}-T_a\right) \\
&\quad+A.U_{tarp/p}\left(T_{cov}-T_1\right)
\end{aligned}$$

… (A3.4)

Assuming that the resistance for the heat conducted from the covering tarpaulin to the bed surface is

$$R_{tarp/p}=\frac{1}{U_{tarp/p}}=\frac{L_{tarp}}{\lambda_{tarp}}+\frac{L_a}{\lambda_a}=\frac{\lambda_a.L_{tarp}+\lambda_{tarp}.L_a}{\lambda_{tarp}.\lambda_a}\quad\Rightarrow\quad U_{tarp/p}=\frac{\lambda_{tarp}.\lambda_a}{\lambda_a.L_{tarp}+\lambda_{tarp}.L_a}$$

and the units for $U_{tarp/p}$ are $\left[\frac{\mathrm{J}}{\mathrm{s.m^2.^oC}}\right]$,

dividing by A, Equation (A3.4) becomes

$$\begin{aligned}&(1-S_1)\beta_{tarp}.I+S_1.\beta_{tarp}.I_{sh}+S_1.0.63\in_{tarp}.\in_{tarp}.\sigma\left[(T_{sh}+273.15)^4-(T_{cov}+273.15)^4\right]\\&\quad=(1-S_1).\in_{tarp}.\sigma\left[(T_{cov}+273.15)^4-(T_{sky}+273.15)^4\right]\\&\quad+\frac{1}{\left(\frac{1}{\in_{tarp}}+\frac{1}{\in_p}\right)-1}\sigma\left[(T_{cov}+273.15)^4-(T_1+273.15)^4\right]+h(T_{cov}-T_a)+U_{tarp/p}(T_{cov}-T_1)\\&\quad=(1-S_1).\in_{tarp}.\sigma\left[(T_{cov}+273.15)^4-(T_{sky}+273.15)^4\right]\\&\quad+\frac{1}{\left(\frac{1}{\in_{tarp}}+\frac{1}{\in_p}\right)-1}\sigma\left[(T_{cov}+273.15)^4-(T_1+273.15)^4\right]+h.T_{cov}-h.T_a+U_{tarp/p}.T_{cov}-U_{tarp/p}.T_1\end{aligned}$$

… (A3.5)

From Equation (A3.5)

$$\begin{aligned}h.T_{cov}+U_{tarp/p}.T_{cov}&=(1-S_1)\beta_{tarp}.I+S_1.\beta_{tarp}.I_{sh}+S_1.0.63\in_{tarp}.\in_{tarp}.\sigma\left[(T_{sh}+273.15)^4-(T_{cov}+273.15)^4\right]\\&\quad-(1-S_1).\in_{tarp}.\sigma\left[(T_{cov}+273.15)^4-(T_{sky}+273.15)^4\right]\\&\quad-\frac{1}{\left(\frac{1}{\in_{tarp}}+\frac{1}{\in_p}\right)-1}\sigma\left[(T_{cov}+273.15)^4-(T_1+273.15)^4\right]+h.T_a+U_{tarp/p}.T_1\end{aligned}$$

$$\begin{aligned}\Rightarrow T_{cov}&=\frac{h.T_a+U_{tarp/p}.T_1+\beta_{tarp}\left[(1-S_1).I+S_1.I_{sh}\right]}{h+U_{tarp/p}}\\&+\frac{\in_{tarp}.\sigma\left\{S_1.0.63.\in_{tarp}\left[(T_{sh}+273.15)^4-(T_{cov}+273.15)^4\right]-(1-S_1)\left[(T_{cov}+273.15)^4-(T_{sky}+273.15)^4\right]\right\}}{h+U_{tarp/p}}\\&-\frac{\frac{1}{\left(\frac{1}{\in_{tarp}}+\frac{1}{\in_p}\right)-1}\sigma\left[(T_{cov}+273.15)^4-(T_1+273.15)^4\right]}{h+U_{tarp/p}}\end{aligned}$$

… (A3.6)

For the covering tarpaulin level and 11:00 ≤ t ≤ 14:00.

The units of Equation (A3.6)

$$\left[{}^{o}\mathrm{C}\right]=\frac{\left[\frac{\mathrm{J.^oC}}{\mathrm{s.m^2.^oC}}+\frac{\mathrm{J.^oC}}{\mathrm{s.m^2.^oC}}+\frac{\mathrm{J}}{\mathrm{s.m^2}}+\frac{\mathrm{J.^oC^4}}{\mathrm{s.m^2.^oC^4}}\right]}{\left[\frac{\mathrm{J}}{\mathrm{s.m^2.^oC}}+\frac{\mathrm{J}}{\mathrm{s.m^2.^oC}}\right]}=\frac{\left[\frac{\mathrm{J}}{\mathrm{s.m^2}}\right]}{\left[\frac{\mathrm{J}}{\mathrm{s.m^2.^oC}}\right]}=\left[{}^{o}\mathrm{C}\right]$$ are correct.

A3.3 HEAT AND MOISTURE TRANSFERS AT THE BED SURFACE

A3.3.1 Heat transfer at the bed surface

a. Word balance

$$\left[\begin{array}{c}\textit{Rate of}\\ \textit{accumulation}\\ \textit{of heat in the}\\ \textit{kernels and}\\ \textit{air at } j = 1\end{array}\right] = \left[\begin{array}{l}\textit{Rate of heat gained on the kernels from solar radiation}\\ \textit{if the bed is not shaded nor covered}\end{array}\right]$$

$$\textit{or}\left[\left(\begin{array}{l}\textit{Rate of heat gained on the kernels}\\ \textit{from solar radiation if the bed is}\\ \textit{shaded but not covered}\end{array}\right)+\left(\begin{array}{l}\textit{Rate of heat gained on the kernels}\\ \textit{from shading tarpaulin radiation}\\ \textit{if the bed is shaded but not covered}\end{array}\right)\right]$$

$$\textit{or}\left[\begin{array}{l}\textit{Rate of heat gained from the covering tarpaulin radiation}\\ \textit{if the bed is covered}\end{array}\right]$$

$$+\left[\begin{array}{l}\textit{Rate of heat gained by conductance from the covering tarpaulin}\\ \textit{if the bed is covered}\end{array}\right]$$

$$+\left[\textit{Rate of heat gained by moisture diffusion from air of } j = 2\right]$$

$$-\left[\begin{array}{l}\textit{Rate of heat lost by the surface radiation to the sky}\\ \textit{if the bed is not shaded or covered}\end{array}\right]$$

$$-\left[\begin{array}{l}\textit{Rate of heat lost by the surface radiation to the ambient air}\\ \textit{if the bed is shaded but not covered}\end{array}\right]$$

$$-\left[\begin{array}{l}\textit{Rate of heat lost by moisture evaporation to the ambient air}\\ \textit{if the bed is not covered}\end{array}\right]$$

$$-\left[\textit{Rate of heat lost by air convection if the bed is not covered}\right]$$

$$-\left[\textit{Rate of heat lost by conduction to grain bulk of } j = 2\right]$$

b. Mathematical equation for all the four cases

$$
\begin{aligned}
\frac{\partial Q_1}{\partial t} = & \left(1 - S_1\right)\left(1 - S_2\right)\beta_p.A_{top}.I + S_1\left(1 - S_2\right)\beta_p.A_{top}.I_{sh} \\
& + S_1\left(1 - S_2\right)0.63.\in_{tarp}.\in_p.A_{top}.\sigma\left[\left(T_{sh} + 273.15\right)^4 - \left(T_1 + 273.15\right)^4\right] \\
& + S_2\frac{1}{\left(\frac{1}{\in_{tarp}} + \frac{1}{\in_p}\right) - 1}A_{top}.\sigma\left[\left(T_{cov} + 273.15\right)^4 - \left(T_1 + 273.15\right)^4\right] + \\
& + S_2.A.U_{tarp/p}\left(T_{cov} - T_1\right) + D_{vp}.\varepsilon_p.h_{gin}.A\frac{C_2 - C_1}{\Delta x_p} \\
& - \left(1 - S_1\right)\left(1 - S_2\right)\in_p.A_{top}.\sigma\left[\left(T_1 + 273.15\right)^4 - \left(T_{sky} + 273.15\right)^4\right] \\
& - S_1\left(1 - S_2\right)\in_p.A_{top}.\sigma\left[\left(T_1 + 273.15\right)^4 - \left(T_a + 273.15\right)^4\right] \\
& - \left(1 - S_2\right)h.A_{top}\left(T_1 - T_a\right) - \left(1 - S_2\right)k_y.h_{gout}.A\left(C_1 - C_a\right) - \lambda_p.A\frac{T_1 - T_2}{\Delta x_p}
\end{aligned}
$$

… (A3.7)

Because half the thickness of the paddy kernel (*d*) on the bed surface is assumed to be exposed to the ambient air or to the sun,

$$a_k = \frac{A_{top}}{V_{top}} \Rightarrow A_{top} = a_k.V_{top} = a_k.A.\frac{d_k}{2}$$

As enthalpy or heat of evaporation is the sum of the latent and sensible heats and considering the average temperature between the two nodes,

$h_{gin} = h_{fg} + c_{pv}\frac{T_2 + T_1}{2}$ *and* $h_{gout} = h_{fg} + c_{pv}\frac{T_1 + T_a}{2} \Rightarrow$ Equation (A3.7) becomes

$$
\begin{aligned}
\frac{\partial Q_1}{\partial t} &= (1-S_1)(1-S_2)\beta_p.a_k.A\frac{d_k}{2}I + S_1(1-S_2)\beta_p.a_k.A\frac{d_k}{2}.I_{sh} \\
&+ S_1(1-S_2)0.63.\in_{tarp}.\in_p.a_k.A\frac{d_k}{2}\sigma\left[(T_{sh}+273.15)^4-(T_1+273.15)^4\right] \\
&+ S_2\frac{1}{\left(\frac{1}{\in_{tarp}}+\frac{1}{\in_p}\right)-1}a_k.A\frac{d_k}{2}\sigma\left[(T_{cov}+273.15)^4-(T_1+273.15)^4\right] \\
&+ S_2.A.U_{tarp/p}(T_{cov}-T_1)+D_{vp}.\varepsilon_p.A\left(h_{fg}+c_{pv}\frac{T_2+T_1}{2}\right)\frac{C_2-C_1}{\Delta x_p} \\
&- (1-S_1)(1-S_2)\in_p.a_k.A\frac{d_k}{2}\sigma\left[(T_1+273.15)^4-(T_{sky}+273.15)^4\right] \\
&- S_1(1-S_2)\in_p.a_k.A\frac{d_k}{2}\sigma\left[(T_1+273.15)^4-(T_a+273.15)^4\right] \\
&- (1-S_2)h.a_k.A\frac{d_k}{2}(T_1-T_a)-(1-S_2)k_y.A\left(h_{fg}+c_{pv}\frac{T_1+T_a}{2}\right)(C_1-C_a)-\lambda_p.A\frac{T_1-T_2}{\Delta x_p} \\
&= -(1-S_2)h.a_k.A\frac{d_k}{2}T_1+(1-S_2)h.a_k.A\frac{d_k}{2}T_a-\frac{\lambda_p.AT_1}{\Delta x_p}+\frac{\lambda_p.AT_2}{\Delta x_p} \\
&+ (1-S_1)(1-S_2)\beta.a_k.A\frac{d_k}{2}I+S_1(1-S_2)\beta_p.a_k.A\frac{d_k}{2}I_{sh} \\
&+ S_2\frac{1}{\left(\frac{1}{\in_{tarp}}+\frac{1}{\in_p}\right)-1}a_k.A\frac{d_k}{2}\sigma\left[(T_{cov}+273.15)^4-(T_1+273.15)^4\right] \\
&+ S_1(1-S_2)0.63\in_{tarp}.\in_p.a_k.A\frac{d_k}{2}\sigma\left[(T_{sh}+273.15)^4-(T_1+273.15)^4\right] \\
&+ S_2.A.U_{tarp/p}(T_{cov}-T_1)+\frac{D_{vp}.\varepsilon_p.A\left(h_{fg}+c_{pv}\frac{T_2+T_1}{2}\right)(C_2-C_1)}{\Delta x_p} \\
&- (1-S_1)(1-S_2)\in_p.a_k.A\frac{d_k}{2}\sigma\left[(T_1+273.15)^4-(T_{sky}+273.15)^4\right] \\
&- S_1(1-S_2)\in_p.a_k.A\frac{d_k}{2}\sigma\left[(T_1+273.15)^4-(T_a+273.15)^4\right] \\
&- (1-S_2)k_y.A\left(h_{fg}+c_{pv}\frac{T_1+T_a}{2}\right)(C_1-C_a)
\end{aligned}
$$

… (A3.8)

for $j = 1$ and $t > 0$.

$$\left[As\ energy\ in\ node\ 1\right] = \left[Energy\ in\ the\ paddy\ dry\ matter\right]$$

$$+\left[Energy\ of\ the\ water\ inside\ the\ kernels\right]$$

$$+\left[Energy\ in\ the\ dry\ air\ in\ the\ node\right]$$

$$+\left[Energy\ of\ the\ water\ vapour\ in\ the\ air\ in\ the\ node\right]$$

<u>Note:</u> The datum temperature is taken as 0^oC; therefore the enthalpy for the water, the paddy dry matter, the dry air and the soil at the temperature is 0.

$$\begin{aligned} \Rightarrow Q_1 = & W_{pd1}.c_{pp}.T_1 \\ & + MC_1.W_{pd1}.c_{pw}.T_1 \\ & + W_{a1}.c_{pa}.T_1 \\ & + H_1.W_{a1}\left(c_{pv}.T_1 + h_{fg}\right) \end{aligned} \qquad \text{... (A3.9)}$$

As $\rho_p = \dfrac{W_{pd1}}{V_1\left(1-\varepsilon_p\right)} \Rightarrow \left(1-\varepsilon_p\right)\rho_p.V_1 = \left(1-\varepsilon_p\right)\rho_p.A\dfrac{\Delta x_p}{2}$

$$\rho_a = \frac{W_{a1}}{V_1.\varepsilon_p} \Rightarrow W_{a1} = \varepsilon_p.\rho_a.V_1 = \varepsilon_p.\rho_a.A.\frac{\Delta x_p}{2}$$

$$H_1 = \frac{W_{v1}}{W_{a1}}\ ;\ C_1 = \frac{W_{v1}}{V_{a1}}\ ;\ \rho_a = \frac{W_{a1}}{V_{a1}} \Rightarrow H_1 = \frac{C_1}{\rho_a}$$

$\Rightarrow$ Equation (Q9) becomes:

$$Q_1 = \left(1-\varepsilon_p\right)\rho_p.A\frac{\Delta x_p}{2}c_{pp}.T_1 + MC_1\left(1-\varepsilon_p\right)\rho_p.A\frac{\Delta x_p}{2}c_{pw}.T_1 + \varepsilon_p.\rho_a.A\frac{\Delta x_p}{2}c_{pa}.T_1 + C_1\varepsilon_p.A\frac{\Delta x_p}{2}c_{pv}.T_1 + C_1.\varepsilon_p A\frac{\Delta x_p}{2}h_{fg}$$

... (A3.10)

$$\Rightarrow T_1 = \frac{2Q_1 - C_1.\varepsilon_p.A.\Delta x_p.h_{fg}}{\left(1-\varepsilon_p\right)\rho_p.A.\Delta x_p.c_{pp} + \left(1-\varepsilon_p\right).\rho_p A.\Delta x_p.c_{pw}MC_1 + \varepsilon_p.\rho_a.A.\Delta x_p.c_{pa} + \varepsilon_p.A.\Delta x_p.c_{pv}.C_1} \quad \text{…(A3.11)}$$

for $j = 1$ and $t > 0$.

The units of Equation (A3.11)

$$\left[{}^\circ C\right] = \frac{\left[J - \frac{kg}{m^3}m^2.m.\frac{J}{kg}\right]}{\left[\frac{kg}{m^3}m^2,m\frac{J}{kg.{}^oC} + \frac{kg}{m^3}m^2,m\frac{J}{kg.{}^oC} + \frac{kg}{m^3}m^2,m\frac{J}{kg.{}^oC} + m^2,m\frac{J}{kg.{}^oC}\frac{kg}{m^3}\right]} = \frac{[J]}{\left[\frac{J}{{}^oC}\right]} = \left[{}^\circ C\right]$$ are correct.

A3.3.2 Moisture transfer in the air at the bed surface

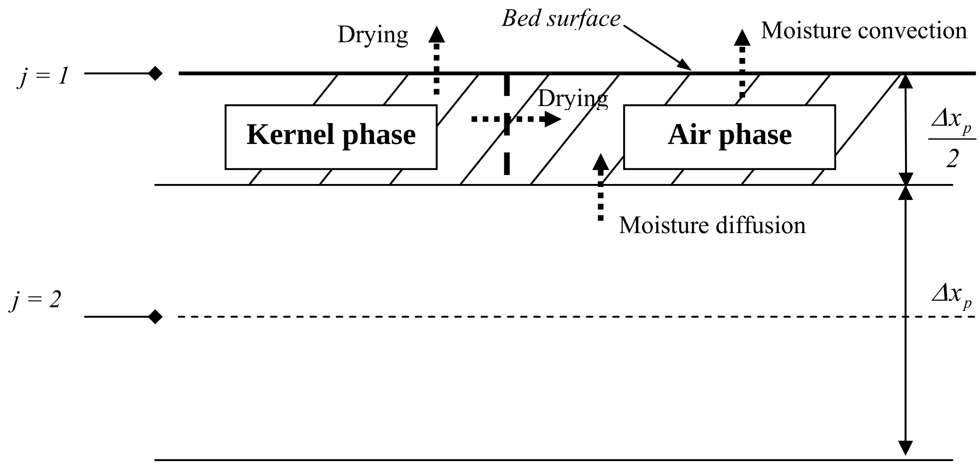


Fig A3.1: Moisture transfer at the bed surface with no cover

a. Word balance

$$\begin{bmatrix} \text{Rate of accumulation} \\ \text{of moisture in the} \\ \text{air in node 1} \end{bmatrix} = \left[\text{Rate of diffusion of moisture in from the air in node 2}\right]$$

$$+\left[\text{Rate of moisture dried out from the kernels in node 1}\right]$$

$$-\begin{bmatrix} \text{Rate of convection of moisture out to the ambient air} \\ \text{if the bed is not covered} \end{bmatrix}$$

b. Mathematical equation

$$\begin{aligned} \varepsilon_m.A\frac{\Delta x_m}{2}\frac{\partial C_1}{\partial t} &= D_{vm}.\varepsilon_m.A\frac{C_2 - C_1}{\Delta x_m} \\ &+ \rho_{bm}.A\frac{\Delta x_m}{2}\left(-\frac{\partial MC_1}{\partial t}\right) \\ &-(1-S_2)k_y.A(C_1 - C_a) \end{aligned} \qquad \ldots \text{(A3.12)}$$

Because $V_{a1} = \varepsilon_m.A.\frac{\Delta x_m}{2}$

Dividing by $\frac{\varepsilon_m.A\Delta x_m}{2}$ and substituting Equation (5.15) of Chapter 5, Equation (A3.12) becomes

$$\frac{\partial C_1}{\partial t}=\frac{2D_{vm}\left(C_2-C_1\right)}{\Delta x_m^2}+\frac{\rho_{bm}\left[k\left(MC_1-MC_{e1}\right)-B\right]}{\varepsilon_m}-\frac{\left(1-S_2\right)2k_y\left(C_1-C_a\right)}{\varepsilon_m.\Delta x_m} \quad \text{... (A3.13)}$$

for j = 1 and t > 0.

The units of Equation (A3.13) $\left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right]=\left[\frac{\text{m}^2}{\text{s}}\frac{\text{kg}}{\text{m}^2.\text{m}^3}\right]+\left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right]-\left[\frac{\text{m}}{\text{s.m}}\frac{\text{kg}}{\text{m}^3}\right]=\left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right]$ are correct.

A3.3.3 Moisture transfer in the kernels at the bed surface

a. Word balance

$$\begin{bmatrix}\textit{Rate of moisture lost from}\\ \textit{the kernels in node 1}\end{bmatrix}=\begin{bmatrix}\textit{Rate of moisture dried out from}\\ \textit{the kernels to the air in the node}\end{bmatrix}$$

$$+\begin{bmatrix}\textit{Rate of moisture dried out from the kernels}\\ \textit{to the ambient air if the surface is not covered}\end{bmatrix}$$

b. Mathematical equation

$$\rho_{bm}.A\frac{\Delta x_m}{2}\left(-\frac{\partial MC_1}{\partial t}\right)=\rho_{bm}.A\frac{\Delta x_m}{2}\left[k\left(MC_1-MC_{e1}\right)-B\right]$$
$$+\left(1-S_2\right).\rho_{bm}.A\frac{d}{2}\left[k\left(MC_1-MC_{ea}\right)-B\right] \quad \text{… (A3.14)}$$

Because $\rho_{bm}=\frac{Mass\ \ of\ \ solids}{Bulk\ \ volume}\Rightarrow Mass\ \ of\ \ solids=\rho_{bm}.Bulk\ \ volume=\rho_{bm}.A\frac{\Delta x_m}{2}$

Dividing by $-\frac{\rho_{bm}.A.\Delta x_m}{2}$, Equation (A3.14) becomes

$$\frac{\partial MC_1}{\partial t}=-k\left(MC_1-MC_{e1}\right)+B-\frac{\left(1-S_2\right).d\left[k\left(MC_1-MC_{ea}\right)-B\right]}{\Delta x_m} \quad \text{… (A3.15)}$$

for $j = 1$ and t > 0.

