PERFORMANCE EVALUATION
OF A PROTOTYPE FLAT-BED GRAIN DRYER

**A THESIS
PRESENTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF MASTER OF
APPLIED SCIENCE IN POSTHARVEST TECHNOLOGY
AT
MASSEY UNIVERSITY**

PYSETH MEAS

1999

ABSTRACT

The performance of a new prototype flat-bed grain dryer designed for experimental research was evaluated using yellow dent maize grain of two hybrids ("Clint" and "Raissa" which are hard and soft, respectively) in three separate experiments. In experiment I, grain samples at three initial moisture contents (approx. 20, 25 and 30 % w.b.) were dried at three air temperatures (58, 80 and 110 °C). Dryer performance parameters such as drying time, drying rate, capacity, efficiencies and energy consumption were determined and the dried grain quality attributes were also evaluated. A thin layer drying model for predicting dried grain moisture ratio was proposed. In experiments II and III, grain samples were dried at 80 °C air temperature from 25 % to 14.5 % moisture content, cooled or tempered before assessment of grain quality attributes. Overall, the dryer performance was good in terms of its operation and effects on quality of dried grain. Both dryer operational performance and dried grain physico-mechanical properties were affected by drying air temperature, grain initial moisture content, and the post-drying treatments. Low initial grain moisture content and high drying temperatures increased dryer capacity and reduced total energy consumption for drying. However, both high drying air temperature and high initial grain moisture content increased the incidence of grain damage. Slow cooling and/or tempering of the dried grain increased grain bulk density and reduced breakage susceptibility, especially when cooled or tempered in an airtight and well insulated container. However, these two post-drying treatments did not affect grain hardness significantly. Finally, a conceptual model for evaluating and optimising the performance of mechanical grain dryer is proposed.

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Chapter 1
INTRODUCTION

1.1 Introduction

Knowledge of the production and utilisation of cereal grains is fundamental to solving the food supply problem facing the majority of the world's population. Grains are not only important direct sources of food for humans, but also make a substantial contribution to the diet, indirectly as fodder, for farm livestock producing meat, milk, and eggs (Lorenz and Kulp, 1991). In most countries grains are among the most important staple foods but they are produced on a seasonal basis, and in many places there is only one harvest a year. Grain storage is essential for marketing and to ensure availability for late consumption for periods varying from one month up to more than a year (Picard and Proctor, 1994).

Since grains are often harvested at moisture contents that are too high for safe storage, immediate and effective treatment of the freshly harvested grains is essential to prevent quality deterioration (Brooker et al., 1992). One of the most affective treatments is drying. It is the most practised grain preservation method that enables grains to attain moisture content sufficiently low to minimise infestation by insects and micro-organisms, such as bacteria and fungi, and to prevent unwanted germination (Hill, 1997). Grain drying has been used since early civilisation to preserve it for food (Hoseney, 1994).

Traditionally, grain crops are harvested during a dry period and simple drying methods such as sun drying are adequate. However, maturity of the crop does not always coincide with a suitably dry period. Furthermore, the introduction of high yielding varieties and hybrids, irrigation, improved farming practices, and multi-cropping have led to the need for alternative drying practices to cope with the increased production. Responding to these, scientific research has been remarkably successful in increasing the quantity and quality of grain through the application of improved drying and storage technologies. Various studies have focused on improving grain quality by introducing new and suitable dryers for different purposes. Nowadays, mechanical or

artificial dryers, long used in developed countries, are finding increased application as farming and grain handling systems improve in many developing countries (Trim and Robinson, 1994).

The need to dry grain artificially arises from the basic need to provide uniformly good quality grain which will facilitate its long terms storage and processing. Artificial grain drying assists this objective by minimising weather effects on the harvest (Bakker-Arkema et al., 1995). Annual postharvest loss of grains is estimated at 10 % and therefore moisture control, primarily by drying, provides an opportunity to prevent losses which occur during harvesting, handling and storing (Hall, 1980).

The performance of grain dryers and good understanding of the effects of drying on grain quality are very important to satisfy the need of grain producers, grain traders, grain processors and grain users since it is generally agreed that improper drying is the major cause of high drying cost and grain deterioration. Poor or defective drying equipment or incorrect drying procedures may result in high costs, low capacity and efficiencies, very fast drying rate, incomplete drying, high milling losses, poor quality or reduced germination capacity of the dried seed (ESCAP, 1995). Nellist and Bruce (1992) stated that the main reasons for testing grain dryers are: (a) to aid the development of a prototype, (b) to confirm the specified performance and (c) to provide information for marketing and operator guidance. Of particular concern is the increase in dryer capacity and drying rate by using drying air temperatures higher than those recommended which can lead to a reduction in grain quality (Radajewski et al., 1988). Hardacre (1997) observed that aggressive commercial drying could result in fine materials (measured by mechanical impact test) in excess of 40 % of the grains but careful commercial drying results in grains with the fine less than 10 % regardless of the grain hardness.

Prototype dryers are often used in grain breeding research to evaluate the quality of grain after drying, thereby assisting in assessing the economic feasibility of new cultivars and hybrids. Recently, a new prototype grain dryer was designed and constructed by the maize breeding team at the New Zealand Crop and Food Research Ltd., Palmerston North, for experimental purposes.

The aim of this study was to investigate the potential of the new grain dryer for achieving high capacity, efficiencies, and drying rates and low costs with minimum reduction in dried grain quality.

1.2 Research Objectives

The specific objectives of this research study were to evaluate the performance of a new prototype flat-bed grain dryer by:

- Determining the effects of initial grain moisture content and drying air temperature on drying time, drying rate, dryer capacity, drying efficiencies and energy consumption;

- Quantifying the effects of grain moisture content and air temperature on grain quality attributes; and

- Quantifying the effects of post-drying treatments (cooling and tempering) on quality attributes of dried grain.

Chapter 2

LITERATURE REVIEW

Grain drying and dryer performance evaluation

2.1 Principles of grain drying

Grain drying is the phase of the postharvest system during which the product is rapidly dried until it reaches the "safe moisture" level (de Lucia and Assennato, 1994). It is accomplished simply by the evaporation of moisture from the grain. In this process, heat is necessary to evaporate moisture from the grain and a flow of air is needed to carry away the evaporated moisture. In mechanical drying systems, airflow is also required to deliver the heat needed for drying. There are two basic mechanisms involved in the drying process; the migration of moisture from the interior of an individual grain to the surface, and the evaporation of moisture from the surface to the surrounding air (Trim and Robinson, 1994). The moisture in grain to be removed during drying is associated with grain in two ways: (1) surface moisture which occurs in the outer surface, and is readily absorbed by the air under proper conditions, and (2) internal moisture which is distributed throughout the inner parts of the grain. Removal of the internal moisture involves capillary action or diffusion of the moisture to the surface (Verma, 1993).

Grain drying can be achieved by circulating air at varying degrees of heat through a mass of grain (de Lucia and Assennato, 1994). As it moves, the air imparts heat to the grain, while absorbing the humidity of the outermost layers. In terms of physics, the exchange of heat and humidity between the air and the product to be dried is characterised by the following phenomena:

- heating of the grain, accompanied by a cooling of the drying air;
- reduction in the moisture content of the grain, accompanied by an increase in the relative humidity of the drying air.

However, this process does not take place uniformly inside the drying chamber or among individual grains, or within each grain. Indeed, the water present in the outer

layers of grain evaporates much faster and more easily than that of the internal layers. Thus it is much harder to lower the moisture content of a product from 25 to 15 percent than from 35 to 25 percent. Trim and Robinson (1994) stated that drying operation must not be considered as merely the removal of moisture since there are many quality factors that can be adversely affected by incorrect selection of drying conditions and equipment. It is important to understand the principles of grain drying (whether the grain is being dried naturally by the sun or by an artificial or mechanical drying system), to ensure that a high quality product is obtained.

Changes in texture and structure during drying of grain, particularly maize, are important in minimising breakage during handling. Excessive cracks reduce value of maize for producing foods such as breakfast cereals. Harsh heat treatment during drying may reduce starch yields, impair quality of the starch and create difficulties in maize wet-milling. If used for alcoholic beverages, overheated maize may also cause difficulties in beer brewing and distillation (FAO, 1984). Broken maize is more easily attacked by insects and produced more grain dust than whole grain, creating many problems in handling, transportation and storage (FAO, 1984).

2.1.1 Grain equilibrium moisture content

Equilibrium moisture content (EMC) is defined as the moisture content of material after it has been exposed to a particular environment for an infinitely long period of time. Alternatively, the EMC can be defined as the moisture content at which the internal product vapour pressure is in equilibrium with the vapour pressure of the environment. This concept is important in the study of grain drying because it determines the minimum moisture content to which grain can be dried under a given set of drying conditions (Brooker et al., 1992).

EMC is dependent on the relative humidity and the temperature of the air and is used to determine whether grain will gain or lose moisture under a given set of conditions of the air. Thus, it is not possible to dry any grain lower than the equilibrium moisture content associated with the temperature and humidity of the drying air (Liu et al., 1998). Hall (1980) explained that grain is in equilibrium with its environment when the

rate of moisture loss to the surrounding atmosphere is equal to the rate of moisture gain from the surrounding atmosphere.

Data in Table 1 show that the equilibrium moisture content of all the grain species increases as the relative humidity of the air increases. For instance, a moisture content of 19.6 % of the shelled maize can only be obtained when the grain exposes to air at 25 °C and 90 % relative humidity. Similarly, to dry the grain to moisture content lower than 19.6 % requires that either the temperature of the drying air increased or its humidity reduced.

TABLE 1 Equilibrium moisture content of some grains at 25 °C related to relative humidity (Trim & Robinson, 1994)

Grain	Relative Humidity (%)							
	30	40	50	60	70	80	90	100
	Equilibrium Moisture Content (% wet basis) at 25 °C							
Barley	8.5	9.7	10.8	12.1	13.5	15.8	19.5	26.8
Shelled Maize	8.3	9.8	11.2	12.9	14.0	15.6	19.6	23.8
Paddy	7.9	9.4	10.8	12.2	13.4	14.8	16.7	-
Milled Rice	9.0	10.3	11.5	12.6	12.8	15.5	18.1	23.6
Sorghum	8.6	9.8	11.0	12.0	13.8	15.8	18.8	21.9
Wheat	8.6	9.7	10.9	11.9	13.6	15.7	19.7	25.6

Figure 1 illustrates further the significant effects of drying air temperature on the EMC of the shelled maize. It demonstrates that by using the drying air at a higher temperature, a lower moisture content of the shell maize can be obtained. The sigmoid shape (S-shaped) of this relationship is always the same, but the numerical values are different with different air temperatures. For example, the EMC of the maize at 70 % RH is about 15.7 % w.b. at 4.5 °C and 10 % w.b. at 50 °C.
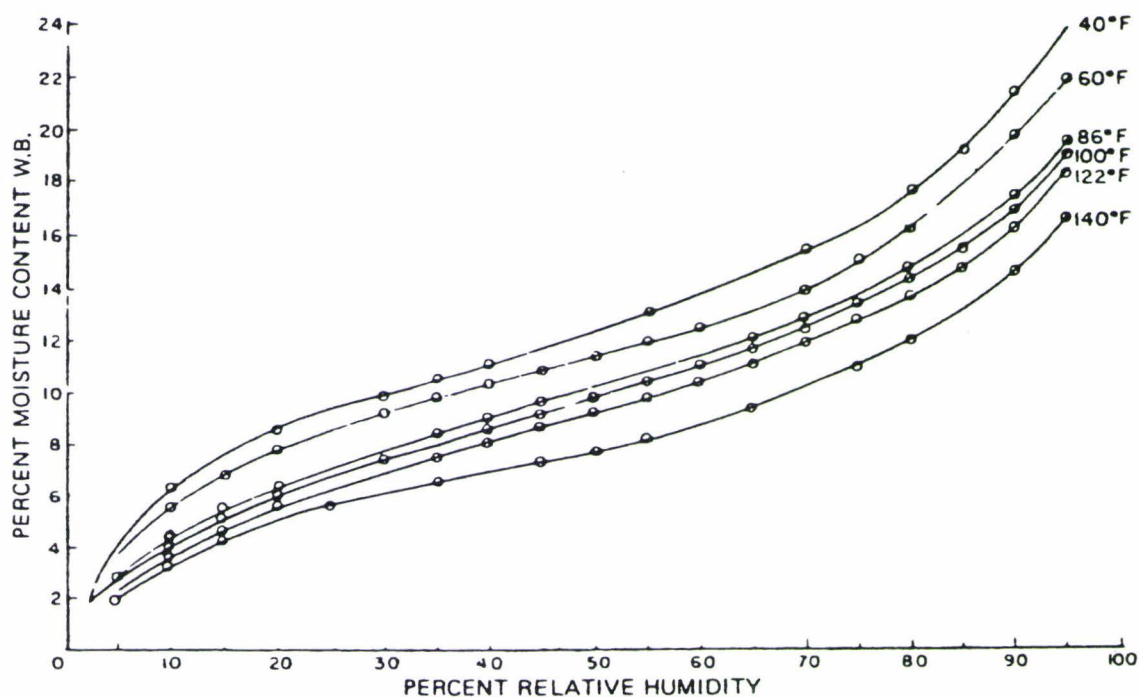
Note: $40\,^{\circ}F = 4.4\,^{\circ}C,\ 60\,^{\circ}F = 15.55\,^{\circ}C,\ 86\,^{\circ}F = 30\,^{\circ}C,\ 100\,^{\circ}F = 37.78\,^{\circ}C,$
$122\,^{\circ}F = 50\,^{\circ}C,\ 140\,^{\circ}F = 60\,^{\circ}C$

FIGURE 1 Equilibrium Moisture Content Curves for Shelled Corn (Brooker et al.,
1974)

Liu et al. (1998) presented a general relationship between the EMC of grains and the air conditions by the following empirical equation:

$$EMC = a - b \ln [- (T + c) \ln RH] \qquad\qquad \dots\dots\dots\dots\dots\dots\dots \quad (1)$$

Where

M_{eq} = equilibrium moisture content (decimal d.b.)

a, b and c = product constants (0.339, 0.059 and 30.205, respectively, for maize)

T = air temperature (°C)

RH = air relative humidity (decimal)

2.1.2 Drying rate

Hill (1997) stated that drying of grain takes place only when there is a net movement of water going out of the grain into the surrounding air so that the grain will give up its moisture content. The author also stated that drying rate is determined by how fast the moisture migrates or diffuses from the interior to the grain surface and by the speed at which the surface moisture is moved into the surrounding air. Thompson and Foster (1963), on the other hand, stated that the effects of drying-air temperature and flow rate can be combined into an expression of drying speed represented by the moisture reduction in percentage per hour. If drying is performed at an excessive rate, the grain becomes susceptible to fissuring, due to the creation of moisture gradients within the product (Driscoll and Srzednicki, 1995).

Drying rate generally increases with increasing moisture content of grain and air temperature or decreases with increase in air humidity (Trim and Robinson, 1994). Figure 2 demonstrates that moisture reduction from drying maize and its drying time vary inversely with the drying air temperature. For instance, it takes from 1 hour at 100 °C to 38 hours at 25 °C to reduce each maize grain sub-lot from 30 to 12% moisture content.
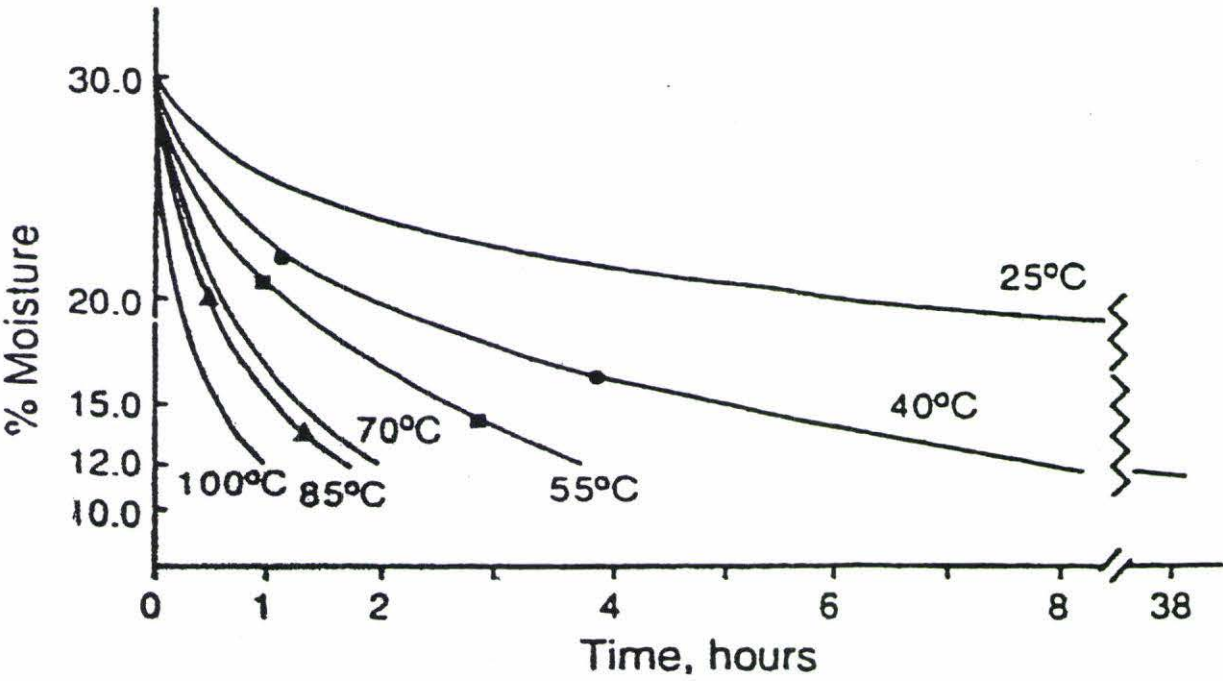
FIGURE 2 Changes in drying rate of maize grain as affected by air temperatures of 25 – 100°C (Peplinski et al., 1994)

2.2 Methods of drying

It is sometimes possible to wilt a crop on the plant for a considerable period of time and so reduce the moisture content to a point where no further drying is necessary. This ideal situation is, however, seldom achieved due to the danger of loss from microbial insect and bird attacks. In some areas, especially when large quantities of crops are produced, grains such as maize ripen during the wet season and if they are not harvested on ripening, losses may occur (Hill, 1997). Therefore, there are many different methods for grain drying available at present. They may be divided into two broad classifications based on the energy source, namely natural and artificial drying.

2.2.1 Natural drying

Natural drying is the most widespread method of grain drying in the tropics. Several limiting factors, such as availability of appropriate weather and labour, make natural drying unsuitable for large scale drying (Trim and Robinson, 1994). The natural drying methods which have been commonly used for grains such as maize are sun drying and crib drying.

a) Sun drying

For economic reasons, traditional sun-drying has changed little over the centuries and remained the preferred method of grain drying in many tropical and subtropical regions. Few controlled scientific experiments have been conducted on the drying technique. In sun-drying process, the grain is spread on mats or paved ground in layers of 5 – 15 cm thickness and is exposed to the ambient conditions (Liu et al., 1998). At its simplest form and in suitable climates, drying can consist of spreading the grain to dry in the sun assisted by frequent turning to expose all grains. The sun supplies an appreciable and inexhaustible source of heat to evaporate moisture from the grain and the wind removes the released moisture (de Lucia and Assennato, 1994).

The fixed costs of sun-drying are low, except when a special drying floor has to be constructed. There are, however, several disadvantages. It is an unreliable process because it is weather dependent, and is affected by: (1) the solar radiation, (2) the ambient air temperature, (3) the ambient relative humidity, (4) the wind velocity, (5) the soil temperature, (6) the grain-layer thickness, and (7) the grain type. The first five factors change with the season and the time of the day (Liu et al., 1998). In sunlight, the crop temperature will rise to a high level after a period of exposure - this can be as high as 60 - 70 °C. This temperature can cause uneven drying of the grains with consequent cracking. Also, moisture from the earth condenses on the bottom layer of grain, resulting in a slow drying rate unless the crop is frequently turned (Trim and Robinson, 1994).

Notwithstanding its disadvantages, it is possible to produce dried grain of superior quality if the sun-drying is practised properly and competently. Of particular importance are the proper selection of the maximum layer thickness and initial moisture content of the grain, and the recognition that during certain periods of the year (i.e. the wet season) adequate sun-drying of grain is not feasible (Bakker-Arkema et al., 1995; Liu et al., 1998). Hill (1997) noted that sun drying can be satisfactory provided the crop is laid out on an impermeable surface (e.g. concrete or plastic) and turned regularly, and there is sufficient labour to cope with moving it under cover at night or if rain threatens.

b) Crib drying

In this method, maize is stored on the cob in cribs until it is required for shelling. The maize crib in its many forms acts as both dryer and a storage structure. The rate and uniformity of drying are controlled by the relative humidity of the air and the ease with which air can pass through the bed of cobs (Trim and Robinson, 1994). It is very slow - perhaps 0.1 % of moisture can be evaporated from the grain per day. Compared with paddy, cob maize can retain its good quality for considerably longer periods (from one to three months) at relatively high moisture contents (higher than 20 %) with natural ventilation (Hill, 1997). Typical cribs used for maize are shown in Figure 3.
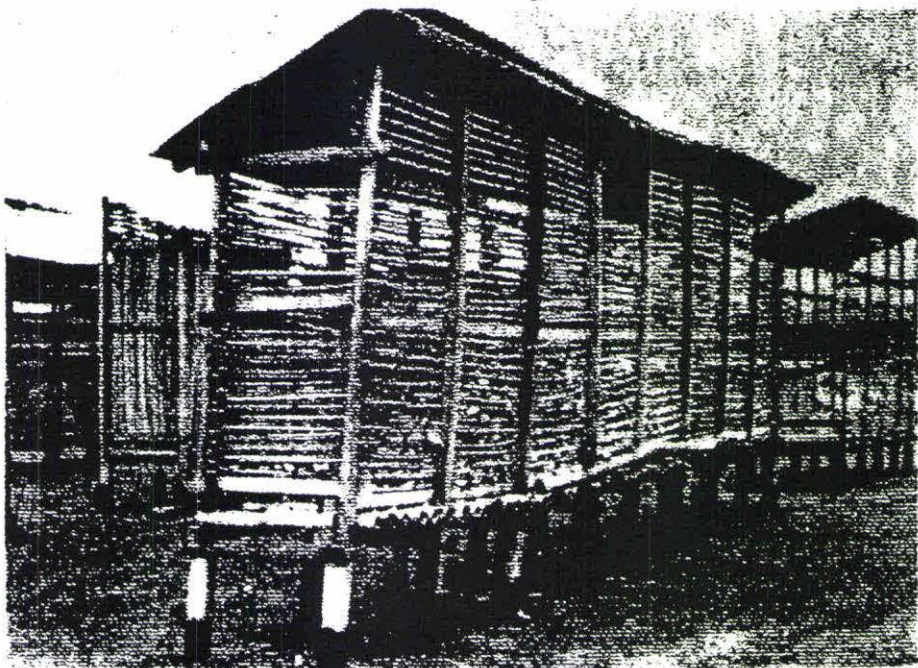
FIGURE 3   Cribs used both for drying and storage of maize (de Lucia and Assennato, 1994)

2.2.2 Artificial or mechanical drying

Artificial or mechanical drying refers to drying using artificial or mechanical dryers. An artificial or mechanical grain dryers is a complete drying system which is made up of fan, heater, ducts and bin. Drying occurs by the passage of air of suitable relative humidity and temperature through the crop until the desired reduction in moisture content is achieved (McLean, 1989). Until now, there has been no consistent classification of mechanical dryers nor of designs of drying installations. The followings are some common classifications:

a) Dryers classified by drying air temperature
i) Low-temperature dryers

Dryers of this type are known as bulk or storage dryers. Drying and storage occur in the same bin. They are the simplest artificial dryers consisting of increasing the air-flow through the crop by means of a fan. Air at ambient conditions or air with its temperature increased by up to 5 °C is used and the principle is that the crop gradually reaches a moisture content in equilibrium with the air (McLean, 1989; Brook, 1992).

Drying a bin of grain with ambient air is possible if (a) the initial moisture content of the grain is not excessive, (b) the average daily relative humidity of the air is not too high, and (c) the airflow rate is sufficient (typically 1 to 3 m^3/min.t). The recommended maximum initial moisture contents of maize and wheat, and the minimum airflow rates, for ambient-air drying under Midwestern U.S.A. conditions are listed in Table 2. In the tropics, the initial moistures are lower and the required airflow rates are higher (Liu et al., 1998). However, relative humidity of the air is not always constant. It is normally higher during the night than during the day and is affected by the ambient temperature (McLean, 1989). A primary task in the design of a low-temperature dryer is the determination of the required specific airflow rate which must be high enough to dry grain to a safe storage moisture content before spoilage occurs (Brooker et al., 1992).

TABLE 2 The maximum initial moisture contents and minimum airflow rates for the ambient air drying of maize and wheat in Midwestern USA (Brooker et al., 1992)

Grain type	Moisture content, (%, w.b.)	Airflow, (m³/m³.min)
Maize	20	2.4
Wheat	18	1.6
Wheat	16	0.8

ii) Medium-temperature dryers

These have been developed for situations where higher moisture extraction rates are required. The principle on which the system operates is that warmer air is blown through a bed of grain of control depth. Temperature rise of up to 14 °C is obtained from either electrical, oil fired or any other sources (Hill, 1997).

iii) High-temperature dryers

High-temperature dryers are commonly rated for capacity on the basis of 10-point moisture removal from maize, i.e. from 25 to 15 % moisture content wet basis (Bakker-Arkema et al., 1995). They are employed for the drying of grain when high drying capacities are required. There are three major types: (a) cross-flow dryers, (b) mixed-flow dryers and (c) concurrent-flow/counter-flow dryers. These dryers are unable to produce grain of the same high quality as low-temperature dryers. However, in many cases a slight decrease in grain quality is acceptable to the end-user of the grain (Liu et al., 1998).

Depending on the initial moisture content of the grain and the intended end-use, these dryers may be used to reduce the time required for drying. The maximum air temperatures are generally quoted for animal feed and they must be reduced progressively if the grain is to be used for bread making, brewing or milling, or seed purposes (Hill, 1997). These are listed in Table 3:

TABLE 3 Maximum air temperatures for drying maize *(Hill, 1997)*

Purpose	Maximum air temperature (^{o}C)
Seed	44
Starch	55
Animal feed	82

Notes: These temperatures must be modified according to initial moisture content of drying grain. They should be lower than the maximum whenever possible in order to reduce the risk of damage.

Bakker-Arkema and Salleh (1985) reported typical drying air temperatures used in high-temperature grain dryers for maize in the USA and China. Table 4 contains values of the temperatures measured in maize dryers at elevator/grain-depot sites in the USA and China. Clearly, the concurrent-flow dryers operated at the highest temperature and the crossflow dryers at the lowest temperature. The disparity in operating temperatures between those measured in the USA and China is due to the different heat sources used in the two countries: natural gas in the USA and coal in China.

TABLE 4 Typical drying-air temperatures employed in different maize-dryer types in the USA and China (Bakker-Arkema; Salleh, 1985)

Dryer Type	USA (^{o}C)	China (^{o}C)
Concurrent-flow	205 – 290	150 - 160
Mixed-flow	130 – 140	120 - 150
Crossflow	85 – 120	90 - 120
Steam dryer	-	130 - 140

b) Dryers classified by movement of grain

i) Batch-in-bin dryers

They are dryers in which the same quantity of grain remains during the drying operation and no grain is removed until the required grain moisture content is attained or until drying is completed (ESCAP, 1995). With this type of dryers, drying and storage of grain occur in the same bin (when air of low temperature is used) or in separate bins (when air of high temperature is used). The bin has a fully perforated floor. A dryer of this type usually has high capacity fan or fans, and possibly loading and unloading equipment, grain spreader and stirrer (Brook, 1992). When the fan(s) and a bin of a certain diameter have been selected, the airflow to the bin is a function

of depth of grain in the bin. In essence, the operator controls the airflow (and specific airflow rate) by the amount of grain added into the bin (Brooker et al.,1992).

The high-temperature batch-in-bin dryers can dry one or two batches per day, with typical volumes up to 500 t (Brook, 1992). There are two types of batch-in-bin systems being used in high-temperature in-bin drying (Brooker et al., 1992): on-floor bin-batch, where the grain is dried on the false floor at the bottom of the bin (Figure 4) and roof bin-batch, where the grain is dried on a cone-shaped perforated floor near the bin roof (Figure 5).