The units of Equation (A3.15) $\left[\frac{1}{\text{s}}\right]=\left[\frac{\text{kg.m}^2\ .\text{m}^3}{\text{m}^2.\text{s.m}^3.\text{kg}}\right]=\left[\frac{1}{\text{s}}\right]$ are correct.

A3.4 HEAT AND MOISTURE TRANSFERS WITHIN THE MATERIALS

A3.4.1 Heat transfer

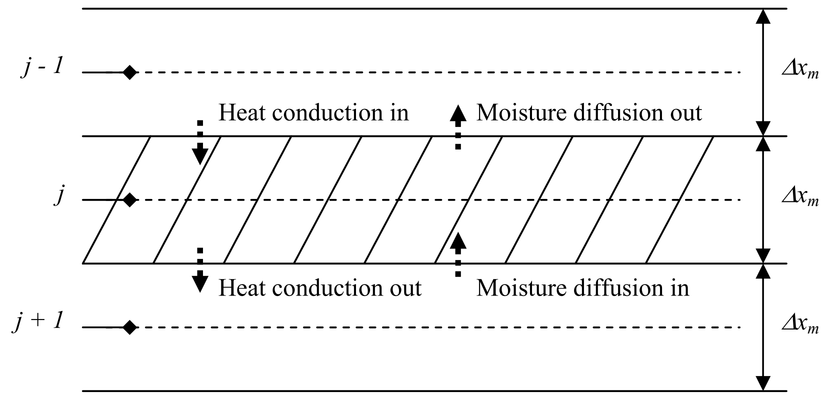


Fig A3.2: Heat and moisture transfers in the kernels and the air inside all the materials exposed to drying

a. Word balance

$$\begin{bmatrix} \textit{Rate of accumulation of} \\ \textit{heat in the solid material} \\ \textit{and air in node } j \end{bmatrix} = \left[\textit{Rate of conduction of heat in from the solid material in node } j-1\right]$$

$$-\left[\textit{Rate of conduction of heat out to the solid material in node } j+1\right]$$

$$+\left[\textit{Rate of heat gained with moisture diffusion from the air in node } j+1\right]$$

$$-\left[\textit{Rate of heat lost with moisture diffusion out to the air in node } j-1\right]$$

b. Mathematical equation

$$\frac{\partial Q_j}{\partial t} = \frac{\lambda_m . A\left(T_{j-1} - T_j\right)}{\Delta x_m} - \frac{\lambda_m . A\left(T_j - T_{j+1}\right)}{\Delta x_m} + \frac{D_{vm}.\varepsilon_m.h_{gi}.A\left(C_{j+1} - C_j\right)}{\Delta x_m} - \frac{D_{vm}.\varepsilon_m.h_{go}.A\left(C_j - C_{j-1}\right)}{\Delta x_m}$$

$$= \frac{\lambda_m . A\left(T_{j-1} - 2T_j + T_{j+1}\right)}{\Delta x_m} + \frac{D_{vm}.\varepsilon_m.A\left(h_{fg} + c_{pv}\dfrac{T_{j+1} + T_j}{2}\right)\left(C_{j+1} - C_j\right)}{\Delta x_m}$$

$$- \frac{D_{vm}.\varepsilon_m.A\left(h_{fg} + c_{pv}\dfrac{T_j + T_{j-1}}{2}\right)\left(C_{j+1} - C_j\right)}{\Delta x_m}$$

… (A3.16)

for j = 2 to J, $J + 3$ to $J + K$ and $J + K + 3$ to $J + K + L$ and $t > 0$.

Notes: Subscripts m for

p (of paddy) = 1 *for j = 2 to J + 1*

h (of husk) or pol (of polystyrene) = 2 *for j = J + 2 to J + K + 1*

s (of soil affected) = 3 *for j = J + K + 2 to J + K + L + 1*

(when husk or polystyrene was used)

and for j = J + 2 to J + K + 1

(when no husk nor polystyrene was used).

The units of Equation (A3.16)

$$\left[\frac{\text{J}}{\text{s}}\right]=\left[\frac{\text{J}}{\text{s.m.}^{\text{o}}\text{C}}\text{m}^2\frac{^{\text{o}}\text{C}}{\text{m}}\right]+\left[\frac{\text{m}^2}{\text{s}}\left(\frac{\text{J}}{\text{kg}}+\frac{\text{J.}^{\text{o}}\text{C}}{\text{kg.}^{\text{o}}\text{C}}\right)\text{m}^2\frac{\text{kg}}{\text{m}^3\text{.m}}\right]-\left[\frac{\text{m}^2}{\text{s}}\left(\frac{\text{J}}{\text{kg}}+\frac{\text{J.}^{\text{o}}\text{C}}{\text{kg.}^{\text{o}}\text{C}}\right)\text{m}^2\frac{\text{kg}}{\text{m}^3\text{.m}}\right]=\left[\frac{\text{J}}{\text{s}}\right]$$ are

correct..

Using the same principle as described in A3.3.1,

$$\Rightarrow T_j=\frac{Q_j-C_j.\varepsilon_m.A.\Delta x_m.h_{fg}}{\left(1-\varepsilon_m\right)\rho_m.A.\Delta x_m.c_{pm}+\left(1-\varepsilon_m\right).\rho_m A.\Delta x_m.cp_w MC_j+\varepsilon_m.\rho_a.A.\Delta x_m.c_{pa}+\varepsilon_m.A.\Delta x_m.c_{pv}.C_j}$$

… (A3.17)

for j = 2 to J, $J + 3$ to $J + K$ and $J + K + 3$ to $J + K + L$ and $t > 0$.

The units of Equation (A3.17)

$$\left[^{\text{o}}\text{C}\right]=\frac{\left[\text{J}-\frac{\text{kg}}{\text{m}^3}\text{m}^2\text{.m.}\frac{\text{J}}{\text{kg}}\right]}{\left[\frac{\text{kg}}{\text{m}^3}\text{m}^2,\text{m}\frac{\text{J}}{\text{kg.}^{\text{o}}\text{C}}+\frac{\text{kg}}{\text{m}^3}\text{m}^2,\text{m}\frac{\text{J}}{\text{kg.}^{\text{o}}\text{C}}+\frac{\text{kg}}{\text{m}^3}\text{m}^2,\text{m}\frac{\text{J}}{\text{kg.}^{\text{o}}\text{C}}+\text{m}^2,\text{m}\frac{\text{J}}{\text{kg.}^{\text{o}}\text{C}}\frac{\text{kg}}{\text{m}^3}\right]}=\frac{[\text{J}]}{\left[\frac{\text{J}}{^{\text{o}}\text{C}}\right]}=\left[^{\text{o}}\text{C}\right]$$ are correct.

A3.4.2 Moisture transfer in the air within the exposed materials

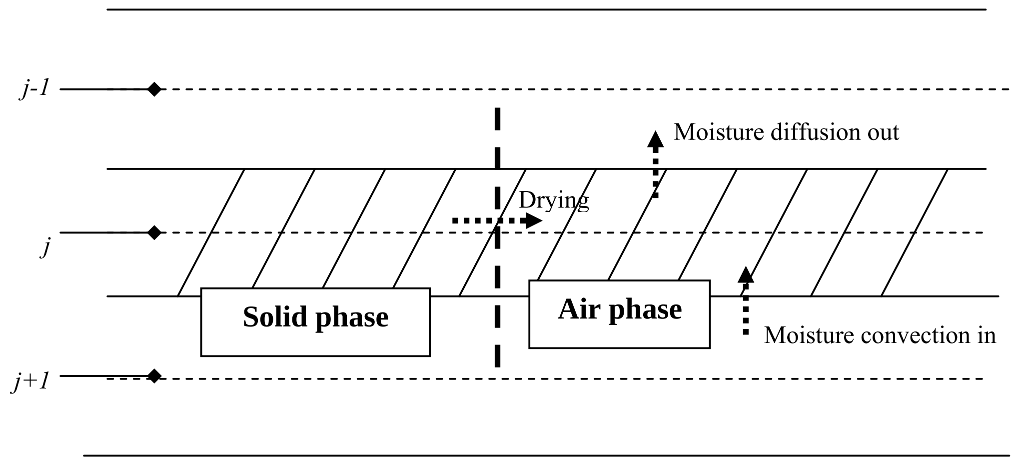


Fig A3.3: Moisture transfer inside all the materials exposed to drying

a. Word balance

$$\begin{bmatrix} \text{Rate of accumulation of} \\ \text{moisture in the air in node } j \end{bmatrix} = \left[\text{Rate of diffusion of moisture in from the air in node } j+1\right]$$

$$- \left[\text{Rate of diffusion of moisture out to the air in node } j-1\right]$$

$$+ \left[\text{Rate of moisture dried out from the solids in the node}\right]$$

b. Mathematical equation

$$\varepsilon_m.\Delta x_m.A\frac{\partial C_j}{\partial t} = \varepsilon_m.D_{vm}.A\frac{C_{j+1}-C_j}{\Delta x_m} - \varepsilon_m.D_{vm}.A\frac{C_j - C_{j-1}}{\Delta x_m} + \rho_{bm}.A.\Delta x_m\left[k\left(MC_j - MC_{ej}\right) - B\right] \quad \ldots \text{(A3.18)}$$

Dividing by $\varepsilon_m.A.\Delta x_m$, Equation (A3.18) becomes

$$\frac{\partial C_j}{\partial t} = \frac{D_{vm}\left(C_{j-1} - 2C_j + C_{j+1}\right)}{\Delta x_m^2} + \frac{\rho_{bm}\left[k\left(MC_j - MC_{ej}\right) - B\right]}{\varepsilon_m} \quad \ldots \text{(A3.19)}$$

for $j = 2$ to J, $J + 3$ to $J + K$ and $J + K + 3$ to $J + K + L$ and $t > 0$.

The units of Equation (A3.19)

$$\left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right] = \left[\frac{\text{m}^2}{\text{s.m}^2}\frac{\text{kg}}{\text{m}^3}\right] + \left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right] = \left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right]$$ are correct.

A3.5 HEAT AND MOISTURE TRANSFER AT THE BOTTOM OF THE RICE BED OR MATERIAL 2

A3.5.1 Heat transfer

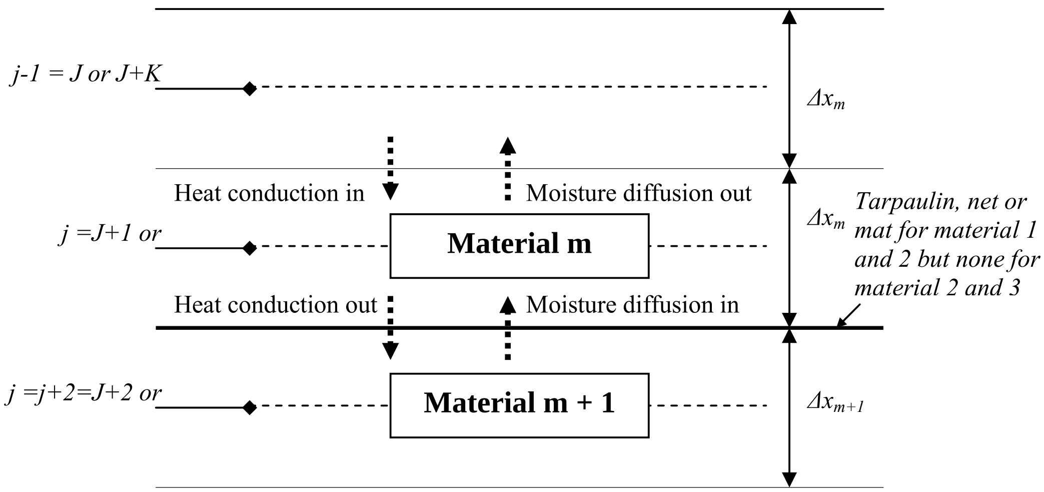


Fig A3.4: Heat and moisture transfer at the bottom of the grain bed or material 2

<u>Note</u>: *For the bottom of the rice bed (j = J + 1), m = 1 and m + 1 = 2 and for the bottom of material 2 (j = J + K + 1), m = 2 and m + 1 = 3.*

a. Word balance when nylon net was the drying pad laid on top of husk

$$\begin{bmatrix} Rate\ of\ accumulation \\ of\ heat\ in\ the\ solids\ and \\ air\ in\ node\ j+K+1 \end{bmatrix} = \begin{bmatrix} Rate\ of\ conduction\ of\ heat\ in\ from\ the \\ solids\ and\ air\ in\ node\ J\ or\ J+K \end{bmatrix}$$

$$+\begin{bmatrix} Rate\ of\ heat\ gained\ with\ moisture\ diffusion\ in\ from\ the\ air \\ in\ node\ J+2\ or\ J+K+2\ if\ tarpaulin\ or\ mat\ is\ not\ used \end{bmatrix}$$

$$-\begin{bmatrix} Rate\ of\ conductance\ of\ heat\ out\ to\ the \\ other\ material\ in\ node\ j+2\ or\ J+K+2 \end{bmatrix}$$

$$-\begin{bmatrix} Rate\ of\ heat\ lost\ with\ moisture\ diffusion \\ out\ to\ the\ air\ in\ node\ J\ or\ J+K \end{bmatrix}$$

b. Mathematical equation

$$\frac{\partial Q_j}{\partial t} = \lambda_m.A\frac{T_{j-1} - T_j}{\Delta x_m}$$

$$+ h_{gi}.A\frac{C_{j+1} - C_j}{\frac{\Delta x_m}{2.\varepsilon_m.D_{vm}} + \frac{\Delta x_{m+1}}{2.\varepsilon_{m+1}.D_{vm+1}} + R_{MTm/m+1}}$$

$$- \frac{A.\left(T_j - T_{j+1}\right)}{\frac{\Delta x_m}{2\lambda_m} + \frac{\Delta x_{m+1}}{2\lambda_{m+1}} + R_{m/m+1}}$$

$$- D_{vm}.\varepsilon_m.h_{go}.A\frac{C_j - C_{j-1}}{\Delta x_m}$$

$$= \frac{\lambda_m.A\left(T_{j-1} - T_j\right)}{\Delta x_m} + \frac{2.\varepsilon_m.\varepsilon_{m+1}.D_{vm}.D_{vm+1}.A\left(C_{j+1} - C_j\right)\left(h_{fg} + c_{pv}\frac{T_{j+1} + T_j}{2}\right)}{\Delta x_m.\varepsilon_{m+1}.D_{vm+1} + \Delta x_{m+1}.\varepsilon_m.D_{vm} + 2.R_{MTm/m+1}.\varepsilon_m.\varepsilon_{m+1}.D_{vm}.D_{vm+1}}$$

$$- \frac{2\lambda_m.\lambda_{m+1}A\left(T_j - T_{j+1}\right)}{\lambda_{m+1}.\Delta x_m + \lambda_m.\Delta x_{m+1} + 2.\lambda_m.\lambda_{m+1}.R_{m/m+1}} - \frac{D_{vm}.\varepsilon_m.A\left(C_j - C_{j-1}\right)\left(h_{fg} + c_{pv}\frac{T_j + T_{j-1}}{2}\right)}{\Delta x_m}$$

... (A3.20)

for $j = J + 1$ and $t > 0$ when tarpaulin is used, otherwise, $R_{MTm/m+1}$ and $R_{m/m+1} = 0$;
for $j = J + K + 1$ and $t > 0$, $R_{MTm/m+1}$ and $R_{m/m+1} = 0$ or does not exist.

where, resistance of the heat flow from rice bed to material 2 below if tarpaulin is used

$$R_{m/m+1} = \frac{L_{tarp}}{\lambda_{tarp}} + \frac{L_a}{\lambda_a} = \frac{\lambda_a.L_{tarp} + \lambda_{tarp}.L_a}{\lambda_{tarp}.\lambda_a}$$ with the units of $\left[\frac{\text{s.m}^2.^{\circ}\text{C}}{\text{J}}\right]$ and

$R_{MTm/m+1}$ resistance to mass transfer from a material to the other one below $\left[\frac{\text{s}}{\text{m}}\right]$.

<u>Notes:</u>

The values of $R_{m/m+1}$ must be high when the drying pad was the tarpaulin and must be 0 for the material that doesn't stop or reduce the heat flow.

The values of $R_{MTm/m+1}$ must be high when the drying pad was the tarpaulin and must be 0 for the material that doesn't stop or reduce the flow of moisture.

The units of Equation (A3.20)

$$\left[\frac{J}{s}\right]=\left[\frac{J.m^2.^oC}{s.m.^oC.m}\right]+\left[\frac{m^2.m^2.m^2.kg.\left(\frac{J}{kg}+\frac{J.^oC}{kg.^oC}\right)}{s.m^3\left(\frac{m.m^2}{s}+\frac{m^2.s.m^2}{s.m.s}\right)}\right]+\left[\frac{J^2.m^2.^oC}{s^2.m^2.^oC^2\left(\frac{J.m}{s.m.^oC}+\frac{J^2.s.m^2.^oC}{s^2.m^2.^o.C^2.J}\right)}\right]$$

$$+\left[\frac{m^2.m^2.kg.\left(\frac{J}{kg}+\frac{J.^oC}{kg.^oC}\right)}{s.m^3m}\right]=\left[\frac{J}{s}\right]$$ are correct.

A3.5.2 Moisture transfer in the air

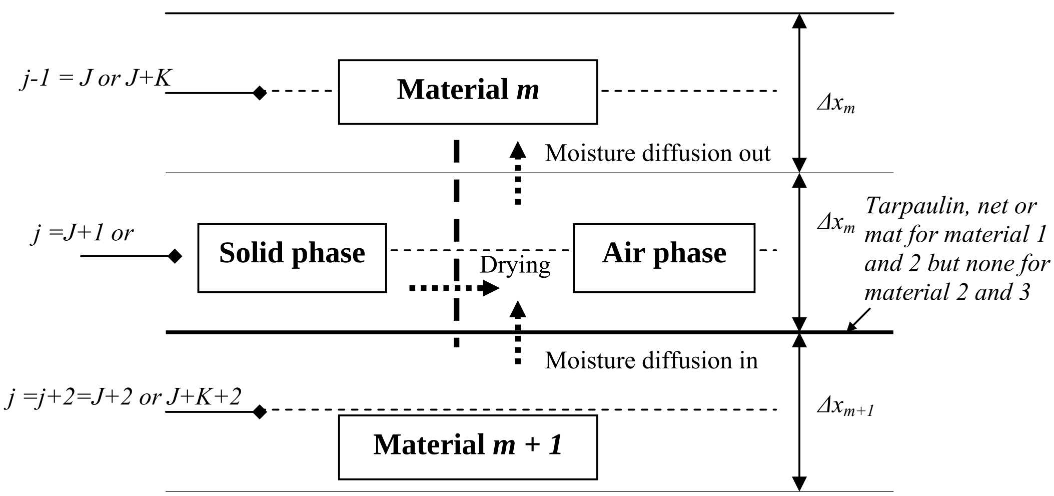


Fig A3.5: Moisture transfer at the bottom of the grain bed or material 2

a. Word balance

$$\begin{bmatrix} Rate\,of\ accumulation \\ of\ moisture\ in\ the\ air \\ at\ J+1\ or\ J+K+1 \end{bmatrix}=\left[Rate\ of\ diffusion\ of\ moisture\ in\ from\ the\ air\ of\ the\ node\ below\right]$$

$$+\left[Rate\ of\ moisture\ dried\ out\ from\ the\ solids\ in\ the\ node\right]$$

$$-\left[Rate\ of\ difusion\ of\ moisture\ out\ to\ the\ node\ above\right]$$

b. Mathematical equation

$$\varepsilon_m.\Delta x_m.A\frac{\partial C_j}{\partial t} = \frac{A\left(C_{j+1}-C_j\right)}{\frac{\Delta x_m}{2.\varepsilon_m.D_{vm}}+\frac{\Delta x_m}{2.\varepsilon_{m+1}.D_{vm+1}}+R_{MTm/m+1}}$$

$$+\rho_{bm}.A.\Delta x_m\left[k\left(MC_j-MC_{ej}\right)-B\right]$$

$$-\frac{\varepsilon_m.D_{vm}.A\left(C_j-C_{j-1}\right)}{\Delta x_m}$$

$$=\frac{2\varepsilon_m.\varepsilon_{m+1}.D_{vm}D_{vm+1}A\left(C_{j+1}-C_j\right)}{\varepsilon_{m+1}.D_{vm+1}.\Delta x_m+\varepsilon_m.D_{vm}.\Delta x_{m+1}+2R_{MTm/m+1}\varepsilon_m.\varepsilon_{m+1}.D_{vm}D_{vm+1}}$$

$$+\rho_{bm}.A.\Delta x_m\left[k\left(MC_j-MC_{ej}\right)-B\right]-\frac{\varepsilon_m.D_{vm}.A\left(C_j-C_{j-1}\right)}{\Delta x_m}$$

… (A3.21)

Dividing by $\varepsilon_m.\Delta x_m.A$, Equation (A3.21) becomes

$$\frac{\partial C_j}{\partial t}=\frac{2.\varepsilon_{m+1}.D_{vm}D_{vm+1}\left(C_{j+1}-C_j\right)}{\Delta x_m\left(\varepsilon_{m+1}.D_{vm+1}.\Delta x_m+\varepsilon_m.D_{vm}.\Delta x_{m+1}+2R_{MTm/m+1}\varepsilon_m.\varepsilon_{m+1}.D_{vm}D_{vm+1}\right)}$$

$$+\frac{\rho_{bm}\left[k\left(MC_j-MC_{ej}\right)-B\right]}{\varepsilon_m}-\frac{D_{vm}\left(C_j-C_{j-1}\right)}{\Delta x_m^2}$$

… (A3.22)

for $j = J+1$ or $j = J+K+1$ and t > 0

The units of Equations (A3.22)

$$\left[\frac{\mathrm{kg}}{\mathrm{m^3.s}}\right]=\left[\frac{\mathrm{m^2m^2.kg}}{\mathrm{s.s.m^3.m}\left[\frac{\mathrm{m^2.m}}{\mathrm{s}}+\frac{\mathrm{m^2.m^2.s}}{\mathrm{s.s.m}}\right]}\right]+\left[\frac{\mathrm{kg}}{\mathrm{m^3.s}}\right]+\left[\frac{\mathrm{m^2.kg}}{\mathrm{s.m^2.m^3}}\right]=\left[\frac{\mathrm{kg}}{\mathrm{m^3.s}}\right]$$ are correct.

A3.6 HEAT AND MOISTURE TRANSFER AT THE TOP OF MATERIAL 2 OR 3

A3.6.1 Heat transfer

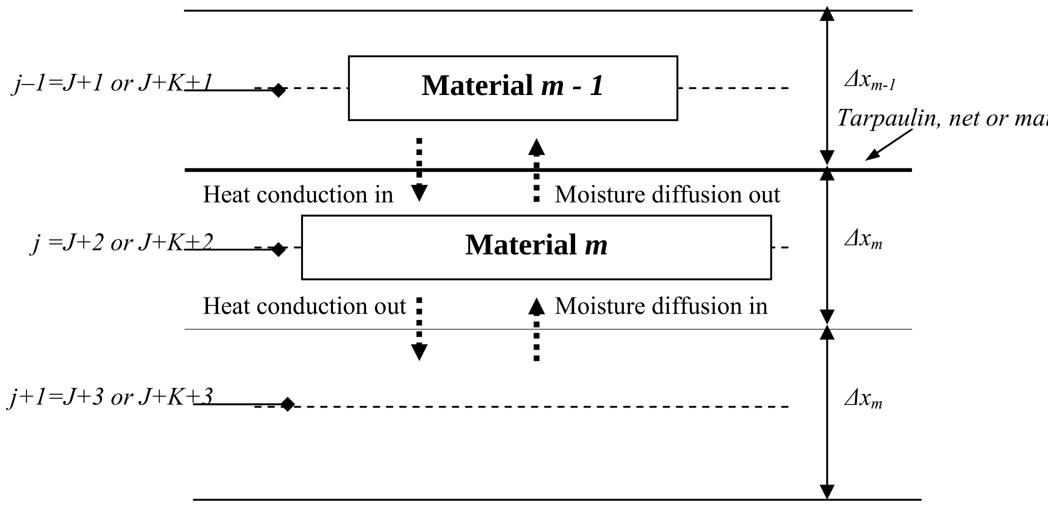


Fig A3.6: Heat and moisture transfers at the top of material 2 or 3

<u>Note</u>: *For the top of material 2 (j = J + 2), m = 2 and m - 1 = 1*
and for the top of material 3 (j = J + K + 2), m = 3 and m - 1 = 2.

b. Mathematical equation

$$\frac{\partial Q_j}{\partial t} = \frac{A.\left(T_{j-1} - T_j\right)}{\frac{\Delta x_{m-1}}{2\lambda_{m-1}} + \frac{\Delta x_m}{2\lambda_m} + R_{m-1/m}}$$

$$+ \frac{D_{vm}.\varepsilon_m.h_{gi}.A\left(C_{j+1} - C_j\right)}{\Delta x_m}$$

$$- \frac{\lambda_m.A\left(T_j - T_{j+1}\right)}{\Delta x_m}$$

$$- \frac{h_{go}.A\left(C_j - C_{j-1}\right)}{\frac{\Delta x_{m-1}}{2.\varepsilon_{m-1}.D_{vm-1}} + \frac{\Delta x_m}{2.\varepsilon_m.D_{vm}} + R_{MTm-1/m}}$$

$$= \frac{2\lambda_{m-1}.\lambda_m A\left(T_{j-1} - T_j\right)}{\lambda_m.\Delta x_{m-1} + \lambda_{m-1}.\Delta x_m + 2.\lambda_{m-1}.\lambda_m.R_{m-1/m}} + \frac{D_{vm}.\varepsilon_m.A\left(C_{j+1} - C_j\right)\left(h_{fg} + c_{pv}\frac{T_{j+1}+T_j}{2}\right)}{\Delta x_m}$$

$$- \frac{\lambda_m.A\left(T_j - T_{j+1}\right)}{\Delta x_m} - \frac{2.\varepsilon_{m-1}.\varepsilon_m.D_{vm-1}.D_{vm}A\left(C_j - C_{j-1}\right)\left(h_{fg} + c_{pv}\frac{T_{J+2}+T_{J+1}}{2}\right)}{\Delta x_{m-1}.\varepsilon_m.D_{vm} + \Delta x_m.\varepsilon_{m-1}.D_{vm-1} + 2.R_{MTm-1/m}.\varepsilon_{m-1}.\varepsilon_m.D_{vm-1}.D_{vm}}$$

… (A3.23)

for $j = J + 2$ and $t > 0$ when tarpaulin is used; otherwise, $R_{MTm-1/m}$ and $R_{m-1/m} = 0$.

for $j = J + K + 2$ and $t > 0$, $R_{MTm-1/m}$ and $R_{m-1/m} = 0$ or do not exist.

The units of Equation (A3.23)

$$\left[\frac{J}{s}\right] = \left[\frac{J^2.m^2.^oC}{s^2.m^2.^oC^2\left(\frac{J.m}{s.m.^oC} + \frac{J^2.s.m^2.^oC}{s^2.m^2.^oC^2.J}\right)}\right] + \left[\frac{m^2.m^2.kg.\left(\frac{J}{kg} + \frac{J.^oC}{kg.^oC}\right)}{s.m^3m}\right] + \left[\frac{J.m^2.^oC}{s.m.^oC.m}\right]$$

$$+ \left[\frac{m^2.m^2.m^2.kg.\left(\frac{J}{kg} + \frac{J.^oC}{kg.^oC}\right)}{s.s.m^3\left(\frac{m.m^2}{s}m + \frac{m^2.m^2.s}{ss.m}\right)}\right] = \left[\frac{J}{s}\right] \text{ are correct.}$$

A3.6.2 The moisture transfer in the air

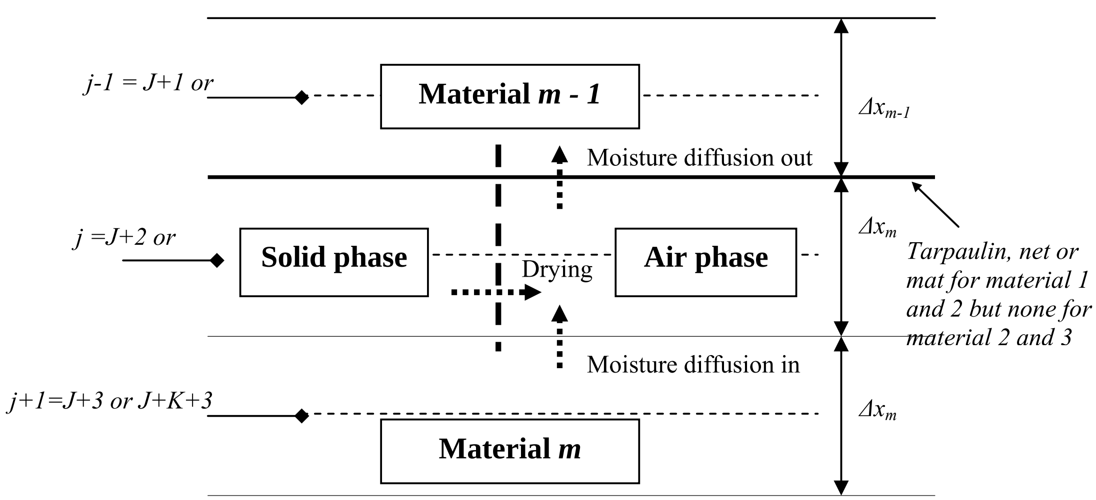


Fig A3.7: Moisture transfer at the top of material 2 or 3

a. Word balance

$$\begin{bmatrix} Rate\ of\ accumulation\ of\ moisture \\ in\ the\ air\ at\ J+2\ or\ J+K+2 \end{bmatrix} = \begin{bmatrix} Rate\ of\ diffusion\ of\ moisture\ in \\ from\ the\ air\ of\ the\ node\ below \end{bmatrix}$$

$$+ \left[Rate\ of\ moisture\ dried\ out\ from\ the\ solids\ in\ the\ node \right]$$

$$- \begin{bmatrix} Rate\ of\ diffusion\ of\ moisture\ out\ to\ the \\ node\ above\ if\ tarpaulin\ or\ mat\ is\ not\ used \end{bmatrix}$$

b. Mathematical equation

$$\varepsilon_m.\Delta x_m.A\frac{\partial C_j}{\partial t} = \frac{\varepsilon_m.D_{vm}.A\left(C_{j+1} - C_j\right)}{\Delta x_m}$$
$$+ \rho_{bm}.A.\Delta x_m\left[k\left(MC_j - MC_{ej}\right) - B\right]$$
$$- \frac{A\left(C_j - C_{j-1}\right)}{\dfrac{\Delta x_m}{2.\varepsilon_m.D_{vm}} + \dfrac{\Delta x_{m-1}}{2.\varepsilon_{m-1}.D_{vm-1}} + R_{MTm-1/m}}$$

$$= \frac{\varepsilon_m.D_{vm}.A\left(C_{j+1} - C_j\right)}{\Delta x_m} + \rho_{bm}.A.\Delta x_m\left[k\left(MC_j - MC_{ej}\right) - B\right]$$
$$- \frac{2\varepsilon_{m-1}.\varepsilon_m.D_{vm-1}D_{vm}A\left(C_j - C_{j-1}\right)}{\varepsilon_{m-1}.D_{vm-1}.\Delta x_m + \varepsilon_m.D_{vm}.\Delta x_{m-1} + 2R_{MTm-1/m}\varepsilon_{m-1}.\varepsilon_m.D_{vm-1}D_{vm}}$$

… (A3.24)

Dividing by $\varepsilon_m.\Delta x_m.A$, Equation (A3.24) becomes

$$\frac{\partial C_j}{\partial t} = \frac{.D_{vm}.\left(C_{j+1} - C_j\right)}{\Delta x_m^2} + \frac{\rho_{bm}\left[k\left(MC_j - MC_{ej}\right) - B\right]}{\varepsilon_m}$$
$$- \frac{2\varepsilon_{m-1}.D_{vm-1}D_{vm}\left(C_j - C_{j-1}\right)}{\Delta x_m\left(\varepsilon_{m-1}.D_{vm-1}.\Delta x_m + \varepsilon_m.D_{vm}.\Delta x_{m-1} + 2R_{MTm-1/m}\varepsilon_{m-1}.\varepsilon_m.D_{vm-1}D_{vm}\right)}$$

… (A3.25)

for $j = J+2$ and $t > 0$ when tarpaulin is used; otherwise, $R_{MTm-1/m} = 0$.

for $j = J+K+2$ and $t > 0$, $R_{MTm-1/m} = 0$ or does not exist.

The units of Equation (A3.25)

$$\left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right] = \left[\frac{\text{m}^2.\text{kg}}{\text{s.m}^2.\text{m}^3}\right] + \left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right] + \left[\frac{\text{m}^2\text{m}^2.\text{kg}}{\text{s.s.m}^3.\text{m}\left[\dfrac{\text{m}^2.\text{m}}{\text{s}} + \dfrac{\text{m}^2.\text{m}^2.\text{s}}{\text{s.s.m}}\right]}\right] = \left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right]$$ are correct.

A3.7 HEAT AND MOISTURE TRANSFER AT THE BOTTOM OF MATERIAL 3

A3.7.1 Heat transfer

No heat and mass transfers were assumed to occur between the node and the one below. Thus,

$$T_j = T_{gr} \qquad \text{... (A3.26)}$$

for $j = J + K + L + 1$ and $t > 0$.

A3.7.2 Moisture transfer in the air

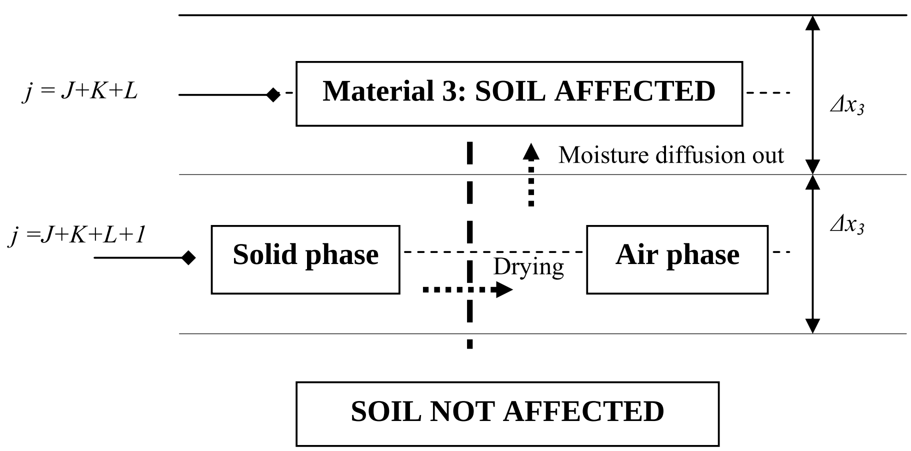


Fig A3.8: Moisture transfer at the bottom node of material 3

a. Word balance

$$\begin{bmatrix} \text{Rate of accumulation of} \\ \text{moisture in the air at } J+K+L+1 \end{bmatrix} = \left[\text{Rate of moisture dried out from the solids in the node}\right]$$
$$- \left[\text{Rate of diffusion of moisture out to the node above}\right]$$

b. Mathematical equation

$$\varepsilon_m.\Delta x_m.A\frac{\partial C_{J+K+L+1}}{\partial t} = \rho_{bm}.A.\Delta x_m\left[k\left(MC_{J+K+L+1} - MC_{eJ+K+L+1}\right) - B\right] - \frac{\varepsilon_m.D_{vm}.A\left(C_{J+K+L+1} - C_{J+K+L}\right)}{\Delta x_m} \quad \text{… (A3.27)}$$

Dividing by $\varepsilon_m.\Delta x_m.A$, Equation (A3.27) becomes

$$\frac{\partial C_{J+K+L+1}}{\partial t} = \frac{\rho_{bm}\left[k\left(MC_{J+K+L+1} - MC_{eJ+K+L+1}\right) - B\right]}{\varepsilon_m} - \frac{D_{vm}\left(C_{J+K+L+1} - C_{J+K+L}\right)}{\Delta x_m^2} \quad \text{… (A3.28)}$$

where $m = 3$, for $j = J + K + L + 1$ and t > 0.

The units of Equations (A3.28) $\left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right] = \left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right] + \left[\frac{\text{m}^2.\text{kg}}{\text{s.m}^3.\text{m}^2}\right] = \left[\frac{\text{kg}}{\text{m}^3.\text{s}}\right]$ are correct.

A3.8 MOISTURE TRANSFER IN THE SOLIDS OF ALL MATERIALS

a. Word balance

$$\begin{bmatrix} \textit{The rate of moisture lost} \\ \textit{from the solids in node } j \end{bmatrix} = \begin{bmatrix} \textit{The rate of moisture dried out from} \\ \textit{the solids to the air in the node} \end{bmatrix}$$

b. Mathematical equation

$$\rho_{bm}.A.\Delta x_m\left(-\frac{\partial MC_j}{\partial t}\right) = \rho_{bm}.A.\Delta x_m\left[k\left(MC_j - MC_{ej}\right) - B\right] \quad \text{… (A3.29)}$$

Dividing by - $\rho_{bm}.A.\Delta x_m$, Equation (A3.29) becomes

$$\frac{\partial MC_j}{\partial t} = -k\left(MC_j - MC_{ej}\right) + B \quad \text{… (A3.30)}$$

for $j = 2$ to $J + K + L + 1$ and $t > 0$.

The units of Equation (A3.30) $\left[\frac{1}{\text{s}}\right] = \left[\frac{1}{\text{s}}\right]$ are correct.

A3.9 INITIAL CONDITIONS

Using Equation (A3.10),

$$Q_1 = \left(1-\varepsilon_p\right)\rho_p.A\frac{\Delta x_p}{2}c_{pp}.T_1 + MC_1\left(1-\varepsilon_p\right)\rho_p.A\frac{\Delta x_p}{2}c_{pw}.T_1 + \varepsilon_p.\rho_a.A\frac{\Delta x_p}{2}c_{pa}.T_1 + C_1\varepsilon_p.A\frac{\Delta x_p}{2}c_{pv}.T_1 + C_1.\varepsilon_p A\frac{\Delta x_p}{2}h_{fg}$$

$$\Rightarrow Q_{1i} = \left(1-\varepsilon_p\right)\rho_p.A\frac{\Delta x_p}{2}c_{pp}.T_{1i} + MC_{1i}\left(1-\varepsilon_p\right)\rho_p.A\frac{\Delta x_p}{2}c_{pw}.T_{1i} + \varepsilon_p.\rho_a.A\frac{\Delta x_p}{2}c_{pa}.T_{1i} + C_{1i}\varepsilon_p.A\frac{\Delta x_p}{2}c_{pv}.T_{1i} + C_{1i}.\varepsilon_p A\frac{\Delta x_p}{2}h_{fg}$$

… (A3.31)

for $j = 1$ and $t = 0$.

Derived from Equation (A3.17),

$$T_j = \frac{Q_j - C_j.\varepsilon_m.A.\Delta x_m.h_{fg}}{\left(1-\varepsilon_m\right)\rho_m.A.\Delta x_m.c_{pm} + \left(1-\varepsilon_m\right).\rho_m A.\Delta x_m.cp_w MC_j + \varepsilon_m.\rho_a.A.\Delta x_m.c_{pa} + \varepsilon_m.A.\Delta x_m.c_{pv}.C_j} \Rightarrow$$

$$Q_j = T_j\left[\left(1-\varepsilon_m\right)\rho_m.A.\Delta x_m.c_{pm} + \left(1-\varepsilon_m\right).\rho_m A.\Delta x_m.cp_w MC_j + \varepsilon_m.\rho_a.A.\Delta x_m.c_{pa} + \varepsilon_m.A.\Delta x_m.c_{pv}.C_j\right] + \\ + C_j.\varepsilon_m.A.\Delta x_m.h_{fg}$$

$$\Rightarrow Q_{ji} = T_{ji}\left[\left(1-\varepsilon_m\right)\rho_m.A.\Delta x_m.c_{pm} + \left(1-\varepsilon_m\right).\rho_m A.\Delta x_m.cp_w MC_{ji} + \varepsilon_m.\rho_a.A.\Delta x_m.c_{pa} + \varepsilon_m.A.\Delta x_m.c_{pv}.C_{ji}\right] + \\ + C_{ji}.\varepsilon_m.A.\Delta x_m.h_{fg}$$

… (A3.32)

for $j = 1$ to $J + K + L + 1$ and $t = 0$.

Appendix A4

MATLAB LANGUAGE FOR THE MODEL

To solve the second model numerically using Matlab, a group of m-files were transformed from the ODEs. A part of the group is suitable for all the dying treatments while the other part needed to be adjusted based on the drying conditions applied for particular treatment.