Flat-bed dryers are the small capacity version of the batch-in-bin dryer types. They have been developed for farm- or village-level use. Its capacity is of the order of 1 to 3 tonnes/day with drying times of 6 to 12 hours (Trim and Robinson, 1994). As the name of this method implies, a shallow bed of grain is dried to the desired average moisture content in a perforated-floored bin, with subsequent removal to storage (Watson, 1987). They are among the first type of small-scale dryers that existed in the humid tropics. By using easily available and inexpensive materials, their structures are usually simple and easy to operate with unskilled labour (Trim and Robinson, 1994; Tumambing, 1995). In order to prevent excessive moisture gradient through the bed, the depth of grain in the bin is relatively shallow (0.4 - 0.7 m) and the air velocity is usually of the order of 0.08 to 0.15 m/s for maize and 0.15 to 0.25 m/s for paddy (Trim and Robinson, 1994).

The temperature of the air used in the flat-bed dryers is usually selected according to the desired safe storage moisture content of the grain (Trim and Robinson, 1994). Tumambing (1995) reported that the drying air temperatures, for paddy, is kept below 43 °C to minimise fissuring and maintain seed viability. In the 2 tonne flat-bed dryer (Figure 6), developed by the University of the Philippines at Los Baños during the early 1960s, drying air flowrate of 12.7 m^3/min.m^2 of drying floor area is used to dry wet paddy from 24 % moisture content down to a safe storage level of 14 % in about 8 hours.
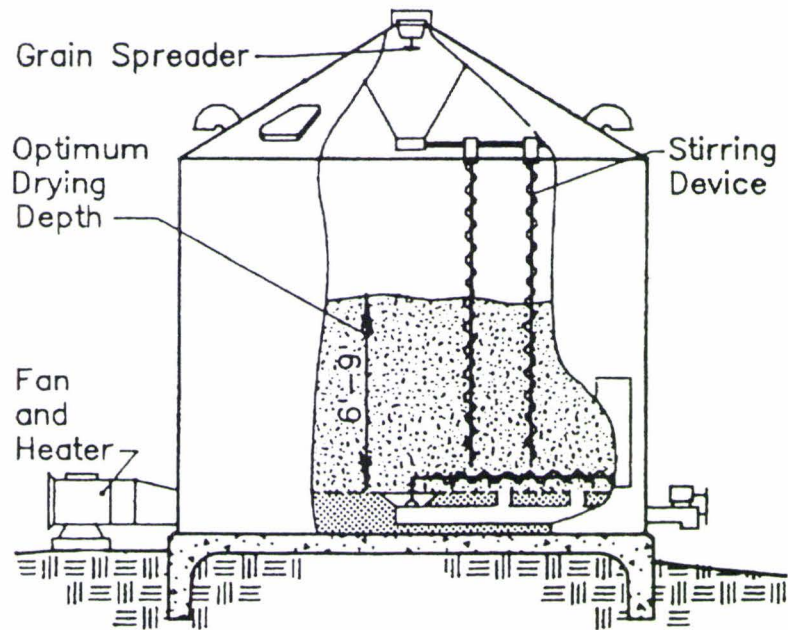
FIGURE 4 Schematic of on-floor bin-batch drying systems (Brooker et al.,1992)
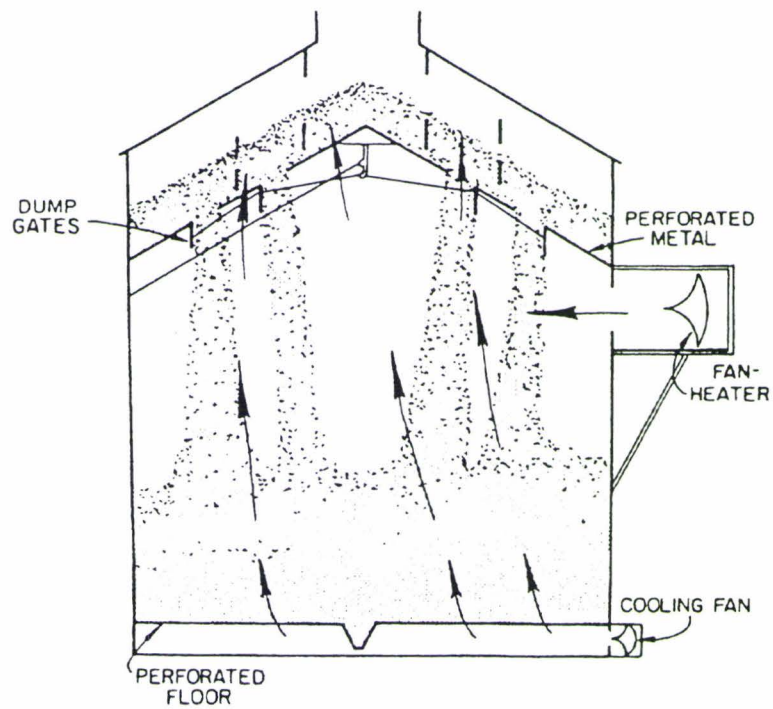
FIGURE 5 Schematic of a roof bin-batch system (Brooker et al.,1992)
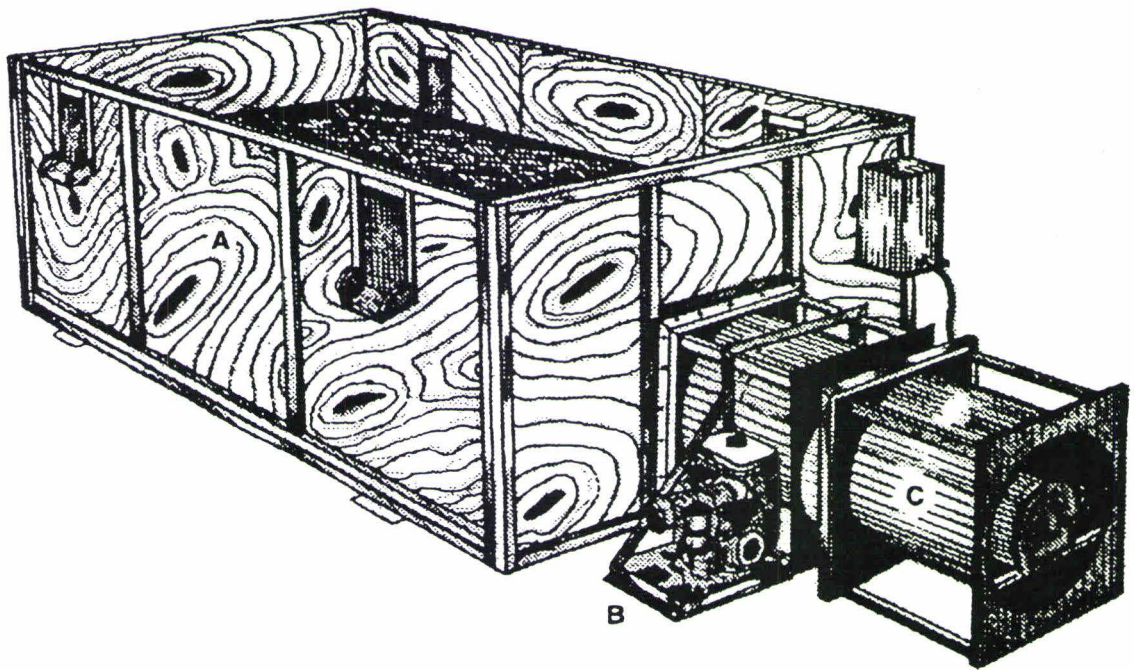
FIGURE 6   The University of the Philippines at Los Baños 2 tonne Flat-bed Dryer
(Tumambing, 1995)

ii) Re-circulating batch dryers

These dryers are mostly portable and can be moved relatively easily from farm to farm. They were designed to re-circulate grain during drying to improve their drying capacity and to avoid the problems of moisture gradients experienced with the bin dryers. The dryer is normally a self-contained unit with annular (ring-shaped) drying chamber around a central plenum chamber (a fan and heater) and a central auger for transporting the grain from the bottom to the top. The grain is discharged from the top when drying is complete (Brooker, 1992). Tumambing (1995) claimed that re-circulating batch dryers are a hybrid of batch and continuous flow dryers.

iii) Continuous-flow dryers

These dryers can be considered as an extension of the re-circulating batch dryers (Brooker et al., 1992). In some systems, the grain is removed from the bottom, cooled, and then conveyed to tempering or storage bins. There are four categories of continuous-flow dryers (Figure 7) based on the way in which grain is exposed to the drying air: cross-flow, counter-flow, concurrent-flow and mixed flow. The air and grain move in perpendicular directions in crossflow dryers, in parallel directions in concurrent-flow dryers, and in opposite direction in counterflow dryers. The flow of the air and grain in mixed-flow dryers is a combination of crossflow, concurrent-flow, and counterflow.
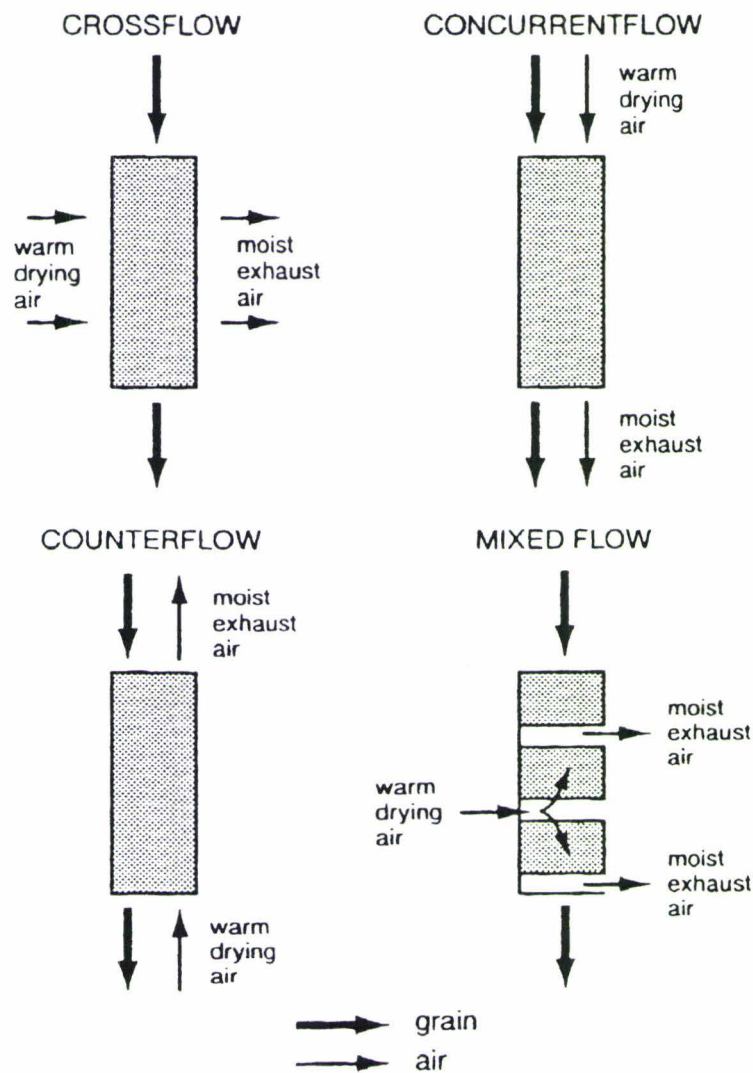
FIGURE 7   Schematics of the four major types of high-temperature grain dryers
(Barker-Arkema et al., 1995)

Barker-Arkema et al. (1995) reported that the choice of particular type of dryer is frequently based on the initial cost, rather than on technical factors such as energy efficiency and grain quality. This has led at times to the employment of inappropriate dryers, and to the production of inferior-grade grain and also the consumption of excessive fossil-fuel energy. For instance, it has been shown that the modern crossflow dryers do not dry grain uniformly; but they are suitable for drying maize as feed, and less expensive than mixed-flow dryers and concurrent-flow dryers (Barker-Arkema et al., 1995). For the drying of rice (and maize for food), mixed-flow and concurrent-flow dryers are recommended because of their superior grain-quality characteristics. The concurrent-flow models have, in general, the best energy efficiency (Barker-Arkema et al., 1995).

2.2.3 Two-stage drying and dryeration

Two-stage drying is normally applied for high temperature dryers. Brooker et al. (1992) noted that this method of drying can increase dryer capacity and efficiency by discharging the grain from the dryer before it is cooled. It is an on-farm practice that is used in three drying processes: dryeration, immediate cooling, or combination cooling.

Dryeration has become an accepted practice by grain processors who export large quantities of maize (Brooker et al., 1992). It is a combination of the terms drying and aeration. This process involves drying with a high-temperature dryer, tempering and finally cooling. The grain is usually dried from about 22 - 28 % moisture content in a high-temperature batch or continuous-flow dryer to an intermediate moisture content of 18 - 20 %, and then moved hot to an in-bin dryer. After tempering for 6 to 8 hours, it is finally dried slowly and cooled with ambient air. The main advantages of this drying technique are the increased drying capacity and the improved energy efficiency and grain quality (Liu et al., 1998). White et al. (1982) reviewed the use of "dryeration" process to allow the hot grain from the dryer to temper for a period of time before being slowly cooled and the authors found that the technique significantly reduced the incidence of stress cracks.

2.3 Grain quality

Grain quality has become an increasingly important issue in the grain trade world-wide due to the increased export competition and more stringiest food-safely demands (Maier, 1994). It is, however, a nebulous term because its meaning depends on the type and the end use of the grain (Brooker et al., 1992). The sale of the product generally depends on the economic laws of supply and demand. Thus when the product is sold the needs of both buyers and sellers must be met. Such needs may vary in respect to quality, which may be evaluated differently by the potential buyers (de Lucia and Assennato, 1994). The commonly desirable properties of shelled maize, according to Brooker et al. (1992) are:

(1) appropriately low and uniform moisture content

(2) high bulk density or test weight;

(3) low percentage of foreign material

(4) low percentage of discoloured, broken, heat-damaged, and shrunken kernels

(5) low breakage susceptibility

(6) high milling quality

(7) high oil content and recovery

(8) high protein content

(9) high nutritive value

(10) high viability

(11) low mould count

(12) low carcinogen content

(13) low insect damage

The relative importance of these properties varies considerably according to the end user. The maize grower is usually interested in the grain seed of high viability; the wet-miller is interested in maize of high starch yield, high oil recovery and high protein quality; the cattle feeder is interested in maize of low mould count and high nutritive value; and the grain dealer focuses mainly on grain with low and uniform moisture content, low percentage of stress crackage, low susceptibility to breakage and high test weight (Brooker et al., 1992).

2.3.1 Grain physical properties

a) Moisture content

Moisture content (MC) of grain denotes the quantity of water per unit mass of either wet or dry grain, usually expressed on a percentage basis. It plays a crucial role in post-harvest processing and is associated with most of the induced grain characteristics (Trim and Robinson, 1994). Moisture content is not an intrinsic quality factor but it does have a significant influence on quality, processing properties and on economics (Watson, 1991). Determination of moisture is an essential step in quality evaluation of cereal grains and products of their processing and the behaviour of grain in both storage and during milling depends to a great extent on its moisture content. Moisture content also influences the keeping quality of flour and bakery products. 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).

The initial moisture content of maize at harvest may be as high as 40 % and the maximum safe storage level is about 13.5 %. However, cob maize of up to 20 % moisture content may be stored in ventilated bins or cribs (Hill, 1997). MC is the overall major factor determining the storage behaviour of grain.

Grain moisture content (wet and dry basis) are generally defined as (Brooker et al., 1992, McLean, 1989; Hall, 1980):

$$MC_{w.b} = \frac{weight\ of\ water}{weight\ of\ undried\ grain} \times 100 \qquad \text{.........................} \quad (2)$$

$$MC_{d.b.} = \frac{weight\ of\ water}{weight\ of\ dry\ matter} \times 100 \qquad \text{........................} \quad (3)$$

To convert moisture content from wet basis ($MC_{w.b.}$) to moisture content dry basis ($MC_{d.b.}$) and vice versa, Equations (4) and (5) should be used (Brooker et al., 1992, McLean, 1989; Hall, 1980):

$$MC_{d.b.} = \frac{100 \times MC_{w.b.}}{100 - MC_{w.b.}} \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (4)$$

$$MC_{w.b.} = \frac{100 \times MC_{d.b.}}{100 + MC_{d.b.}} \qquad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (5)$$

Both indices of MC can be determined by indirect and direct methods in which the moisture content of the product must be maintained from the time the sample is obtained until the determination is made. In indirect methods, the measurement of an electrical property of grain (either conductance or capacitance) is required. They are generally used when purchasing and selling grains. Direct methods, on the other hand, which are mostly used in laboratories, determine the amount of water in the grain by removing the moisture from the grain (Brooker et al., 1992). The two most common laboratory methods are:

- *Oven methods* - Several oven procedures are available for moisture determination. Two procedures are generally used: (1) grind the grain and dry in the oven from 1 to 2 hours at 130 °C; and (2) place the whole grain in the oven at 103 °C for 72 to 96 hours. The amount of weight loss is calculated and the moisture content of the grain can be determined using equation (3) (Brooker et al., 1992).

- *Distillation methods* - the moisture is removed by heating the grain in oil and either collected volume or weight of water removed from the grain in condensed vapour is determined. In the Brown-Duvel distillation method, the whole grain is weighed and placed in oil. The oil is heated and the evaporised moisture is condensed and measured in a graduated cylinder (Brooker et al., 1992). The Brown-Duvel method was once a standard procedure but is no longer used, having been superseded by electronic meters (Christensen et al., 1992).

b) Bulk density

Bulk density (BD) or test weight (TW) of grain is the weight of grain in a given volume, usually expressed as kilograms per hectolitre (kg/hl) (Hardacre et al., 1997). It

affects the bin volume required to store a certain tonnage of grain. For example, a decrease in test weight of maize from 708 kg/m^3 to 643 kg/m^3 means that the storage volume has to be increased by about 10 % in order to store the same mass of grain (Brooker et al., 1992). BD has been accepted in the past as a measurement of grain hardness (Watson, 1991). It is also a measure of grain size and shape and kernel structure and integrity as influenced by disease, frost damage, cracking and other factors leading to grain deterioration (Brenton-Rule et al., 1998).

Bulk density has been included in grading quality standards since 1918 (Stroshine et al., 1986). Paulsen and Hill (1985) reported the results of commercial dry milling runs in which high bulk density maize with low breakage susceptibility gave a higher yield of flaking grits than low bulk density maize with high breakage susceptibility.

Bulk density of grain usually increases during drying process as its moisture content decreases. The increase depends on (1) the degree of kernel damage, (2) the initial moisture content, (3) the temperature reached by the grain during the drying process, (4) the final moisture content, and (5) the grain hybrid. However, bulk density is not considered as a reliable indicator of grain quality and no consistent correlation have been established between a high bulk density value and favourable end use properties in the United State grain market (Brooker et al., 1992).

Grain bulk density is hybrid dependent (Hardacre et al., 1997), and thus hybrids with inherently lower average bulk densities are not necessarily of poor quality. However, their potential uses in the marketplace will differ from those of a hybrid with a high bulk density. Hybrids with low bulk density may suit the wet milling or animal feed industries while those of high bulk density have potential for dry milling. Brenton-Rule et al. (1998) suggested that for bulk density to be useful as a quality indicator, each hybrid must have its own specifications. End-users should assess which hybrids are suitable for their operations, then establish critical bulk density levels relative to hybrid performance.

To determine kernel density of maize grain, Kirleis and Stroshine (1990) weighed 100 kernels and measured the volume of 95 % ethanol displaced by the weighed maize sample. The authors, later on, used AACC method 55-10 to determine the grain bulk

density in pounds per bushel and converted to kilogram per hectolitre using the factor 1.2875 in their study. Joshi et al. (1993) and Jain and Bal (1997), on the other hand, used a standard hectometre vessel to measure bulk densities of pumpkin and pearl millet grains. They filled the vessel with clean grains and gently tapped five times to cause the grains to settle. After initial settling, the hectometre vessel was further filled with grains and again tapped twice. A sharp edge flat was used to remove excess grains to level the surface at the top of the vessel.

c) Stress cracks and breakage susceptibility

Stress cracks in maize grain are internal fissures in the kernel endosperm which may not be open at the surface underneath the pericarp. They originate at the centre of the floury endosperm and propagate radially outward, toward the kernel periphery along the boundary of starch granules (Gunasekaran et al., 1985). A typical maize kernel stress crack has a maximum width of about 58 ± 14 µm (Brooker et al. 1974). Their formation is caused by stresses inside the kernel, resulting primarily from differential zones of moisture content as water moves from the interior of the kernel and evaporates at the surface during high temperature drying (Watson, 1991). Gunasekaran and Paulsen (1985) reported that several factors such as grain moisture content, grain temperature, thickness of horny endosperm, maize genotype, and temperature of drying air affect percentage of stress-crack kernels.

A measurement of the tendency for the maize kernels to break is a significant quality attribute. Stress-crack evaluation can be useful not only to detect maize that has been dried rapidly, but also in predicting increases in fine material that may be expected from breakage during handling (Thompson and Foster, 1963). Highly stress cracked maize may likely yield less recoverable starch than sound kernels (Gunasekaran et al., 1985), always causes low germination and reduces market value due to likely insect and microbial attack (Thompson and Foster, 1963). Dry millers expect a lower yield of the more valuable large grits in maize dried with a high percentage of stress cracks. During wet milling, kernels with stress cracks and subsequent broken kernels steep more rapidly and lose part of their starch in the steep water before the sound kernels steep adequately. Also, the protein in the endosperm of severely stress-cracked kernels,

due to high kernel temperatures during drying, is case-hardened which makes separation of protein and starch more difficult (Almeida-Dominguez et al., 1998).

The most common problem associated with stress cracking is breakage susceptibility of the kernels. As the number of stress cracks in maize increases the susceptibility to breakage also increases (Litchfield and Fortes, 1982; Thompson and Foster, 1963). Breakage susceptibility of grain is defined as the potential for kernel fragmentation or breakage when subjected to impact forces during handling and transport, (AACC, 1983). Gunasekaran and Paulsen (1985) noted that because maize grain may be handled as many as 20 times from harvest to export, buyers (domestic and foreign) prefer grains that are resistant to breakage during handling. Breakage resistance of maize can be defined as the ability of the kernels to safely withstand various stresses during conditioning, handling and transportation.

Breakage is important because small fragments affect the price by influencing the grade factors of test weight and broken corn and foreign material (BCFM). Small kernel pieces plus BCFM segregate during bin filling and create resistance to air flow in the stored grain. Without adequate air movement to control temperature and moisture, the segregated material will promote the development of moulds and insects (Martin et al., 1987).

Methods proposed to measure breakage susceptibility can be classified into two groups: (1) subjective methods that measure the extent to which whole kernels develop stress cracks, and (2) methods that measure the amount of cracked grain formed when whole grains are impacted or ground (Miller et al., 1981). At present a candling procedure is used to manually inspect maize kernels for presence of stress cracks. For maize, a 150 W light source is used in a box with a small glass covered opening and individual single kernels are held with the germ side over the light. The stress cracks are then classified as single, multiple and checked (i.e., kernels with two or more intersecting cracks). However, this process takes considerable amount of time and effort and tend to be less accurate owing to fatigue of the human eye if large samples are involved (Gunasekaran et al, 1985). Stress cracks can also be visible by x-ray and scanning electron microscope techniques (Brooker et al., 1992).

Kirleis and Stroshine (1990), on the other hand, used a Stress Crack Index (SCI, %) to assess the severity of stress cracking in artificially dried maize:

$$SCI = SCK + 3\ MCK + 5\ CHK \qquad\qquad .... (6)$$

Where
   SCK = single cracked kernels (%)
   MCK = multiple cracked kernels (%)
   CHK = checked kernels (%).

Their results indicated that SCI of the dried maize grain increased to maximum values as the drying temperature went from 27 to 60 °C, remained about the same at 60 and 82 °C, and decreased at 93 °C.

In order to provide rapid and reliable methods of estimating the potential for breakage during subsequent handling, several devices for measuring breakage susceptibility have been developed and used (Gunasekaran, 1988). Ultimately, the devices may be also useful for predicting the relative value of maize for end uses such as dry milling (Paulsen and Hill, 1985).

Although many devices measure breakage susceptibility, the Stein Breakage Tester (SBT) has been used frequently (Stroshine et al., 1986). The Stein breakage tester is generally considered to be the most suitable device for determination of breakage susceptibility of maize. It is the device recommended for use by AACC Method 55-20 (AACC, 1983). In the test, a 100 g sample is placed in a 9 cm-diameter steel cylinder and an impeller centrally located in the cylinder and rotating at 1790 rpm throws the kernels against the sides of a container for 2 min. After that, the sample is screened on a 4.76 mm round-hole sieve; the maize remaining on the sieve is weighed, and the weight loss is expressed as the percent breakage of the sample (Brooker et al., 1992).

d) Hardness of grain

Hardness of grain is defined as resistance of grain to grinding (Martin et al., 1987). It is related to the protein content and kernel physical properties including kernel density,

bulk density, and the ratio of hard to soft endosperm. It is also related to storability, attack by storage insects, breakage susceptibility caused by drying, storage, handling, or processing (milling characteristics, power requirements, dry and wet milling yields), production of special foods, and the grain classification (Watson, 1987).

It is of great significance to producers, processors, and workers in grain trade. Maize dry millers seek a maximum amount of endosperm recovered as large grits. Selection of maize lots on the basis of kernel density, bulk density or breakage susceptibility can significantly improve flaking grit yields. Similarly, varietal differences in dry-milling quality among commercial hybrids have been demonstrated, with "hard" hybrids exhibiting more desirable milling characteristics (Pomeranz et al., 1984). Kirleis and Stroshine (1990) reviewed that food maize processors also prefer "hard" hybrids which usually exhibit more desirable milling characteristics than the "softer" one.

The Stenvert Hardness Test (SHT) has been reported as a useful tool for measuring kernel hardness. Brenton-Rule et al. (1998) recommended SHT for testing maize grain attributes in New Zealand. Samples with high Stenvert hardness values are more reliable in dry milling and give higher grit recovery. The authors stated that the SHT determines the hard:soft endosperm ratio of grain samples and, by inference, an indication of the milling potential. Grain hardness is dependent mainly on hybrid, but is also affected by agronomic practices and climate (Brenton-Rule et al., 1998).

Pomeranz et al (1985) described a SHT using 20-g maize samples which were ground in a Glen Creston Type 4 micro-hammer mill, and using a 2.0-mm aperture screen and a hammer speed of 3,600 rpm. The time required to collect 17 ml of whole meal, measured to the nearest 0.1 sec, was used as a measure of grain hardness. Martin et al. (1987) summarised the information usually recorded in a SHT and their interpretations:

1. Time (s): resistance to grinding;
2. Column height: height in receptacle (mm) of freshly ground product;
3. Volume C/F: Coarse to Fine particle ratio determined by height of freshly ground corn in the receptacle; visual distinction was made by yellow colour of horny endosperm);

4. Weight C/F: Coarse to Fine particle ratio determined by weight of sieved fractions; particles larger than the 0.71-mm sieve opening were coarse and mostly endosperm; particles smaller than the 0.5-mm sieve opening were fine and mostly starch.

2.3.2 Nutritive quality and chemical properties

For a vast majority of the world population, cereal-based foods are the major source of energy and nutrients. In the North American diet, cereal foods provide about 20 – 25 % of total energy. Cereal grains do not contain vitamin B12, and they are low in certain important nutrients. However, they are the major source of several of the approximately 40 different nutrients we need for good health (Ranhotra, 1991).

Hoseney (1994) stated that cereal grains store energy in the form of starch and amount of the starch varies but is generally between 60 and 75 % of the weight of the grain. Thus much of the food that humans consume is in the form of starch which is an excellent source of energy. The author also stated that protein of cereal grains is also an important nutrient in human diet. The type and amount of protein is important from a nutritional standpoint.

Because maize is one of the main food and feed grains, its nutritive value is a very important quality factor. The high starch content is an energy source for humans, ruminant and non-ruminant animals (Brooker et al., 1992). The chemical components and nutritive value of maize do not lose their susceptibility to change when the grain is harvested. Subsequent links in the food chain, such as storage and processing, may also cause the nutritional quality of maize to decrease significantly or, even worse, make it unfit for either human and animal consumption or industrial use (FAO, 1992). Grain constituents such as proteins, sugars and gluten may be adversely affected when the grain attains excessive temperatures. The feeding value of grain can be lowered if it is inadequately dried. It was found that high-temperature drying of feed grain reduced its feed value in non-ruminants but not in ruminants. The decrease in the feed value of maize dried at high temperatures was attributed mainly to the deleterious heating effect

on several amino acids in the proteins of maize, particularly on lysine (Brooker et al., 1992).