A4.1 The m files applicable to all the treatments

A4.1.1 The main function file (File name: Ricebedfun)

```
function rates=ricebedfun(t,Dvs)

% Define global variables

global a;   % Specific surface area of the exposed materials in a bulk
(m2/m3)
global A;   % Flat surface area of the drying bed (m2)
global betp; % Absorptivity of solar radiation of the paddy (decimal)
global bettarp; % Absorptivity of solar radiation of the tarpaulin
(decimal)
global cp; % Specific heat of the materials (J/kg.oC)
global cpa; % Specific heat of air (J/kg.oC)
global cpv; % Specific heat of water vapor (J/kg.oC)
global cpw; % Specific heat of water (J/kg.oC)
global d;   % Thickness of the paddy kernel (m)
global dx;  % Spatial step in the materials (m)
global emisp;    % Emissivity of the paddy (decimal)
global emistarp;    % Emissivity of the tarpaulin (decimal)
global Fe; % Emissivity correction
global h;   % Convective heat transfer coefficient (W/m2.oC)
global hfg;  % Latent heat of evaporation (J/kg)
global J;   % Number of nodes in the rice bed (decimal)
global K;   % Number of nodes in the husk or polystyrene (decimal)
global ky;  % Convective moisture transfer coefficient (m/s)
global L;   % Number of nodes in the soil (decimal)
global por; % Porosivity of air in the materials' bulk (decimal)
global rhoa;    % Density of air (kg/m3)
global rho;   % True density of the materials (kg/m3)
global rhob;   % Bulk density of the materials (kg/m3)
global stef;    % Stefan-Boltzmann constant (5.669 e-8 W/m2.K4)
global Ti;   % Initial temperature of system (C)
global Utarpp;
global Rmm;
global Rmtmm;
global Tsky;
global Tsh Tcov;
global tShadeOn;
global tShadeOff;
global tCoverOn;
global tCoverOff;
```

```
global lam;
global S1;
global S2;

% Calulate consequential varables
% Calculate new values for dependent variables
Q=Dvs(1:(J+K+L+1),1);
C=Dvs((J+K+L+2):(J+K+L+1+J+K+L+1),1);
MC=Dvs(((J+K+L+1+J+K+L+2):(J+K+L+1+J+K+L+1+J+K+L+1)),1);

% Temperature at the bed surface

m=1;
T(1)=(2*Q(1)-C(1)*por(m)*A*dx(m)*hfg)/((1-
por(m))*rho(m)*A*dx(m)*cp(m)+...
    MC(1)*(1-por(m))*rho(m)*A*dx(m)*cpw+por(m)*rhoa*A*dx(m)*cpa+...
    C(1)*por(m)*A*dx(m)*cpv);


for j=2:J+K+L+1
    if j<=J+1
        m=1;
    elseif j<=J+K+1
        m=2;
    else
        m=3;
    end

    T(j)=(Q(j)-C(j)*por(m)*A*dx(m)*hfg)/((1-
por(m))*rho(m)*A*dx(m)*cp(m)+...
        MC(j)*(1-
por(m))*rho(m)*A*dx(m)*cpw+por(m)*rhoa*A*dx(m)*cpa+...
        C(j)*por(m)*A*dx(m)*cpv);
end

if t>=tShadeOn & t<=tShadeOff
    S1=1;
else
    S1=0;
end

if t>=tCoverOn & t<=tCoverOff
    S2=1;
else
    S2=0;
end

options = optimset('Display','off'); % Turn off Display
TshAndTcov = fsolve(@(u) FindTshAndTcov(u,t,T(1)), [Tsh,Tcov],
options);
Tsh=TshAndTcov(1);
Tcov=TshAndTcov(2);

%Place the values to the right place

dQ=zeros(J+K+L+1,1);
dC=zeros(J+K+L+1,1);
dMC=zeros(J+K+L+1,1);

% For note 1 (At the bed surface)
```

```
 m=1;
dQ(1)=-(1-S2)*h*a*A*d/2*T(1)+(1-S2)*h*a*A*d/2*Ta(t) ...
    -lam(m)*A/dx(m)*(T(1)-T(2)) ...
    +(1-S1)*(1-S2)*betp*a*A*d/2*I(t) ...
    +S1*(1-S2)*betp*a*A*d/2*Ish(t) ...
    +S2*Fe*stef*a*A*d/2*((Tcov+273.15)^4-(T(1)+273.15)^4) ...
    +S1*(1-S2)*0.63*emistarp*emisp*stef*a*A*d/2*((Tsh+273.15)^4-
(T(1)+273.15)^4) ...
    +S2*A*Utarpp*(Tcov-
T(1))+Dv(T(1),C(1),m)*por(m)*A/dx(m)*(hfg+cpv/2*(T(2)+T(1)))*(C(2)-
C(1)) ...
    -(1-S1)*(1-S2)*emisp*stef*a*A*d/2*((T(1)+273.15)^4-
(Tsky+273.15)^4) ....
    -S1*(1-S2)*emisp*stef*a*A*d/2*((T(1)+273.15)^4-(Ta(t)+273.15)^4)
....
    -(1-S2)*ky*A*(hfg+cpv/2*(T(1)+Ta(t)))*(C(1)-Ca(t));
dC(1)=2*Dv(T(1),C(1),m)/dx(m)^2*(C(2)-C(1))+rhob(m)/por(m)*(k(MC(1)-
MCe(C(1),T(1),m),m)*(MC(1)-MCe(C(1),T(1),m))-B(MC(1)-
MCe(C(1),T(1),m),m))-(1-S2)*2*ky/(por(m)*dx(m))*(C(1)-Ca(t));
dMC(1)=-k(MC(1)-MCe(C(1),T(1),m),m)*(MC(1)-MCe(C(1),T(1),m))+B(MC(1)-
MCe(C(1),T(1),m),m)-(1-S2)*d/dx(m)*...
    (k(MC(1)-MCe(C(1),T(1),m),m)*(MC(1)-MCe(Ca(t),Ta(t),m))-B(MC(1)-
MCe(C(1),T(1),m),m));

for j=[2:J,J+3:J+K,J+K+3:J+K+L]
    if j<=J+1
        m=1;
    elseif j<=J+K+1
        m=2;
    else
        m=3;
    end
    dQ(j)=lam(m)*A/dx(m)*(T(j-1)-
2*T(j)+T(j+1))+Dv(T(j),C(j),m)*por(m)*A/dx(m)*(hfg+...
        cpv/2*(T(j+1)+T(j)))*(C(j+1)-C(j))-
Dv(T(j),C(j),m)*por(m)*A/dx(m)*(hfg+cpv/2* ...
        (T(j)+T(j-1)))*(C(j+1)-C(j));
    dC(j)=Dv(T(j),C(j),m)/dx(m)^2*(C(j-1)-
2*C(j)+C(j+1))+rhob(m)/por(m)*(k(MC(j)-MCe(C(j),T(j),m),m)*...
        (MC(j)-MCe(C(j),T(j),m))-B(MC(j)-MCe(C(j),T(j),m),m));
end

for j=2:J+K+L+1
    if j<=J+1
        m=1;
    elseif j<=J+K+1
        m=2;
    else
        m=3;
    end

    dMC(j)=-k(MC(j)-MCe(C(j),T(j),m),m)*(MC(j)-
MCe(C(j),T(j),m))+B(MC(j)-MCe(C(j),T(j),m),m);
end

% For node J+1 or J+K+1 (At the bottom of material 1 and 2);
dQ(J+1)=dQ(J+K+1)

for j=[J+1,J+K+1]
    if j<=J+1
```

```
        m=1;
    else
        m=2;
    end
    dQ(j)=lam(m)*A/dx(m)*(T(j-1)-T(j)) ...

+(2*por(m)*por(m+1)*Dv(T(j),C(j),m)*Dv(T(j+1),C(j+1),(m+1))*A*(C(j+1)-
C(j))*(hfg+cpv*(T(j+1)+T(j))/2))...
/(por(m+1)*Dv(T(j+1),C(j+1),(m+1))*dx(m)+por(m)*Dv(T(j),C(j),m)*dx(m+1
)..
+2*Rmtmm(m)*por(m)*por(m+1)*Dv(T(j),C(j),m)*Dv(T(j+1),C(j+1),(m+1)))..
.
        -2*lam(m)*lam(m+1)*A*(T(j)-
T(j+1))/(lam(m+1)*dx(m)+lam(m)*dx(m+1)+ 2*lam(m)*lam(m+1)*Rmm(m))...
        -Dv(T(j),C(j),m)*por(m)*A/dx(m)*(hfg+cpv/2*(T(j)+T(j-
1)))*(C(j)-C(j-1));

    dC(j)=2*por(m+1)*Dv(T(j),C(j),m)*Dv(T(j+1),C(j+1),(m+1))*(C(j+1)-
C(j))/(dx(m)*(por(m+1)*Dv(T(j+1),C(j+1),(m+1))*dx(m)+...

por(m)*Dv(T(j),C(j),m)*dx(m+1)+2*Rmtmm(m)*por(m)*por(m+1)*Dv(T(j),C(j)
,m)*Dv(T(j+1),C(j+1),(m+1))))+rhob(m)/...
        por(m)*(k(MC(j)-MCe(C(j),T(j),m),m)*(MC(j)-MCe(C(j),T(j),m))-
B(MC(j)-MCe(C(j),T(j),m),m))-Dv(T(j),C(j),m)/dx(m)^2*(C(j)-C(j-1));
end

% For nodes J+2 or J+K+2 (Within the soil under the bed)

for j=[J+2,J+K+2]
    if j<=J+K+1
        m=2;
    else
        m=3;
    end  %check to see what the m and m+1 terms should be (m and m-1
but which way round?)
    dQ(j)=2*lam(m-1)*lam(m)*A*(T(j-1)-T(j))/(lam(m)*dx(m-1)+lam(m-
1)*dx(m)+2*lam(m-1)*lam(m)*Rmm(m-1))...
        +Dv(T(j),C(j),m)*por(m)*A*(C(j+1)-
C(j))/dx(m)*(hfg+cpv*(T(j+1)+T(j))/2)...
        -lam(m)*A*(T(j)-T(j+1))/dx(m)...
        -2*por(m-1)*por(m)*Dv(T(j-1),C(j-1),(m-
1))*Dv(T(j),C(j),m)*A*(C(j)-C(j-1))*(hfg+cpv*(T(j)+T(j-1))/2)...
        /(por(m)*Dv(T(j),C(j),m)*dx(m-1)+por(m-1)*Dv(T(j-1),C(j-1),(m-
1))*dx(m)...
        +2*Rmtmm(m-1)*por(m-1)*por(m)*Dv(T(j-1),C(j-1),(m-
1))*Dv(T(j),C(j),m));
    dC(j)=Dv(T(j),C(j),m)*(C(j+1)-
C(j))/dx(m)^2+rhob(m)/por(m)*(k(MC(j)-MCe(C(j),T(j),m),m)*(MC(j)-...
        MCe(C(j),T(j),m))-B(MC(j)-MCe(C(j),T(j),m),m))...
        -2*por(m-1)*Dv(T(j-1),C(j-1),(m-1))*Dv(T(j),C(j),m)*(C(j)-C(j-
1))/...
        (dx(m)*(por(m-1)*Dv(T(j-1),C(j-1),(m-
1))*dx(m)+por(m)*Dv(T(j),C(j),m)*dx(m-1)...
        +2*Rmtmm(m-1)*por(m-1)*por(m)*Dv(T(j-1),C(j-1),(m-
1))*Dv(T(j),C(j),m)));
end

m=3;

%5th kind of boundary condition at bottom of layer 3
```

```
%dQ(J+K+L+1)=lam(m)*A*(T(J+K+L)-T(J+K+L+1))/dx(m)-
Dv(T(J+K+L+1),C(J+K+L+1),m)*por(m)*A*...
%    (C(J+K+L+1)-C(J+K+L))*(hfg+cpv*(T(J+K+L+1)+T(J+K+L))/2)/dx(m);
%1st kind of boundary condition at bottom of layer 3

dQ(J+K+L+1)=eps;
dC(J+K+L+1)=rhob(m)/por(m)*(k(MC(J+K+L+1)-
MCe(C(J+K+L+1),T(J+K+L+1),m),m)*(MC(J+K+L+1)-MCe(C(J+K+L+1),...
    T(J+K+L+1),m))-B(MC(J+K+L+1)-MCe(C(J+K+L+1),T(J+K+L+1),m),m))-
Dv(T(J+K+L+1),C(J+K+L+1),m)*(C(J+K+L+1)-C(J+K+L))/dx(m)^2;

dHrad=+S2*betp*stef*a*A*d/2*((Tcov+273.15)^4-(T(1)+273.15)^4) ...
    +S1*(1-S2)*betp*stef*a*A*d/2*((Tsh+273.15)^4-(T(1)+273.15)^4) ...
    -(1-S1)*(1-S2)*emisp*stef*a*A*d/2*((T(1)+273.15)^4-
(Tsky+273.15)^4) ....
    -S1*(1-S2)*emisp*stef*a*A*d/2*((T(1)+273.15)^4-(Ta(t)+273.15)^4);
dHconv=-(1-S2)*h*a*A*d/2*T(1)+(1-S2)*h*a*A*d/2*Ta(t);% convection
involves convective heat transfer coef
dHcond=+S2*A*Utarpp*(Tcov-T(1));
dHevap=-(1-S2)*ky*A*(hfg+cpv/2*(T(1)+Ta(t)))*(C(1)-Ca(t)); %
evaporation involves convective mass transf coef
dHsol=+(1-S1)*(1-S2)*betp*a*A*d/2*I(t)+S1*(1-S2)*betp*a*A*d/2*Ish(t);

m=1;
dHcon2mat2=-2*lam(m)*lam(m+1)*A*(T(j)-
T(j+1))/(lam(m+1)*dx(m)+lam(m)*dx(m+1)+ 2*lam(m)*lam(m+1)*Rmm(m));
dHdiffrommat2=(2*por(m)*por(m+1)*Dv(T(j),C(j),m)*Dv(T(j+1),C(j+1),(m+1
))*A*(C(j+1)- C(j))*(hfg+cpv*(T(j+1)+T(j))/2))...

/(por(m+1)*Dv(T(j+1),C(j+1),(m+1))*dx(m)+por(m)*Dv(T(j),C(j),m)*dx(m+1
)...

+2*Rmtmm(m)*por(m)*por(m+1)*Dv(T(j),C(j),m)*Dv(T(j+1),C(j+1),(m+1)));
dMbot=2*por(m+1)*Dv(T(j),C(j),m)*Dv(T(j+1),C(j+1),(m+1))*(C(j+1)-
C(j))/(dx(m)*(por(m+1)*Dv(T(j+1),C(j+1),(m+1))*dx(m)+...

por(m)*Dv(T(j),C(j),m)*dx(m+1)+2*Rmtmm(m)*por(m)*por(m+1)*Dv(T(j),C(j)
,m)*Dv(T(j+1),C(j+1),(m+1))));
dMtop=-(1-S2)*2*ky/(por(m)*dx(m))*(C(1)-Ca(t));

rates=[dQ;dC;dMC;dHrad;dHconv;dHcond;dHevap;dHsol;dHcon2mat2;dHdiffrom
mat2;dMbot;dMtop];
t
```

A4.1.2 The function file for water activity of rice kernel (File name: Aw.m)

```
function awout=aw(C,T)

R=8.3144;

% Calculate new values for dependent variables

awout=C.*R.*(T+273.15)./(18e-3*Psat(T));

i=find(awout>1);

awout(i)=1; % set the aw not to be bigger than 1.
```

A4.1.3 The function file for water concentration (Ca.m)

```
function Caout=Ca(t)

Caout=RH2C(RHa(t),Ta(t));
```

A4.1.4 The function file for covering and shading times (FindTshAndTcov.m)

```
function out=FindTshAndTcov(d,t,T)

global S1 S2 bettarp emistarp emisp stef h Tsky Utarpp Fe
Tsh=d(1);
Tcov=d(2);

out(1)=0;
if S1==1
    out(1)=(2*h*Ta(t)+bettarp*I(t)-emistarp*stef*(((Tsh+273.15)^4-
(Tsky+273.15)^4)+...
        S2*0.63*emistarp*((Tsh+273.15)^4-(Tcov+273.15)^4)+(1-
S2)*0.63*emisp*((Tsh+273.15)^4-(T(1)+...
        273.15)^4)))/(2*h)-Tsh;
end

out(2)=0;
if S2==1
    out(2)=(h*Ta(t)+Utarpp*T(1)+bettarp*((1-
S1)*I(t)+S1*Ish(t))+emistarp*stef*...
        (S1*0.63*emistarp*((Tsh+273.15)^4-(Tcov+273.15)^4)-(1-
S1)*((Tcov+273.15)^4-(Tsky+...
        273.15)^4))-Fe*stef*((Tcov+273.15)^4-
(T(1)+273.15)^4))/(h+Utarpp)-Tcov;
end
```

A4.1.5 The function file for solar intensity monitored in experiment (I.m)

```
function Iout=I(t)

% If parabolic equation is used

global aI bI cI

Iout=aI*(t+8*3600).^2+bI*(t+8*3600)+cI;

n=find(Iout<0);
Iout(n)=0;

% If real data is used

%global Idata; % Call in Idata

%t=t+8*3600;

%Iout=interp1(Idata(:,1),Idata(:,2),t);% Throw in Idata in Excel.
% All rows in column 1 is t and all rows in column 2 is I
```

```
%n=find(Iout<0);
%Iout(n)=0;
```

A4.1.6 The function file for solar intensity under shade (Ish.m)

```
function ish=Ish(t)

ish=0.05*I(t);
```

A4.1.7 The function file for equilibrium moisture content of rice kernel (MCe.m)

```
function MCeout=MCe(C,T,m)

global C1 C2 C3 C4

% Define global variables

if nargin==1
    T=25;
    m=1;
end

% Calculate new values for dependent variables

AW=aw(C,T);

if m==1
    MCeout=C1(m)-C2(m)*log(-(T+C3(m))*log(AW-C4(m)));
else
    MCeout=0;
end;
```

A4.1.8 The function file for saturated vapour pressure in the air (Psat.m)

```
function Psatout=Psat(T)

% Calculate new values for dependent variables

Psatout=exp(23.4795-(3990.56./(T+233.833)));
```

A4.1.9 The function file to convert RH to water concentration (RH2C.m)

```
function Cout=RH2C(RH,T)

R=8.3144;

Cout=RH/R/(T+273.15).*18e-3.*Psat(T);
```

A4.1.10 The function file for ambient air RH monitored in experiment

```
function RHaout=RHa(t)

global aRHa bRHa cRHa dRHa
RHaout=aRHa*(t+8*3600).^3+bRHa*(t+8*3600).^2+cRHa*(t+8*3600)+dRHa;
n=find(RHaout<0);
RHaout(n)=0;
n=find(RHaout>100);
RHaout(n)=99.99; % Not to allow RH > or = 100 as it give imaginary
value
RHaout=RHaout/100;
```

A4.1.11 The function file for equilibrium moisture content of rice kernel (RHe.m)

```
function RHeout=RHe(MC,T,m)

global C1 C2 C3 C4

% Define global variables
if nargin==1
    T=25;
    m=1;
end

RHeout=C4(m)+exp(-exp(-(MC-C1(m))/C2(m))/(T+C3(m)));
```

A4.1.12 The function file for ambient temperature monitored in experiment (Ta.m)

```
function Taout=Ta(t)

global aTa bTa cTa dTa

Taout=aTa*(t+8*3600)^3+bTa*(t+8*3600).^2+cTa*(t+8*3600)+dTa;
```

A4.1.13 The script file to set all the globals

```
%Setglobals

global a;   % Specific surface area of the exposed materials in a bulk
(m2/m3)
global A;   % Flat surface area of the drying bed (m2)
global betp; % Absorptivity of solar radiation of the paddy (decimal)
global bettarp; % Absorptivity of solar radiation of the tarpaulin
(decimal)
global cp; % Specific heat of the materials (J/kg.oC)
global cpa; % Specific heat of air (J/kg.oC)
global cpv; % Specific heat of water vapor (J/kg.oC)
global cpw; % Specific heat of water (J/kg.oC)
global d;   % Thickness of the paddy kernel (m)
global dx;  % Spatial step in the materials (m)
global emisp;    % Emissivity of the paddy (decimal)
global emistarp;    % Emissivity of the tarpaulin (decimal)
```

```
global Fe; % Emissivity correction
global h;   % Convective heat transfer coefficient (W/m2.oC)
global hfg;  % Latent heat of evaporation (J/kg)
global J;   % Number of nodes in the rice bed (decimal)
global K;   % Number of nodes in the husk or polystyrene (decimal)
global ky;  % Convective moisture transfer coefficient (m/s)
global L;   % Number of nodes in the soil (decimal)
global por; % Porosivity of air in the materials' bulk (decimal)
global rhoa;    % Density of air (kg/m3)
global rho;   % True density of the materials (kg/m3)
global rhob;   % Bulk density of the materials (kg/m3)
global stef;    % Stefan-Boltzmann constant (5.669 e-8 W/m2.K4)
global Tgr;  % Temperature of the ground (oC)
global Ti;   % Initial temperature of system (C)
global Utarpp;
global Rmm;
global Rmtmm;
global Tsky;
global Tsh Tcov;
global tShadeOn;
global tShadeOff;
global tCoverOn;
global tCoverOff;
global lam;
global aI bI cI;;
%global Idata;
%global RHadata;
%global Tadata;
global aRHa bRHa cRHa dRHa;
global aTa bTa cTa dTa;
global C1 C2 C3 C4
global n
```

A4.2 The m files that needed to adjusted

A4.2.1 The main script file (Ricebed.m)

```
% Script file for sun drying of rice in bed

tic;

% Define global variables

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Estimating (initializing) the values for Tsh and Tcov
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Tsh=30;
Tcov=30; %both are sensible values for the solver routine. Just in
case they are needed.
A=1;
dx=zeros(1,3);
dx(1)=L1/(J+0.5);
dx(2)=L2/K;
dx(3)=L3/L;

por=1-(rhob./rho)+eps;
stef=5.6696e-8;
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Get initial conditions
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

To1=To(1); %initial temp of layer 1
To2=ones(K,1)*To(2);%inital temp of layer 2
To3=ones(L,1)*To(3); %inital temp of layer 3

Co1=Co(1); %inital water concentration of layer 1
Co2=ones(K,1)*Co(2);%inital water concentration of layer 2
Co3=ones(L,1)*Co(3);%inital water concentration of layer 3

MCo1=MCo(1); %inital moisture of layer 1
MCo2=ones(K,1)*MCo(2);%inital moisture of layer 2
MCo3=ones(L,1)*MCo(3);%inital moisture of layer 3

Balanceso=zeros(9,1); %Initial conditions of the balance dependent
variables at start of whole simulation

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Sets up arrays for C,MC and Q with values at t=0
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

C=ones(1,J+K+L+1)*Co(1);
MC=ones(1,J+K+L+1)*MCo(1);
T=ones(1,J+K+L+1)*To(1);
Balances=zeros(1,9); %Put the initial condition into the array
"Balances" which stores all the components of the heat balances

C(1,J+2:J+K+L+1)=Co(2);
MC(1,J+2:J+K+L+1)=MCo(2);
T(1,J+2:J+K+L+1)=To(2);

C(1,J+2:J+K+L+1)=Co(3);
MC(1,J+K+2:J+K+L+1)=MCo(3);
T(1,J+K+2:J+K+L+1)=To(3);

Q=zeros(1,J+K+L+1);
m=1;
Q(1,1)=T(1,1)*((1-por(m))*rho(m)*A*dx(m)/2*cp(m)+MC(1,1)*(1-
por(m))*rho(m)*A*dx(m)/2*cpw+...

por(m)*rhoa*A*dx(m)/2*cpa+C(1,1)*por(m)*A*dx(m)/2*cpv)+C(1,1)*por(m)*A
*dx(m)/2*hfg;
for j=2:J+K+L+1
    if j<=J+1
        m=1;
    elseif j<=J+K+1
        m=2;
    else
        m=3;
    end
    Q(1,j)=T(1,j)*((1-por(m))*rho(m)*A*dx(m)*cp(m)+MC(1,j)*(1-
por(m))*rho(m)*A*dx(m)*cpw+ ...

por(m)*rhoa*A*dx(m)*cpa+C(1,j)*por(m)*A*dx(m)*cpv)+C(1,j)*por(m)*A*dx(
m)*hfg;
end
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

t=tstir(1);
while t(end)<tstir(end)

% beginning of the solver loop

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% set initial values at the begining of each stir
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

Ci=ones(J+K+L+1,1)*Co1;
MCi=ones(J+K+L+1,1)*MCo1;
Ti=ones(J+K+L+1,1)*To1;

Ci(J+2:J+K+1)=Co2;
MCi(J+2:J+K+1)=MCo2;
Ti(J+2:J+K+1)=To2;

Ci(J+K+2:J+K+L+1)=Co3;
MCi(J+K+2:J+K+L+1)=MCo3;
Ti(J+K+2:J+K+L+1)=To3;

Balancesi=Balanceso; %Sets initial condition of this current stir as
either starting
% value or the value at end of last stir interval as listen in
Ricebedfun
% rows 197 to 213

Qi=zeros(J+K+L+1,1);
m=1;
Qi(1)=Ti(1)*((1-por(m))*rho(m)*A*dx(m)/2*cp(m)+MCi(1)*(1-
por(m))*rho(m)*A*dx(m)/2*cpw+...

por(m)*rhoa*A*dx(m)/2*cpa+Ci(1)*por(m)*A*dx(m)/2*cpv)+Ci(1)*por(m)*A*d
x(m)/2*hfg;

for j=2:J+K+L+1
    if j<=J+1
        m=1;
   elseif j<=J+K+1
        m=2;
    else
        m=3;
    end
    Qi(j)=Ti(j)*((1-por(m))*rho(m)*A*dx(m)*cp(m)+MCi(j)*(1-
por(m))*rho(m)*A*dx(m)*cpw+ ...

por(m)*rhoa*A*dx(m)*cpa+Ci(j)*por(m)*A*dx(m)*cpv)+Ci(j)*por(m)*A*dx(m)
*hfg;
end

Dvi=[Qi ; Ci ; MCi ;Balancesi];

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Solve all the equations
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

options=odeset('OutputFcn',@odeplot,'RelTol',1e-3);
```

```
nextstir=find(tstir>t(end));
 [tt,Dvs]=ode23s('ricebedfun',
[t(end):tstep:tstir(nextstir(1))],Dvi,options);

% Dvs are dependent variables predicted
timer=toc/60

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Data manipulation - adding the new results on to the end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

t=[t; tt];
Q=[Q; Dvs(:,1:(J+K+L+1))];
C=[C; Dvs(:,(J+K+L+2):(J+K+L+1+J+K+L+1))];%C is dependent variable
with its values in all
MC=[MC; Dvs(:,(J+K+L+1+J+K+L+2):(J+K+L+1+J+K+L+1+J+K+L+1))];
Balances=[Balances; Dvs(:,3*(J+K+L+1)+1:3*(J+K+L+1)+9)];
clear T;

% Temperature are in this case CVs

m=1;
T(:,1)=(2*Q(:,1)/A/dx(m)-C(:,1)*por(m)*hfg)./((1-
por(m))*rho(m)*(cp(m)+MC(:,1)*cpw)+por(m)*(rhoa*cpa+C(:,1)*cpv));

for j=2:J+K+L+1
    if j<=J+1
        m=1;
    elseif j<=J+K+1
        m=2;
    else
        m=3;
    end
    T(:,j)=(Q(:,j)-C(:,j)*por(m)*A*dx(m)*hfg)./((1-
por(m))*rho(m)*A*dx(m)*cp(m)+MC(:,j)*(1-por(m))*rho(m)*A*dx(m)*cpw+
...
        por(m)*rhoa*A*dx(m)*cpa+C(:,j)*por(m)*A*dx(m)*cpv);
    %T(:,J+K+L+1)=Tgrs;
end

nn=size(T,1);% Number of rows for T in matrix T
To1=(sum(T(nn,2:J+1))+T(nn,1)/2)/(J+0.5);% Initial T = weighted
average of all Ts at row nn
MCo1=(sum(MC(nn,2:J+1))+MC(nn,1)/2)/(J+0.5);
Co1=(sum(C(nn,2:J+1))+C(nn,1)/2)/(J+0.5);
To2=T(end,J+2:J+K+1);
MCo2=MC(end,J+2:J+K+1);
Co2=C(end,J+2:J+K+1);
To3=T(end,J+K+2:J+K+L+1);
MCo3=MC(end,J+K+2:J+K+L+1);
Co3=C(end,J+K+2:J+K+L+1);
Balanceso=Dvs(end,3*(J+K+L+1)+1:3*(J+K+L+1)+9)';

RH=zeros(size(T));
for j=1:J+K+L+1
RH(:,j)=aw(C(:,j),T(:,j));
end
```

```
end;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%end of while loop
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

gd=figure;
plot(t/3600,T);
hold on;
title('Change in temperature');
xlabel('time [hr]');
ylabel('Temperature [oC]');
grid on
legend
('T(1)','T(2)','T(3)','T(4)','T(5)','T(6)','T(7)','T(8)','T(9)','T(10)
','T(11)','T(12)','T(13)','T(14)','T(15)','T(16)');

ge=figure;
plot(t/3600,C);
hold on;
title('Change in concentration');
xlabel('time [hr]');
ylabel('Concentration [kg/m3]');
legend ('C(1)','C(2)','C(3)','C(4)','C(5)','C(6)');

gf=figure;
plot(t/3600,MC);
hold on;
title('Change in moisture content');
xlabel('time [hr]');
ylabel('Moisture content [%]');
grid on
legend ('MC(1)','MC(2)','MC(3)','MC(4)','MC(5)','MC(6)');

figure
plot(t/3600,RH);
hold on;
title('Change in water activity');
xlabel('time [hr]');
ylabel('Water activity');
grid on
legend ('RH(1)','RH(2)','RH(3)','RH(4)','RH(5)','RH(6)');

%bit of code to calculate Shade and Cover temperature at each time

global S1 S2
for i=1:size(t,1)
    if t(i)>=tShadeOn & t(i)<=tShadeOff
        S1=1;
    else
        S1=0;
    end

    if t(i)>=tCoverOn & t(i)<=tCoverOff
        S2=1;
    else
        S2=0;
    end

options = optimset('Display','off'); % Turn off Display
```

```
TshAndTcov = fsolve(@(u) FindTshAndTcov(u,t(i),T(i,1)), [Tsh,Tcov],
options);
Tsh(i)=TshAndTcov(1);
Tcov(i)=TshAndTcov(2);

end
Tsh=Tsh';
Tcov=Tcov';

SensFract=sum(Balances(:,1:7),2)./Balances(:,5); % To compare heat
accummulated in bed with the heat input by the sun
EvapFract=100*Balances(:,4)./Balances(:,5); % To compare heat
eveporated with the heat input by the sun
RadFract=100*Balances(:,1)./Balances(:,5); % To compare heat radiated
in by tarpaulin and out by the bed surface with the same heat input
ConvFract=100*Balances(:,2)./Balances(:,5);
CondFract=100*Balances(:,3)./Balances(:,5);
DiffFract=100*Balances(:,7)./Balances(:,5);
ConBotFract=100*Balances(:,6)./Balances(:,5);
MassFract=100*Balances(:,8)./Balances(:,9);

Comparisons=[RadFract,ConvFract,CondFract,EvapFract,ConBotFract,DiffFr
act,SensFract,MassFract];
figure
plot(t,Comparisons);

outputdata=[t Tsh Tcov T MC RH Comparisons]; % To list all the data in
text file. Comparisons are the calculated data listed in row 248.

% To save the simulation results in a text file

save 'Treat 091.txt' outputdata -ascii
```

A4.2.2 The function file for the second coefficient of the drying rate (B.m)

```
function Bout=B(deltaMC,m)

% For CAR 11 variety

if deltaMC<0.222
    Bout=0;
else Bout=0.00076619;
end
% For Pka Knhey variety

%if deltaMC<0.218
    %Bout=0;
%else Bout=0.00081067;
%end

if m>1
    Bout=0;
end
```

A4.2.3 Function file for moisture diffusivity in different materials (Dv.m)

```
function Dvout=Dv(T,C,m)

global por;
global rho;
global n;
global rhoa;

kt=((1-
por(m))*rho(m)*n(m)*522*101300*rhoa)/(por(m)*Psat(T)*(18*rhoa+29*C));

% Diffusivity in the open air, Da

%Da=1.7255e-7*(T+273.15)-2.552e-5;

% Diffusivity in the rice bed, Dp

% Diffusivity in other porous material, Dv

%Dp=1.7255e-7*(T+273.15)-2.552e-5;
Dp=1.5*(1.7255e-7*(T+273.15)-2.552e-5);
%Dp=2*(1.7255e-7*(T+273.15)-2.552e-5);

if m==1
    Dvout=Dp;

else
    Dvout=Dp/(1+kt);

end

if Dvout==0
    Dvout=eps;
end
```

A4.2.4 The function file for the first coefficient of the drying rate (k.m)

```
function kout=k(deltaMC,m)

% For CAR 11 variety

if deltaMC<0.22
    kout=0.00012148;
else kout=0.00356761;
end
% For Pka Knhey variety

%if deltaMC<0.218
    %kout=0.00013779;
%else kout=0.003385975;
%end

if m>1
    kout=0;
end
```

A4.2.5 The script file for material properties (Matprop.m)

```
%%% Material number %%%

%1 CAR11 Rice
%2 Pka Knhey Rice
%3 Soil
%4 Husk
%5 Polystyrene
%6 Mat

%MPcp=[1040, 1040, 1840, 1683, 1210, 1206]; % lowest SI
MPcp=[1115, 1115, 1870, 1870, 1210, 1340]; % best SI
%MPcp=[1190, 1190, 1900, 2057, 1210, 1474]; % highest SI

%MPrhob=[522, 555, 1750, 110, 22, 621];
MPrhob=[576, 600, 1800, 120, 22, 690];
%MPrhob=[630, 645, 1850, 130, 22, 759];

%MPrho=[1050, 1050, 3000,670 , 21, 855];
MPrho=[1145, 1135, 3250, 705, 22, 950];
%MPrho=[1240, 1220, 3500,740 , 23, 1045];

%MPlam=[0.08, 0.08, 0.47, 0.06, 0.027, 0.05];
MPlam=[0.125, 0.125, 0.52, 0.07, 0.0315, 0.06];
%MPlam=[0.17, 0.17, 0.57, 0.08, 0.036, 0.07];


MPn=[1, 1, 0.413, 0.1404, Inf, 0.1404];

MPC1=[0.308782384984721,0.308782384984721,0,0.308782384984721,0,0];
MPC2=[0.0513373025556444,0.0513373025556444,0,0.0513373025556444,0,0];
MPC3=[35.5859704839562,35.5859704839562,0,35.5859704839562,0,0];
MPC4=[0.00631436,0.00631436,0,0.00631436,0,0];
```

A4.2.6 The script file for particular treatment (SUexp--)

```
%SUexp1
Setglobals

%set material layers and define properties
Matprop
layers=[2 3 3]; %1 CAR11 Rice %2 Pka Knhey Rice %3 Soil %4 Husk %5
Polystyrene %6 Mat
cp=MPcp(layers);
rhob=MPrhob(layers);
rho=MPrho(layers);
lam=MPlam(layers);
n=MPn(layers);
%n(2:3)=Inf; %reset n in layers 2 and 3 to Inf to effectively
illiminate diffusion in soil for checking purposes
% REMOVE THE ABOVE n AFTER COMPARISON WITH OLD MODEL

C1=MPC1(layers);
C2=MPC2(layers);
C3=MPC3(layers);
C4=MPC4(layers);
```

```
 % layer 1 (grain bed) depth
%L1=0.018;
L1=0.02; % for 2-cm bed
%L1=0.022;

%L1=0.028;
%L1=0.03; % for 3-cm bed
%L1=0.032;

% layer 2 depth

L2=0.1; % for soil

%L2=0.038;
%L2=0.04; % for polystyrene
%L2=0.042;

%L2=0.0015;
%L2=0.002; % for mat
%L2=0.0025;

%L2=0.065;
%L2=0.07; % for husk
%L2=0.075;

% layer 3 depth
L3=0.1; % only for soil
clear MPcp MPrhob MPrho MPlam MPn MPC1 MPC2 MPC3 MPC4;
%---------------------------------------------

%set up shade and cover variables

tShadeOn=1e30; % %Set to very big number if not applied
tShadeOff=1e40;
tCoverOn=1e30;
tCoverOff=1e40;

%tShadeOn=10800;%Set to the real numbers when applied
%tShadeOff=21600;
%tCoverOn=10800;
%tCoverOff=21600;
%---------------------------------------------

%set up start time and stirring

tstir=[1800,8*3600]; % When no stirring at all

%tstir=[1800,3600:3600:8*3600]; % When stirring every an hour

%tstir=[1800,3600,7200,10800,25200,28800]; % When stirring not applied
% when the bed was under cover and shade

tstep=300;
%---------------------------------------------

%Set up nodes
J=24;
%K=24;
```

```
%L=24;
K=12;
L=12;
%---------------------------------------------

%ambient conditions
aI=-0.0000025811;
bI=0.2152574928;
cI=-3770.3858997473;

% When raw data is used instead of equation
%Idata=xlsread('Idata.xls'); %reads in table of Idata from spreadsheet
Idata.xls

aRHa=0.0000000000095;
bRHa=-0.0000012377207;
cRHa=0.0520899826407;
dRHa=-654.886360303482;

%RHadata=xlsread('RHadata.xls'); %reads in table of RHadata from
spreadsheet RHadata.xls

aTa=-0.0000000000033;
bTa=0.0000004360977;
cTa=-0.0184745269721;
dTa=283.051091547729;

%Tadata=xlsread('Tadata.xls'); %reads in table of Tadata from
spreadsheet Tadata.xls
%---------------------------------------------

%Initial conditions
MCo=[0.27,0,0]; %MCo=0.277; %MCo=0.289;

Tgrs=25;

To=[26,Tgrs,Tgrs];

RHo1=RHe(MCo(1),To(1),1);
Co=[RH2C(RHo1,To(1)),RH2C(RHa(0),To(2)),RH2C(RHa(0),To(3))];
%---------------------------------------------
%General properties
emisp=0.85;  %emisp=0.8; %emisp=0.9;
betp=0.85; %betp=0.8; %betp1=0.9;
emistarp=0.97; %emistarp=0.95; %emistarp=0.99;
bettarp=0.97; %bettarp=0.95; %bettarp=0.99;
Fe=1/((1/emisp+1/emistarp)-1);
Tsky=12.6; % Tsky=5.7; % Tsky=20;

hfg=2424500; %hfg=2260000; %hfg=2589000;
rhoa=1.12;
cpa=1007;
cpv=1875;
cpw=4183;

h=16.9; %h=12.5; %h=15.5;

ky=h/(cpa*rhoa);%ky=h/(1.5*cpa*rhoa);%ky=h/(0.5*cpa*rhoa);
```

```
%d=0.00212;%d=0.00196;%d=0.00228; % CAR11

d=0.00196;%d=0.00178; %d=0.00214;% Pka Knhey

a=1000;%a=800;%a=1200;% CAR11

%a=1100;%a=860;%a=1340;% Pka Knhey

lamtarp=0.42; %lamtarp=0.37; %lamtarp=0.47;

Ltarp=0.6e-3; %Ltarp=0.5e-3; %Ltarp=0.7e-3;

lama=0.0263;

lammat=0.06;

La=1e-3; %La=0.8e-3; %La=1.2e-3;

% Resistance to heat flow between materials 1 & 2 and 2 & 3

Utarpp=lamtarp*lama/(lama*Ltarp+lamtarp*La);

Rmm=[1/Utarpp,0]; % when tarpaulin is used
%Rmm=[La/lama,0]; % when net is used
%Rmm=[(lama*L2+lammat*La)/(lammat*lama),0]; %When mat is used

% Resistance to mass flow between the exposed materials

Rmtmm=[Inf,0]; % when tarpaulin is used (resistance is so big, no
moisture transfer)
%Rmtmm=[0,0]; % When net is used
Rmtmm=[0,0]; % When mat is used, The mat was wet

% Run rice bed file

Ricebed
```

Appendix A5

NUMERICAL AND ANALYTICAL ERROR CHECKING

A5.1 Numerical error checking

To check for numerical errors in the numerical solution, the numbers of space steps within the grain bed (*J*) and materials 2 and 3 (*K* and *L*), time steps, and thickness of the soil affected by the drying were considered. Differences in temperature of the grain at the bottom and middle of the drying bed with the first and third kinds of boundary conditions, temperature of the grain at the surface of the bed under unsteady state conditions, moisture concentration in the air at the bottom of the drying bed with first and third kind of boundary conditions and moisture content (MC) of the grain within the bed were used as the test variables.

The results found at the nodes that were located at 0, 3.3333, 6.6667, 10, 13.3333, 16.6667 and 20 mm from the bed surface are presented. These correspond to nodes 1, 5, 9, 13, 17, 21 and 25 when $J = 24$ and as 1, 6, 11, 16, 21, 26 and 31 when $J = 30$.

A5.1.1 Number of space steps in the grain bed

In this check, the number of space steps in the grain bed was changed from 6 to 12, 18, 24, 30, 36 and 42 in the solutions of the model. As expected, simulation time and the discrepancies between the values of the three predicted variables were found to increase and decrease, respectively, as the number of space steps (*J*) was increased. Therefore, selection of the number was based on the fact that the simulation time was not so long and the discrepancies were not significant.

Table A5.1 shows the maximum discrepancies of the three variables for two adjacent numbers of the space steps that happen to each of the nodes after the drying was started for the unstirred grain of Experiment One/04. The maximum discrepancies in the three variables were 0.05^{o}C, 0.8% and 0.003, respectively, between the *J* values of 24 and 30.