2.3.3 Grain viability

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

The viability of grain is directly linked to the temperature attained by grain during drying. The types of damage associated with the use of excessive heat during the drying of grain include loss of viability, the production of abnormal seedlings, internal cracks, split grain coats and discoloration. 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 and seed germination. A high percentage of checked or crazed kernels in maize sample almost assure 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.

Grain destined for use as seed must be dried in a manner that preserves the viability of the seed. Drying temperatures must be kept below a certain maximum temperature to avoid damaging the germinating ability of grain seeds. Seed embryos are killed by temperature greater than 40 - 42 °C and therefore low temperature drying regimes must be used. It is essential that batches of grain of different varieties are not mixed in any way and therefore the dryer and associated equipment used must be designed for easy cleaning. In this respect simple flat-bed dryers are more suitable than continuous-flow dryers (Trim and Robinson, 1994).

2.3.4 Mould growth

Cereal grains are hosts to a large number of different types of microflora. These include the types that invade the grains as well as those that are surface contaminants. The most important of the microflora, as far as grain storage is concerned, are the fungi, which grow at a much lower interseed relative humidity than other microflora (Hoseney, 1994). Seed-born pathogens rarely kill the seed, but may cause seedling stunting or abnormalities, reduced plant growth and lowered crop yields (Hampton, 1994).

The extent of contamination by moulds is largely determined by the temperature of the grain and the availability of water and oxygen. Moulds can grow over a wide range of temperatures, from below freezing to temperatures in excess of 50 °C. In general, for a given substrate, the rate of mould growth will decreases with decreasing temperature and water availability (Coker, 1994).

Certain nutritional factors are destroyed in mouldy cereal grains and feeds (Pomeranz, 1992). Many changes in maize grain quality are linked to the growth of mould and other micro-organisms. Mould growth causes damage to individual grains resulting in a reduction in value. It impairs sensory characteristics, nutritional value and functional properties (in milling, baking, malting, etc.) of the grain, and may result in production of a variety of mycotoxins (FAO, 1984). The rate of development of micro-organism is dependent on the grain moisture content, grain temperature, and the degree of physical damage to individual grains (Hill, 1997). A high percentage of maize in Guatemala, for example, was found contaminated by fungal growth because of the high moisture level in storage. The seed germination capacity was almost completely or totally destroyed (FAO, 1984).

Rainfall during ctritical phases of crop development can, for example, lead to mould contamination and mycotoxin production (Coker, 1994). In post-harvest handling, on the other hand, drying too slow can lead to mould growth in high moisture content grain, rapid loss of vigour and eventually germination loss. Drying too fast, however, can cause cracking and splitting (including internal cracking), case hardening, discoloration and loss of germination and vigour (Hill, 1997).

2.3.5   Grain safety (as food material)

Implications of hygienic and nutritive deterioration have been studied only to a limited extent and are poorly defined, partly because the effects of feeding deteriorated stored products are sometimes difficult to demonstrate. However, consumption of cereal grains infested by insects or mites may cause digestive or similar ailments. Workers handling infested commodities have been affected by skin rashes and various kinds of dermatitis from the presence of insects or mites or of their cast-off skins, hairs, or excreta (Pomeranz, 1992).

There have been many reports on the formation of toxic compounds in mould-damaged foods and feeds. A diet containing mouldy oilseed meals may retard the growth of poults. Oxidation of unsaturated fatty acids in damaged grain is involved in the appearance of muscular dystrophy in pigs (Pomeranz, 1992).

Mycotoxin contamination of foods and feeds affects the marketing and utilisation of grains, because mycotoxins may cause or contribute to human and animal health problems. Mycotoxins are fungal metabolites that are toxic to animals, and mycotoxicoses are diseases resulting from ingestion of toxic fungal metabolites contaminating the food or feed supply (Wilson and Abramson, 1992). Under certain circumstances mycotoxin development can be a particular hazard. A variety of animal management problems and disease symptoms have been observed as a result of ingestion of mouldy maize. Among the major problems encountered in farms are diarrhoea, milk reduction, unthriftiness, lack of weight gain and general food refusal. Moreover, an extensive outbreak of apparent human aflatoxicosis in India involved mouldy maize; affected were 400 people and over 100 deaths were reported (FAO, 1984).

Since the occurrence of mould (such as mycotoxins) on grain is a consequence of bio-deterioration, it follows that the mould problem is best addressed by controlling those agents (temperature, moisture and pest) which encourage spoilage. In overall, appropriate post-harvest handling (such as cleaning, drying and storage) of grains does present many opportunities for controlling the mycotoxin production (Coker, 1994). However, despite the best efforts of the agricultural community, mycotoxins will

continue to be present in a wide range of foods and feeds. Consequently, strategies are required for the removal of mycotoxins from grains. Currently, two approaches are utilised; namely, the identification and segregation of contaminated material and, secondly, the destruction (detoxification) of the mycotoxin(s) (Coker, 1994).

2.4 Grain quality grade standards

Because every buyer or user of the grain is not interested in the same quality factor, general criteria of the grain quality must be established and accepted by all parties in the grain trade. The most appreciable measurement is called "grain quality grade standards". The term "standard" in this context, according to Clarke and Orchard (1994), refers to the measures that serve as a basis for making comparisons or judging the accuracy of unknown samples. According to Brooker et al.(1992), the purposes of "grain quality grade standards" are to:

(1) facilitate marketing,

(2) identify economic factor important to end users, and

(3) reflect storability.

However, the grain quality factors considered in the standards for a grain species are not the same for every country. Tables 5, 6 and 7 below illustrate the grade standards for maize in some major corn-exporting countries (the United States, Argentina and South Africa):

TABLE 5 Grade standard for yellow corn in the United States (Brooker et al., 1992)

Grade Factor	No.1	No.2	No.3	No.4	No.5[a]
Moisture[b] (max. %)	14.0	15.5	17.5	20.0	23.0
Test weight (min. lb)	56.0	54.0	52.0	49.0	46.0
BCFM (max. %)	2.0	3.0	4.0	5.0	7.0
Heat damage (max. %)	0.1	0.2	0.5	1.0	3.0
Total damage (max. %)	3.0	5.0	7.0	10.0	15.0

[a] *Quality below No.5 on any factor is labelled "sample grade"*
[b] *Excluded from the standard since 1987*

TABLE 6 Grade standard for dent corn in Argentina (Brooker et al., 1992)

Grade Factor	Maximum Percent Allowable			
	No.1	No.2	No.3	No.4
Damaged kernels	3.0	5.0	8.0	12.0
Broken kernel	2.0	3.0	5.0	5.0
Foreign material	1.0	1.5	1.5	2.0

TABLE 7 Grade standard for dent corn in South Africa (Brooker et al., 1992)

Grade Factor	Maximum Percent Allowable		
	No.1	No.2	No.3
Defective corn kernel	9.0	20.0	30.0
Other coloured corn kernel	2.0	5.0	5.0
Foreign matter	0.3	0.5	0.75
Sum of the above three defects	9.0	20.0	30.0
Pink corn	12.0	12.0	12.0

These three countries distinguish differently between broken corn, damage and foreign material. The Argentinean standard separates foreign materials (i.e. all non-maize particles), broken kernels, and damaged kernels (i.e., fermented, sprouted, mouldy, burned); the broken kernels are those passing through a triangular hole 3.17 mm on each side. The South African standard combines the mouldy kernels with the broken pieces passing through a 6.35 mm round-hole sieve, and defines this quality as defective corn. In the United States, the broken corn is combined with the foreign materials into the BCFM (Broken Corn and Foreign Material) factor that contains all material in a sample passing through a 4.76 mm round-hole screen. Thus, the numerical grades of the three countries for corn cannot be compared directly (Brooker et al., 1992).

2.5 Evaluation of dryer performance

Postharvest losses of grain, due to delayed or improper drying or lack of drying facilities, are still high especially when harvesting coincides with rainy season. However, as it was stated earlier, drying operation must not be considered as merely the removal of moisture since many grain quality attributes can be adversely affected by incorrect selection of drying conditions and equipment (Trim and Robinson, 1994).

Performance evaluation of existing or new dryers is therefore critical to facilitate the selection of drying parameters to ensure optimum grain quality.

Poor or defective drying facilities or incorrect drying procedures may result in very fast drying rate, incomplete drying and uneven moisture re-absorption within the grain mass. Improper drying results in high cost, low efficiencies, high milling losses, poor quality of the grain or reduced germination capacity of the dried seeds (ESCAP, 1995).

Increasing emphasis on grain quality and energy conservation has created a need to develop drying systems that will deliver a better quality product with lower energy consumption for drying (Gustafson et al., 1978). In the design and utilisation of grain dryers it is important to understand the effects of drying parameters such as drying air temperature, drying time, air flow rate, tempering time and temperature on quality of the dried grain (Abe et al., 1992).

Evaluation of performance of grain dryers and understanding the effects on grain properties are, therefore, very important to satisfy the need of grain producers, grain traders, grain processors and grain users. There are two broad criteria for evaluating dryer performance, namely operational performance and effects on dried grain quality (ESCAP, 1995). These will be briefly reviewed in the following sub-section.

2.5.1 Operational performance
a) Drying efficiency

The drying efficiency of the drying operation is an important factor in the assessment and selection of the optimum dryer for particular task. There are three groups of factors affecting drying efficiency: (a) those related to the environment, in particular, ambient air conditions; (b) those specific to the crop; and (c) those specific to the design and operation of the dryer (Trim and Robinson, 1994).

There are several different ways of expressing the efficiency of drying. Adeyemo (1993) reviewed that drying efficiency (expressed in terms of fuel efficiency, sensible

heat utilisation efficiency and drying efficiency) are very important consideration in dryer selection. Drying efficiency (DE) is based on how well a drying system converts sensible heat to latent heat which can be expressed as follows:

$$DE = \frac{HU}{HA} \times 100\% = \frac{WWE \times LHV}{WF \times HVF} \times 100\% \qquad \dotfill (7)$$

Where

HU = heat utilised for moisture removal (kJ)

HA = heat available for moisture removal (kJ)

WWE = weight of water evaporated (kg)

LHV = latent heat of vaporisation (kJ/kg)

WF = weight of fuel utilised (kg)

HVF = heat value of fuel (kJ/kg)

b) Drying capacity

Arinze et al. (1996) defined drying capacity (DC) of a dryer as the rate at which the wet product can be dried to specified moisture content while the dryer is operated at specified drying conditions. The capacity is one of the most important factors in designing and utilisation of grain dryers. Decision making by purchasers or operators of grain dryers would be simplified if manufacturers or designers used common criteria to describe the performance of their products (McLean, 1989). For instance, what weight of maize at 25 % moisture content can be dried to 14 % when drying air temperature is 58 °C. If the capacity of the dryer is inadequate, an extreme possibility encountered in practices would be that: (a) harvesting will be delayed to the extent that grain will be overripe and shattered, or (b) its moisture content rises in the field and thus additional fuel or energy will be required to dry it when eventually it is harvested or (c) the grain that have been harvested will be deteriorated when drying has to be delayed or (d) the amount of grain to be dried is very small comparing to the high capacity of dryers.

c) Specific total energy consumption

ESCAP (1995) defined the specific total energy consumption as the total energy used per kilogram of water evaporated. The utilisation of the world's reserves of fossil fuel is a controversial subject which makes it appropriate that the energy requirements of grain drying systems are considered when new installations are planned (McLean, 1989).

d) Labour requirements, ease and safety of operation

Good design of grain dryer should not be very complicated to operate nor require many workers or operators. It is also necessary for the design and operation of grain dryer to be carried out safely by those who operate, or have reason to visit grain drying (McLean, 1989). ESCAP (1995) listed the ease and safety features and hazards, relating to operation of grain dryers, which are of the following:

     i/   fire and electrical hazards

     ii/   unguarded power transmission shafts, belts, pulleys, etc.

     iii/ noise level

     iv/ unusual vibration

     v/   dust emission control

     vi/ ease or difficulty of loading and unloading grain

     vii/ ease or difficulty of making adjustments

     viii/ ease or difficulty of cleaning and repairing parts and

     ix/ other significant operational, safety and hazardous features of the dryer.

e) Economic performance

It would be of great benefit if artificial or mechanical dryers could be designed and managed in ways to reduce or minimise their capital and drying costs. It is obvious that wide-spread introduction of grain dryers can not be avoided in the near future in many

countries. However, to be successful the dryers would have to be economical in its capital and running (or drying) costs (Ofoche et al., 1991). To achieve this goal, dryers should be designed taking full consideration of costs, local environmental conditions, and skill and material available.

Despite the utilisation period of most of the grain dryers are only a few weeks per year, variation in the capital cost of grain dryers and their specific energy consumption do exist. It may be necessary to calculate the worthwhile factors of purchasing an expensive dryer with low fuel or energy consumption by contrast with a less expensive one (McLean, 1989). In India, for instance, an important reason for not using dryers is their high initial costs. Most of the commercially available dryers are designed to suit the needs of the processing industry and their output capacity is therefore far above the needs of individuals, or even of farmer groups (Shukla and Patil, 1988).

The major expenses with grain dryer is for fan(s), motor(s) and heated air system (Hall, 1980). Cost of fuel and/or power for drying grain is dependent greatly on weather conditions. The cost of drying grain with unheated or heated forced air varies greatly with atmospheric temperature, humidity, and grain moisture content (Hall, 1980).

2.5.2 Effects on dried grain

Drying process has been known to the quality of the dried grain. Damage to grain may be caused by either drying it too slowly or too rapidly. If grain is dried too slowly and for too long a period, undesirable deterioration such as mould growth occurs. When grain is dried too rapidly, a different type of damage also occurs. Hardacre et al. (1997) argued that damaged maize grain includes all the kernels and the pieces of kernels that are heat damaged, sprouted, frosted, severely ground or weather damaged, diseased, or otherwise materially damaged.

Previous studies have shown that maize grain dried from higher moisture content cracked and broke easier than those that dried from lower moisture content (Thompson and Foster, 1963; Ross and white, 1972; Weller et al., 1990). Ross and white (1972)

concluded that moisture content prior to drying affected stress crack formation in dried maize. Higher grain initial moisture content increased the incidence of cracking in dried grain. Thompson and Foster (1963) also observed that the percentage of maize kernels with stress cracks decreased from 97.8 to 93.2 % as moisture content prior to drying decreased from approximately 30 to 20 % (w.b.).

Fast drying, hence high drying rate and capacity, can normally be obtained by using air of high temperature and flowrate. Rapid drying, however, makes grain more brittle and more subject to damage when handled. Extremely rapid drying results in grain of reduced bulk density with kernels that are enlarged or puffed. If grains is dried at high temperatures, discoloration and other kinds of heat damage may occur (Foster, 1973).

Thompson and Foster (1963) found that internal damage was frequently the consequence of high-temperature drying process and as the number of stress cracks in the maize grain increased the susceptibility to breakage increased. When handled and transported, the kernels with stress cracks break more readily than sound kernels leading to considerable amounts of broken grains and fine material. The authors also reported that shelled maize dried with heated air at 60 to 115 °C was two to three times more susceptible to breakage than the same corn dried with unheated air.

Peplinski et al (1994) reported that as air-drying temperature increased from 25 to 100 °C, maize kernel test weight and germination decreased, kernel breakage susceptibility and percentage of floating kernels increased, and 100-kernel weight and stress-cracked kernels were unchanged. Brooker et al. (1992) reported that the feed efficiency (average daily gain, daily maize intake and feed/gain ratio of rats), and thus the nutritive value of the maize, was affected when the grain was dried at 50 °C. They became worst for the higher air temperature.

For each of the three maize hybrids (hard, intermediate, and soft), Kirleis and Stroshine (1990) found that Stenvert hardness values remained relatively constant when grain was dried at temperatures from 27 up to 60 °C. The hardness declined only slightly, but not significantly, at the higher drying temperatures. At drying temperatures of 60 to 93 °C, bulk density was significantly different among the three tested hybrids and decreased in the following order: Hard > intermediate > soft. The

authors concluded that Stein breakage susceptibility was primarily influenced by hardness. Stein breakage was greatest for the soft hybrid and least for the hard hybrid.

2.6 Grain drying models

Systematic studies of grain drying characteristics would be needed to develop drying prediction equations suitable for use in the modelling of the drying processes. One useful relationship in grain drying is the heat balance equation (Brook, 1992), which relates the heat used to evaporate water from grain to the heat loss from the drying air as it reaches the grain temperature. The relationship assumes that there are no heat gains or losses from the system. The heat balance can be written as follows:

$$W_a \times c_a \times (T_a - T_g) = W_g \times (MC_o - MC_e) \times L \qquad \text{...............................} (8)$$

Where

W_a = mass (weight) of air (kg/h)

c_a = specific heat of air (kJ/kg.$^{\circ}$C)

T_a = heated air temperature ($^{\circ}$C)

T_g = exhaust air temperature ($^{\circ}$C)

W_g = mass (weight) of grain (kg)

MC_o = initial grain moisture content (decimal, d.b.)

MC_e = equilibrium grain moisture content (decimal, d.b.) and

L = latent heat of vaporisation of moisture from grain (kJ/kg).

Based on the assumption that drying of grain in deep bed can be taken as the sum of several thin layers, many researchers have used thin layer equation to predict drying of grain in deep bed. Michael and Ojha (1978) stated one of the features of the thin layer drying is that the grain depth is limited up to 20 cm. Thus, thin layer drying refers to the drying of grain fully exposed to the ventilating air causing all grains to dry uniformly throughout the drying layer.

2.6.1 Thin-layer drying model

Thin-layer drying equations can be used for predicting the drying rate of grain as affected by drying air temperature, air-flow rate, initial grain moisture content, and the air relative humidity. They are also used to predict the length of time required to dry the grain to the required moisture level, both in static and continuous cross-flow dryers (Ofoche et al., 1991).

Numerous empirical and semi-empirical thin-layer drying models have been published in the literature describing the drying behaviour of agricultural crops during convective drying (Abe and Afzal, 1997). The most commonly used thin layer drying models are described below:

a) *The exponential model*

This is a lumped model analogous to Newton's law of cooling in heat transfer and is often used to describe mass transfer in thin-layer grain drying:

$$MR = \frac{MC - MC_e}{MC_o - MC_e} = exp(-kt) \qquad \text{..............................} \quad (9)$$

Where

MR = moisture ratio

MC_e = equilibrium moisture content (% d.b.)

MC_o = initial moisture content (% d.b.)

MC = moisture content at time t (% d.b.)

k = drying constant

t = drying time (h).

b) *The Page equation*

This is an empirical modification of the exponential model to include an additional exponent (n):

$$MR = \frac{MC - MC_e}{MC_o - MC_e} = exp(-kt^n) \qquad \text{............................} \quad (10)$$

Several researchers have successfully applied one or both of the exponential and Page models to describe their test results for several crops including: maize (Allen, 1960; Li and Morey, 1984; Misra and Brooker, 1980; Ross and White, 1972; Westerman et al., 1973), peanut (Hummeida and Sheikh, 1989), and pecans (Chinnan, 1984).

Hummeida and Sheikh (1989) studied the effects of air velocity, drying air temperature and relative humidity, and initial pod moisture content on drying characteristics of two peanut hybrids. For the various drying conditions and based on the exponential model the authors determined drying equations and the values of the corresponding drying constants. The authors concluded that a general drying form, as shown by Equation (11), predicted the drying performance of two peanut varieties with coefficients of determination (R^2) ranging between 0.981 and 0.998. The drying rate was affected more by the drying air conditions than by the initial pod moisture content.

$$MC = (MC_o - MC_e) \, exp \, (-Kt) + MC_e \qquad \text{.................................. (11)}$$

Li and Morey (1984) dried 150-g sample of yellow dent maize in wire-mesh tray of 17.8 x 17.8 cm at 27, 49, 71, 93 and 116 °C. The authors used the Page model to fit the experimental data while the time (t) was expressed in minute. The purpose of the experiment was to determine thin-layer drying rates (as affected by drying air temperature, airflow rate, initial moisture content, and relative humidity) and to develop an equation that fits the data and is suitable for use in a deep-bed drying model. The drying constants, k and n, for each drying temperature were determined using linear regression on the transformed equation:

$$ln \, (-ln \, MR) = ln \, k + n \, (ln \, t) \qquad \text{.....................…............. (12)}$$

Data points having moisture ratios above 0.25 were used in the regression procedure. Coefficients of determination, R^2, were all greater than 0.98. General expressions were found for k and n as functions of drying temperature (T in °C) for the five temperatures. The regression analysis for k and n as a function of temperature, with an adjusted R^2 of 0.997, yielded:

$$k = 2.216 \times 10^{-2} + 1.113 \times 10^{-4}T + 3.435 \times 10^{-6}T^2 \quad \text{..............................} \quad (13)$$

$$n = 0.5409 + 1.498 \times 10^{-3}T + 2.561 \times 10^{-6}T^2 \quad \text{..............................} \quad (14)$$

The authors also compared the moisture contents predicted by equation (12) with k and n calculated with Equations (13) and (14), respectively, to the observed moisture contents. There were generally good agreements between the observed and predicted moisture content above 15 % (d.b.) with errors less than one percentage.

Based also on the Page model, Liu et al., (1998) reported that if the effect of initial moisture content is considered, the air flow is from 0.1 to 0.5 $m^2/s/m^2$ and relative humidity (RH) of the drying air is from 5 - 40 %, the typical equations of the moisture ratio (MR) for the drying rate of maize are:

$$MR = exp\ (\ -kt^n\ ) \quad \text{....................} \quad (15)$$

$$k = 1.091 \times 10^{-2} + 2.767 \times 10^{-6}\ T^2 + 7.286 \times 10^{-6}\ T.MC_o \quad \text{........................} \quad (16)$$

$$n = 0.5375 + 1.141 \times 10^{-5}MC_o^2 + 5.183 \times 10^{-5}T^2 \quad \text{........................} \quad (17)$$

Where

k, n = drying coefficients

t = time (min)

T = heated air temperature (27 - 116 °C)

MC_o = initial grain moisture content (23 - 36 % d.b.).

c) The diffusion model

The solution depends on the initial and boundary conditions considered, on whether the diffusion coefficient (D) is considered to be constant or to vary, and on the shape of the grain (Shivhare et al., 1992):

$$MR = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} exp(-\frac{n^2\pi^2 D}{r_o^2}t) \quad \text{.....................................} \quad (18)$$

Where

n - integer

t - time (h)

r - equivalent radius of kernel (cm).

This model was used by several researchers (Steffee and Singh, 1982; Bruce, 1985; Shivhare et al., 1992) to characterise moisture diffusion of drying grain such as brown and rough rice and maize. After drying their maize with microwave, Shivhare et al. (1992) reported that the model was significant at the 0.0001 level with $R^2 = 0.867$.

d) Approximation of the diffusion models

The simplest approximate form of the diffusion model, when only one term of the infinite series is used, can be represented by:

$$MR = A \ exp \ (-Bt)$$ .... (19)

Where A and B are constants to be determined using the experimental data. This model has been used by Handerson (1974) and was observed to become effective after 2 to 3 hours of drying.

2.6.2 Fixed-bed or deep-bed drying model

In order to find the approximate moisture content at any grain depth in a fixed-bed drying during drying, Hukill (1947) and Hukill (1974) developed and used classic drying curves, called bulk-drying curves (Figure 8), at constant inlet-air conditions. The author assumed that the energy required for evaporating moisture from the grain is equal to the change in enthalpy of the air passing through the grain.

The unique terms of this simulation are: the moisture ratio (MR), the half-response time (t^*), the time unit (Y), and the depth factor (D). A mathematical expression for the curves are given by the following equations:

$$MR = \frac{MC - MC_e}{MC_o - MC_e} = \frac{2^D}{2^D + 2^Y - 1}$$ .... (20)

$$D = \frac{x \rho_p h_{fg} (MC_o - MC_e)}{G_a c_a t^* [T(in) - T(out)]}$$ .... (21)

$$Y = \frac{t}{t^*}$$ .... (22)

Where

MC = observed moisture content (decimal, d.b.),

MC_o = initial moisture content (decimal, d.b.)

MC_e = equilibrium moisture content (decimal, d.b.)

t^* = half-response time (is time when MR = 0.5 and is calculated from thin layer drying equation)

t = the length of the drying time (min)

x = the grain depth (m)

ρ_p = grain dry matter bulk density (kg.m^{-3})

h_{fg} = heat of vaporisation (kJ.kg^{-1})

G_a = the ratio of airflow rate per unit bed area (m^{3}min^{-1}m^{-2}) and specific volume of the air (m^3.kg)

c_a = specific heat (kJ.kg^{-1}.^{o}C^{-1})

$T(in)$ = inlet drying-air temperature (^{o}C)

$T(out)$ = exhaust air temperature (^{o}C).

Teter (1987), Brooker et al. (1992) and Trim and Robinson (1994) stated that the curves are helpful in visualizing drying processes and the deep-bed model requires minimum computation time. It is useful in approximating the drying rate of natural air and low-temperature bin dryers. For the simulation of high-temperature drying, or when greater accuracy is required, however, other models such as the Partial Differential Equation model or the Heat-mass Balance model are recommended (Brooker et al, 1992).
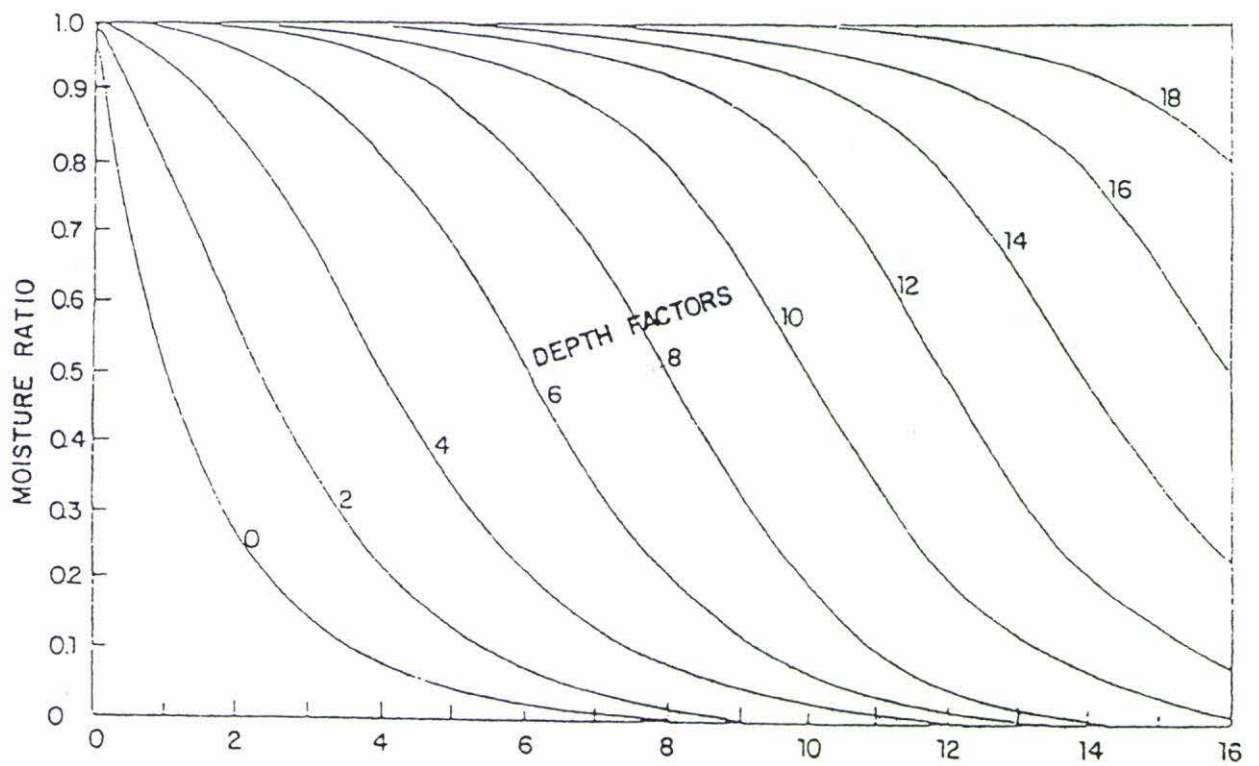
FIGURE 8   Deep-bed drying curves (Hukill, 1974)

2.7 Summary of the literature review

Grains are important direct sources of food for humans and feed for farm livestock. As they are produced on a seasonal basis, it is essential to store the grains for late consumption for periods varying from one month up to more than a year. Grains are often harvested at moisture contents that are too high for safe storage. Drying is the most practised grain preservation method that enables grains to attain moisture content sufficiently low to ensure good quality grain that is free of fungi and micro-organisms and that has desirable quality characteristics for marketing and final use.