Table A5.1: Maximum discrepancies between the three dependent variables at specific nodes after some time of drying when the number of space step in the bed was changed

J	6 vs 12	12 vs 18	18 vs 24	24 vs 30	30 vs 36	36 vs 42
Temperature	0.56°C after 0.58 h at the surface node	0.18°C after 0.58 h at the surface node	0.09°C after 0.58 h at the surface node	0.05°C after 0.42 h at the surface node	0.03°C after 0.58 h at the surface node	0.02°C after 0.75 h at the surface node
MC	1.5% after 1.75 h at the surface node	1.2% after 1.5 h at the surface node	0.9% after 1.25 h at the surface node	0.8% after 1 h at the surface node	0.7% after 0.83 h at the surface node	0.6% after 0.83 h at the surface node
Water activity	0.016 after 3.17 h at the 11/12 node	0.007 after 3.17 h at the 16/18 node	0.004 after 3.42 h at the 21/24 node	0.003 after 3.42 h at the 26/30 node	0.002 after 2.75 h at the 31/32 node	0.002 after 2.75 h at the 36/42 node

The comparisons of the three variables during drying for these two (24 and 30) space steps are shown in Fig A5.1. The predictions were matched closely with each other.

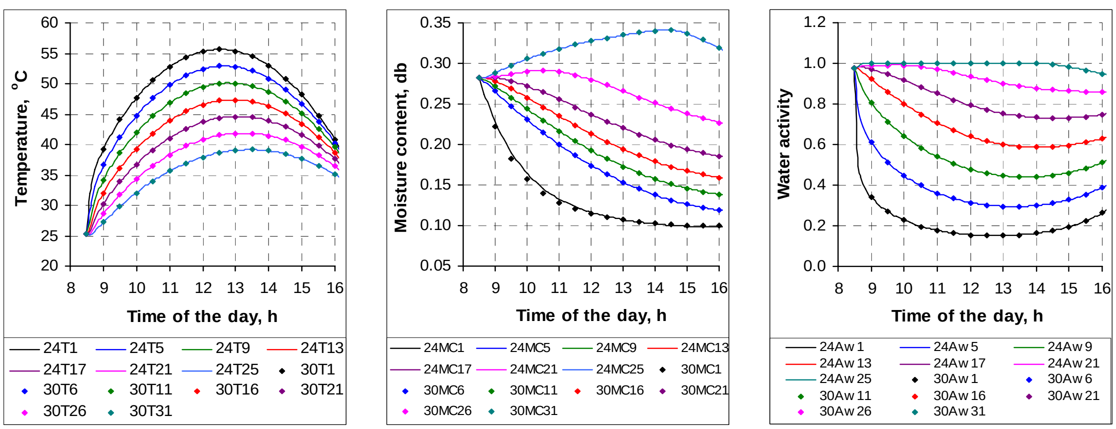


Fig A5.1: Predicted temperature, MC and water activity within the bed for J 24 and 30 for the unstirred grain of Experiment One/04

Notes:

24T1, 24MC1, 24Aw1 denote the temperature, MC and water activity at node 1 for J of 24

30T1, 30MC1, 30Aw1 denote the temperature, MC and water activity at node 1 for J of 30

A5.1.2 Magnitude of time step in the solution

The effects of time step were checked by changing the value of the relative tolerance (Rel Tol) of the Matlab solver from 0.001 to 0.0001 when *J* was 24. The simulation time and discrepancies were found to increase and decrease respectively, as the value of relative tolerance was decreased.

Table A5.2: Maximum discrepancies between the three dependent variables at specific node after some time of drying when the Rel Tol was changed from 0.001 to 0.0001

Variables	*Maximum discrepancy*
Temperature, ^{o}C	0.014 at 5.42 h after the start at the surface node
MC, % db	0.003 at 2.17 h after the start at the surface node
Water activity, dec	0.0004 at 5.75 h after the start at the bottom node

The comparisons of the three predicted variables during drying between the two values of the tolerance are shown in Fig A5.2 and Table A5.2. Differences were small enough that a Rel Tol of 0.001 was deemed adequate for all other model simulations.

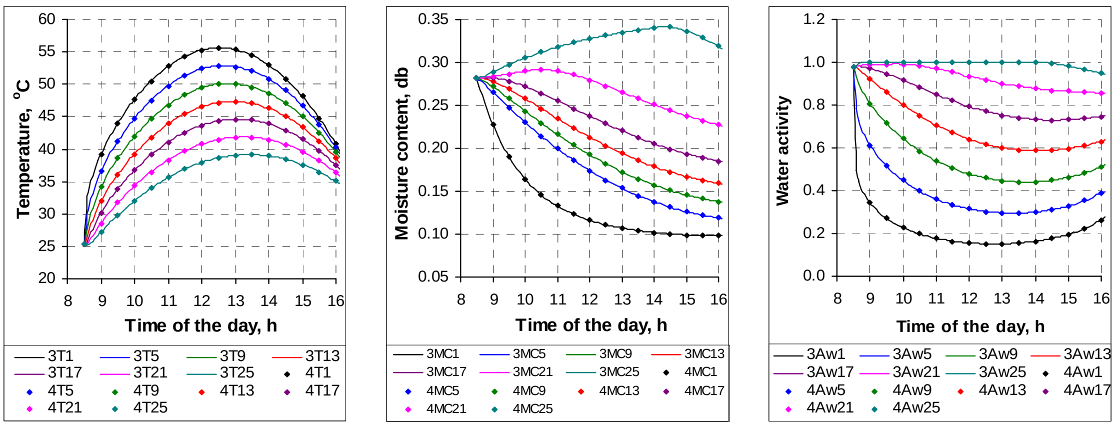


Fig A5.2: Temperature, MC and water activity within the bed for Rel Tol 10^{-3} and 10^{-4}

<u>Notes</u>:
3T1, 3MC1, 3Aw1 denote the temperature, MC and water activity at node one for the tolerance value of 0.001 or 10^{-3}
4T1, 4MC1, 4Aw1 denote the temperature, MC and water activity at node one for the tolerance value of 0.0001 or 10^{-4}

A5.1.3 Depth of the soil affected by the drying

The depth of the soil modelled below the drying bed may affect the predictions. A numerical check was also performed by varying the ratio of rice and soil depths to the rice depth, ($m' = \frac{L_{p+soil}}{L_p}$ with L_p = 2 cm) from 3 to 8.

The ratio needed to be increased to at least seven in order to lower the differences in the predicted variables, especially the temperature to an acceptable level (Fig A5.3). A soil depth of 20 cm (*m'* = 10) was applied for all subsequent predictions.

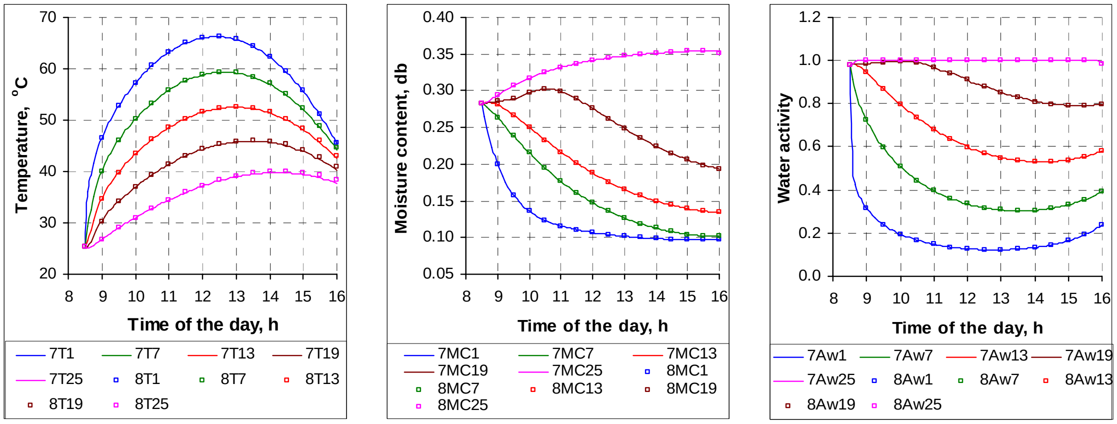


Fig A5.3: Comparison of temperature, MC and water activity within the bed for m' of 7 and 8

Notes:
7T1, 7MC1, 7Aw1 denote the temperature, MC and water activity at node one for m' of 7
8T1, 8MC1, 8Aw1 denote the temperature, MC and water activity at node one for m' of 8

A5.1.4 Number of space steps within the materials below the grain bed

The number of space steps in material below the grain bed was varied from 3 to 24. Fig A5.4 shows that the predicted variables were not significantly different when the number of nodes within each of the materials 2 and 3 was set to 12 or 24. The maximum discrepancies for the temperatures, MCs and water activities were only 0.01C, 0.006% db and 0.003, respectively. For that reason, to reduce the time needed for the numerical solution, the number of nodes in each of the two materials was, therefore, selected as 12.

In summary, it was found that with more than 24 space steps in the grain bed, a relative tolerance of 0.001, a soil depth of 20 cm and 12 space steps in non-grain materials, the predicted temperatures, MC and water activity changed little. The conclusion was that running the solution with 24 space steps in the bed, 0.001 relative tolerance, 20 cm of soil depth and 12 space steps in non-grain materials were sufficient to avoid significant numerical errors.

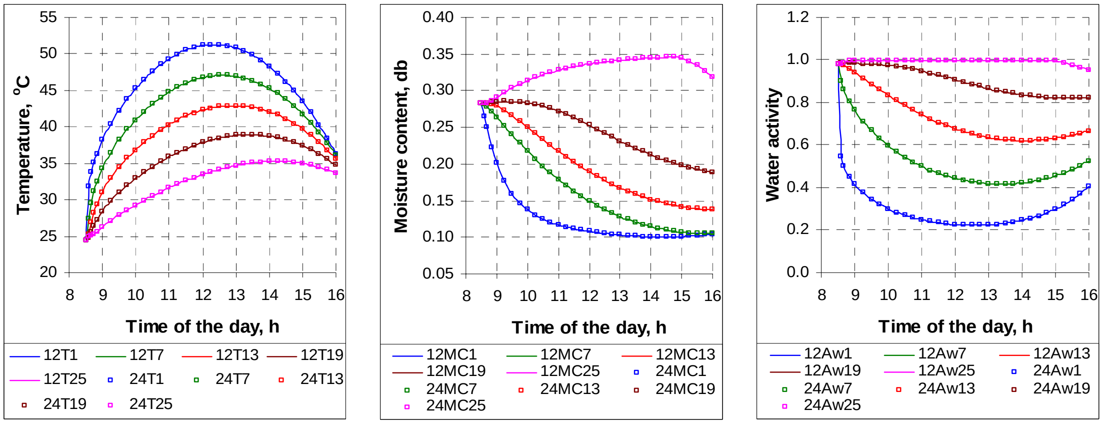


Fig A5.4: Temperature, MC and water activity within the bed for K, L of 12 and 24

<u>Notes:</u>
12T1, 12MC1, 12Aw1 denote the temperature, MC and water activity at node one for K = L = 12
24T1, 24MC1, 24Aw1 denote the temperature, MC and water activity at node one for K = L = 24.

A5.2 Checks against analytical solutions

After numerical error checking confirmed that there were negligible errors in the Matlab numerical solutions, the model was simplified to allow comparison of the results with analytical solutions to demonstrate confidence in the model solution before applying it to the drying process.

A5.2.1 Temperature of the grain at the bottom and at the middle of the drying bed

A. First kind of boundary condition

An analytical solution exists for heat conduction through an infinite slab with the fixed kind of boundary conditions (Carslaw, 1959).

This situation was approximated by

- Setting the grain bed and the soil below to have the same thickness of R' = 2 cm so as to form an infinite slab of combined thickness of $2R'$,

- Turning off the solar radiation (I = 0), emission to the ambient air (ϵ = 0) and moisture diffusion within the slab (D_v = 0),
- Setting component specific heat capacities to be equal ($c_{pa} = c_{pv} = c_{pw}$) and the bulk densities and the thermal properties of the grain and the soil to be the same, and
- Making the temperatures at the boundaries the same as the ambient air and the ground temperature ($T_a = T_{gr} = T_{boundary} = 60^{o}C$) and setting the convective heat transfer was very high (10000 $W/m^2\,^{o}C$).

The temperatures of the grain at the bottom and middle of the bed during the drying obtained from the analytical solution were compared with the ones produced by the numerical solution using the same situations as described above.

On the whole, the temperatures at the bottom and in the middle of the bed obtained from both solutions are indistinguishable (Fig A5.5). The maximum differences for the temperatures observed during a seven and a half hour simulation were 0.07 and $0.1^{o}C$ at the bottom and middle, respectively. The finding indicated that the term formulated to describe the convection mechanism at the slab (or the bed) surfaces and heat conduction within the bed had been correctly implemented in the model.

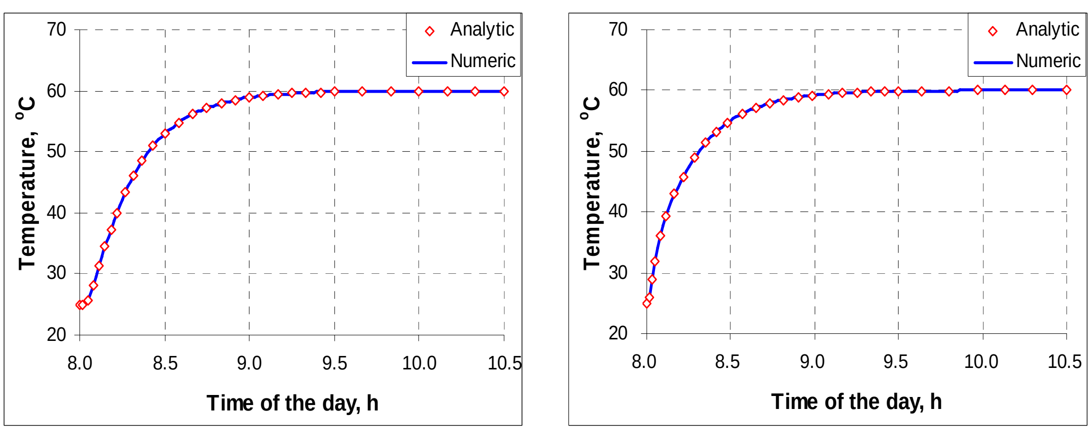


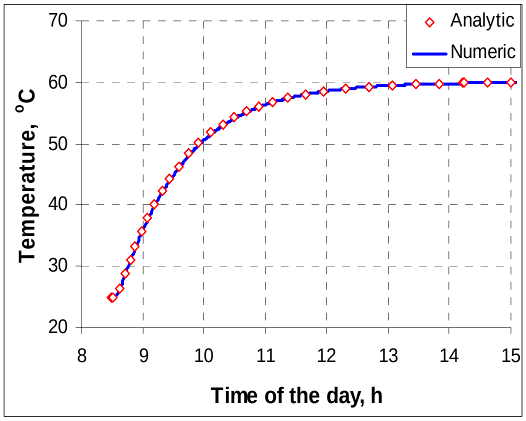
Fig A5.5: Comparison of temperatures at the bottom and in the middle of the bed from analytical and numerical solutions for heat conduction with the first kind of boundary condition

B. Third kind of boundary condition

Another analytical solution exists for heat conduction in an infinite slab with the third kind of boundary condition (Carslaw, 1959). To approximate the situation, the following assumptions were made:

- All the heat that was transferred by convection at the surface of the slab was always the same as the heat that was conducted in the slab to or from the surface.
- In order to avoid rewriting the equations and code describing the heat and mass transfer for the bottom of the slab that was in the soil, only the temperature patterns within the top half of the slab were determined in the two solutions. At the same time, the thermal conductivity of the soil (λ_p) was set to zero.
- The ambient air and the initial grain temperatures were set as constants (T_a = 60 and T_i = 25^{o}C).
- To reduce the difference between the temperatures obtained from the two solutions, the number of space steps was doubled to J = 24 for the numerical solution.
- As the air and the moisture were assumed not to have any effect on the heat transfer in the slab, the specific heats of air (c_{pa}), water vapour (c_{pv}) and water (c_{pw}), the diffusivity of moisture (D_v) as well as the drying constant and convective moisture transfer coefficient were all turned to zero
- To eliminate the heat being lost from the grain to the ambient air, the emissivity was turned to zero.
- As no phase change was assumed to happen in the slab, the latent heat of evaporation (h_{fg}) was also turned to zero.

The temperatures at the bottom and in the middle of the bed obtained from numerical solutions were indistinguishable from the analytical solution (Fig A5.6). The maximum differences in the temperatures of 0.32 and 0.49^{o}C were observed between the two solutions for the bottom and the middle of the bed, respectively. This finding reconfirmed that the terms describing convection and conduction mechanisms at the slab (or bed) surfaces, had been correctly implemented in the model.



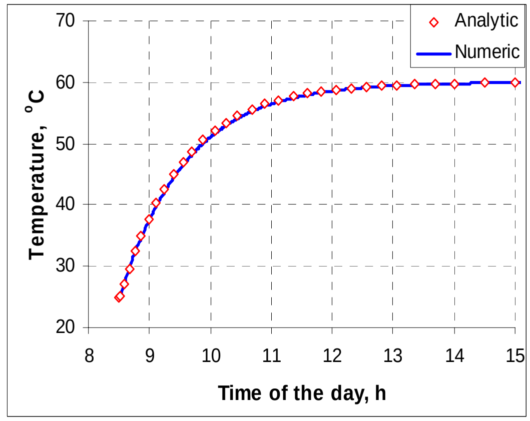


Fig A5.6: Comparison of temperatures at the bottom and in the middle of the bed from analytical and numerical solutions under the third kind of boundary condition

A5.2.2 Moisture concentration in the air at the bottom of the drying bed

Similar analytical solutions exist for mass diffusion in an infinite slab with first and third kinds of boundary conditions (Carslaw, 1959).

A. First kind of boundary condition

To approximate mass transfer with the first kind of boundary condition, a large value of convective moisture transfer coefficient (k_y) of 1 m/s was used so as to cause the condition of the concentration at the boundary of the slab to be in equilibrium with the ambient air. The ambient air temperature and relative humidity (RH_a) were assumed to stay constant all the time (T_a = 30°C and RH_a = 0.40) and the bed depth (L_p) or the half thickness of the slab (R') of 0.2 m was used.

The heat transferred or developed by the solar radiation, the air, the water vapour, free water, emissivity, convection, phase change and drying between the grain kernels and the air within the bed were all turned off (by setting I, c_{pa}, c_{pv}, c_{pw}, ϵ, h, h_{fg} and k to zero). The moisture diffusivity of 0.00002679 m^2/s, initial RH of 0.9703, initial moisture concentration of 0.294 kg/m^3 and moisture concentration in the ambient air (C_a) of 0.0121 kg/m^3 were analytically calculated, using the equations described in the Matlab script and respective function files to represent an equilibrium.

Figure A5.7 shows the comparison of the changes in moisture concentrations at the bottom of the grain bed for the first kind of boundary condition found from the analytical and numerical solutions. Despite some discrepancies (maximum of 0.000035 kg/m^3) between the two results, the changes are virtually indistinguishable.

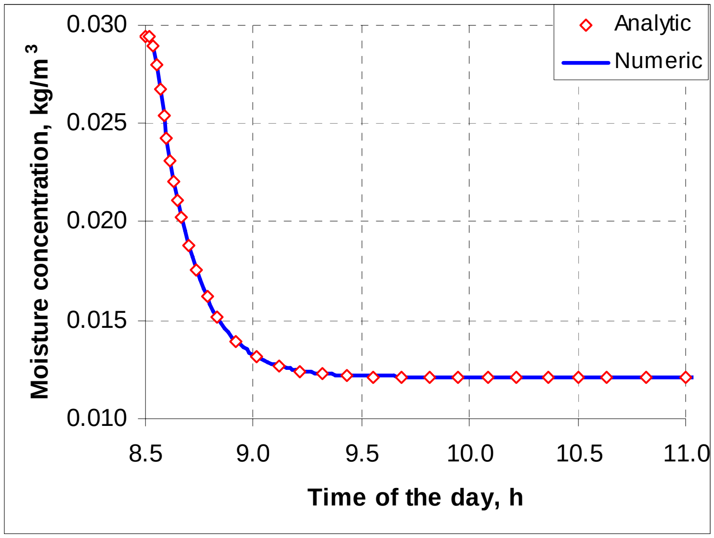


Fig A5.7: Comparison of the numerical and analytical solutions for moisture concentrations at the bottom of the bed for diffusion with the first kind of boundary condition

B. With the third kind of boundary condition

For the third kind of boundary condition, a value of moisture transfer coefficient (k_y) of 0.00010032 m/s was used in the numerical solution and 0.00020064 m/s (= 0.00010032 m/s / porosity of 0.5) was used in the analytical solution. The ambient air temperature and RH as well as the bed or slab thickness, D_v, RH_i, C_i, C_a, I, c_{pa}, c_{pv}, c_{pw}, ϵ_p, h, h_{fg}, k, λ_p and λ_s remained the same as they were applied in the previous condition. This condition corresponds to Biot number of 1.49795 as defined by

$$Bi = \frac{k_y.R}{D_v} \quad \text{… (A5.1)}$$

Figure A5.8 shows the comparison of the changes in moisture concentrations at the bottom of the grain bed for the third kind of boundary condition found from the two solutions. Despite some discrepancies (with maximum of 0.0002 kg/m^3), the changes are virtually indistinguishable.