The drying conditions for specific grains and situations are many and varied. Drying will take place under any conditions where grain is exposed to a flow of unsaturated air so that the grain will give up its moisture content. It is not possible to dry any grain lower than the equilibrium moisture content associated with the temperature and humidity of the drying air.

At present, there are many types of artificial grain dryers in addition to the natural methods of drying in order to facilitate high drying capacity. Artificial grain drying assists this objective by minimising weather effects on the harvest. At the same time, it is generally agreed that improper drying is the major cause of high drying cost, low efficiencies, and poor grain quality. Poor or defective drying facilities or incorrect drying procedures may result in very fast drying rate, incomplete drying and uneven moisture re-absorption within the grain mass.

Drying grain of high moisture content too slowly (as in sun or crib drying in inclement weather or in deep bed with unheated air) provides conditions for: mould growth; rapid loss of vigour and eventually germination loss; deterioration due to sprouting, weathering and respiration heating; and discoloration all leading to both quantitative and qualitative losses. Very fast drying accomplished using large volumes of high temperature air, however, if carried through the completion, is likely to be inefficient in energy use and liable to damage the grain by over-heating and/or over-drying. Fast drying can cause cracking and splitting (including internal cracking), case hardening, discoloration and loss of germination and vigour.

Grain quality has become an increasingly important issue in the grain trade. Grain quality grade standards have been used in many countries. They are the general criteria of the grain quality established and accepted by all parties in the grain trade. The most common grain quality attributes are: moisture content, density, Stress cracks or breakage susceptibility, hardness, viability and mould contamination. However, the relative importance of these properties varies considerably according to the end user.

Moisture content of grain denotes the quantity of water per unit mass of either wet or dry grain. It plays a crucial role in post-harvest processing and is associated with most of the induced grain characteristics. Determination of moisture is an essential step in quality evaluation of cereal grains and products of their processing and the behaviour of grain in both storage and during milling.

Density of grains is important in storage and transportation since it establishes the size of container for either purpose. Bulk density (BD) or test weight (TW) of grains is usually expressed as kilograms of grain per hectolitre (kg/hl). It was reported that high bulk density maize with low breakage susceptibility gave a higher yield of flaking grits than low bulk density maize with high breakage susceptibility.

Formation of stress cracks in maize grain is caused by stresses inside the kernel, resulting primarily from differential zones of moisture content as water moves from the interior of the kernel and evaporates at the surface during high temperature drying. Stress cracks in grains have been found correlated well with the grain breakage susceptibility. Their values are usually used to predict the possibility of grain being broken when handled and transported.

Grain hardness is of great significance to producers, processors, and workers in grain trade. It is defined as resistance of grain to grinding and is related to the protein content and kernel physical properties including bulk density and the ratio of hard to soft endosperm. It is also related to storability, attack by storage insects, breakage susceptibility caused by drying, storage, handling, or processing. Hardness in maize influences grinding power requirements, dust formation, nutritional properties, processing for food products and the yield of products from dry and wet milling

operations. Hardness of maize is genetically controlled, but it can be modified by both cultural practices and post-harvest handling conditions.

Because maize is one of the main food and feed grains, its nutritive value is a very important quality factor. Freedom of the kernel from fungi is recognised as a quality characteristic. Certain nutritional factors are destroyed in mouldy cereal grains and feeds. The extent of contamination by moulds is, largely, determined by the temperature of the grain and the availability of water and oxygen. Appropriate harvesting and handling cannot completely restore grain original nutritional value but can do much to reduce fungal contamination of maize and can thus prevent the need for chemical decontamination measures.

The design and operation of mechanical dryers which are cost-effective and efficient, and which have minimum detrimental impact on grain quality is a major continuing challenge for the cereal industry. Mechanical dryers are important for commercial drying of grains and as aids for evaluating new cultivars and postharvest research. Performance evaluation of new and existing dryer designs facilitates the optimisation of dryer parameters, drying conditions and dried grain quality.

Chapter 3

GENERAL MATERIALS AND METHODS

3.1 Background information

Two hybrids of yellow dent maize grain (250 kg each) named "Clint" and "Raissa" which are hard and soft, respectively, were dried in three experiments using a prototype flat-bed grain dryer. The experiments were designed to evaluate the performance of the dryer and dried grain quality attributes as affected by different drying, cooling and tempering conditions. The grains were obtained from the Crop and Food Research Institute, Palmerston North, New Zealand. The "Clint" hybrid was planted in October 1997, on the experimental site of the Crop and Food Research in Palmerston North. The "Raissa" hybrid was planted in October 1997, in Aorangi, Kairanga, in the Manawatu Region, New Zealand. The prototype dryer was designed and constructed by the Crop and Food Research for research purposes (Meas, 1998).

3.2 Preparation of the grain materials

3.2.1 Harvesting

The "Clint" cobs were manually harvested in May and June 1998, and a tractor PTO-powered single small husker-sheller (Haban, USA) was used to shell the grains at a moisture content of around 22 %. (Note: All the grain moisture contents cited in this thesis are on a wet basis if not otherwise stated). The "Raissa" was harvested and shelled by a commercial combine harvester (John Deer, USA) in May 1998, at a moisture content of around 24 %. The shelled grains were sealed in plastic bags on the same day and put in plastic buckets with seal-able lids, to avoid moisture absorption, and then stored at 5 °C. Since the grains of both hybrids were harvested at the moisture contents no greater than about 25 %, physical damage caused by the combine harvester and the husker-sheller was presumably minimal (Hardacre et al., 1997).

3.2.2 Establishment of different moisture contents

The shelled maize grain were cleaned on June 25, 1998 using an office clipper tester and cleaner (Model 400/c, Seedburo Equipment Company, IL, USA) to remove the broken and/or foreign materials. In order to carry out the experimental work in the time available, it was necessary to artificially dry or wet the grain to obtain three different moisture contents (approx. 20, 25 and 30 %). For each desired moisture content, later on called initial moisture content, the grain of each hybrid was divided into three lots and treated as follows:

1) One lot was spread on large tables in thin layer (Approx. 1 cm depth) and exposed to room temperature (natural drying) for about 24 hours in order to obtain grain with 20 % moisture content. During the drying period, moisture content of the grain was checked regularly using a portable calibrated grain moisture meter (Wile 20, Ot-techdas Oy, Helsinski, Finland).

2) The second lot was thoroughly mixed with an appropriate amount of water in order to obtain the grain with 25 % moisture content. Based on the relationship between the volume of water per tonne of grain and the moisture content of grain as shown in Equation (23) (McLean, 1989), the volume of water required to be added to reach the desired moisture content was determined according to equation (24):

$$V_w = \frac{MC_1 - MC_2}{100 - MC_2} \times 1000 \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots (23)$$

$$V = m_g \frac{MC_1 - MC_2}{100 - MC_2} \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots (24)$$

Where

V_w and V = volume of adding water (l/t and ml/g, respectively)

m_g = original weight of grain (g)

MC_1 and MC_2 = desired and initial moisture content of grain, respectively (%)

3) To obtain the grain with 30 % moisture content, the third lot was soaked in fresh water for 3 h and 20 min (for the "Raissa") and for 4 h and 15 min (for the "Clint"). During the soaking periods, grain samples were withdrawn; drained; wiped (using tissue to remove water from the grain surface) and assessed regularly for moisture content, using the same grain moisture meter.

When the desired moisture content was achieved, the grain in each lot was thoroughly mixed, sealed in plastic bags and put in plastic buckets with lids for further storage at 5 °C. Until drying could be conducted, each bucket containing grains was turned up-side down once a day to assist in maintaining uniform grain moisture content. The grain samples were taken out of the cool store and equilibrated at room temperature (approx. 20 °C) for about 2 hours prior to drying.

3.3 Testing equipment

3.3.1 The prototype flat-bed grain dryer

The prototype flat-bed grain dryer (Figures 9 and 10) has four main parts: a centrifugal fan powered by an electric motor; a heating section consisting of eight 2-kW electric heaters; a central plenum chamber and three removable rectangular boxes used as drying bins. Each of the drying bins consists of a vertical column 40 x 40 x 40 cm with the capacity to hold about 40 kg of maize grain. The sides of the bins are made of sheet metal and the bottoms are made of metal mesh. The heating section and the plenum chamber are made of sheet metal and insulated with 5-cm thick fibreglass to minimise heat loss to the surroundings.

Drying air temperature and flowrate can be set using an electric-relay system (Grain Dryer Controller, Gewiss GW46006, Electro-engineering Ltd., Palmerston North, New Zealand) that controls the speed of the fan motor and number of heaters operated for particular drying condition. The dryer can produce drying air of up to 130 °C, and the maximum airflow of about 0.22 m/s. When operating, the fan propels drying air into the plenum chamber. The air passes through heaters in the heating section and then to drying grains in the bins through the perforated metal floors. For cooling, ambient air is also propelled by the fan into the chamber and then through the grain when the
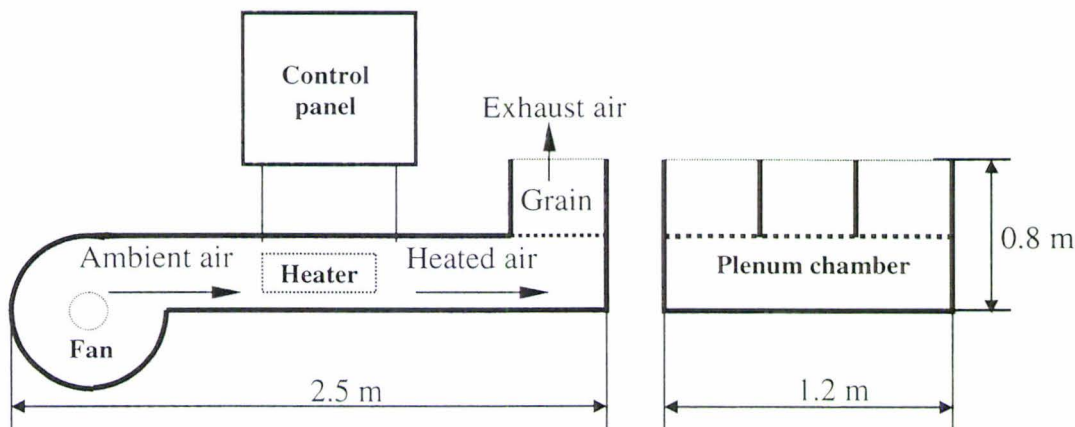
FIGURE 9 Schematic diagram of the prototype flat-bed grain dryer

FIGURE 10 The prototype flat-bed grain dryer

heaters are automatically switched off. Cardboard with a round hole (90 mm-diameter) in the middle was used to cover each drying bin. The hole facilitates measurement of the flowrate and temperature of the exhaust air.

3.3.2   The Stein breakage tester

The breakage tester (Figure 11) was designed and constructed by the Crop and Food Research Ltd. based on the Stein breakage tester. It consists of a cylindrical cup (the test chamber into which a steel impeller fits with a small clearance between the bottom and sides), an electric motor (0.2 hp, Class E120), 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 inside wall of the cylinder. The stop-watch system cuts the power supply from the tester at the end of a predetermined set time (in this case 6 min) and the fan blows air to cool the motor in order to keep the tester at a constant temperature for long testing period.

3.3.3   The Stenvert hardness tester

This tester is also owned by the Crop and Food Research Ltd. and has been used for experimental purposes (Li et al., 1996). The main part of the tester (Figure 12) is a 14-690 micro hammer-cutter mill (Type 5, Glen Creston Ltd., Stanmore, Middlesex, England) with vertical straight-in feed and plunger for bulkier and light-weight materials. There is a swinging hammer mill with a grooved grinding chamber in the machine. A 2-mm aperture particle screen was fitted to the chamber during this study. The mill was equipped with a computerised data logging system to log the instantaneous electric power consumption (the power used by the tester to mill whole grain sample) and the resistance time (the time taken to mill 17 ml of meal) during the milling test. Based on the results of several studies, Hardacre et al. (1997) recommended breakage tester and the hardness tester for analysing maize grain quality in New Zealand.
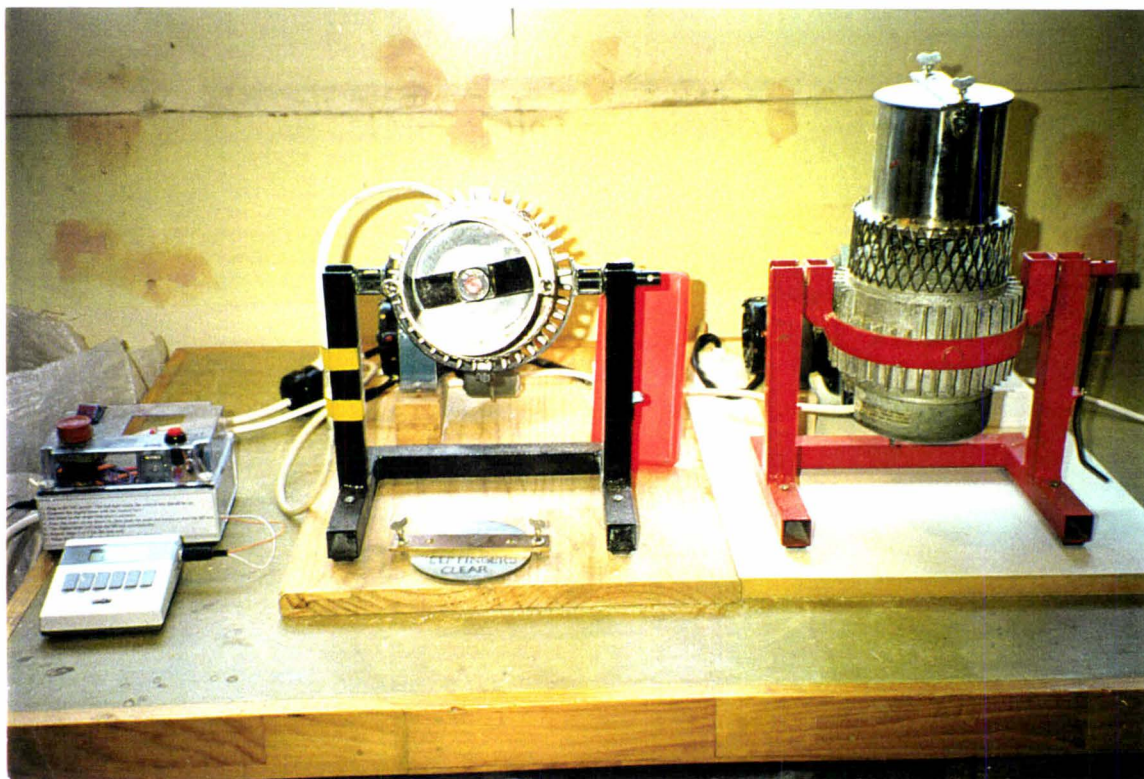
FIGURE 11 The Stein breakage tester. (From left to right: stop-watch system, test Chamber – top view, and test chamber – side view)
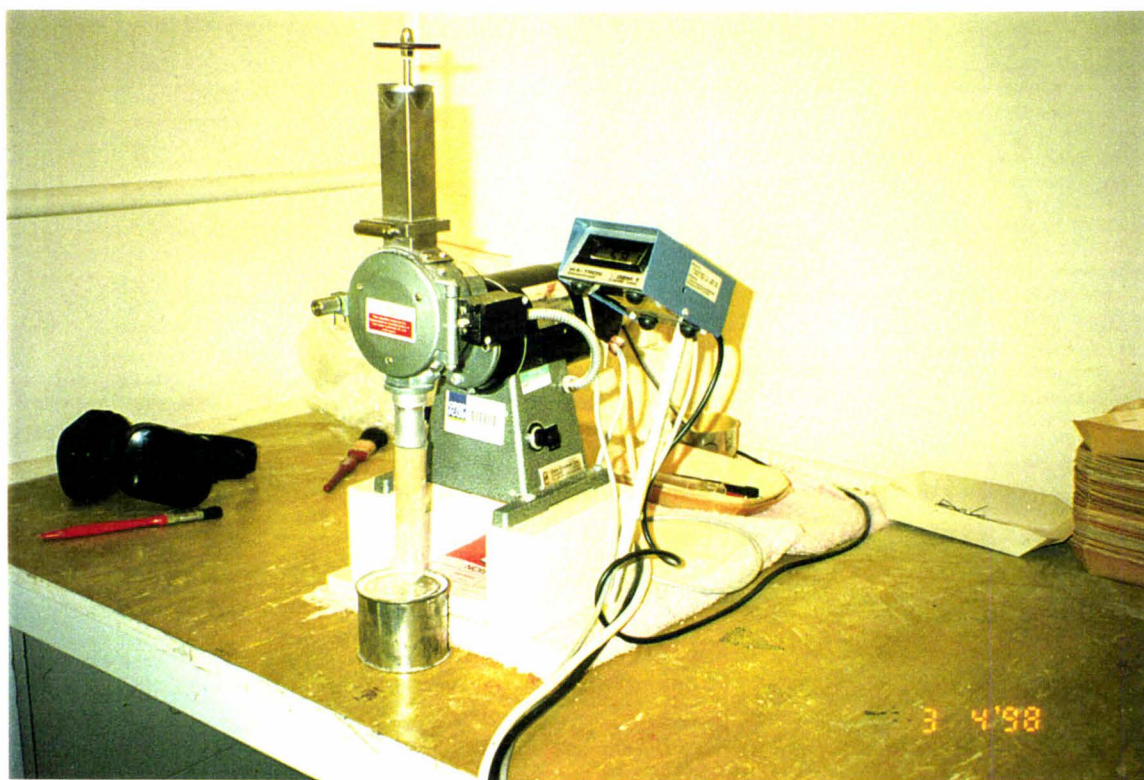
FIGURE 12 The Stenvert hardness tester

3.4 Grain quality tests

3.4.1 Moisture content and bulk density

Before drying, initial moisture contents of all grain samples were measured using the oven method (72 hours at 103 °C) in three replications. After drying, each sample was measured for its moisture content (%) and bulk density (kg/hl) in three replications using a computerised grain analysis system (DICKEY-John GAC2000, DICKEY-John Corporation, Illinois, USA). Calibration of the machine for moisture was checked using oven-drying techniques.

3.4.2 Breakage susceptibility

The breakage test used in this study was developed by the Crop and Food Research as an objective and quantitative measurement of physical damage in grain caused during drying or storage (Hardacre et al., 1997). Breakage susceptibility of the grain dried under each particular drying condition was determined in three replications using the above described grain breakage tester. After checking for moisture content, with the DICKEY-John moisture meter, dried grains were divided using a grain divider (Model H-3985, Humboldt MFG.Co, Norridge, IL, USA) to obtain a 50-g sample of whole (unbroken) grain kernels for one breakage test. The divisions were carried out repeatedly until the convenient working sample size was reached.

Each sample was subjected to breakage in the tester for 6 minutes and then manually sieved using a 4.75 mm-aperture sieve (Pattern No. 667924, Endecotts Ltd., London, England) to separate the fine material and broken kernels from sound kernels. Breakage susceptibility (BS) was determined as follows:

$$BS = \frac{W_f + W_b}{W_s} \times 100\,\% \qquad\qquad \dots\dots\dots\dots\dots\dots\dots\dots \text{(25)}$$

Where W_f = weight of fine material which passed through the sieve (g)

$\quad\quad W_b$ = weight of broken grains which remained on the sieve but were

$\quad\quad\quad\quad$ split through germ and became smaller than half size of the kernels (g)

$\quad\quad W_s$ = sample weight (g)

Similar methods had been used by many researchers (Thompson and Foster, 1963; Kirleis and Stroshine, 1990; Weller et al., 1990; Fortes and Okos, 1980; Miller et al., 1981).

3.4.3 Hardness

The test was conducted in three replications based on the method used by Li et al (1996). The hardness of all the dried samples was determined using the Stenvert Hardness Tester by setting the mill speed for 3,600 rpm, when unloaded. Each time, a 20 g-sample, obtained by the same sampling method as used for breakage test, was ground in the tester and the resistance time and energy consumption were recorded by the computerised data logging system. Each sample was dropped into the mill when the speed indicator of the tester steadily showed 570 to 572 rpm (there is a transmission system inside the tester). At this point, the computer program also gave a green note saying that the tester was ready.

After dropping sample into the mill, the computer system recorded the resistance time until the ground meal reached a marked level of a receptacle (to contain 17 ml) which was placed right under the mill chamber. At that time a key of the computer's keyboard needed to be pressed. When the electric power of the mill was below 7 Watts, the milling stopped and the grinding energy was determined by integration of the area under a power versus time curve produced by the data logging system.

Li et al. (1996) reported that the milling energy and resistance time were the most effective Stenvert Hardness Test parameters for assessing grain hardness. The authors concluded that the Stenvert hardness test was proven to be a quick and simple method of comparing the endosperm hardness of diverse maize hybrids at constant moisture content. In addition, the test had the benefit of measuring large number of kernels in each test so providing a better estimate than tests based on single kernels.

Since the dried maize samples ranged in moisture content from 12.53 to 14.27 %., the quality test results had to be corrected to 14 % moisture content using formulas developed by the Crop and Food research Ltd. The breakage and hardness testers were

calibrated by testing a standard sample two times during each day of testing. All the quality tests were conducted at room temperature (approx. 18 $^{\circ}$C).

3.5 Data analysis

Treatment effects were statistically analysed for variance using SAS package (version 6.12) and treatment means were separated using the Duncan Multiple Range Test (Steel and Torrie, 1980; Ganesh, 1998). Where appropriate, the moisture ratio of dried grain was modelled using relevant thin-layer drying model.

Chapter 4

EXPERIMENT I

Determination of the effects of grain initial moisture content and drying air temperature on dryer performance

4.1 Introduction

As reviewed in Chapter two, the initial moisture content of maize at harvesting may be as high as 40 % and the maximum safe storage level is 13.5 % (Hill, 1997). Grain drying, which has been used since early civilisation to preserve it for food, is therefore necessary to achieve the desired storage regime. However, it must also be remembered that rapid drying of grain especially of high moisture content at a high temperature, as well as sudden cooling, can provoke damage to the dried grain such as cracking and breaking during their handling and milling (de Lucia and Assennato, 1994).

Previous studies have found that moisture variation of drying grain strongly influences the drying capacity. Maize grain dried from higher moisture content cracked and broke easier than that dried from lower moisture content (Thompson and Foster, 1963; Weller et al., 1990).

Fast drying, hence high drying rate and capacity, can normally be obtained by using air of high temperature and flowrate. Drying air temperature has the most significant effect on drying rate of all variables studied over their respective ranges (Li and Morey, 1984). Increase in drying rate equally increased the drying efficiency (Adeyemo, 1993). Increasing drying temperature, however, increases the incidence of grain damage (Brooker et al., 1992; Gunasekaran and Paulsen, 1985; Gunasekaran et al., 1985; Peplinski et al., 1989; Peplinski et al., 1994; Thompson and Foster, 1963).

Likewise, Hardacre and Pyke (1998) stated that poorly controlled drying conditions, or rapid drying at high temperatures can damage the grain, causes unwanted chemical changes by cooking the grain, alters the physical characteristics by causing stress fractures, lowers bulk densities and cause voids in the endosperm. This damage is associated with:

- reduction in the mechanical strength of the grain which can be measured using a mechanical impact (MI) test. A low MI value (<10 %) indicates that drying conditions were acceptable. If the drying conditions are too aggressive, either due to high temperatures in the dryer or rapid cooling, MI values will be high (>20 %).

- changes in grain quality will also be reflected by changes in bulk density (BD) of grain. If the BD of the grain following commercial drying is about 1.5 kg/hl less than the predicted BD (Equation 26), the grain decreased in quality in dryer due to internal fracturing and the formation of small voids in the grain. Generally, this may result when the dryer is operated at too high a temperature for the given moisture content of the wet grain. During careful drying, the BD of the dried grain may exceed the calculated BD.

The bulk density of the wet grain samples (BD_w) can be corrected to bulk density at the dry grain moisture content (BD_d) using Equation (26), where MC_o and MC_f are initial and final moisture contents, respectively. (Hardacre et al., 1997; Hardacre and Pyke, 1998; Brenton-Rule et al., 1998) :

$$BD_d = BD_w + 0.3 \times (MC_o - MC_f) \qquad .... \ (26)$$

Despite being used for research purposes for some time, the prototype flat-bed grain dryer designed and constructed by the Crop and Food Research, Ltd. has not been properly evaluated. The specific performance of the dryer and its drying effects on dried grain quality are not known.

4.2 Research aim and objectives

The overall aim of this study was to investigate the potential of the new prototype flat-bed grain dryer to achieve minimum reduction in dried grain quality with maximum capacity, efficiencies and minimum energy consumption under different drying conditions. The specific objectives were to:

• Determine the effects of grain initial moisture content and drying air temperature on drying time, drying rate, dryer capacity, drying efficiency and dryer energy consumption;

• Quantify the effects of grain initial moisture content and drying air temperature on quality attributes of the dried grain.

4.3 Experimental design and methodology

4.3.1 Methodology

Drying was conducted in July 1998. Yellow dent maize grain of two hybrids ("Clint" and "Raissa") at three initial moisture contents (approx. 20, 25 and 30 %) were dried at three drying air temperatures (58, 80 and 110 °C) in three replications. The flowrate of the drying air was set constant at 0.16 m/s for all the drying treatments but it was automatically doubled during cooling when the temperature of the cooling air, indicated by the dryer system, reduced to 25 °C.

During each drying run, a 5-kg sample of one hybrid at one moisture content was dried in one of the three drying bins. The depth of the drying sample was approx. 5 cm. A 100- to 150-g grain sample in each drying bin was put in a small metal-mesh bag and put in with the bulk to dry all together in the bin (Figure 13).

During the drying process, the small metal-mesh bags containing the grains were taken out of the drying bins every 10 minutes and weighed in order to monitor the moisture content of the drying samples. The initial and transient weights of the mesh bags were recorded onto a computer software that can calculate and display the actual moisture content, a "moisture versus time" curve for drying process, approximate total drying time and time needed to complete the drying. Drying was stopped when the moisture contents of the samples were reduced to predetermined values: 16 % at 110 °C, 15.4 % at 80 °C and 14.6 % at 58 °C. These target moisture contents have been set higher than the final moisture content due to further water losses can occur during cooling.
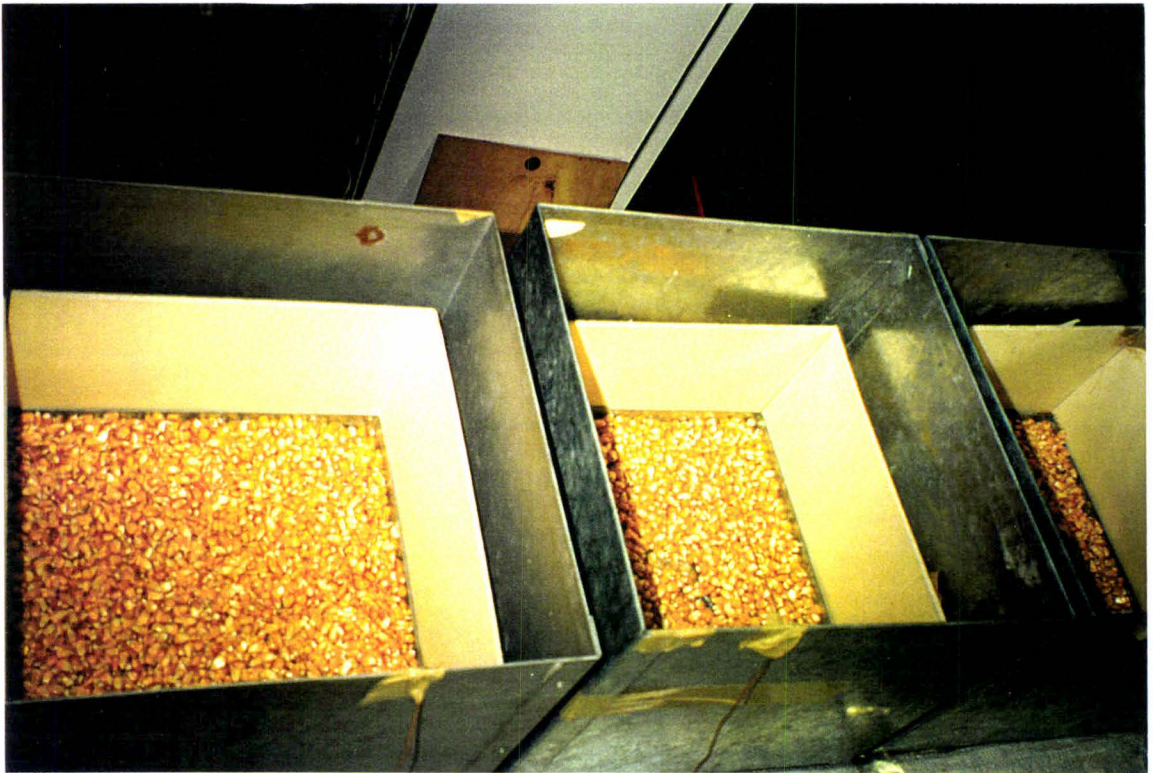
FIGURE 13 Grain samples being dried in the system

As the samples in the three drying bins did not reach the target moisture contents at the same time, wooden boards were inserted under the drying bins to stop the drying air getting into the bins when the samples reached the predetermined value. Cooling, by blowing the ambient air through the samples, was started for all the three bins when the last sample reached the target moisture content and continued until the temperature of the exhaust air reduced to approx. 26 °C.

Apart from the drying with the dryer, grain samples of each hybrid were also dried at the room temperature (approx. 20 °C) from each of the three initial moisture contents to serve as control. A sample of 1 kg was put in a perforated tray, spread in thin layer (approx. 1.5 cm) and left in the laboratory for about one week until the moisture content equilibrated with the room environment. All the dried samples were, after that, put in heavy paper bags and stored at room temperature (approx. 18 °C) for about two weeks prior to their quality (bulk density, breakage and hardness) measurements.

Other parameters, such as the temperature and humidity of the ambient air; the temperature of the heated air; the temperature and flow of the exhaust air and the electric power consumed by the dryer, were also measured and recorded during the drying process. The temperature and the humidity of the ambient air were measured and recorded, every 5 minutes, by the Cambell Scientific CR10 data logger placed beside the drying system. The temperature of the heated air was read from the dryer control system, every 2 minutes at the beginning of drying until it reached the setting point (58, or 80, or 110 °C) and during the cooling process until it reduced to 26 °C. This setting temperature was shown constant for other drying time. The flow of the air exhausted from the grain was measured and recorded at the same time as for the heated air, using a turbo meter, or wind speed indicator, (Davis Instruments, California, USA) placed over the holes of the drying bin covers. The temperature of the air was measured and recorded, every 10 minutes, using thermocouple immersion probe (model 80PK-2A, type K, John Fluke Mfg. Co., Inc., Washington, USA) placed 20 cm above the dried grains - right under the holes of the drying bin covers.

The power consumption for each drying run was read and recorded three times: at the beginning (x_1); when the sample in any drying bin reached the target moisture content

(x_2); and at the end of the cooling process (x_3). The power consumed by one of the drying bins (PCB) was estimated as follows:

$$PCB = \frac{1}{3}[(x_2 - x_1) + (x_3 - x_{2L})]$$ .... (27)

Where x_{2L} is the power reading when the sample in the slowest drying bin reached the target moisture content.

4.3.2 Data analysis

a) Dryer capacity and drying rate determinations

The drying capacity (DC) of a dryer is the rate at which the wet product can be dried to a specified moisture content while the dryer is operated at specified drying conditions (Arinze et al., 1996). For each replication, the DC (kg of moist grain per hour) was determined using the formula below:

$$DC = \frac{W}{T} \times 60 \times n_b$$ .... (28)

Where

  W = weight of grain in one drying bin (5 kg in this study)

  T = drying time (min)

  n_b = number of drying bins (3 in this study)

The average drying rate (ADR), expressed in kg of water removed per hour, for each drying run was determined using Equation (29) (Appendix A) :

$$ADR = M \times \frac{MC_o - MC_f}{100 \times T} \times 60 \times n_b$$ .... (29)

Where

  M = dry matter of grain in one drying bin (kg)

  MC_o = grain initial moisture content (% d.b)

  MC_f = moisture content of the grain at the end of drying (% d.b.)

  T = drying time (min)

  n_b = number of drying bin (3 in this study).

As the grain moisture content was recorded at 10-min interval, the drying rate (DR-expressed in kg of moisture or water removed in one hour) at each 10-min interval was determined using the following formula:

$$DR = R \times \frac{W_i - W_{i+10}}{10000} \times 60 \times n_b \qquad \text{.. (30)}$$

Where

R = weight ratio of the grain in one drying bin (5000 g) and of the grain in metal mesh bag (g)

W_i = weight of grain in a metal mesh bag at the beginning of a 10-minute interval (g)

W_{i+10} = weight of grain in a metal mesh bag at the end of the 10-min interval (g)

n_b = number of drying bin (3 in this study).

b) Dryer efficiency

According to Adeyemo (1993), the efficiency of dryers may be expressed in terms of fuel efficiencies, sensible heat utilisation efficiency and drying efficiency. Based on how well the drying system converts sensible heat to latent heat, drying efficiencies for this study (namely heat utilisation factor (HUF), coefficient of performance (COP), and total heat efficiency (THE)) were determined in percentage based on the formulae stated by Hall (1980) and Aguilar and Boyce (1966) and used by Chakraverty and More (1983):

$$HUF = \frac{t_d - t_e}{t_d - t_a} \times 100 \qquad \text{.. (31)}$$

$$COP = \frac{t_e - t_a}{t_d - t_a} \times 100 \qquad \text{.. (32)}$$

$$THE = \frac{t_d - t_e}{t_d - t_{aw}} \times 100 \qquad \text{.. (33)}$$

Where

t_a = dry bulb temperature of the ambient air ($^{\circ}$C)

t_d = dry bulb temperature of the heated air ($^{\circ}$C)

t_e = dry bulb temperature of the exhaust air ($^{\circ}$C)

t_{aw} = wet bulb temperature of the ambient air ($^{\circ}$C).

c) Drying models

Since the depth of grain dried in each drying bin was approx. 5 cm, the following Page models for thin-layer drying were chosen to characterise the drying rates of the two maize hybrids. Michael and Ojha (1978) stated one of the features of the thin layer drying is that the grain depth is limited up to 20 cm.

Firstly, the drying rates were modelled based on generalised relationships between the drying constants (k and n) and drying air temperature (T) and initial grain moisture content (MC_o) when the air relative humidity varies from 5 to 40 % as stated by Liu et al. (1998) (see Appendix B) :

$$MR = exp\ (\ -kt^n\ ) \qquad\qquad \text{.........…..….......} \quad (34)$$

$$k = 1.091\ x\ 10^{-2} + 2.767\ x\ 10^{-6}\ T^2 + 7.286\ x\ 10^{-6}\ T.MC_o \quad \text{.........................} \quad (35)$$

$$n = 0.5375 + 1.141\ x\ 10^{-5}MC_o^{2} + 5.183\ x\ 10^{-5}T^2 \qquad \text{.........................} \quad (36)$$

Where

k, n = drying coefficients

t = time (min)

T = heated air temperature (27 - 116 $^{\circ}$C)

MC_o = initial grain moisture content (23 - 36 % d.b.).

Secondly, values of the drying constants (k and n) were determined for each drying condition using linear regression on the transformed equation of The Page model (Misra and Brooker, 1980 and Li and Morey, 1984) (see Appendix C) :

$$ln\ (-ln\ MR) = ln\ k + n\ (ln\ t) \qquad \text{..............................} \quad (37)$$

d) Statistical analysis

Data were analysed statistically based on factorial design using the SAS package (Version 6.12) and treatment means were compared using the Duncan Multiple Range Test (Section 3.5).

4.4 Results

4.4.1 Effects of grain initial moisture content and drying air temperature on the dryer performance

a) Drying time and dryer capacity

There was no significant difference between the grain hybrids for both drying time and drying capacity (Table 8). The grains were dried from any moisture content to the predetermined level in shorter time by increasing the drying temperature. The longest drying time was approx. 4 h and 30 min for drying the "Clint" from the highest moisture content (approx. 30 %) at the lowest temperature (58 $^\circ$C). The shortest time was about 45 min when both hybrids were dried from the lowest moisture content (approx. 20 %) at the highest temperature (110 $^\circ$C).

The data also indicate that the dryer capacity varied inversely with the drying time and significantly with the grain initial moisture content and the drying air temperature. The dryer could dry the grain of up to approx. 20 kg/h from 20 % moisture content using 110 $^\circ$C air temperature. This capacity decreased for the higher grain moisture contents and the lower air temperatures. The differences of time and capacity, as affected by the moisture content and temperature, were not significantly different between the two hybrids.

There were significant interactions (P $\leq$ 0.05) between the drying air temperature and grain initial moisture content on drying time and dryer capacity, indicating that the effects of the drying air temperature was affected by the grain initial moisture content. As the grain moisture content increased, the differences of the drying time for each air temperature increased. The capacity of the dryer dropped as the initial moisture contents increased from 25 to 30 % and the drop was higher at low grain initial moisture content.

TABLE 8 Effects of grain initial moisture content and drying air temperature on drying time (min)

Tempe-rature °C	Clint Moisture content, %				Raissa Moisture content, %			
	20	25	30	Mean	20	25	30	Mean
58	95.33 ± 5.33	196.33 ± 8.09	270.67 ± 16.75	187.40 ± 26.01[a]	97.33 ± 5.81	173.67 ± 9.28	236.67 ± 11.62	169.20 ± 20.66[a]
80	50.67 ± 3.28	97.00 ± 7.37	139.67 ± 9.26	95.78 ± 13.33[b]	54.33 ± 2.60	94.00 ± 5.29	134.67 ± 6.12	94.33 ± 11.85[b]
110	45.33 ± 1.33	72.33 ± 1.67	87.33 ± 1.45	68.33 ± 6.19[c]	48.67 ± 0.67	70.67 ± 2.73	85.33 ± 7.88	68.22 ± 5.85[c]
Mean	63.78 ± 8.14[c]	121.90 ± 19.22[b]	165.90 ± 27.82[a]	117.19 ±13.83[A]	66.78 ± 7.90[c]	112.81 ± 15.91[b]	152.22 ± 22.71[a]	110.59 ± 11.50[A]

TABLE 9 Effects of grain initial moisture content and drying air temperature on dryer capacity (kg/h)

Tempe-rature °C	Clint Moisture content, %				Raissa Moisture content, %			
	20	25	30	Mean	20	25	30	Mean
58	9.50 ± 0.50	4.60 ± 0.18	3.35 ± 0.21	5.82 ± 0.95[c]	9.31 ± 0.55	5.21 ± 0.27	3.82 ± 0.19	6.12 ± 0.84[c]
80	17.91 ± 1.12	9.38 ± 0.69	6.50 ± 0.44	11.27 ± 1.76[b]	16.64 ± 0.79	9.63 ± 0.53	6.71 ± 0.30	10.99 ± 1.50[b]
110	19.88 ± 0.57	12.46 ± 0.29	10.31 ± 0.17	14.22 ± 1.46[a]	18.50 ± 0.25	12.77 ± 0.48	10.72 ± 0.96	14.00 ± 1.21[a]
Mean	15.76 ± 1.64[a]	8.81 ± 1.16[b]	6.72 ± 1.02[c]	10.43 ± 1.05 [A]	14.82 ± 1.43[a]	9.21 ± 1.12[b]	7.09 ± 1.04[c]	10.37 ± 0.93[A]

Note: Means for each grain moisture content or air temperature with the same letter (within each column or each row) are not significantly different at 5 % level.

b) Drying rate

The drying temperatures significantly affect the average drying rate (Table 10). The dryer produced a higher drying rate when the hybrids had a higher initial moisture content or at a higher drying air temperature. However, the resulting drying rates were not significant different between 25 and 30 % grain initial moisture contents.

As the initial moisture content increased, the drying rate for "Clint" hybrid at 58 °C did not increase much (from approx. 0.58 to 0.70 kg/h). It increased from approx. 1.25 to 1.53 kg/h and from approx. 1.49 to 2.38 kg/h, at 80 and 110 °C-air temperatures, respectively, as the moisture content increased from 20 to 25 %. The drying rate decreased slightly as the moisture increased from 25 to 30 % (to approx. 1.42 and 2.31 kg/h, respectively). The drying rate for the "Raissa" had the same trends at 58 and 80 °C but it increased all the time, at 110 °C, as the moisture content increased.

For both hybrids, higher drying air temperatures produced significantly higher drying rates. The drying rate for the "Clint" and the "Raissa" of 25 and 30 % moisture contents were approx. 1.50 and 1.7 kg/h in average and were significantly higher than the drying rate for the grain of 20 % moisture content (approx. 1.11 and 1.33 kg/h, respectively). Between the two hybrids, the average drying rates (approx. 1.37 and 1.59 kg/h, respectively) were not significantly different.

Figure 14 shows the trends of the drying rate for grains of different moisture contents dried at different drying air temperatures. The plots are means of the three replications. The drying rate initially increased with the drying time, reached a peak (after 20 min) and then decreased until it reached its minimum value at the end of the process. This is due to the initial heating of the grain to the equilibrium drying air temperature and the consequent variation in the moisture content across the interior section of the grain kernel. The plots also show the drying rate was higher for the grain dried at higher air temperatures.
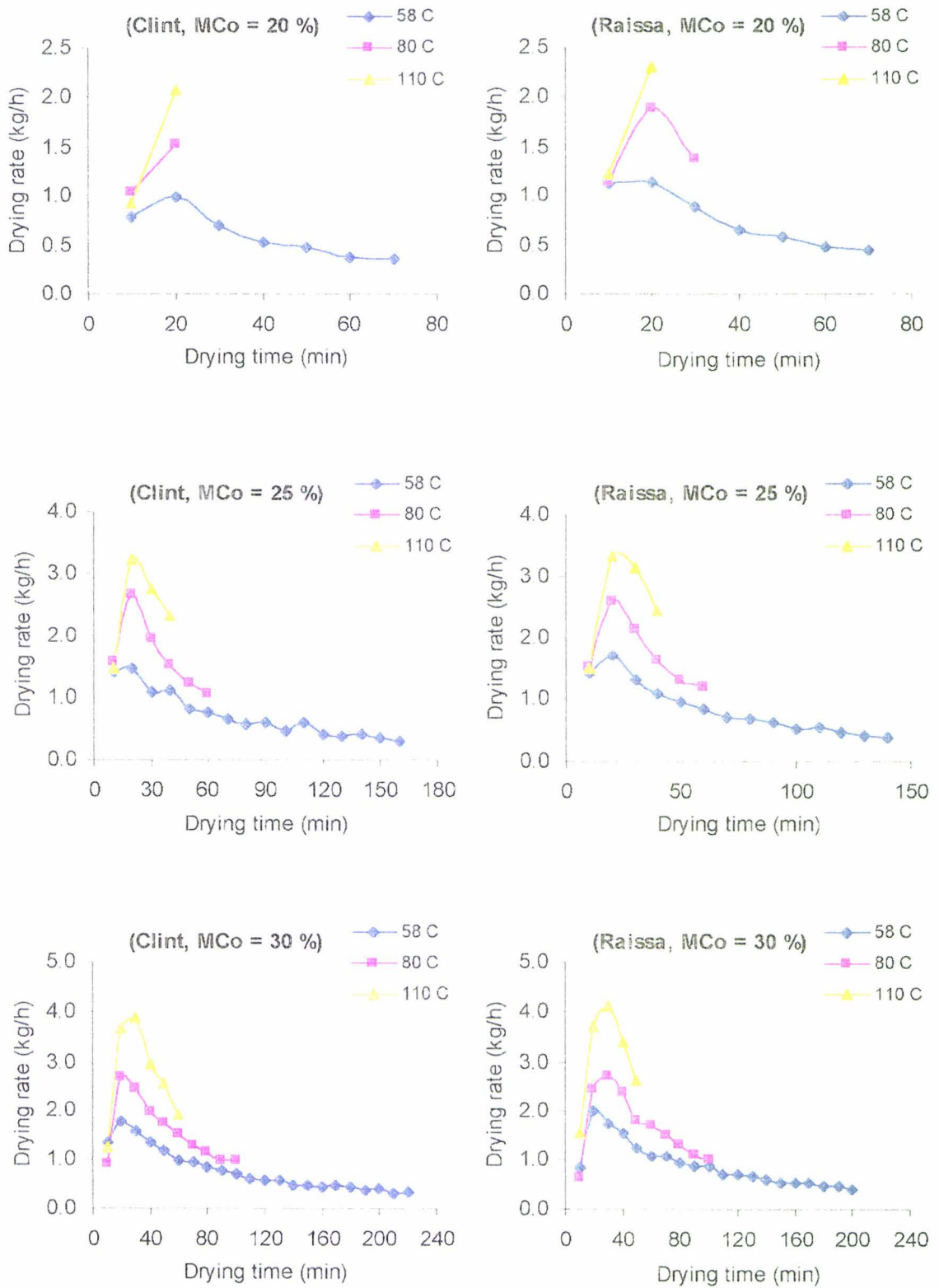
FIGURE 14 Effects of the grain initial moisture content and drying air temperature on drying rate

TABLE 10 Effects of grain initial moisture content and drying air temperature on drying rate (kg/h)

Tempe-rature °C	Clint				Raissa			
	Moisture content, %				Moisture content, %			
	20	25	30	Mean	20	25	30	Mean
58	0.58 ± 0.04	0.68 ± 0.03	0.70 ± 0.05	0.65 ± 0.03^c	0.73 ± 0.06	0.80 ± 0.05	0.86 ± 0.04	0.79 ± 0.03^c
80	1.25 ± 0.13	1.53 ± 0.15	1.42 ± 0.11	1.40 ± 0.08^b	1.43 ± 0.12	1.64 ± 0.12	1.59 ± 0.10	1.56 ± 0.06^b
110	1.49 ± 0.06	2.38 ± 0.12	2.31 ± 0.43	2.06 ± 0.19^a	1.81 ± 0.12	2.55 ± 0.15	2.93 ± 0.33	2.43 ± 0.20^a
Mean	1.11 ± 0.14^b	1.53 ± 0.25^a	1.48 ± 0.27^a	1.37 ± 0.13^A	1.33 ± 0.17^b	1.67 ± 0.26^a	1.79 ± 0.32^a	1.59 ± 0.15^A

TABLE 11 Effects of grain initial moisture content and drying air temperature on dryer energy consumption (kW)

Tempe-rature °C	Clint				Raissa			
	Moisture content, %				Moisture content, %			
	20	25	30	Mean	20	25	30	Mean
58	1.80 ± 0.22	3.31 ± 0.12	4.82 ± 0.09	3.31 ± 0.44^a	1.53 ± 0.35	3.09 ± 0.09	4.07 ± 0.40	2.90 ± 0.40^a
80	1.22 ± 0.17	2.56 ± 0.06	3.80 ± 0.10	2.53 ± 0.38^b	1.27 ± 0.12	2.48 ± 0.35	3.56 ± 0.22	2.43 ± 0.35^{ab}
110	1.11 ± 0.09	1.93 ± 0.10	2.96 ± 0.11	2.00 ± 0.27^c	1.06 ± 0.13	1.93 ± 0.02	3.00 ± 0.09	2.00 ± 0.28^b
Mean	1.38 ± 0.14^c	2.60 ± 0.21^b	3.86 ± 0.27^a	2.61 ± 0.23^A	1.29 ± 0.13^c	2.50 ± 0.20^b	3.54 ± 0.21^a	2.44 ± 0.21^A

Note: Means for each grain moisture content or air temperature with the same letter (within each column or each row) are not significantly different at 5 % level.

c) Energy consumption

The energy consumed by the dryer was significantly affected by the initial moisture content of the grains and the drying air temperature. The consumption of the dryer was high when drying any of the two hybrids with high moisture contents, especially at low drying air temperature. Within each moisture content, the energy was reduced when higher temperature was used (Table 11).

The dryer used the largest amount of drying energy (approx. 5 kWh) when drying the "Clint" hybrid from 30 % at 58 °C. The smallest amount of energy (approx. 1 kWh) was used to dry any of the hybrids from the lowest moisture content at the highest temperature. From the lowest moisture content, the energy used to dry the "Clint" at 110 and 80 °C were almost the same and was not far from the energy consumed by the dryer at 58 °C. The differences between the energy consumption of the dryer at each drying temperature increased with the initial moisture content. In average, the energy taken by the dryer to dry the "Clint" (approx. 2.61 kW) seemed to be higher than to dry the "Raissa" (approx. 2.44 kW) but the statistical analysis indicates that they were not significantly different.

d) Drying efficiencies

There were some effects of the grain initial moisture content and drying temperature on the drying efficiencies determined by the Heat Utilisation Factor (HUF), the Coefficient of Performance (COP) and the Total Heat Efficiency (THE).

i/ Heat Utilisation Factor :

HUF was not significantly affected by the grain initial moisture content when the dryer dried the hard "Clint" hybrid, but the factor was significantly affected by the drying air temperature (Table 12). The highest air temperature (110 °C) caused the significant highest HUF (approx. 42.4 %) for the drying system compared with the two lower air temperatures. The HUF values reduced to approx. 23.6 % at 80 °C and, further, to approx. 20.5 % at 58 °C but they were not significantly different.

For the "Raissa" hybrid, on the other hand, the HUF value was significantly the highest (37.2 %) when the moisture content was the lowest (20 %). Between the other two moisture contents (25 and 30 %), the HUF values of approx. 32.9 and 31.6 %, respectively, were not significantly different. The three drying temperatures significantly affected the HUF. It increased with increasing the drying temperature. The maximum HUF of the dryer was approx. 48.2 % when drying the "Raissa" from 20 % moisture content at 110 °C. The average HUF for the dryer when drying the "Raissa" hybrid (approx. 33.9 %) was significantly higher than the average HUF for the dryer when drying the "Clint" hybrid (approx. 28.8 %). These indicate that the dryer had fairly low heat utilisation efficiency.

ii/ Total Heat Efficiency :

In this study, the THE of the dryer was partly affected by the grain initial moisture content and the drying air temperature (Table 14). For "Clint" hybrid, THE was not significantly affected by the different moisture contents, but was significantly affected by the temperature. The 110 °C produced the highest THE (approx. 41.4 % in average) which was significantly higher than the THE produced at 80 or 58 °C (approx. 22.8 and 19.4 % in average, respectively). These two latest values were not significantly different.

For the "Raissa" hybrid, the THE of the dryer when drying the grain of 20 % moisture content was significantly higher (approx. 36.2 in average) than the THE when drying other two higher moisture contents. The THE increased significantly from approx. 23.30 to 43.87 % with the drying temperature. The average THE produced by the dryer when drying the "Clint" and the "Raissa" hybrids of approx. 27.8 % and 32.8, respectively were significantly different.

TABLE 12 Effects of grain initial moisture content and drying air temperature on heat utilisation factor of the dryer (%)

Tempe-rature °C	Clint				Raissa			
	Moisture content, %				Moisture content, %			
	20	25	30	Mean	20	25	30	Mean
58	23.46 ± 5.47	17.52 ± 1.59	20.37 ± 4.03	20.45 ± 2.19^b	27.65 ± 1.15	24.79 ± 1.59	21.50 ± 1.46	24.65 ± 1.14^c
80	27.66 ± 1.59	21.80 ± 1.41	21.32 ± 3.00	23.60 ± 1.47^b	35.82 ± 3.05	30.41 ± 1.04	30.46 ± 2.70	32.23 ± 1.51^b
110	45.50 ± 4.18	40.28 ± 3.59	41.34 ± 2.05	42.37 ± 1.87^a	48.24 ± 2.26	43.51 ± 0.98	42.95 ± 1.13	44.90 ± 1.15^a
Mean	32.21 ± 3.95^a	26.53 ± 3.69^a	27.68 ± 3.76^a	28.81 ± 2.16^B	37.24 ± 3.20^a	32.91 ± 2.84^b	31.64 ± 3.25^b	33.93 ± 1.78^A

TABLE 13 Effects of grain initial moisture content and drying air temperature on coefficient of performance of the dryer (%)

Tempe-rature °C	Clint				Raissa			
	Moisture content, %				Moisture content, %			
	20	25	30	Mean	20	25	30	Mean
58	76.54 ± 5.47	82.48 ± 1.59	79.63 ± 4.03	79.55 ± 2.19^a	72.35 ± 1.15	75.21 ± 1.59	78.50 ± 1.46	75.35 ± 1.14^a
80	72.34 ± 1.59	78.20 ± 1.41	78.68 ± 3.00	76.40 ± 1.47^a	64.18 ± 3.05	69.59 ± 1.04	69.54 ± 2.70	67.77 ± 1.51^b
110	54.50 ± 4.18	59.72 ± 3.59	58.66 ± 2.05	57.63 ± 1.87^b	51.76 ± 2.26	56.49 ± 0.98	57.05 ± 1.13	55.10 ± 1.15^c
Mean	67.79 ± 3.95^a	73.47 ± 3.69^a	72.32 ± 3.76^a	71.19 ± 2.16^A	62.76 ± 3.20^b	67.09 ± 2.84^a	68.36 ± 3.25^a	66.07 ± 1.78^B

Note: Means for each grain moisture content or air temperature with the same letter (within each column or each row) are not significantly different at 5 % level.

TABLE 14 Effects of grain initial moisture content and drying air temperature on total heat efficiency of the dryer (%)

Tempe-rature °C	Clint				Raissa			
	Moisture content, %				Moisture content, %			
	20	25	30	Mean	20	25	30	Mean
58	22.48 ± 5.26	16.24 ± 1.58	19.36 ± 3.97	19.36 ± 2.15^b	26.31 ± 0.92	23.09 ± 1.42	20.50 ± 1.27	23.30 ± 1.04^c
80	27.01 ± 1.56	20.88 ± 1.27	20.42 ± 2.84	22.77 ± 1.46^b	34.95 ± 2.96	29.32 ± 1.15	29.35 ± 2.59	31.20 ± 1.51^b
110	44.58 ± 4.05	39.10 ± 3.53	40.37 ± 1.95	41.35 ± 1.85^a	47.32 ± 2.18	42.29 ± 0.89	42.02 ± 1.17	43.87 ± 1.15^a
Mean	31.36 ± 3.90^a	25.41 ± 3.68^a	26.71 ± 3.74^a	27.83 ± 2.15^B	36.19 ± 3.24^a	31.57 ± 2.89^b	30.62 ± 3.25^b	32.79 ± 1.80^A

Note: Means for each grain moisture content or air temperature with the same letter (within each column or each row) are not significantly different at 5 % level.

4.4.2   Effects grain initial moisture content and drying air temperature on quality attributes of dried grain

a) Bulk Density

Analysis of variance for change in bulk density shows that grain bulk density was significantly affected by interaction of the grain initial moisture content and the drying air temperature. However, the density of the two maize hybrids decreased as the moisture content and drying temperature increased (Table 15).

The bulk density of the dried "Clint" was at its highest value (approx. 78 kg/hl) when it was dried at the ambient air temperature. It decreased as the moisture content increased from 25 to 30 % but increased as the moisture content increased from 20 to 25 % moisture content. Black spots, presumably growing fungi, was observed within the grain samples dried with this air would be the cause of this irregularity. At 58 and 80 °C, the density decreased almost linearly as the moisture content increased. At 110 °C, the density dropped more sharply when the moisture increased from 20 to 25 % than when the moisture increased from 25 to 30 %.

The trend in the bulk density for "Clint" hybrid was the same as for "Raissa" hybrid dried from all the three moisture contents at all the three temperatures produced by the dryer. When dried at the ambient air, the density of the latest hybrid decreased almost linearly with increasing the moisture content. The lowest density (approx. 66 kg/hl) resulted as the grain dried at the highest temperature from the highest moisture content.

Under each drying condition, the bulk density of the "Clint" was always higher than the bulk density of the "Raissa". The overall difference between the two hybrids (from approx. 74.73 kg/hl, for the "Clint", to approx. 71.59 kg/hl, for the "Raissa") was shown statistically significant ($P \leq 0.05$).