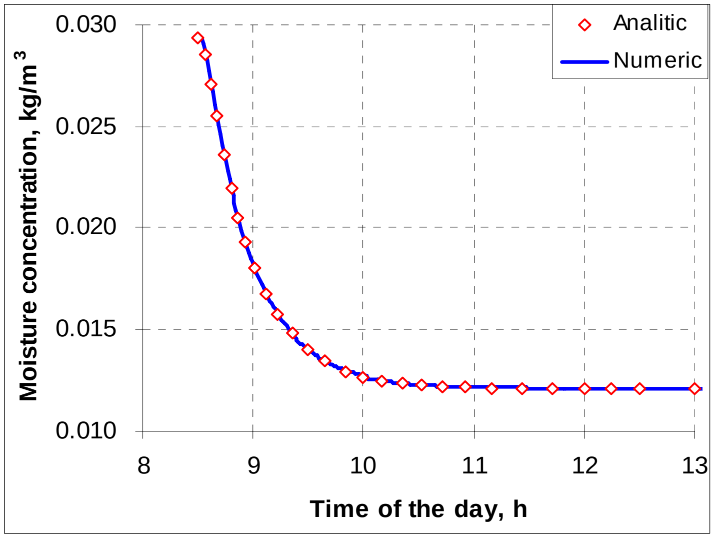


Fig A5.8: Comparison of the numerical and analytical solutions of moisture concentration at the bottom of the bed under the third kind of boundary condition

A5.2.3 Temperature of the grain at the surface of the bed unsteady state conditions

The temperature of the grain at the surface of the drying bed ($j = 1$) can be analytically solved, based on the rate of accumulation of heat in the kernels and air (Equation A3.8 of Appendix A3) for the case that no shading and no covering were applied when there was no conduction within the bed, no heat being radiated from the bed surface to the ambient air, no heat being carried with water diffusion, no heat being transferred by convection with moisture, the bed is fully solid, and solar radiation and ambient air temperature were constant. This was approximated by setting $\lambda_p = 0$, $\epsilon = 0$, $c_{pw} = 0$, $k_y = 0$, $\varepsilon = 0$, $I = 900$ W/m^2 and $T_a = 60^oC$.

As shown in Fig A5.9, the temperatures obtained from the two solutions were almost identical. The maximum difference in temperature observed was about 0.47^oC. This finding confirmed the term describing diffusion of moisture, radiation, convection mechanisms at the slab or bed surface had been correctly implemented.

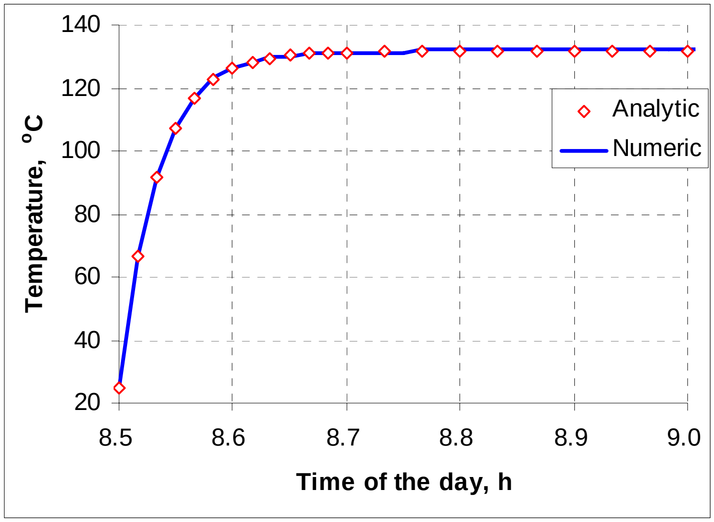


Fig A5.9: Comparison of the numerical and analytical solutions for temperatures at the bed surface under unsteady state condition

A5.2.4 Moisture content of the grain within the bed

An analytical solution to determine the MC of the grain within the bed (from nodes 1 to J) exists. It was performed based on the rate of moisture lost from the kernels:

$$\frac{\partial MC_j}{\partial t} = -\frac{k.a}{\rho_{bp}}\left[MC_j - MC_e\left(C_j\right)\right] \qquad \text{… (A5.2)}$$

Simplifying that

$\in = 0$ (No heat being radiated from the bed surface to the ambient air)

$\varepsilon = 0.99$ (Almost air within the bed)

$h_{fg} = 0$ (No phase change happened for the moisture)

$I = 0$ (constant)

$T_i = T_a = 25^oC$ (constant)

In the case that the RH throughout the bed and the temperature are constant, the equilibrium MC will also be constant. Rearranging and integrating Equation A5.2 yields

$$MC = MC_e + \left(MC_i - MC_e\right) exp\left(-\frac{k.a.t}{\rho_{bp}}\right) \qquad \text{… (A5.3)}$$

The MC during the whole drying time was compared with that obtained from the numerical solution (Fig A5.10). The MCs were indistinguishable. The maximum difference in MC observed was only 0.005%. This finding also reconfirmed the term describing the diffusion mechanism of moisture within the slab or bed had been correctly implemented in the model.

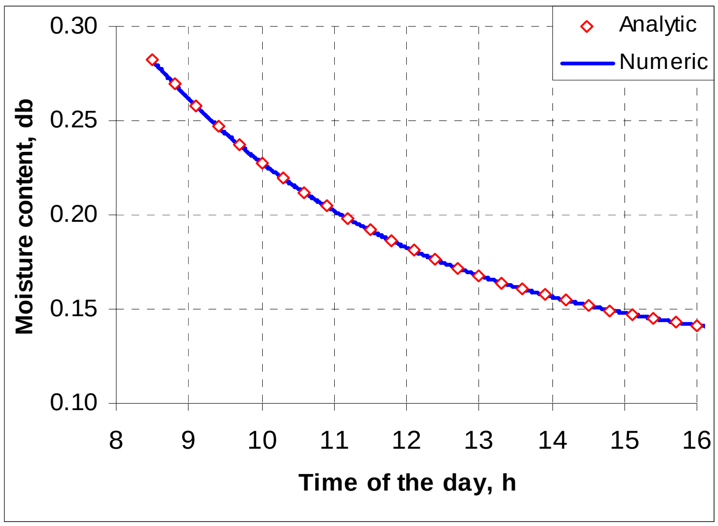


Fig A5.10: Comparison of the numerical and analytical solutions for MC of the grain within the drying bed

Appendix A6

MEASUREMENTS OF THE GRAIN PHYSICAL PROPERTIES

A6.1 Moisture equilibration process

Before the measurements, the grain of the two varieties of about 16% initial moisture content (MC) were conditioned in a controlled atmosphere or had a calculated amount of water added to obtain samples with MCs of approximately 14, 17, 18, 20, 21, 22 and 27%. The methods were carried out as described in Section 3.3.5.1.

A6.2 Length, width and thickness of the paddy kernel

Ten grain kernels were randomly selected from each of the equilibrated samples for determination of length, width and thickness (Table A6.1). A digital Vernier calliper with the resolution of 0.001 mm was used to measure the kernel dimensions directly. The length of the kernel was the distance from its tip to tip. The width of the kernel was its maximum diameter. The maximum diameter was not always located at the centre of the kernel. The thickness of the kernel was its minimum diameter at the centre. Morita and Singh (1979) and Wratten *et al.* (1969) also used a micrometer to measure the kernel dimensions. They obtained the average kernel length and width by dividing total length and total width or diameter of a number of the kernels aligned from tip to tip and touching along the width or maximum diameter, respectively, by the number of the kernels.

A6.3 Volume, surface area and specific surface area of the paddy kernel

Assuming that the grain kernel has a spheroid shape, according to Mohsenin (1986), volume (V_{sph}) and surface area (S_{sph}) of a prolate spheroid (formed when an ellipse rotates about its major axis) was estimated (Table A6.1), using the kernel dimensions found with the following equations:

$$V_{sph} = \frac{4}{3}\pi.a_{sph}.b_{sph}^{2} \quad \text{… (A6.1)}$$

$$S_{sph} = 2.\pi.b_{sph}^{2} + 2.\pi\frac{a_{sph}.b_{sph}}{e_{sph}}sin^{-1}e_{sph} \quad \text{… (A6.2)}$$

$$e_{sph} = \sqrt{1 - \left(\frac{b_{sph}}{a_{sph}}\right)^{2}} \quad \text{… (A6.3)}$$

The specific area of the grain was calculated, based on its bulk density assuming that the porosity was 0.5.

Table A6.1: Kernel dimensions and corresponding volume, surface area and specific surface area (mean ± 95% confidence interval)

MC	**Length**	**Width**	**Thickness**	**Volume**	**Surface area**	**Specific surface area**
% wb	*mm*	*mm*	*mm*	*mm^3*	*mm^2*	*m^2/m^3*
CAR11						
13.58	11.02 ± 1.14	2.64 ± 0.18	2.08 ± 0.12	32.14 ± 4.49	65.42 ± 6.46	1017.78 ± 174.09
17.09	10.86 ± 1.30	2.69 ± 0.16	2.06 ± 0.26	32.07 ± 5.73	64.93 ± 7.71	1012.11 ± 217.14
20.19	10.82 ± 0.58	2.73 ± 0.25	2.16 ± 0.16	33.87 ± 4.61	66.67 ± 4.79	984.35 ± 151.45
20.75	10.90 ± 0.97	2.69 ± 0.31	2.13 ± 0.27	33.15 ± 6.59	66.15 ± 7.22	997.82 ± 226.33
22.32	10.60 ± 1.61	2.68 ± 0.21	2.14 ± 0.14	32.24 ± 6.00	64.40 ± 8.93	998.88 ± 231.83
Pka Knhey						
13.45	9.11 ± 1.05	2.41 ± 0.19	1.89 ± 0.11	22.05 ± 3.43	49.45 ± 5.37	1121.36 ± 212.93
16.35	9.25 ± 0.76	2.46 ± 0.29	1.86 ± 0.08	22.60 ± 3.75	50.42 ± 4.76	1115.68 ± 212.97
20.42	9.14 ± 0.95	2.50 ± 0.34	1.91 ± 0.15	23.27 ± 4.75	50.93 ± 5.95	1094.41 ± 257.34
20.44	9.25 ± 0.87	2.46 ± 0.25	1.93 ± 0.09	23.34 ± 3.65	51.27 ± 4.98	1098.62 ± 202.07
22.28	9.16 ± 0.94	2.48 ± 0.25	1.95 ± 0.19	23.53 ± 4.21	51.28 ± 5.55	1089.58 ± 228.03

Note: The confidence level was calculated based on the methods described by Campanella et al. (1999).

A6.4 Kernel weight

The weight of a kernel (Table A6.2) was determined as the average of the total weight of a hundred kernels randomly selected from each of the samples. The weighing process was repeated three times.

A6.5 Bulk and true densities and porosity

The bulk density of the samples (Table A6.2) was measured using the method given by Morita and Singh (1979). Each of the equilibrated samples was placed in a cylindrical container with 62 mm inside diameter and 35 mm depth. Uniform density in the container was obtained by either no tapping at all, or tapping 10 times. The excess on the top of the container was removed by sliding a ruler along the top edge of the container. After the excess had been removed, the sample was weighed using an electronic balance (BP 3100 S, Sartorius Ag Gottingen, Germany) with capacity and sensitivity of 3100 g and of 0.01 g, respectively and the bulk density was obtained simply by dividing the weight by the volume of the container. The measurements were repeated three times for each of the samples.

To obtain the true density of the grain samples (Table A6.2), the kernel weight and volume were determined. Water was added to a tall and narrow measuring cylinder and the initial weight and volume were recorded. Two hundred kernels from each of the samples were added to the water in the cylinder and the increased weight and volume were measured. Adding the grain to the water was done quickly so that the grain did not have time to adsorb too much water; therefore, the increased weight and volume were the weight and volume of the kernels only.

The porosity (Table A6.2) was calculated using the following relationship:

$$\varepsilon_p = 1 - \frac{\rho_{bp}}{\rho_p} \qquad \text{… (A6.4)}$$

Table A6.2: Weight, volume, true density, bulk density and porosity of the kernels and grain

MC	Kernel weight	Kernel volume	True density	Bulk density		Porosity	
				not shaken	*shaken*	*not shaken*	*shaken*
% wb	*mg*	*mm^3*	*kg/m^3*	*kg/m^3*	*kg/m^3*		
CAR11							
13.8			1153 ± 99	548 ± 23	593 ± 28	0.53 ± 0.05	0.49 ± 0.05
20.1	32.6 ± 2.2	27.7 ± 3.3	1180 ± 60	580 ± 23	615 ± 13	0.51 ± 0.03	0.48 ± 0.03
Pka Knhey							
13.5			1157 ± 106	568 ± 12	610 ± 16	0.51 ± 0.05	0.47 ± 0.05
19.7	23.3 ± 1.1	20.0 ± 0.0	1164 ± 55	588 ± 12	614 ± 8	0.49 ± 0.03	0.47 ± 0.03
26.8			1224 ± 55	622 ± 24	642 ± 14	0.49 ± 0.03	0.46 ± 0.03

An alternative test was trialled to estimate the true density (Table A6.3) by placing the samples in water, ethanol (CH_3CH_2OH) and calcium chloride ($CaCl_2$) of different concentrations. According to Weast (1971), water-ethanol solutions of 96% and 56% and water-calcium chloride solutions of 10-, 24-, 30- and 40-% concentrations have relative densities of 800, 900, 1084, 1218, 1282 and 1398 kg/m^3, respectively. Table L3 lists the percentage of kernels of the two varieties at different MCs that were found to float when subjected to the solutions. As can be seen, no kernel from the two varieties with any level of MC floated when subjected to the water-ethanol solutions. Some kernels, especially from the samples with lower MC, were observed to float when added to the water. When subjected to the water-calcium chloride solution of 40-% concentration, all the kernels floated. This means that the density of all the samples is higher than the density of the 56-%-water-ethanol solutions of 800 to 900 kg/m^3 but is lower than the density of the 40% water-calcium chloride of about 1400 kg/m^3. The estimated ranges of the density of all the samples are also listed in Table A6.3. An obvious trend that can be observed from reading the data is that the higher the MC, the lower probability that the kernels floated, which indicates that the density is increased with the MC.

Table A6.3: Percentage of paddy kernels floated in different water solutions and the estimated true density

MC, *% wb*	**Ethanol**		**Water**	**Calcium Chloride**				**Estimated true density**
	96% *800**	56% *900**	*1000**	10% *1084**	24% *1218**	30% *1282**	40% *1398**	*kg/m^3*
CAR11								
13.78	0	0	1	30	98	100	100	1150 ± 100
20.05	0	0	0	15	90	100	100	1150 ± 100
Pka Knhey								
13.49	0	0	2	30	98	100	100	1100 ± 100
19.72	0	0	0	20	80	99	100	1150 ± 100
26.81	0	0	0	5	40	80	100	1175 ± 125

<u>Note:</u> ** The solution's density in kg/m^3 according to Weast, 1971.*

In summary, based on all these measurements, it can be concluded that

- The weight of the grain kernels increased with the MC
- The true density increased when the MC increased
- The bulk density increased with the MC. This was due to the change in the true density. The density of the grain that was tapped was always about 25 to 30 kg/m^3 higher than the same grain that was not tapped
- The porosity reduced when the MC increased. For the range of MC change tested, porosity of the grain that was tapped was always about 2 to 4% higher

than that of the untapped. This indicated that, as the grain was wetter or tapped, the kernels could be more compacted so as to reduce the porosity, and

- The kernels' dimension such as length, width and thickness seemed to remain constant for the range of the MCs tested. This was difficult to reconcile with information found from the literature that consistently indicated that the grain, like many other substances, shrinks during the dehydration process. Likewise, the changes in the kernel weight, porosity and densities found from our tests confirmed that the moisture must have some effects on the dimensions. The measuring method using a simple Vernier calliper was believed to be inappropriate.

Calculations show that the average change in volume per grain kernel when going from 13.5 to 26.8% MC is 2.2 mm^3. This is smaller than the error in the volume calculations shown in Table A6.1, based on the errors in the length, width and thickness measurement and hence explains why no significant changes were noted in the dimensions.

Appendix A7

RESULTS OF THE SENSITIVITY ANALYSIS

Table A7.1: Differences in the temperature predicted by the model

SI	**At 11:55**					**At 15:55**				
	T_1	T_7	T_{13}	T_{19}	T_{25}	T_1	T_7	T_{13}	T_{19}	T_{25}
a_k	**1.444**	**1.270**	**1.088**	**0.902**	**0.707**	-0.156	-0.022	0.083	0.163	0.224
c_{ph}	-0.037	-0.090	-0.143	-0.194	-0.241	0.006	0.017	0.032	0.056	0.091
c_{pmat}	-0.002	-0.004	-0.006	-0.008	-0.009	0.000	0.000	-0.001	0.000	0.001
c_{pp}	-0.026	-0.051	-0.066	-0.072	-0.069	0.082	0.140	0.156	0.139	0.100
c_{ps}	-0.016	-0.031	-0.046	-0.061	-0.076	-0.017	-0.027	-0.039	-0.051	-0.063
d_k	0.585	0.516	0.443	0.368	0.289	-0.067	-0.013	0.030	0.064	0.089
D_v	0.047	0.086	0.131	0.175	0.163	-0.181	-0.346	-0.492	-0.604	-0.669
h_{fg}	-0.006	0.005	0.016	0.026	0.036	-0.012	-0.031	-0.050	-0.070	-0.091
I	**6.945**	**6.066**	**5.171**	**4.260**	**3.315**	**6.809**	**6.145**	**5.351**	**4.526**	**3.708**
k_y	0.001	0.003	0.004	0.005	0.005	-0.006	-0.009	-0.011	-0.013	-0.013
L_a	0.098	0.195	0.291	0.385	0.474	0.000	-0.002	-0.007	-0.017	-0.036
L_h	0.015	0.039	0.067	0.104	0.151	0.066	0.163	0.262	0.363	0.466
L_{mat}	**0.173**	**0.423**	**0.669**	**0.914**	**1.173**	0.087	0.204	0.308	0.385	0.419
L_p	0.309	-0.077	-0.487	-0.913	-1.290	0.196	0.410	0.442	0.310	0.021
L_{tarp}	0.006	0.011	0.017	0.021	0.026	-0.002	-0.001	-0.001	-0.001	-0.001
RH_a	-0.010	-0.020	-0.028	-0.032	-0.029	0.018	0.032	0.044	0.055	0.062
T_a	**4.753**	**4.122**	**3.481**	**2.835**	**2.190**	**5.015**	**4.441**	**3.883**	**3.338**	**2.795**
T_{sky}	**2.507**	**2.194**	**1.872**	**1.543**	**1.201**	**2.579**	**2.257**	**1.942**	**1.637**	**1.341**
$\beta_p,\ \epsilon_p$	**1.755**	**1.536**	**1.305**	**1.066**	**0.817**	-0.038	0.077	0.167	0.236	0.286
$\beta_{tarp},\ \epsilon_{tarp}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
λ_h	-0.083	-0.207	-0.338	-0.483	-0.644	-0.123	-0.301	-0.477	-0.646	-0.801
λ_{mat}	-0.060	-0.146	-0.231	-0.313	-0.393	-0.030	-0.071	-0.107	-0.134	-0.146
λ_p	**-1.281**	**0.026**	**1.397**	**2.812**	**4.205**	**0.235**	**0.157**	**0.433**	**0.999**	**1.816**
λ_s	-0.091	-0.183	-0.276	-0.370	-0.464	-0.077	-0.156	-0.231	-0.303	-0.371
λ_{tarp}	-0.002	-0.003	-0.005	-0.006	-0.008	0.003	0.000	0.000	0.000	0.000
ρ_h	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ρ_{mat}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ρ_p	0.003	0.016	0.030	0.042	0.040	-0.043	-0.079	-0.111	-0.135	-0.146
ρ_s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ρ_{bh}	-0.030	-0.074	-0.118	-0.160	-0.199	0.005	0.014	0.027	0.047	0.076
ρ_{bmat}	-0.001	-0.004	-0.006	-0.008	-0.010	0.000	0.000	0.000	0.000	0.001
ρ_{bp}	-0.031	-0.052	-0.083	-0.118	-0.120	0.208	0.364	0.449	0.462	0.401
ρ_{bs}	-0.026	-0.052	-0.079	-0.105	-0.132	-0.023	-0.046	-0.068	-0.089	-0.109