TABLE 15 Effects of grain initial moisture content and drying air temperature on bulk density of dried grain (kg/hl)

Tempe-rature °C	Clint				Raissa			
	Moisture content, %				Moisture content, %			
	20	25	30	Mean	20	25	30	Mean
20	77.58 ± 0.00	77.91 ± 0.00	76.44 ± 0.00	77.31 ± 0.22^a	76.00 ± 0.00	74.57 ± 0.00	72.85 ± 0.00	74.47 ± 0.46^a
58	77.09 ± 0.14	75.31 ± 0.21	72.63 ± 0.12	75.01 ± 0.65^b	74.49 ± 0.04	72.11 ± 0.28	69.60 ± 0.12	72.06 ± 0.71^b
80	76.24 ± 0.23	73.92 ± 0.21	71.46 ± 0.49	73.87 ± 0.71^c	73.41 ± 0.14	70.61 ± 0.19	67.83 ± 0.45	70.62 ± 0.82^c
110	75.74 ± 0.17	72.57 ± 0.50	69.83 ± 0.33	72.71 ± 0.87^d	72.46 ± 0.20	68.90 ± 0.41	66.28 ± 0.68	69.21 ± 0.93^d
Mean	76.66 ± 0.23^a	74.93 ± 0.61^b	72.59 ± 0.75^c	74.73 ± 0.43^A	74.09 ± 0.40^a	71.55 ± 0.64^b	69.14 ± 0.76^c	71.59 ± 0.49^B

TABLE 16 Effects of grain initial moisture content and drying air temperature on breakage susceptibility of dried grain (%)

Tempe-rature °C	Clint				Raissa			
	Moisture content, %				Moisture content, %			
	20	25	30	Mean	20	25	30	Mean
20	1.86 ± 0.35	1.24 ± 0.06	1.20 ± 0.18	1.43 ± 0.16^c	1.21 ± 0.18	1.96 ± 0.21	1.24 ± 0.08	1.47 ± 0.15^c
58	13.37 ± 1.53	22.19 ± 1.31	25.21 ± 2.41	20.26 ± 1.99^b	13.18 ± 0.60	20.62 ± 2.97	23.24 ± 1.70	19.02 ± 1.81^b
80	15.68 ± 0.56	23.11 ± 1.87	28.23 ± 0.90	22.34 ± 1.92^b	14.23 ± 3.13	28.57 ± 3.47	33.95 ± 3.12	25.58 ± 3.36^a
110	19.28 ± 1.52	28.83 ± 2.84	31.17 ± 3.17	26.43 ± 2.24^a	18.29 ± 2.53	30.14 ± 3.31	33.94 ± 0.35	27.45 ± 2.65^a
Mean	12.55 ± 2.02^b	18.84 ± 3.25^a	21.45 ± 3.69^a	17.61 ± 1.83^A	11.73 ± 2.11^b	20.32 ± 3.58^a	23.10 ± 4.10^a	18.38 ± 2.06^A

Note: Means for each grain moisture content or air temperature with the same letter (within each column or each row) are not significantly different at 5 % level.

b) Breakage susceptibility

Breakage susceptibility of both hybrids was also affected by the drying temperature and the moisture content. As the temperature and/or the moisture content increased, the dried grain became more susceptible to breakage (Table 16). The highest damage (above 30 %) occurred for grain dried from the highest moisture content (30 %) at the highest air temperature (110 °C and 80 to 110 °C, for the "Clint" and "Raissa", respectively).

Statistical analysis indicates that there were interaction effects between the grain moisture content and the drying air temperature on the breakage susceptibility. The breakage was almost constantly low (approx. 1.5 %) for the two hybrids dried at the ambient temperature from all the three moisture contents. At the three air temperatures produced by the dryer (58, 80 and 110 °C), the breakage increased as the moisture content increased. When the moisture content increased from 20 to 25 %, drying the grain at these temperatures increased the breakage significantly larger than when the moisture content increased from 25 to 30 %.

For the "Clint" hybrid, the 110 °C and 20 °C drying resulted in the highest and the lowest damage, respectively. The 80 °C-air temperature caused about 2 % more breakage than the 58 °C-air temperature but their effects were not significantly different from each other. For the "Raissa", the effects of the 80 and 110 °C air temperatures (approx. 25.58 and 27.45 % breakage susceptibility) were not shown statistically significant between each other but they were significantly the highest compared with the effects of other temperatures. Drying the grain at 58 °C caused significantly more breakage than drying it at the ambient air temperature. The difference between the drying effects on the two hybrids (approx. 17.61 and 18.38 % breakage susceptibility for the "Clint" and the "Raissa", respectively) was not big enough to be statistically significant.

c) Stenvert hardness

Hardness is an important intrinsic property of maize because it is closely related to the ratio of corneous to floury endosperm that affect dry-milling flaking grit yields (Kirleis and Stroshine, 1990). According to the results listed in Table 17 and Table 18, there were no clear effects of the moisture content of the grain and/or temperature of the air on hardness properties of the two hybrids.

For the "Raissa" hybrid, the effects on the Stenvert energy consumption was not significantly different. The mean of the resistance time was, however, significantly lower when it was dried from 30 % moisture content than when it was dried from the other two lower moisture contents. The resistance time were not significantly affected by the three drying air temperatures produced by the dryer.

For the "Clint" hybrid, the Stenvert energy consumption and resistance time indicated that drying from 20 % moisture content produced significantly harder grain than when it was dried from higher moisture contents. The two indicators were significantly the highest for the grain of 20 % moisture contents. Results of the samples dried by the dryer show that the dried grain was harder when it was dried at lower air temperature. The energy consumption and resistance time was significantly higher for the grain dried at 58 °C than the same grain dried at 110 °C. The consumption for the grain dried at 80 °C was also significantly different from the grain dried at 110 °C, but not significantly different from the grain dried at 58 °C. Whereas, the resistance time for the grain dried at 80 °C was not significantly different from the grain dried at 110 °C or at 58 °C.

Interaction effects indicated by the statistical analysis would confirm all of these inconsistencies. However, the overall results indicate that the dried "Clint" was significantly harder than the dried "Raissa". The Stenvert milling energy and resistance time were approx. 10 kJ and 31 s, respectively, for the "Clint" but they were significantly smaller (approx. 7.8 kJ and 18 s, respectively) for the "Raissa".

TABLE 17 Effects of grain initial moisture content and drying air temperature on Stenvert energy consumption (kJ)

Tempe-rature °C	Clint				Raissa			
	Moisture content, %				Moisture content, %			
	20	25	30	Mean	20	25	30	Mean
20	9.34 ± 0.12	9.26 ± 0.12	9.68 ± 0.21	9.43 ± 0.10^b	7.51 ± 0.07	7.99 ± 0.24	7.81 ± 0.48	7.77 ± 0.17^a
58	10.50 ± 0.24	10.05 ± 0.12	10.40 ± 0.26	10.32 ± 0.13^a	7.96 ± 0.22	7.77 ± 0.22	7.59 ± 0.27	7.77 ± 0.13^a
80	10.43 ± 0.06	10.20 ± 0.32	10.27 ± 0.22	10.30 ± 0.12^a	7.74 ± 0.12	7.53 ± 0.13	7.63 ± 0.31	7.63 ± 0.11^a
110	10.76 ± 0.09	9.19 ± 0.21	9.18 ± 0.22	9.71 ± 0.28^b	8.15 ± 0.19	7.81 ± 0.16	7.38 ± 0.09	7.78 ± 0.14^a
Mean	10.26 ± 0.18^a	9.68 ± 0.16^b	9.88 ± 0.18^b	9.94 ± 0.10^A	7.84 ± 0.10^a	7.78 ± 0.10^a	7.60 ± 0.14^a	7.74 ± 0.07^B

TABLE 18 Effects of grain initial moisture content and drying air temperature on Stenvert resistance time (s)

Tempe-rature °C	Clint				Raissa			
	Moisture content, %				Moisture content, %			
	20	25	30	Mean	20	25	30	Mean
20	29.80 ± 0.67	28.67 ± 0.52	28.83 ± 1.36	29.10 ± 0.50^c	18.87 ± 0.23	20.30 ± 0.85	18.40 ± 1.30	19.19 ± 0.54^a
58	34.83 ± 0.62	33.30 ± 0.61	33.07 ± 0.76	33.73 ± 0.43^a	19.17 ± 0.38	17.20 ± 1.30	16.87 ± 0.87	17.74 ± 0.59^{ab}
80	33.73 ± 0.47	32.33 ± 0.81	31.47 ± 0.95	32.51 ± 0.51^{ab}	19.07 ± 0.74	16.43 ± 0.90	15.43 ± 1.01	16.98 ± 0.70^b
110	36.07 ± 1.09	29.47 ± 0.57	27.43 ± 1.05	30.99 ± 1.38^b	19.37 ± 0.17	17.07 ± 0.38	14.43 ± 0.39	16.96 ± 0.73^b
Mean	33.61 ± 0.78^a	30.94 ± 0.64^b	30.20 ± 0.80^b	31.58 ± 0.48^A	19.12 ± 0.20^a	17.75 ± 0.60^a	16.28 ± 0.61^b	17.72 ± 0.34^B

Note: Means for each grain moisture content or air temperature with the same letter (within each column or each row) are not significantly different at 5 % level.

4.4.3   Drying models

a)   Application of the Page model based on general forms of k and n by Liu et al. (1998)

Analysis of the moisture ratio, using the formulae for k and n (Liu et al., 1998), was only done for both hybrids dried from approx. 20 and 25 % to approx. 15 % moisture content at 58 °C drying air temperature (Refer to Appendix B for the ranges of grain initial moisture content and drying air temperature applicable for Liu et al's model).

Results of the analysis showed that during drying the experimental moisture ratio reduced at slower rate than the predicted values for both hybrids (Figure 15 and Figure 16). As the drying was proceeded, the fitness reduced further. For instance, after 160 min of drying, the experimental moisture ratios of "Clint" dried from approx. 25 % moisture content at 58 °C drying air temperatures was about 0.23 % higher than the predicted moisture ratio. The experimental moisture ratio of "Raissa" dried from approximately the same moisture content at the same drying air temperatures was about 0.19 % higher than the predicted moisture ratio at 140 min of drying.
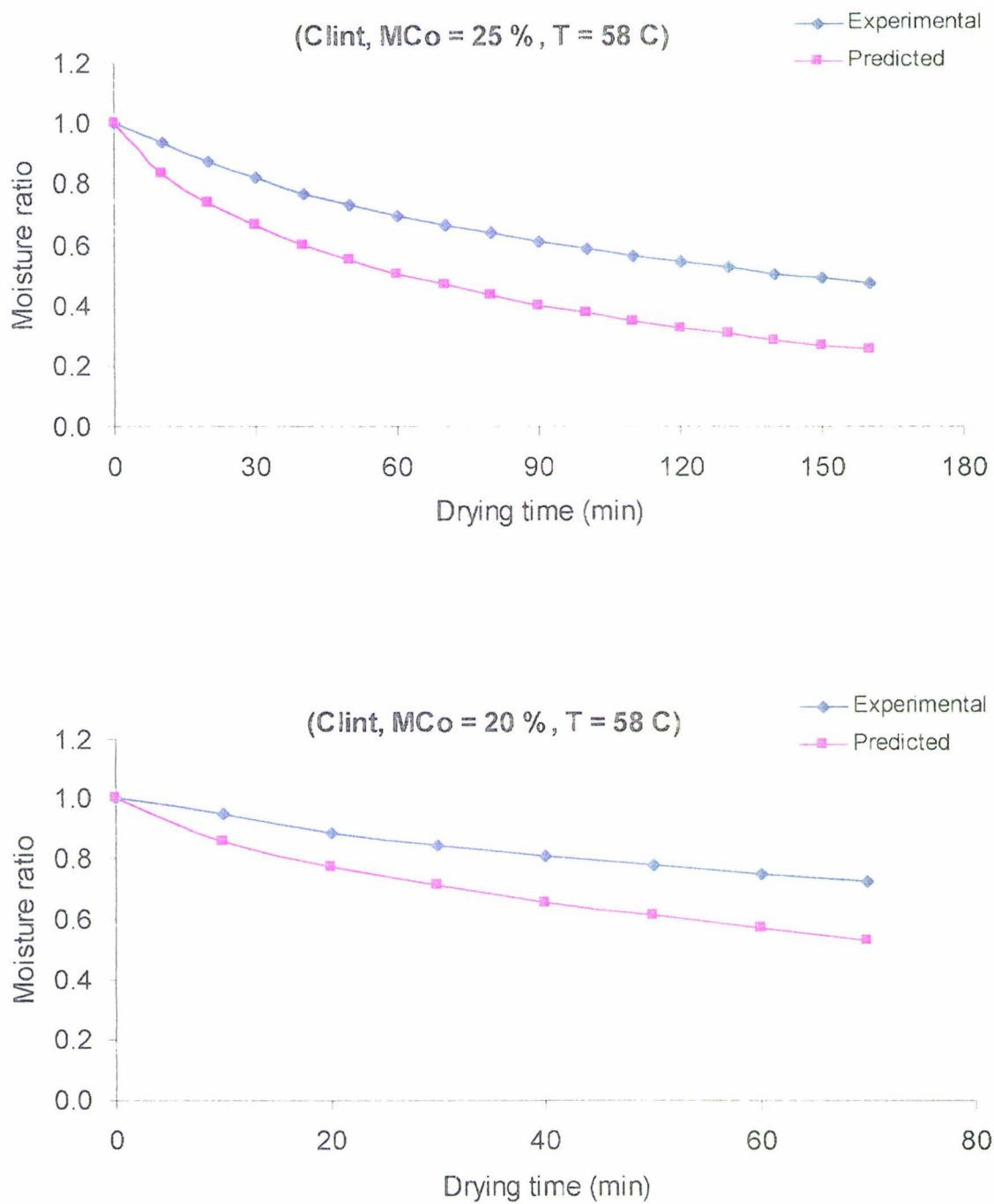
FIGURE 15   Comparison of the experimental and predicted moisture ratios of "Clint"
maize hybrid based on Liu et al' (1998) generalized relationships
between drying constants (k and n), initial grain moisture content and
drying air temperature
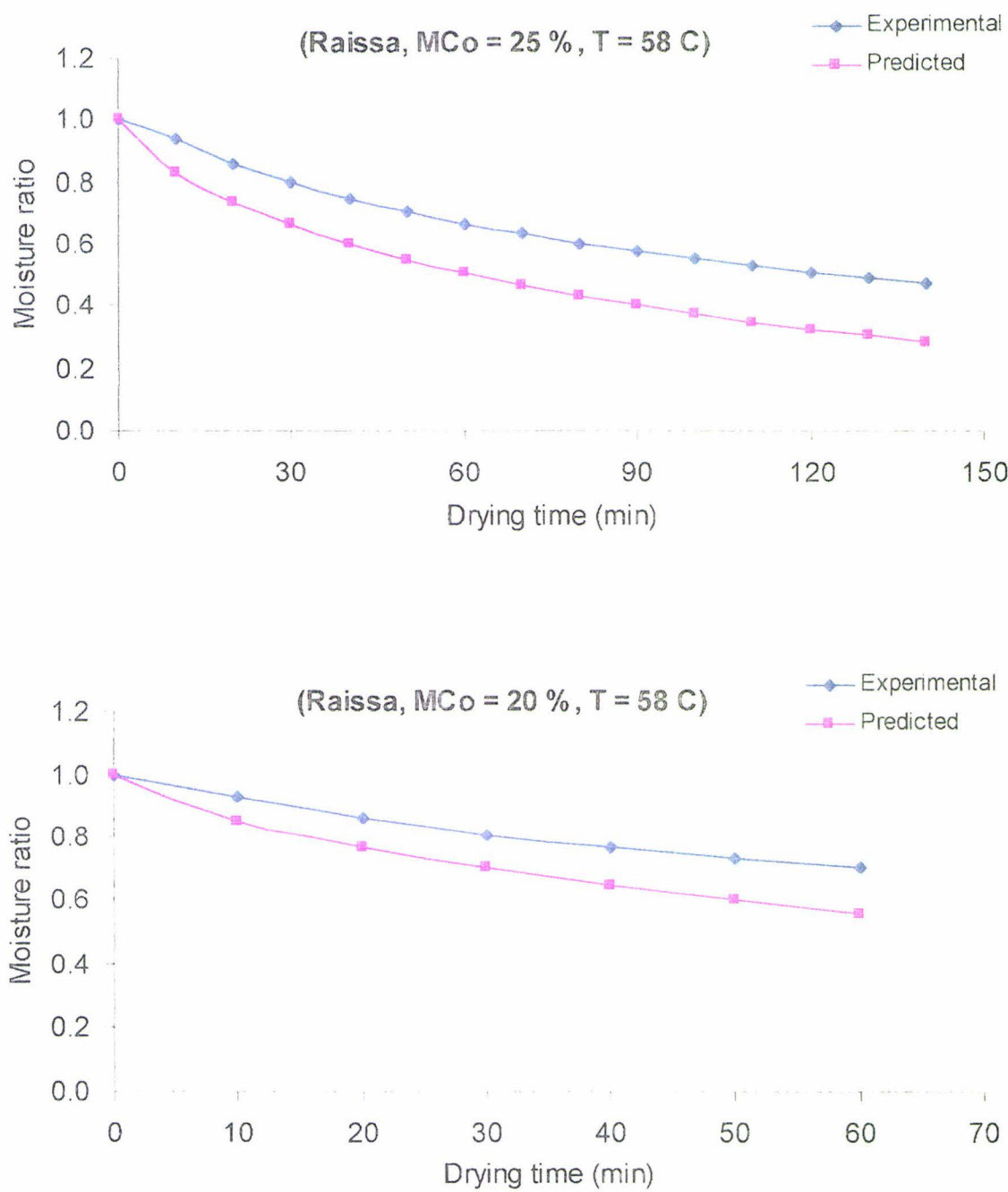
FIGURE 16   Comparison of the experimental and predicted moisture ratios of
"Raissa" maize hybrid based on Liu et al' (1998) generalized
relationships between drying constants (k and n), initial grain moisture
content and drying air temperature

b) Application of the Page model based on determination of the specific drying constants (k and n)

Following Misra and Brooker (1980) and Li and Morey (1984) (see Appendix C), values of the drying constants (k and n) for each grain initial moisture content and drying temperature were determined using linear regression on the transformed form of the Page model :

$$ln \ (-ln \ MR) = ln \ k + n \ (ln \ t) \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (38)$$

Determination of the drying constants for both hybrids dried from approx. 20 % moisture content at the air temperatures ≥ 80 °C was discarded from the analysis due to there were only three moisture ratios observed during the experiment.

Values of the drying constants and the coefficients of determination (R^2) between the observed and predicted moisture ratios are presented in Table 19. The fitness of the comparison between the experimented and predicted were mostly very good with the values of $R^2 \geq 0.9678$.

Graphical comparisons of the two observed and predicted moisture ratios calculated from Equations (C.2 and C.3 - Appendice C) are shown in Figures 17 to 22 .

TABLE 19   The specific coefficients of the Page thin-layer drying model for "Clint" and "Raissa" maize hybrids

Moisture Content, %	Tempera-ture,°C	Clint			Raissa		
		k	n	R^2	k	n	R^2
20	58	0.00692	0.9224	0.9817	0.00940	0.8996	0.9911
25	58	0.01127	0.8357	0.9933	0.01031	0.8842	0.9892
25	80	0.00541	1.1486	0.9798	0.00456	1.1992	0.9844
25	110	0.00188	1.5202	0.9906	0.00168	1.5718	0.9923
30	58	0.00825	0.9033	0.9881	0.00455	1.0505	0.9791
30	80	0.00214	1.3184	0.9678	0.00120	1.4644	0.9684
30	110	0.00094	1.6924	0.9865	0.00149	1.5875	0.9939
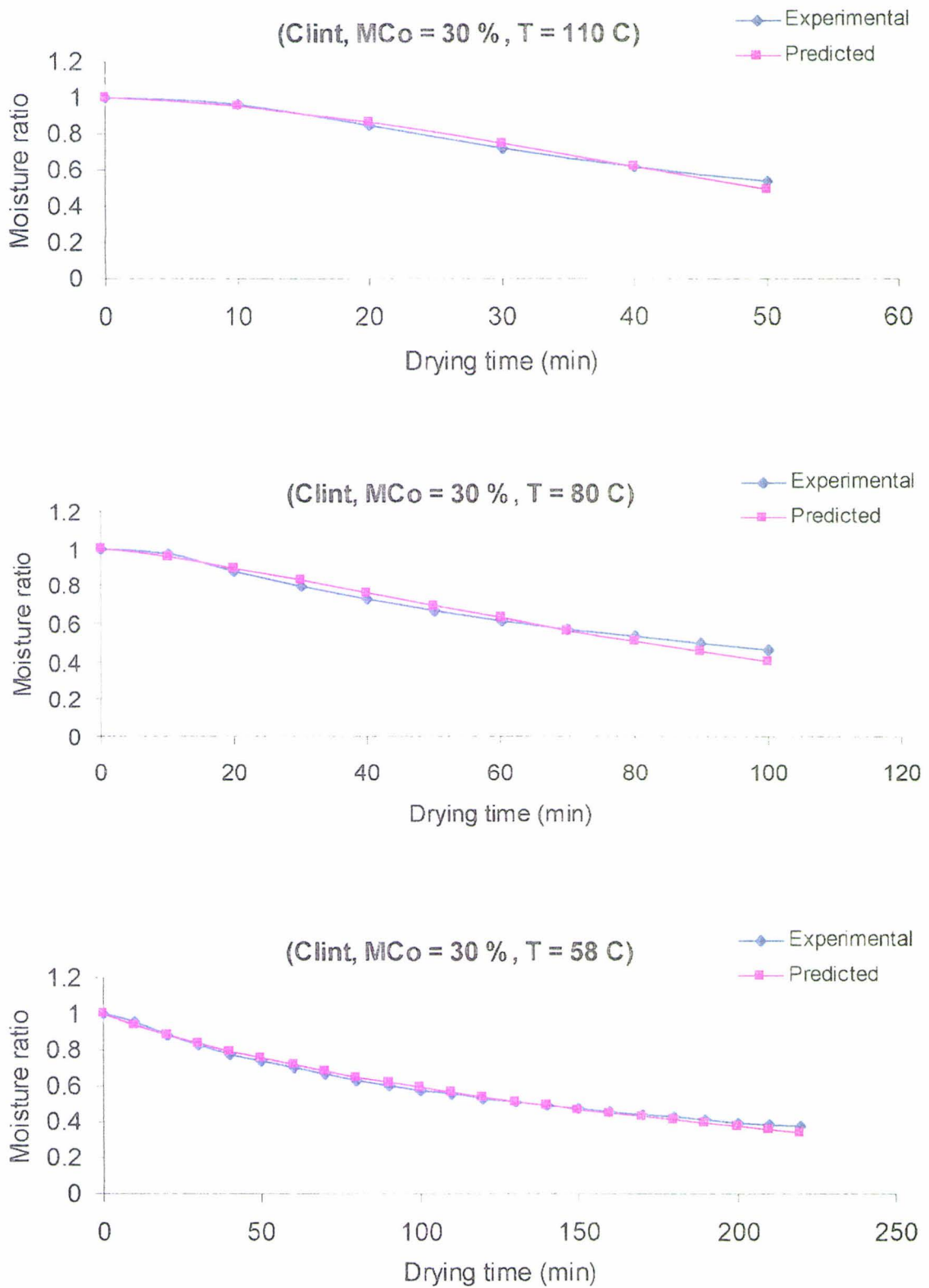
Figure 17 Comparison of the experimental and predicted moisture ratios of "Clint" maize hybrid dried from approx. 30 % to approx. 15 % moisture content based on specific constants of thin-layer drying model
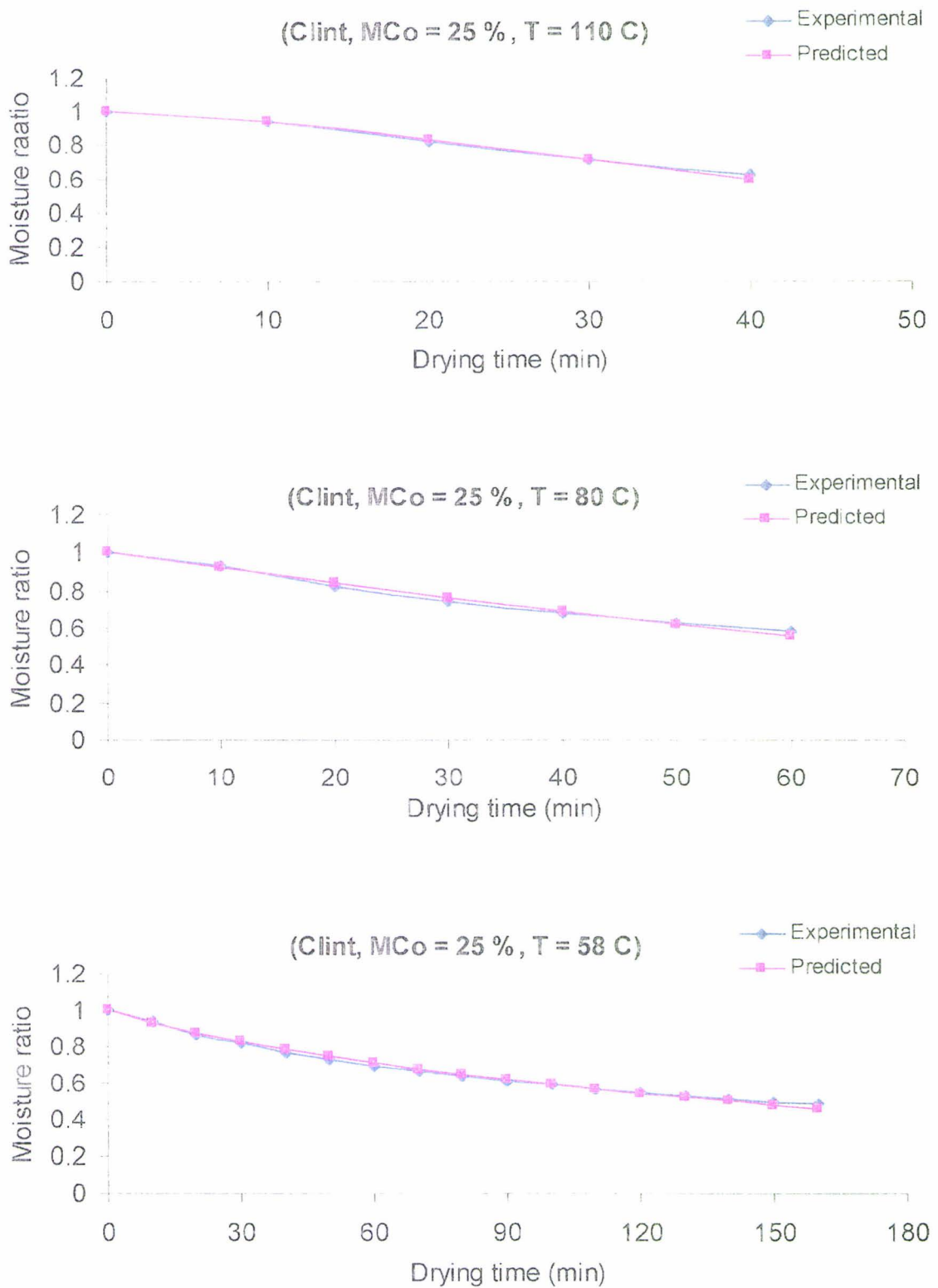
Figure 18   Comparison of the experimental and predicted moisture ratios of "Clint" maize hybrid dried from approx. 25 % to approx. 15 % moisture content based on specific constants of thin-layer drying model
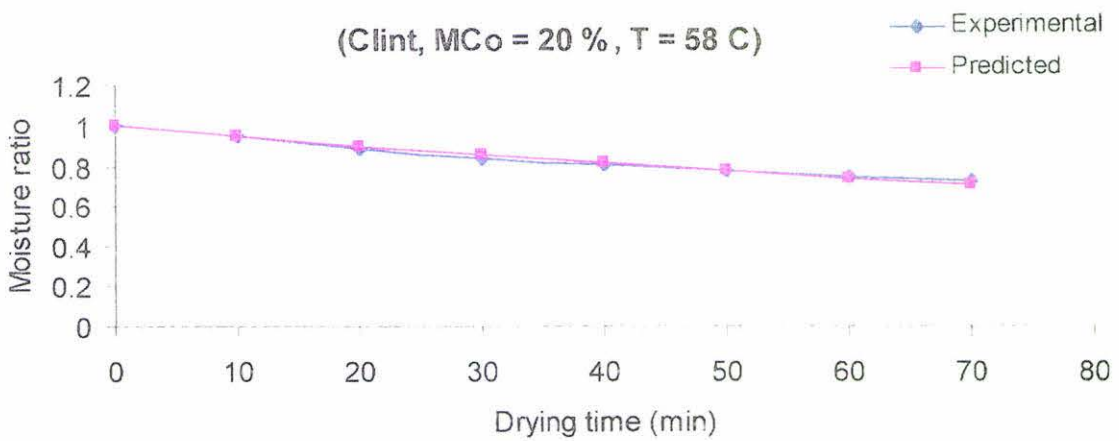
Figure 19 Comparison of the experimental and predicted moisture ratios of "Clint"
maize hybrid dried from approx. 20 % to approx. 15 % moisture content
based on specific constants of thin-layer drying model
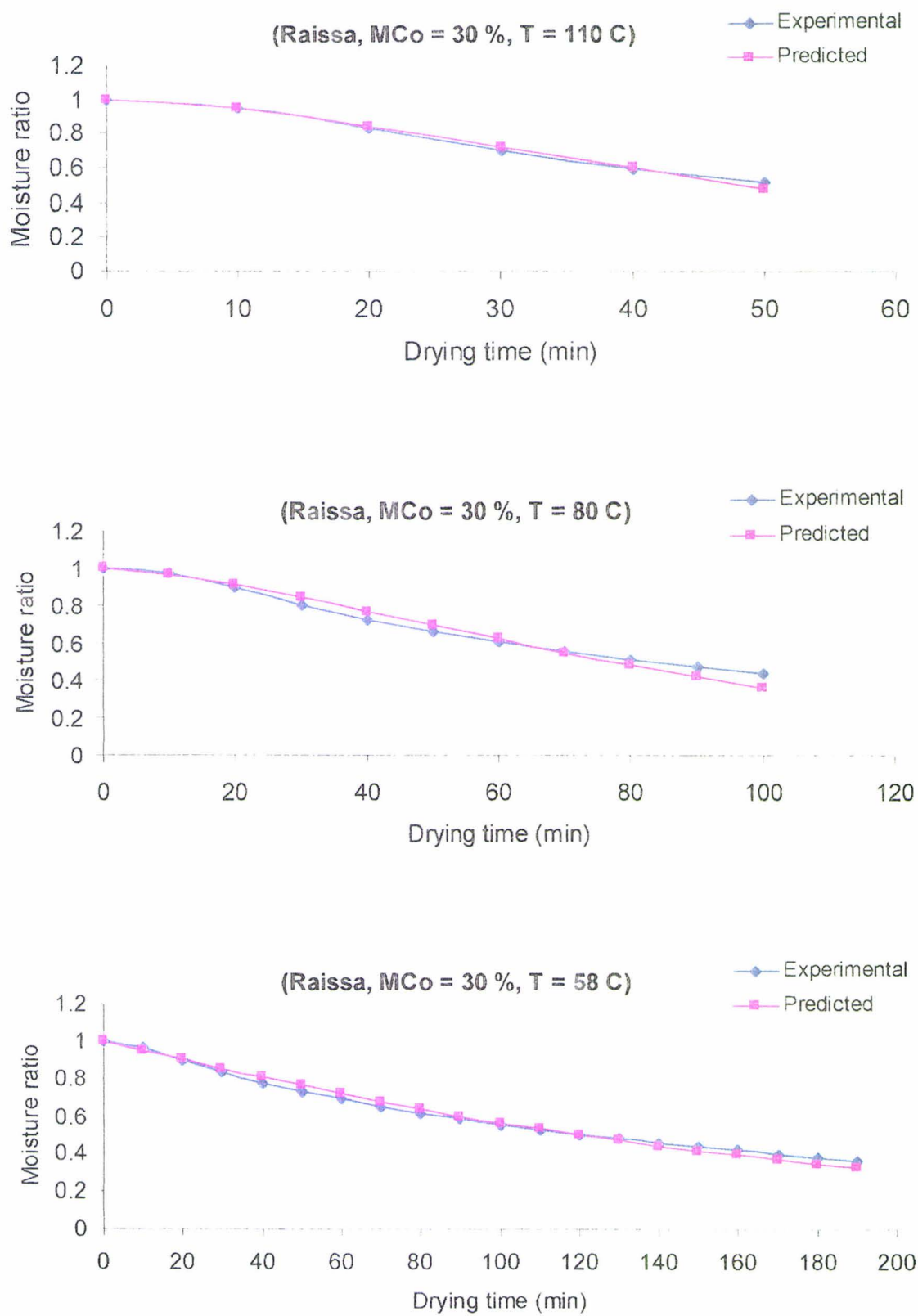
Figure 20 Comparison of the experimental and predicted moisture ratios of "Raissa" maize hybrid dried from approx. 30 % to approx. 15 % moisture content based on specific constants of thin-layer drying model
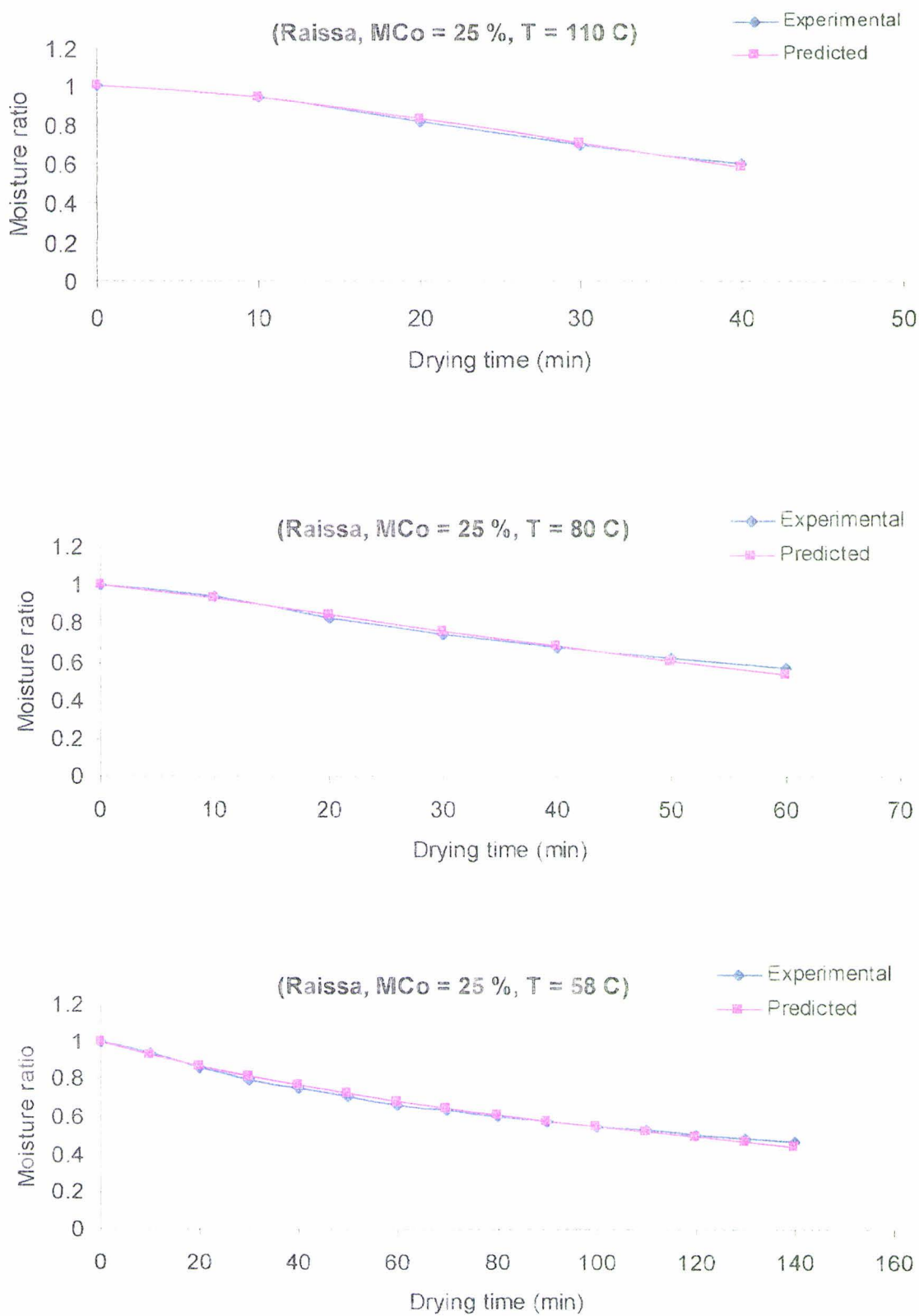
Figure 21 Comparison of the experimental and predicted moisture ratios of "Raissa" maize hybrid dried from approx. 25 % to approx. 15 % moisture content based on specific constants of thin-layer drying model
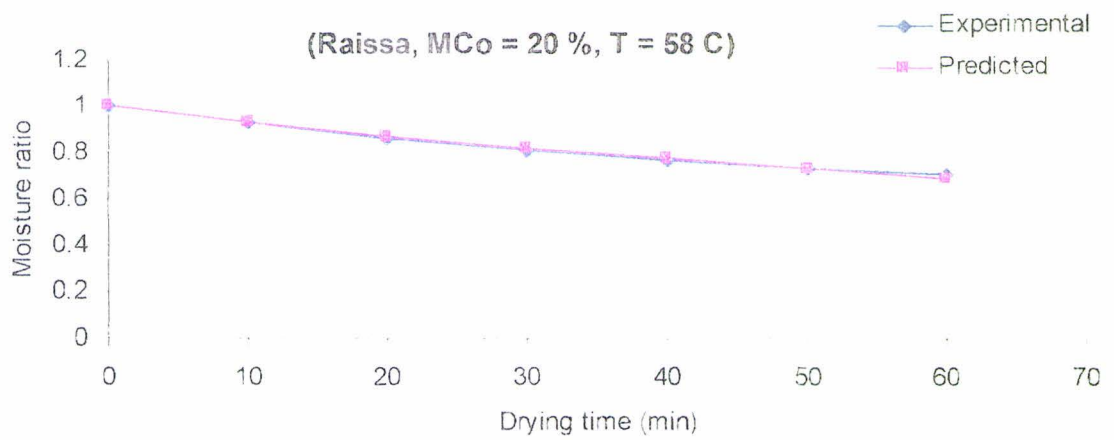
Figure 22   Comparison of the experimental and predicted moisture ratios of "Raissa" maize hybrid dried from approx. 20 % to approx. 15 % moisture content based on specific constants of thin-layer drying model

4.5 Discussion

The drying time for both hybrids increased significantly with increasing initial moisture content of grain, but decreased with the drying air temperature. This means that the higher the moisture content, the longer the drying took time and the grain could be dried from any moisture content to the predetermined level in shorter time by increasing the drying temperature.

The capacity of the dryer increased when drying grain at lower moisture content and/or at higher drying air temperature. However, the capacity varied inversely with the drying time. This can be explained that with the same size of the drying sample, capacity of the dryer was related only on the drying time. The shorter the drying time the more capacity was produced by the dryer and vice versa.

In terms of average drying rate, the dryer could remove approx. between 0.6 to 3 kg of moisture in one hour from the 15-kg drying sample when the grain initial moisture content and drying air temperature varied from approx. 20 to 30 % and 58 to 110 °C, respectively. These mean that the dryer produced higher drying rate, when drying the grain of higher moisture content or when the drying grain was subjected to the air of higher temperature.

The important factors to note here are that (a) the moisture holding capacity of the heated air is increased with the increase of its temperature (Hall, 1980) and (b) drying of cereal grains occurs almost exclusively during the falling rate period (Brooker et al., 1974; Brooker et al., 1992). As the moisture content of grain is lower or the grain becomes drier, the rate at which it loses moisture will decrease. Brook (1992) stated that these are important concepts that will be useful when attempting to understand the performance of grain drying systems. On the other hand, Patil and Ward (1989) explained the high drying rate at high initial moisture contents of rapeseed is due to the availability of more moisture at the surface of the grain. At lower initial moisture content the moisture has to be transferred from the interior to the surface of the grain. The last authors also reported that the rapeseed dried at a faster rate at higher air temperature due to the greater sensible heat in the drying air.

The dryer consumed high energy when drying any of the two hybrids from high moisture content, especially at using low air temperature. Within each moisture content, the energy was reduced when higher temperature was used. The above concepts related to the grain initial moisture content and drying air temperature could also be used to explain this phenomenon.

The Heat Utilisation Factor (HUF), Coefficient Of Performance (COP) and Total Heat Efficiency (THE) of the dryer were partly affected by the grain initial moisture content and the drying air temperature. The higher the air temperature and/or the lower the grain initial moisture content, the dryer produced the higher HUF and THE but the lower COP. Adeyemo (1993) found similar trend for the efficiency of the convention dryer when drying maize grain. The author concluded that increase in drying rate equally increased the drying efficiency of the dryer. On the whole, the maximum average HUE value of 45 % indicates that the prototype dryer had fairly low heat utilisation efficiency. Increasing the depth of the drying grain would assure the low energy requirement and could be one of the options to increase the drying efficiencies. Brook (1992) reviewed that in full scale drying tests, drying efficiencies for continuous flow, dryeration and combination drying systems are 51, 78 and 79 %, respectively.

According to Aguilar and Boyce (1966), THE is defined as the ratio of the sensible heat used in drying to the sum of the sensible heat in the ambient air and the heat added. As it is a function of the ambient wet bulb temperature, which is not dependent on the dryer, it is not possible to compare dryers with this ratio unless some fixed basis is established. COP on the other hand, is defined as the heat equivalent of the moisture evaporated at the air dry bulb temperature to the heat supplied to the drying air. Related to HUF, it can be expressed as:

$$COP = HUF - 1 \qquad\qquad .... (39)$$

Therefore, HUF would decrease from 100 % towards 0 % as drying efficiency decreases; whereas COP would increase with decreasing efficiency. HUF seems more logical to use although these ratios are in fact the same.

The hard hybrid (Clint) showed lower but no significant different with the soft hybrid (Raissa) in breakage susceptibility but the "Clint" bulk density and hardness characteristics indicated that the hybrid is significantly heavier and harder than the "Raissa" hybrid. These phenomena could help explain why food maize processors prefer "hard" hybrids, which are usually low in breakage susceptibility and high in bulk density. The bulk density and the breakage susceptibility of the two hybrids tended to decrease and increase, respectively, as the initial moisture content and drying temperature increased. These results agree with those previously reported by Hall (1972) and Gunasekaran and Paulsen (1985). Kirleis and Stroshine (1990) had also found that for each of their tested hybrids, Stenvert hardness test values remained relatively constant for maize dried at temperatures up to 60 °C and then declined only slightly, but not significantly, at the higher drying temperatures (93.3 °C).

The level of the damage was very small for both hybrids dried at the ambient air temperature but the drying took a longer time and the dried samples developed pathological problems such as mould or fungal infection.

Analysis of the Page model based on general form of drying constants (k and n) as stated by Liu et al. (1998) could be done only for few drying conditions applied in this experiment (for both hybrids dried from ≤ 25 % at 58 °C). And generally, there was not good agreement between the observed and the predicted moisture ratios. Characteristics of different maize hybrids and inconsistency of the ambient air would be the main causes of the difference. The drying conditions designed and applied in this experiment, however, produced their own specific drying constants. The fitness of the comparison between the observed and predicted (using the coefficients found) were mostly very good.

4.6 Conclusions

The observations and results of this study suggest that the prototype dryer is suitable for research purposes. Its automatic-control systems make it simple and one trained personnel would be enough to operate it.

Both the grain initial moisture content and drying air temperature affected the dryer performance and some of the grain quality attributes. In summary,

1. Drying time varied from approx. 45 to 270 min depending on the grain initial moisture content and the drying air temperature. It increased as the moisture content was increased and/or the air temperature was decreased.

2. The drying capacity varied inversely with the drying time. The dryer capacity of approx. 20 kg/h was the maximum as the "Clint" was dried from 20 % moisture content at 110 °C. It decreased, to the lowest value (approx. 3.5 kg/h), with decreasing the air temperature and increasing the moisture content of the drying grain.

3. The average drying rate was also the highest (approx. 2.93 kg of water evaporated in one hour) when the "Raissa" sample of 30 % moisture content was dried at 110 °C air temperature. It decreased as the air temperature and the moisture decreased.

4. The energy consumed by dryer decreased as the air temperature increased and the moisture content decreased for both hybrids. Its maximum and minimum values were approx. 5 and 1 kWh respectively.

5. On the whole, the dryer had fairly low heat utilisation efficiencies. The efficiencies were found decreased as the grain moisture content was increased and/or as the air temperature was decreased.

6. In order to increase the dryer capacity and to decrease the drying energy consumption, therefore, air of high temperature would be needed. However, using higher air temperature for drying would cause more damage to the grain, especially when its initial moisture content is high.

7. There was not good agreement between the observed and predicted grain moisture ratios based on the thin-layer drying model (the Page model) reported by Liu et al. (1998). However, There was good agreement between the observed and predicted moisture ratio based on the Page model using the specific drying constants.

Characteristics of different maize hybrids and the inconsistency of the ambient air could be the main suspecting factors.

8. Breakage and bulk density of the dried grain were affected more badly as the air temperature and the moisture content increased. The most damage was shown with the highest breakage (35 %) and the lowest bulk density (66 kg/hl). This means that high harvest moisture, combined with high drying temperature caused big damage to the dried grain.

9. The hardness characteristics of the dried grain decreased at higher initial moisture content and/or at higher drying air temperature. However, the analysis did not indicate these effects substantially and clearly. The only clear indication was that "Clint" hybrid is harder than "Raissa" hybrid.

Chapter 5

EXPERIMENT II

Effects of cooling
on grain quality attributes of hard and soft maize hybrids

5.1 Introduction

Previous studies have shown that improper artificial drying can reduce the quality and economic value of dried maize grain. Excessive drying air temperatures and high initial grain moisture contents increase the degree of damage to maize kernels in normal a one-pass high temperature grain dryer. Rapid or sudden cooling of grain can also contribute to stress crack development and breakage (Hardacre et al., 1997; Trim and Robinson, 1994; de Lucia and Assennato, 1994; Kunze, 1979; Gustafson et al., 1978). Kernel stress cracks caused by harsh drying techniques increase the amount of breakage that occurs when grain is handled, causing a loss of millable materials (Freeman, 1973).

Kunze (1979) reported that rapid and substantial moisture adsorption by dried rice grain causes it to be stressed and possibly to crack or fissure. Thereafter, the kernel is likely to break when it is milled. White and Ross (1972) discussed stress cracking in maize as affected by drying air temperature, cooling rate and overdrying. In both the white and yellow maize grain tested, there were fewer checked kernels when the grain was cooled slowly after drying. In another study, White et al. (1982) found very few stress cracks when popcorn samples were first removed from a drying apparatus. Stress cracks developed only after some period of time had elapsed. They concluded that rapid cooling adds to the drying stress already present by drying and increased the number of stress cracks. Allowing the dried grain kernels to cool slowly resulted in a dramatic reduction in the number of stress-cracked kernels. The length of this delay period, the eventual number of stress cracks, and the severity of the developed cracks all appear to be related to the moisture gradient existing in the popcorn kernels when they are removed from the dryer.

Thompson and Foster (1963) reported that a reduction of stress cracking in maize grain was achieved by delaying the cooling process until after a tempering period. Likewise,

Gustafson and Morey (1979) claimed that when compared to rapid cooling, delayed or slow cooling reduced the breakage susceptibility of the maize samples dried at high temperature.

5.2 Research aim and objectives

The aims of this experiment were to investigate whether various cooling methods could reduce the susceptibility of the dried grain to damage and to determine the effects of the cooling methods on quality attributes of the grain. The specific objective of this experiment was to quantify quality attributes such as bulk density, breakage susceptibility and hardness of dried maize grain as affected by different cooling methods.

5.3 Experimental design and methodology

In this experiment, samples of both the yellow dent maize hybrids ("Clint" and "Raissa") of approx. 25 % moisture content were dried at air temperature of 80 °C in three replicates. During each drying run, a 5-kg sample was dried in one of the three drying bins and dummy maize grains were put in the other two bins (also 5 kg for each bin). This approach was particularly adopted because observations made in Experiment I (Chapter 4) showed that grain samples in the three drying bins reached target moisture content at different times. The dummy grains were used for each replicate drying run, thereby minimising wastage of good grain.

Drying was carried out until the moisture content of the dried samples reached 14.5 %. This target moisture content was chosen based also on observations made in Experiment I that cooling could reduce the moisture content of the dried grain further by approximately 0.5 %. The grains in the experimental drying bin was mixed thoroughly and divided into four portions for the following four cooling treatments:

Treatment 1: Slow cooling

One portion of approximately 0.75 kg was immediately put and sealed in a vacuum bottle (A-GEE preserving jar, Figure 23) and placed in a sealed chilly bin overnight at ambient room conditions (approx.16 °C and 80 % RH);

Treatment 2: Slow to medium cooling

Another portion (approx. 0.75 kg) was immediately put and sealed in other vacuum bottle of the same type and placed in a cold room (maintained at approx. 7 °C temperature and 30 % relative humidity) overnight;

Treatment 3: Medium to fast cooling

One portion of approximately 1 kg was immediately removed from the bin, spread on a perforated metal tray (25 x 50 cm, Figure 24) and exposed freely, for about 6 hours, at ambient room conditions (approx. 18 °C and 80 % RH) until the grain temperature equilibrated with the room environment;

Treatment 4:Fast cooling

The rest of the dried grains were kept in the drying bin and cooled with the ambient air blown by the dryer at the speed of approx. 0.16 m/s. This cooling process was applied until the temperature of the exhaust air reduced to about 26 °C.

After the designed cooling treatments, the grain samples were gently put in paper bags and stored at ambient room conditions (19 °C and 30 % RH) in the seed testing laboratory at the Crop and Food Research Ltd. for about two weeks yielding final moisture content ranging from 12 to 14.5 %. Samples were then assessed for moisture content, bulk density, breakage susceptibility and Stenvert hardness as discussed in Chapter 3 (Section 3.4). The test results were also corrected to the moisture content of 14 %, to eliminate variability of the quality factors due to differences in moisture content after the various design treatments (Hardacre et al., 1997).

5.4 Data analysis

Statistical analysis of data was carried out using the SAS package (version 6.12) based on a 2 x 4 factorial design, where the main factors were the two maize hybrids and the four cooling treatments.

FIGURE 23   The vacuum bottles used for cooling and tempering dried grain

FIGURE 24   The perforated metal-mesh trays used for the medium to fast cooling
                treatment

5.5 Results

5.5.1 Effects of cooling on breakage susceptibility and bulk density of dried grain

The cooling treatments significantly affected the breakage susceptibility of both maize cultivars (Table 20), although there was a significant interaction between the hybrids and cooling treatments (P $\leq$ 0.05). For "Raissa", the breakage susceptibilities were significantly different for each cooling treatment, whereas for "Clint", cooling at ambient conditions (Treatment 3) and in the grain dryer (Treatment 4) had the same effect. Breakage susceptibility was highest when grains were fast cooled in the dryer (Treatment 4) (and at the ambient condition for "Clint") and least when cooled in the chilly bin (Treatment 1). When the results for each maize hybrid were combined, there was no significant difference in breakage susceptibility between the soft "Raissa" and the hard "Clint" hybrids.

TABLE 20   Effects of cooling on the breakage susceptibility and bulk density of dried grain

Cooling Treatment	Breakage susceptibility, %		Bulk density, Kg/hl	
	Clint	**Raissa**	**Clint**	**Raissa**
Chilly bin	13.59 ± 0.51^c	13.88 ± 0.68^d	74.67 ± 0.09^a	71.24 ± 0.27^a
Cold room	21.17 ± 1.71^b	20.07 ± 2.00^c	74.09 ± 0.39^{ab}	70.90 ± 0.18^a
Ambient	30.41 ± 0.55^a	27.67 ± 1.00^b	73.43 ± 0.10^b	70.36 ± 0.14^{ab}
Dryer	30.26 ± 0.39^a	34.92 ± 0.89^a	73.56 ± 0.17^b	69.88 ± 0.16^b
Mean	23.86 ± 2.15^A	24.14 ± 2.44^A	73.94 ± 0.17^A	70.59 ± 0.18^B

Note: Means with the same letter (for the cooling treatments in each column and for the hybrids in the bottom row) are not significantly different at 5 % level

The cooling treatments significantly affected the bulk density of dried grain for both maize hybrids, and in general, the hard "Clint" grain had higher bulk density than the soft "Raissa" grain (P $\leq$ 0.05) (Table 20). For both hybrids, grains cooled in the dryer (Treatment 4) had the lowest bulk density while those cooled in the chilly bin (Treatment 1) had the highest bulk density. However, there was no difference in bulk density between the grains cooled in the chilly bin or cold room.

5.5.2 Effects the cooling on hardness of dried grain

As shown in Table 21, grain hardness of the two maize hybrids indicated by the Stenvert energy consumption and the Stenvert resistance time were not affected significantly ($P \leq 0.05$) by the four cooling treatments. However, the mean results show that the energy and time consumed by the Stenvert tester to mill the "Clint" (hard hybrid) samples were significantly higher (approx. 29.55 and 82.13 %, respectively) than the energy and time consumed to mill the "Raissa" samples (soft hybrid).

TABLE 21 Effects of cooling on hardness characteristics of dried grain

Cooling Treatment	Stenvert energy consumption, kJ		Stenvert resistance time, s	
	Clint	Raissa	Clint	Raissa
Chilly bin	9.26 ± 0.16^a	7.62 ± 0.30^a	28.70 ± 0.10^a	16.60 ± 0.68^a
Cold room	9.74 ± 0.23^a	7.20 ± 0.20^a	29.60 ± 0.85^a	16.20 ± 0.62^a
Ambient	9.75 ± 0.34^a	7.44 ± 0.11^a	29.80 ± 1.14^a	16.33 ± 0.33^a
Dryer	9.65 ± 0.23^a	7.37 ± 0.07^a	30.13 ± 0.87^a	15.80 ± 0.12^a
Mean	9.60 ± 0.12^A	7.41 ± 0.09^B	29.56 ± 0.39^A	16.23 ± 0.23^B

Note: Means with the same letter (for the cooling treatments in each column and for the hybrids in the bottom row) are not significantly different at 5 % level

5.6 Discussion

The four cooling treatments had significant effects on the breakage susceptibility and bulk density but not on the hardness of the dried grain of both maize hybrids. The results corroborate with the findings of Pomerance et al. (1984). The authors reported the relationship between breakage susceptibility and bulk density demonstrating that high breakage susceptibility significantly reduced the bulk density of dried grain. In terms of these two quality factors, both "Clint" and "Raissa" seemed to have less damage when they were cooled inside the chilly bin. The most damage happened to the grain that was cooled by the dryer. Cooling the grain by leaving it in the cold room and with the ambient air were the second and third best methods, respectively. Compared to "Raissa", "Clint" is significantly harder and has greater bulk density.

These results suggest that since drying grain with heated air establishes a temperature and moisture gradient in each kernel (Kunze, 1979 and Foster, 1973), cooling it slowly especially in an airtight and well insulated container would account for the reduction in

grain breakage susceptibility. The containers used in the present study (vacuum bottle and sealed chilly bin) ensured very negligible rate of moisture loss from the grain (or gained by the grain from the ambient environment) such that moisture re-distribution inside the grain predominated. Thus, the higher rate of heat loss (or cooling) due mainly to conduction in grain cooled in cold room (Treatment 2) might also account for the higher breakage susceptibility compared with grain cooled in chilly bin at ambient room conditions (Treatment 1) for both cultivars.

When grain is cooled with the ambient air, moisture and heat loss occur more rapidly due mainly to increased airflow around the grain, and the temperature difference between the air and the grain. When the ambient air is blown through the grain in the dryer (approx. 0.16 m/s), one would expect faster cooling rates, higher moisture gradients in grains and thus more susceptible to damage.

Kunze (1979) explained that rice grains that were rapidly placed into a vial after drying fissured from the effects produced by the reclining moisture gradient. Exposure to the ambient environment may make relatively dried grain fissure more because the low moisture grain surface can pick up or adsorb additional moisture from the environment. The author asserted that rice grains were not fissured at the end of drying, but fissures developed after some period of time had elapsed. On this basis, he hypothesised that cracking or fissuring of rice grain after drying is caused by a diffusion of moisture within the grain resulting from the moisture gradient existing in the grain when it is removed from the dryer.

The author also suggested that the external cells expand as they absorb moisture from the central portions of the grain while the cells in the central portion contract as they lose moisture. The net result is the development of compressive stresses near the surface and tensile stresses near the centre, which (if large enough) can lead to internal fissuring. The author also noted that a low moisture grain surface may pick up additional moisture from the environment and, thereby, hasten the development of fissures. It follows that a low moisture grain with no initial moisture gradient could also fissure by exposed to a high humidity environment provided the rate of moisture gain by the external grain cells is rapid enough to cause high tensile stresses to develop in the centre portion of the grain.

The results obtained in this study are in agreement with those previously reported by other researchers for maize and other grain cultivars (White et al., 1982; Litchfield and Okos, 1988; Hardacre and Pyke, 1998; Brenton-Rule et al., 1998). These researchers demonstrated that stresses increased rapidly after transition from the drying stage to the cooling stage, due to rapid adjustment of the grain temperature and moisture gradients from stage to stage. Rapid cooling may add to the drying stress already present after drying and thereby increase the number of stress cracks. Allowing the dried grain kernel to cool slowly would result in a dramatic reduction in the number of stress-cracked kernels. Slow cooling requirements, however, create a constraint to dryer design due to a reduction in drying capacity, particularly for commercial-scale dryers.