Notes: The data listed in the table are for SI high – SI low;

- *Positive (bold) means when SI is high, prediction is significantly high*
- *Negative (underlined) means when SI high, prediction is significantly low.*

Table A7.2: Differences in the moisture content predicted by the model

SI	**At 11:55**					**At 15:55**				
	MC_1	MC_7	MC_{13}	MC_{19}	MC_{25}	MC_1	MC_7	MC_{13}	MC_{19}	MC_{25}
a_k	-0.097	-0.381	-0.456	-0.400	0.005	-0.025	-0.257	-0.337	-0.458	-1.003
c_{ph}	0.004	0.011	0.015	0.020	0.072	0.011	0.028	0.031	0.031	0.027
c_{pmat}	0.000	0.001	0.001	0.001	0.004	0.001	0.001	0.001	0.001	0.002
c_{pp}	0.002	0.027	0.052	0.068	-0.008	-0.006	-0.004	0.003	0.020	0.113
c_{ps}	0.000	0.001	0.003	0.012	0.004	0.001	0.004	0.008	0.026	0.141
d_k	0.070	-0.157	-0.189	-0.167	0.002	0.108	-0.104	-0.137	-0.187	-0.414
D_v	0.053	-0.937	-2.069	-2.830	0.116	0.037	-0.591	-1.558	-3.361	-9.367
h_{fg}	0.001	0.004	0.002	-0.011	-0.006	0.001	0.000	-0.002	-0.007	0.009
I	-0.457	-1.685	-2.006	-1.749	-0.045	-0.780	-1.996	-2.170	-2.571	-4.122
k_y	-0.022	-0.061	-0.067	-0.087	0.000	-0.008	-0.046	-0.056	-0.088	-0.230
L_a	-0.003	-0.013	-0.033	-0.114	-0.036	-0.002	-0.022	-0.052	-0.144	-0.576
L_h	0.000	-0.001	0.000	-0.002	-0.040	-0.016	-0.035	-0.042	-0.052	-0.073
L_{mat}	-0.020	-0.049	-0.070	-0.078	-0.425	-0.069	-0.156	-0.175	-0.191	-0.229
L_p	**-0.136**	**0.596**	**1.352**	**2.188**	**-0.050**	**-0.150**	**0.349**	**0.987**	**2.393**	**8.540**
L_{tarp}	0.000	-0.001	-0.002	-0.006	-0.002	0.000	-0.001	-0.003	-0.008	-0.033
RH_a	0.693	0.234	0.256	0.328	0.001	**0.761**	**0.406**	**0.397**	**0.518**	**1.365**
T_a	-0.371	-0.206	-0.326	0.220	-0.032	**-0.271**	**-0.020**	**-0.138**	**0.054**	**1.791**
T_{sky}	-0.164	-0.606	-0.724	-0.647	-0.021	-0.278	-0.717	-0.780	-0.928	-1.531
β_p, $\in_p$	-0.114	-0.378	-0.444	-0.398	-0.021	-0.037	-0.289	-0.370	-0.499	-1.085
β_{tarp}, $\in_{tarp}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
λ_h	0.007	0.016	0.023	0.032	0.183	0.048	0.111	0.128	0.148	0.185
λ_{mat}	0.007	0.017	0.024	0.027	0.155	0.024	0.054	0.061	0.066	0.079
λ_p	0.115	0.322	0.073	-0.944	-0.159	0.024	0.240	0.032	-0.958	-7.012
λ_s	0.003	0.007	0.020	0.077	0.023	0.007	0.022	0.051	0.155	0.846
λ_{tarp}	0.000	0.000	0.001	0.002	0.001	0.000	0.000	0.001	0.002	0.009
ρ_h	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ρ_{mat}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ρ_p	0.013	-0.220	-0.488	-0.701	0.026	0.010	-0.136	-0.366	-0.807	-2.699
ρ_s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	-0.001
ρ_{bh}	0.004	0.009	0.013	0.017	0.060	0.009	0.023	0.026	0.026	0.023
ρ_{bmat}	0.000	0.001	0.001	0.001	0.004	0.001	0.001	0.001	0.002	0.002
ρ_{bp}	**0.010**	**0.537**	**1.084**	**1.528**	**-0.074**	**-0.014**	**0.314**	**0.765**	**1.653**	**5.442**
ρ_{bs}	0.001	0.002	0.006	0.022	0.006	0.002	0.007	0.015	0.044	0.244

Table A7.3: Differences in the water activity predicted by the model

SI	At 11:55					At 15:55				
	a_{w1}	a_{w7}	a_{w13}	a_{w19}	a_{w25}	a_{w1}	a_{w7}	a_{w13}	a_{w19}	a_{w25}
a_k	-0.015	-0.021	-0.020	-0.012	0.000	0.003	-0.006	-0.011	-0.014	-0.017
c_{ph}	0.000	0.000	0.000	0.001	0.001	0.000	0.001	0.002	0.001	0.001
c_{pmat}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
c_{pp}	0.000	0.001	0.001	0.002	0.000	-0.002	-0.001	-0.001	0.000	0.002
c_{ps}	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.001	0.001	0.002
d_k	-0.006	-0.008	-0.008	-0.005	0.000	0.001	-0.003	-0.005	-0.006	-0.007
D_v	0.012	-0.056	-0.095	-0.081	0.000	0.006	-0.020	-0.067	-0.116	-0.147
h_{fg}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
I	-0.074	-0.097	-0.092	-0.052	0.000	-0.184	-0.131	-0.106	-0.088	-0.065
k_y	-0.005	-0.004	-0.004	-0.003	0.000	-0.001	-0.002	-0.002	-0.003	-0.003
L_a	0.000	-0.001	-0.002	-0.004	0.000	0.000	-0.002	-0.003	-0.005	-0.006
L_h	0.000	0.000	0.000	0.000	-0.001	-0.001	-0.001	-0.002	-0.003	-0.006
L_{mat}	-0.001	-0.001	-0.003	-0.002	-0.001	-0.003	-0.006	-0.008	-0.009	-0.009
L_p	**-0.003**	**0.033**	**0.059**	**0.062**	**0.000**	**-0.003**	**0.013**	**0.046**	**0.090**	**0.134**
L_{tarp}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
RH_a	**0.021**	**0.019**	**0.015**	**0.012**	**0.000**	**0.053**	**0.037**	**0.028**	**0.023**	**0.022**
T_a	0.026	0.003	-0.006	0.006	0.000	**0.061**	**0.041**	**0.025**	**0.019**	**0.031**
T_{sky}	-0.026	-0.035	-0.034	-0.020	0.000	-0.070	-0.048	-0.038	-0.032	-0.024
β_p, $\in_p$	-0.018	-0.024	-0.023	-0.013	0.000	-0.001	-0.009	-0.013	-0.016	-0.018
β_{tarp}, $\in_{tarp}$	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
λ_h	0.000	0.000	0.000	0.001	0.004	0.003	0.004	0.006	0.009	0.012
λ_{mat}	0.000	0.000	0.001	0.001	0.000	0.001	0.002	0.003	0.003	0.003
λ_p	**0.020**	**0.027**	**0.013**	**-0.019**	**0.000**	-0.005	0.003	-0.007	-0.038	-0.090
λ_s	0.000	0.000	0.001	0.004	0.000	0.002	0.002	0.003	0.007	0.012
λ_{tarp}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ρ_h	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ρ_{mat}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ρ_p	0.003	-0.013	-0.023	-0.022	0.000	0.001	-0.005	-0.016	-0.030	-0.042
ρ_s	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ρ_{bh}	0.000	0.000	0.000	0.001	0.001	0.000	0.001	0.001	0.001	0.000
ρ_{bmat}	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
ρ_{bp}	**0.002**	**0.032**	**0.049**	**0.044**	**0.000**	**-0.004**	**0.010**	**0.033**	**0.061**	**0.086**
ρ_{bs}	0.000	0.000	0.000	0.001	0.000					

Appendix A8

RESULTS OF REGRESSION ANALYSIS OF THE PROPOSED PARAMETERS THAT COULD AFFECT HRY

Table A8.1: Correlation matrix for the proposed parameters for Pka Knhey variety

	ADR	***MDR***	***Max T_1***	***MAT***	***MDT***	***DT_{bulk}***	***$BBMC_{crit}$***	***$BLMC_{crit}$***	***$BFRMC_{crit}$***	***$REWET_{bb}$***	***$REWET_{bb\ bulk}$***	***$STRESS_{max\ DR}$***	***$STRESS_{bulk}$***	***TT_g***
ADR	**1**	0.76	0.65	0.75	-0.62	-0.48	0.29	-0.52	-0.57	-0.23	-0.53	0.75	0.25	0.60
MDR	0.76	**1**	0.47	0.64	-0.70	-0.58	0.46	-0.26	-0.72	-0.57	-0.74	0.98	0.26	0.25
Max T_1	0.65	0.47	**1**	0.81	-0.40	-0.46	0.09	-0.43	-0.48	-0.21	-0.41	0.48	-0.21	0.56
MAT	0.75	0.64	0.81	**1**	-0.79	-0.64	0.28	-0.35	-0.49	-0.22	-0.45	0.65	0.02	0.77
MDT	-0.62	-0.70	-0.40	-0.79	**1**	0.63	-0.36	0.06	0.30	0.18	0.35	-0.73	-0.27	-0.49
DT_{bulk}	-0.48	-0.58	-0.46	-0.64	0.63	**1**	0.08	0.36	0.32	0.18	0.30	-0.59	0.38	-0.22
$BBMC_{crit}$	0.29	0.46	0.09	0.28	-0.36	0.08	**1**	0.30	-0.45	-0.55	-0.63	0.48	0.38	0.22
$BLMC_{crit}$	-0.52	-0.26	-0.43	-0.35	0.06	0.36	0.30	**1**	0.25	-0.21	0.01	-0.25	0.24	-0.25
$BFRMC_{crit}$	-0.57	-0.72	-0.48	-0.49	0.30	0.32	-0.45	0.25	**1**	0.70	0.84	-0.71	-0.03	-0.31
$REWET_{bb}$	-0.23	-0.57	-0.21	-0.22	0.18	0.18	-0.55	-0.21	0.70	**1**	0.91	-0.59	-0.11	-0.06
$REWET_{bb\ bulk}$	-0.53	-0.74	-0.41	-0.45	0.35	0.30	-0.63	0.01	0.84	0.91	**1**	-0.76	-0.13	-0.24
$STRESS_{max\ DR}$	0.75	0.98	0.48	0.65	-0.73	-0.59	0.48	-0.25	-0.71	-0.59	-0.76	**1**	0.26	0.26
$STRESS_{bulk}$	0.25	0.26	-0.21	0.02	-0.27	0.38	0.38	0.24	-0.03	-0.11	-0.13	0.26	**1**	0.19
TT_g	0.60	0.25	0.56	0.77	-0.49	-0.22	0.22	-0.25	-0.31	-0.06	-0.24	0.26	0.19	**1**

Note: Highlighted are the pair parameters that were found to be closely correlated (with R of higher than 0.9)

Table A8.2: Correlation matrix for the proposed parameters for CAR11 variety

	ADR	***MDR***	***Max T_1***	***MAT***	***MDT***	***DT_{bulk}***	***$BBMC_{crit}$***	***$BLMC_{crit}$***	***$BFRMC_{crit}$***	***$REWET_{bb}$***	***$REWET_{bb\ bulk}$***	***$STRESS_{max\ DR}$***	***$STRESS_{bulk}$***	***TT_g***
ADR	1	0.76	0.63	0.73	-0.56	-0.11	0.16	-0.35	-0.58	-0.21	-0.19	0.76	0.40	0.34
MDR	0.76	1	0.22	0.55	-0.71	-0.10	0.49	0.01	-0.68	-0.53	-0.18	0.99	0.52	0.09
Max T_1	0.63	0.22	1	0.80	-0.31	-0.15	-0.08	-0.30	-0.18	0.17	-0.23	0.24	-0.01	0.51
MAT	0.73	0.55	0.80	1	-0.77	-0.18	0.16	-0.10	-0.33	-0.05	-0.17	0.58	0.34	0.74
MDT	-0.56	-0.71	-0.31	-0.77	1	0.28	-0.38	-0.18	0.20	0.16	-0.03	-0.75	-0.54	-0.54
DT_{bulk}	-0.11	-0.10	-0.15	-0.18	0.28	1	0.18	0.05	-0.28	-0.15	-0.20	-0.12	0.29	-0.14
$BBMC_{crit}$	0.16	0.49	-0.08	0.16	-0.38	0.18	1	0.30	-0.35	-0.43	-0.04	0.48	0.42	-0.08
$BLMC_{crit}$	-0.35	0.01	-0.30	-0.10	-0.18	0.05	0.30	1	0.22	-0.30	-0.13	0.01	0.08	-0.01
$BFRMC_{crit}$	-0.58	-0.68	-0.18	-0.33	0.20	-0.28	-0.35	0.22	1	0.68	0.34	-0.64	-0.27	-0.09
$REWET_{bb}$	-0.21	-0.53	0.17	-0.05	0.16	-0.15	-0.43	-0.30	0.68	1	0.39	-0.49	-0.32	0.03
$REWET_{bb\ bulk}$	-0.19	-0.18	-0.23	-0.17	-0.03	-0.20	-0.04	-0.13	0.34	0.39	1	-0.15	-0.07	0.00
$STRESS_{max\ DR}$	0.76	0.99	0.24	0.58	-0.75	-0.12	0.48	0.01	-0.64	-0.49	-0.15	1	0.54	0.12
$STRESS_{bulk}$	0.40	0.52	-0.01	0.34	-0.54	0.29	0.42	0.08	-0.27	-0.32	-0.07	0.54	1	0.10
TT_g	0.34	0.09	0.51	0.74	-0.54	-0.14	-0.08	-0.01	-0.09	0.03	0.00	0.12	0.10	1

Note: Highlighted are the pair parameters that were found to be closely correlated (with R of higher than 0.9)

Table A8.3: Ranking all the parameters based on their p-values and R^2 for Pka Knhey variety

With HRY_{MILL}			**With HRY_{MI}**		
Parameter	**p**	**R^2**	**Parameter**	**p**	**R^2**
ADR	0.002	0.141	*TT_g*	0.0001	0.406
$BBMC_{crit}$	0.007	0.112	*MAT*	0.002	0.284
Max T_1	0.009	0.105	*ADR*	0.002	0.270
MAT	0.010	0.103	*Max T_1*	0.007	0.222
TT_g	0.013	0.096	*MDT*	0.014	0.186
$REWET_{bb\ bulk}$	0.016	0.027	*$REWET_{bb}$*	0.052	0.120
MDT	0.060	0.056	*$BLMC_{crit}$*	0.117	0.080
$STRESS_{max\ DR}$	0.078	0.049	*$STRESS_{bulk}$*	0.177	0.060
MDR	0.129	0.037	*DT_{bulk}*	0.332	0.031
$REWET_{bb}$	0.194	0.027	*MDR*	0.359	0.028
DT_{bulk}	0.222	0.024	*$STRESS_{max\ DR}$*	0.363	0.028
$BFRMC_{crit}$	0.235	0.023	*$REWET_{bb\ bulk}$*	0.415	0.022
$STRESS_{bulk}$	0.322	0.016	*$BBMC_{crit}$*	0.440	0.020
$BLMC_{crit}$	0.376	0.013	*$BFRMC_{crit}$*	0.956	0.0001

Table A8.4: Ranking all the parameters based on their p-values and R^2 for CAR11 variety

With HRY_{MILL}			With HRY_{MI}		
Parameter	**p**	**R^2**	**Parameter**	**p**	**R^2**
Max T_1	0.0001	0.2287	*Max T_1*	0.0003	0.3523
TT_g	0.0007	0.1714	*MAT*	0.0004	0.3420
MAT	0.0017	0.1473	TT_g	0.0027	0.2624
ADR	0.0139	0.0936	*ADR*	0.0106	0.1984
$BBMC_{crit}$	0.0357	0.0692	*MDT*	0.0625	0.1109
$REWET_{bb\ bulk}$	0.0492	0.0610	$STRESS_{max\ DR}$	0.1672	0.0626
DT_{bulk}	0.0660	0.0535	*MDR*	0.1841	0.0580
$STRESS_{bulk}$	0.1796	0.0289	$BFRMC_{crit}$	0.2137	0.0510
$BFRMC_{crit}$	0.3020	0.0172	$REWET_{bb\ bulk}$	0.2659	0.0411
MDT	0.5337	0.0063	$REWET_{bb}$	0.4245	0.0214
MDR	0.6815	0.0027	DT_{bulk}	0.7408	0.0037
$STRESS_{max\ DR}$	0.7366	0.0018	$STRESS_{bulk}$	0.8850	0.0007
$REWET_{bb}$	0.7606	0.0015	$BLMC_{crit}$	0.9597	0.00009
$BLMC_{crit}$	0.8523	0.0006	$BBMC_{crit}$	0.9808	0.00002

Table A8.5: Regression summary for HRY_{MILL} for Pka Knhey variety

Parameter	BETA	St. Err. of BETA	B	St. Err. of B	t(60)	p-level
Intercept			75.186	15.676	4.796	0.00001
ADR	-0.600	0.240	-217.816	86.974	-2.504	0.015
Max T_1	-0.746	0.274	-1.302	0.479	-2.722	0.009
MAT	0.737	0.314	0.623	0.265	2.348	0.023
DT_{bulk}	0.839	0.306	0.352	0.128	2.740	0.008
$BBMC_{crit}$	-0.552	0.190	-0.116	0.040	-2.908	0.005
$BLMC_{crit}$	-0.295	0.162	-130.039	71.192	-1.827	0.073
$STRESS_{max\ DR}$	0.898	0.264	231.517	68.148	3.397	0.001
$STRESS_{bulk}$	-0.416	0.234	-147.113	82.761	-1.778	0.081

$R = 0.657$, $R^2 = 0.432$, Adjusted $R^2 = 0.349$
$F(8,55) = 5.222$, $p < 0.00007$, Std. Error of estimate: 2.377.

Table A8.6: Regression summary for HRY_{MI} for Pka Knhey variety

Parameter	BETA	St. Err. of BETA	B	St. Err. of B	t(26)	p-level
Intercept			72.680	15.184	4.787	0.00007
Max T_1	-1.015	0.275	-1.905	0.517	-3.686	0.00116
MAT	1.520	0.590	1.382	0.536	2.577	0.01654
MDT	0.588	0.301	0.589	0.302	1.952	0.06267
DT_{bulk}	0.358	0.203	0.161	0.092	1.763	0.09067
$REWET_{bb}$	-0.484	0.105	-22.892	4.983	-4.594	0.00012
$STRESS_{bulk}$	-0.363	0.158	-138.016	59.900	-2.304	0.03018
TT_g	-0.830	0.232	-1.042	0.292	-3.572	0.00154

$R = 0.878$, $R^2 = 0.771$, Adjusted $R^2 = 0.704$
$F(7,24) = 11.515$, $p < 0.00001$, Std.Error of estimate: 1.738.

Table A8.7: Regression summary for HRY_{MILL} for CAR11 variety

Parameter	**BETA**	**St. Err. of BETA**	**B**	**St. Err. of B**	**t(26)**	**p-level**
Intercept			75.640	7.846	9.640	1.7E-13
MDR	-1.039	0.256	-318.459	78.339	-4.065	0.00015
MDT	-1.231	0.268	-1.116	0.243	-4.587	0.00003
DT_{bulk}	0.325	0.103	0.165	0.053	3.146	0.00265
$BLMC_{crit}$	-0.336	0.128	-107.063	40.823	-2.623	0.01122
$REWET_{bb}$	-0.510	0.155	-22.422	6.833	-3.281	0.00178
$REWET_{bb\ bulk}$	0.246	0.107	1.760	0.768	2.293	0.02562
TT_g	-0.930	0.155	-1.243	0.207	-6.004	0.0000001

$R = 0.699$, $R^2 = 0.489$, Adjusted $R^2 = 0.425$
$F(7.56) = 7.662$, $p < 0.00001$, Std. Error of estimate: 2.208.

Table A8.8: Regression summary for HRY_{MI} for the CAR11 variety

Parameter	**BETA**	**St. Err. of BETA**	**B**	**St. Err. of B**	**t(26)**	**p-level**
Intercept			66.451	10.221	6.501	0.000001
Max T_1	-0.353	0.157	-0.438	0.194	-2.258	0.033
$BLMC_{crit}$	-0.509	0.162	-137.222	43.581	-3.149	0.004
$BFRMC_{crit}$	0.757	0.219	0.030	0.009	3.456	0.002
$REWET_{bb}$	-0.743	0.223	-27.660	8.312	-3.328	0.003
TT_g	-0.245	0.143	-0.277	0.162	-1.710	0.099

$R = 0.787$, $R^2 = 0.620$, Adjusted $R^2 = 0.547$
$F(5,26) = 8.474$, $p < 0.00007$, Std. Error of estimate: 1.674.