5.7 Conclusions

After drying using the prototype grain dryer (described in Chapter 3) and cooling using four different treatments, the breakage susceptibility, bulk density, Stenvert hardness energy consumption and resistance time were determined for the two (hard and soft) maize hybrids. Based on the results and observations obtained, the following conclusions were made:

1. The cooling treatments significantly affected the breakage susceptibility and bulk density of the two hybrids but the grain hardness attributes were not affected.

2. Slow cooling reduced the damage of dried grain. For instance, cooling the dried grain by blowing ambient air through it resulted in breakage susceptibility over 30% while cooling grain in vacuum bottle placed in chilly bin reduced the amount of damage to about 14 %.

3. The cooling treatment (for instance, Chilly bin) which resulted in the highest reduction in breakage susceptibility also resulted in the highest grain bulk density though causing the grain attain higher value.

4. Based on the overall treatment effects on grain quality attributes, the best cooling treatment was the chilly bin, followed by the cold room and the ambient-air treatments. The worst treatment was cooling the grain in the dryer.

Chapter 6

EXPERIMENT III

Effects of tempering
on grain quality attributes of hard and soft maize hybrids

6.1 Introduction

Stress cracks or fissures are often created in grain by artificial drying. As a result damaged kernels cause increased susceptibility to breakage, insect and microbial attack, decreased rate of seed germination, increased hazard for elevator dust explosions, increased respiration, and restricted aeration (Litchfield and Okos, 1988). Trim and Robinson (1994) reported that several research studies have been conducted to determine drying procedures that produce high quality of dried grain. Most grain kernels were found not fissured immediately after drying, and tempering the grain or a certain period of time before cooling could help prevent subsequent stress cracking and susceptibility to breakage. Fast dryers operating at high temperatures will tend to cause high fissuring if the grain if not allowed to temper.

Short term tempering and multipass, or multistage, drying have been shown to be effective for quality of dried grains such as maize and rice (Emam et al., 1979; Foster, 1973; Gustafson et al., 1982; Omar and Yamashita, 1987; Sabbah et al., 1972; Thompson and Foster, 1963; Trim and Robinson, 1994). Eman et al. (1979) dried maize samples (30 %) at temperatures of 100 and 130 °C and then tempered and cooled them. The authors found that breakage, as measured by a Stein breakage test on conditioned samples, decreased with increased tempering time. At low final moisture contents (13.5 %), grain breakage susceptibility was reduced by 50 % due to one hour of tempering, and to 25 % following ten minutes of tempering. Likewise, Omar and Yamashita (1987) reported that tempering dried rice grain gave shorter drying time and less fissuring, hence safer with less grain broken and greater energy saving.

In one of three maize-drying systems tested, Foster (1973) initially dried maize grain rapidly with hot air to approx. 16 % moisture content. After tempering the partially dried grain for 4 to 10 hours, the grain was cooled slowly and then finally dried by

ventilation with ambient air. While the test indicated that the optimum tempering time was near eight hours, there was evidence of some benefits from tempering for less time.

6.2 Research aim and objectives

The aim of this experiment was to quantify the effects of tempering time (in the range of 4 to 11.5 h) on maize grain quality attributes after drying using the prototype flat-bed grain dryer described in Chapter 3. The specific objective of this experiment was to quantify the changes in breakage susceptibility, bulk density and hardness of dried maize grain as affected by different tempering times.

6.3 Experimental design and methodology

In this experiment, drying was conducted in three replications using similar grain samples ("Clint" and "Raissa" maize hybrids) and under the same drying conditions as described in Experiment II (Chapter 5). The samples were dried in all the three bins (5 kg per bin). Grain in each drying bin provided a replicate sample and when the grain in any drying bin reached 14.5 % moisture content, it was mixed thoroughly and divided into 5 lots or sub-samples. Each sub-sample was assigned to one of the following five tempering treatments (0, 4, 6.5, 9 and 11.5 hours). For one of the 4-, 6.5-, 9- and 11.5-hour treatments, a sub-sample of approx. 0.83 kg was put in a vacuum bottle (the same bottle used for Experiment II – Chapter 5) and placed immediately inside an oven (maintained at 70 °C temperature). For the 0-hour tempering treatment, the dried grain was transferred directly into paper bag.

After the predetermined tempering times, the vacuum bottles were taken out of the oven and the tempered grains were gently transferred into paper bags. All the grain samples were stored at ambient conditions (19 °C and 30 % RH) in the seed testing laboratory at the Crop and Food Research Ltd. for about two weeks yielding final moisture content ranging from 12 to 14.5 %. Samples were then assessed for moisture content, bulk density, breakage susceptibility and Stenvert hardness as discussed in Chapter 3 (Section 3.4). The test results were also corrected to the moisture content of

14 %, to eliminate variability of the quality factors due to differences in moisture content after the various design treatments (Hardacre et al., 1997).

6.4 Data analysis

Statistical analysis of data was also carried out using the SAS package (version 6.12) based on a 2 x 5 factorial design, where the main factors were the two maize hybrids and the five tempering treatments.

6.5 Results
6.5.1 Effects of tempering on breakage susceptibility and bulk density of dried grain

The breakage susceptibility and the bulk density of the two hybrids were significantly affected ($P \leq 0.05$) by the tempering treatments but there was no significant difference between samples tempered for 4 hours or more (Table 22). In general, tempering reduced the breakage susceptibility by approx. 87 and 78.5 %, respectively, for the hard "Clint" and soft "Raissa" maize hybrids, but increased the grain bulk density by approx. 3.75 % for both hybrids.

Under each treatment "Clint" was heavier and broke less than "Raissa". On average, the bulk density of "Clint" was significantly higher (approx. 3.37 kg/hl) than the bulk density of "Raissa", but the breakage susceptibility of approx. 8.42 and 9.86 % for the "Clint" and the "Raissa", respectively, were not statistically different ($P \leq 0.05$).

TABLE 22 Effects of tempering on breakage susceptibility and bulk density of dried grain

Tempering Time, h:min	Breakage, %		Bulk Density, kg/hl	
	Clint	Raissa	Clint	Raissa
0:00	28.12 ± 2.84^a	28.60 ± 2.17^a	73.58 ± 0.12^b	70.17 ± 0.19^b
4:00	3.39 ± 0.41^b	4.14 ± 0.52^b	75.91 ± 0.02^a	72.69 ± 0.24^a
6:30	3.95 ± 0.26^b	5.19 ± 0.65^b	76.30 ± 0.25^a	72.82 ± 0.24^a
9:00	3.07 ± 0.66^b	5.23 ± 1.02^b	75.92 ± 0.08^a	72.71 ± 0.36^a
11:30	3.57 ± 0.39^b	6.15 ± 1.08^b	76.35 ± 0.17^a	72.81 ± 0.11^a
Mean	8.42 ± 2.68^A	9.86 ± 2.55^A	75.61 ± 0.28^A	72.24 ± 0.29^B

Note: Means with the same letter (for the tempering treatments in each column and for the hybrids in the bottom row) are not significantly different at 5 % level

6.5.2 Effects of tempering on hardness characteristics of dried grain

Tempering significantly reduced grain hardness in both hybrids as shown by reductions in Stenvert energy consumption and resistance time during milling (Table 23). There was also a significant interaction between type of hybrid and tempering time (P ≤ 0.05). In general, the no tempering treatment significantly increased the Stenvert energy consumption, but there was no difference between the tempering times after 4 hours of tempering. Also, the Stenvert resistance time generally declined with increasing tempering time but this effect was not statistically significant for "Raissa". Overall, the "Clint" hybrid required higher energy consumption and resistance time than the "Raissa" hybrid during milling at each tempering treatment and when the results were combined.

TABLE 23 Effects of tempering on the hardness characteristics of dried grain

Tempering	Stenvert energy consumption, kJ		Stenvert resistance time, s	
Time, h:min	Clint	Raissa	Clint	Raissa
0:00	9.78 ± 0.16^a	7.67 ± 0.19^a	29.63 ± 0.60^a	16.07 ± 0.43^a
4:00	9.04 ± 0.09^b	7.06 ± 0.08^b	28.57 ± 0.4^{4ab}	15.97 ± 0.18^a
6:30	8.74 ± 0.18^b	7.34 ± 0.14^{ab}	26.37 ± 0.38^c	17.00 ± 0.25^a
9:00	8.65 ± 0.14^b	7.33 ± 0.06^{ab}	25.77 ± 0.52^c	16.13 ± 0.72^a
11:30	8.93 ± 0.15^b	7.07 ± 0.12^b	$26.60 \pm 0.^{3ab}$	15.73 ± 0.98^a
Mean	9.03 ± 0.12^A	7.30 ± 0.08^B	27.39 ± 0.43^A	16.18 ± 0.25^B

Note: Means with the same letter (for the tempering treatments in each column and for the hybrids in the bottom row) are not significantly different at 5 % level

6.6 Discussion

Results of the Stenvert energy consumption and the Stenvert resistance time confirmed that "Clint" was overall harder than "Raissa". Tempering reduced grain hardness significantly in both hybrids, however the degree of change in grain hardness varied considerably between the two hybrids, presumably due to difference in structural changes associated with tempering in both hybrids.

Only the breakage susceptibility and the bulk density of the samples with no tempering time were significantly different from the breakage susceptibility and bulk density of

the other samples, indicating that the effects of tempering occurred earlier during the tempering process. The results support the hypothesis of Kunze (1979) and Foster (1973) indicating that changes in moisture distribution, and to a lesser extent temperature distribution, control the stress and breakage development. Tempering hot grain before cooling appeared to be a key to reduced brittleness. Thermal stresses are thought to be also responsible for the formation of the resulting stress cracks and breakage and allowing hot grain from the dryer to temper for a period of time has been found to significantly reduce the incidence of breakage susceptibility and increase bulk density of dried grain.

The results are also in agreement with the reports made by other researchers such that fast dryers operating at high temperatures tend to cause high fissuring if the grain is not tempered (Trim and Robinson, 1994). Short term tempering have been shown to be effective for quality of dried grains such as maize and rice (Emam et al., 1979; Foster, 1973; Gustafson et al., 1982; Omar and Yamashita, 1987; Sabbah et al., 1972; Thompson and Foster, 1963; Trim and Robinson, 1994).

"Clint" broke less and was heavier than "Raissa" under all the tempering treatments. On average, the bulk density of the "Clint" was significantly higher than the bulk density of the "Raissa" but the breakage susceptibility of the two hybrids were not statistically different. These were probably due to the results of the natural character differences between the two maize hybrids. Hardacre et al. (1997) noted that bulk density of maize grain is hybrid dependent and comparison of bulk density as an indication of quality can only be made within the same hybrid.

Tempering time requirement is, therefore, important to reduce the level of damage occurred in dried grain. However, according to Gustafson et al. (1982), tempering application creates a constraint to dryer design and capacity, especially in commercial-scale dryers.

6.7 Conclusions

After drying using the prototype grain dryer (described in Chapter 3) and tempering using five different treatments, the breakage susceptibility, bulk density, Stenvert hardness energy consumption and resistance time were also determined for the two (hard and soft) maize hybrids. Based on the results and observations obtained, the following conclusions were made:

1. Tempering the dried maize appeared to be a key to reduced its brittleness and increase its bulk density.

2. Tempering the dried grain of both hybrids for 4 to 11.5 hours reduced the breakage susceptibility from approx. 28 % by about 80 % and increased the bulk density by about 3.75 %. The bulk density of "Clint" hybrid was always about 3.37 kg/hl higher than of "Raissa" hybrid.

3. Tempering dried grain beyond 4 hours did not alter the breakage susceptibility and bulk density significantly, eliminating the need for prolonged tempering and associated time and energy costs.

4. Tempering appeared to reduce the grain hardness although the extent of this effect varied slightly between the hard and soft maize hybrids. Overall, "Clint" hybrid had higher bulk density, Stenvert energy consumption and resistance time, and thus, was less susceptible to mechanical damage than "Raissa" hybrid.

Chapter 7

GENERAL DISCUSSION AND SUMMARY

7.1 General aspects of grain drying

In order to have good quality grains (for the purposes of safe storage, high milling yield, high nutritive value, high viability thus high in overall grain values), freshly harvested (usually wet) grain need to be quickly dried to reduce its moisture content. The moisture content that is considered safe for maize grain is approx. 14 %.

The two common methods for reducing moisture content of maize grain are natural drying and artificial drying. The advantages and disadvantages of each method are summarised in Figure 25 in relation to the operation and desired grain quality attributes. In the natural drying, shelled maize grains are dried in the sun, maize cobs are stored and dried in cribs, or the cobs are left to dry on the plant by delayed harvesting.

In one of the natural drying methods called "sun drying", shelled maize grains are spread on the ground and exposed to the effects of sun and wind. In the process, the sun supplies an appreciable and inexhaustible source of heat to evaporate moisture around and within the grain kernels and the wind removes the evaporated moisture away. It is impossible to dry grain when the ambient air is wet or its relative humidity is high.

In order to process the drying quickly and uniformly, dried grain must be stirred regularly. The grains should be also covered or collected to avoid moisture re-absorption at wet night or when the rain comes or to avoid being harmfully heated by the sun (especially during the hot noon period). Therefore, this process or method of drying is weather dependent, labour intensive and, thus, would not be recommended for large scale drying. However, it is fairly cheap compared to other methods of maize drying. It can adequately dry grain to safe level of moisture content without causing much damage if the weather and/or the drying are appropriate.

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                        ┌─────────────────────┐
                        │    MAIZE GRAIN      │
                        └──────────┬──────────┘
                                   │
                                   ▼
┌─────────────────┐      ┌─────────────────┐      ┌─────────────────────┐
│ Natural Drying  │◄─────│     Drying      │─────►│  Artificial Drying  │
└─────────────────┘      └─────────────────┘      └─────────────────────┘
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Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
• Low Cost if Good Weather • High Grain Quality if Appropriate	• Weather Dependence • Low Capacity • Labour Intensive • Grain Overripe • Moisture Content Changes • Cracks if Climate Changes • Bird & Insect Attacks • Grain Shattering	• Weather Independence • Less Labour Requirement • High Capacity	• High Initial Cost • High Skill • Damaged Grain if not Appropriate Management

GOOD QUALITY GRAIN

- Appropriate Moisture Content
- Low Breakage Susceptibility
- High Bulk Density
- High Nutritive Values
- Desired Hardness
- High Viability
    - ⇒ **SAFE** for **STORAGE**
    - ⇒ **HIGH MILLING YIELD**
    - ⇒ **MORE VALUES**

FIGURE 25 Flow diagram for requirements and methods of grain drying

In another method of natural drying, harvested maize cobs (usually with the grain moisture content in excess of 20 %) are stored in cribs. The grains are safe for remarkable long time (from one to three months) with this kind of natural ventilation (Trim and Robinson, 1994). The rate and uniformity of drying are controlled by the relative humidity of the air and the ease with which air can pass through the bed of cobs. Trim and Robinson (1994) reviewed that crib widths (in West Africa) should not exceed 0.6 m. Cost of this drying method would depend solely on the materials for the crib construction.

By delayed harvesting, maize cobs are left on the plant and supposed to dry naturally. This is considered the cheapest among the other methods. It can usually be applied during dry harvesting season or when the weather is dry in order to save some drying energy. In inappropriate weather (e.g. wet or rain), the moisture content of the grains will be increased and, then, more energy would be required to dry them after harvest. The grains dried by this method are very susceptible to damage. If the climate changes (for example when the night is wet or cold and the day is hot and dry), the grains would be vulnerable to cracks resulting in breakage. The dried grains would be also susceptible to bird and insect attacks, fungal problems, overripe and shattering.

Artificial drying of grain is not weather dependent and can usually produce high drying capacity, thus appropriate for harvesting grain in any season for large-scale production of grain. There are different types of grain dryers invented and being used in artificial grain drying. In these systems, the air is generally heated (more or less to reduce its relative humidity or to increase its drying capability), by means of their heat source(s), and blown or sucked through layer of dried grains by means of their fan(s).

In order to apply this drying technique, however, grain handlers need to do investment on construction or purchasing dryer(s) as the initial cost and on drying management as running or drying cost. Skilled or trained worker(s) would be employed to construct or operate the dryer(s). Inappropriate design, selection and drying management would result in unnecessary expensive drying, low drying efficiency, low capacity, hazardous drying and high level of grain damage. These could include the problems of : (a) grain deterioration due to delayed drying of wet grain (for instance, when the dryer capacity is too small), (b) wasting money (when the dryer capacity and the consumption are too

high), (c) inappropriate to specific grain characteristics, and (d) reliability, complexity and danger in the dryer utilisation. Apart from the knowledge of the dryer operation, the dryer operator must also be aware of the effects of different drying conditions (such as grain initial and final moisture contents and drying air humidity, temperature and flow) on the dried grain quality.

Therefore, grain dryers should be first tested and evaluated to find out their specific performance within specific range of drying conditions before they can be commercially produced (if prototypes) or selected to use by grain handlers in order to suit their own (also specific) purpose(s).

Figure 26 shows some of the most common parameters considered in evaluation of grain dryers before they are being used for commercial purposes or specific use in grain artificial drying. Depending on the specific use, however, test codes and procedures may be modified in view of the prevailing ambient conditions, especially air temperature and relative humidity as well as the specific conditions of the grain samples. Generally, there are two main aspects in evaluation of grain dryers. Those are the dryer operational performance and the effects of drying on dried grain quality.

In determining the operational performance of grain dryers, the following factors should be aimed at: (a) drying efficiency, (b) drying capacity, (c) energy consumption, (d) total cost, (e) simplicity and reliability, and (f) safety of operation (ESCAP, 1995 and McLean, 1989). The following parameters, which are mostly used as the main factors in determining grain quality in grade trade, should be considered in evaluating the drying effects on dried grain quality: (a) desired and uniform grain moisture content, (b) grain breakage susceptibility (in rice, this parameter would be changed to percentage of cracked grain, head rice recovery and total milling recovery), (c) grain bulk density, (d) grain hardness, (e) grain nutritive values and, (f) grain viability.
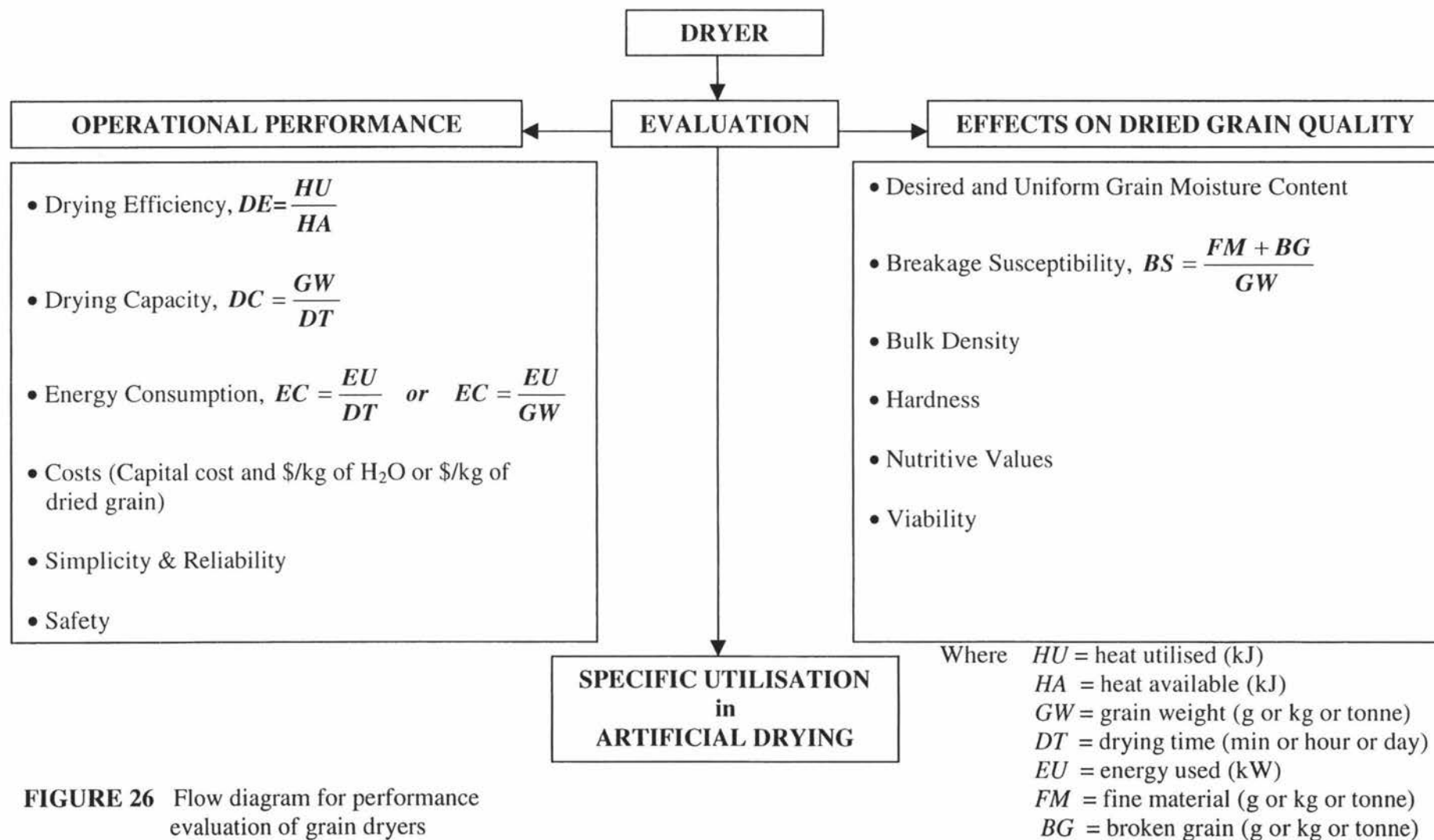
FIGURE 26 Flow diagram for performance evaluation of grain dryers

The flow diagram contains the following text:

DRYER

EVALUATION

OPERATIONAL PERFORMANCE

- Drying Efficiency, $DE = \dfrac{HU}{HA}$

- Drying Capacity, $DC = \dfrac{GW}{DT}$

- Energy Consumption, $EC = \dfrac{EU}{DT}$ *or* $EC = \dfrac{EU}{GW}$

- Costs (Capital cost and \$/kg of H_2O or \$/kg of dried grain)

- Simplicity & Reliability

- Safety

EFFECTS ON DRIED GRAIN QUALITY

- Desired and Uniform Grain Moisture Content

- Breakage Susceptibility, $BS = \dfrac{FM + BG}{GW}$

- Bulk Density

- Hardness

- Nutritive Values

- Viability

SPECIFIC UTILISATION in ARTIFICIAL DRYING

Where HU = heat utilised (kJ)
HA = heat available (kJ)
GW = grain weight (g or kg or tonne)
DT = drying time (min or hour or day)
EU = energy used (kW)
FM = fine material (g or kg or tonne)
BG = broken grain (g or kg or tonne)

7.2 Dryer operational performance

The operational performance of the prototype flat-bed dryer studied was quite good in successfully drying the two maize hybrids from different moisture contents using different drying air temperatures. The drying of grain for safe storage, or for quality testing, from 20 - 30 % initial moisture content to 13 - 15 % average dry moisture content was completed within working hours (less than 5 hours) even when the lowest air temperature (58 °C) was employed. Regulated by its automatic control systems, the dryer was capable of producing constant drying temperature throughout any drying process and one person was to run a drying session alone as well as monitor grain moisture content regularly.

The three levels of the grain initial moisture content (approx. 20, 25 and 30 %) and the drying-air temperature (58, 80 and 110 °C) would cover most conditions applicable for freshly harvested grain encountered in the real practice. These two factors (designed as drying conditions) significantly affected most of the measured parameters relevant to the dryer operational performance.

The higher the moisture content of the grain, the longer the drying took time. The grain could be dried from any moisture content to the predetermined level in shorter time by increasing the drying temperature. With the same size of the drying sample, capacity of the dryer was related mainly by the drying time. The dryer capacity varied inversely with the drying time.

The drying capacity and drying rate both increased when the air temperature increased, but the capacity increased as the moisture content decreased and the drying rate increased as the moisture content increased. The maximum capacity of the dryer was obtained when grain of the lowest initial moisture content was dried at the highest air temperature. The amount of moisture that the dryer could remove from the grain in a particular time reached its maximum value when the air temperature and the initial grain moisture content were the highest. These can be explained by the fact that there is more water or moisture to be removed from the grain of higher moisture content and higher air temperature has more moisture carrying capacity than the air of lower temperature.

Similar observations have been made by many researchers on maize and other grains such as rice, bean and cotton (Abe and Afzal, 1997; Barker and Laird, 1996; DiMattia et al., 1996; Li and Morey, 1984; Meiering et al., 1977; Peplinski et al., 1994; Shivhare et al., 1992; Tagawa et al., 1996). These authors reported that moisture variation strongly influences the drying capacity, but the authors mentioned that if dryer performance is to be measured with acceptable accuracy it is necessary to work at, or near, steady state.

It was found that increasing drying rate also increased the drying efficiencies. Adeyemo (1993) reported similar relationship between the drying rate of maize grain and the dryer efficiencies. The HUF, THE, and COP values found in these studies indicate that the dryer had fairly low heat utilisation efficiency. Increasing the depth of the drying grain would assure the low energy requirement and could be one of the options to increase the drying efficiencies.

According to Aguilar and Boyce (1966), THE is defined as the ratio of the sensible heat used in drying to the sum of the sensible heat in the ambient air and the heat added. As it is a function of the ambient wet bulb temperature, which is not dependent on the dryer, it is not possible to compare dryers with this ratio unless some fixed basis is established.

Taking the thin-layer drying into account, the application of the Page model based on general form of drying constants (Liu et al., 1998) could be done only for few drying conditions that were applied in Experiment I (for both hybrids dried from ≤ 25 % moisture content at 58 °C air temperature). And generally, there was not good agreement between the observed and the predicted moisture ratios. The drying conditions designed and applied in this experiment, however, produced their own specific drying constants. The fitness of the comparison between the observed and predicted (using the coefficients found) were mostly very good. Characteristics of different maize hybrids and inconsistency of the ambient air would be the main causes of the difference.

The energy consumed during drying was linearly related to the initial grain moisture content and inversely related to drying air temperature. These findings can be used to

explain why in practice grain handlers adopt the following practices to save some drying energy :

- leaving their crop partly dry in the field before harvesting in order to reduce the grain initial moisture content and/or,

- using high drying-air temperature because energy consumption of a grain dryer decreases with an increase in the temperature of the drying air (McLean, 1989 and Brook, 1992).

However, if improperly controlled, these conditions exacerbate grain losses due to shattering, attack by birds and insects in the field, as well as physical damage during postharvest handling. Optimisation of both dryer parameters and drying conditions is therefore recommended to obtain the most satisfactory results.

7.3 Effects of drying on quality attributes of dried grain

Experiment I (Chapter 4) showed that the incidence of grain damage, as indicated by the grain breakage susceptibility and bulk density, increased as the drying air temperature increased. Within each of the three air temperatures produced by the dryer (58, 80 and 110 °C), the breakage increased and the bulk density decreased as the moisture content increased.

The effects of the drying on the grain quality were similar to the results reported by previous studies (Brown et al., 1979; Hall, 1972; Gunasekaran and Paulsen, 1985; Fortes and Okos, 1980, Thompson and Foster, 1963; and Weller et al., 1990). The relationship of the grain bulk density and breakage susceptibility found in this study agree with the results reported by Pomerance et al. (1984) which showed that high breakage susceptibility significantly reduced the bulk density of dried grain.

Thompson and Foster (1963) reported that stress cracks, a parameter which increases breakage susceptibility, increased with increased grain initial moisture content, drying air temperatures and flow rate. They observed that the percentage of kernels with stress

cracks decreased from 97.8 to 93.2 % as harvest moisture decreased from approximately 30 to 20 % (wet basis). Brown et al. (1979) and Weller et al. (1990) also reported that the frequency of stress crack formation differed among grain lots and affected by treatments such as grain initial moisture content and drying air temperature. Grain dried with low-temperature air had a negligible amount of kernel stress cracking and the incidence of stress cracks increased as the harvest moisture increased within the drying air temperatures of 49, 71 and 93 °C. Brown et al. (1979) observed that the bulk density of maize lots dried with both the batch and dryeration methods tended to decrease as drying temperature was increased, particularly in lots harvested at 28 and 30 % moisture.

The results found in this study, however, seem to disagree with the findings of Kirleis and Stroshine (1990) who observed that bulk density changes within each hybrid over the entire range of drying temperatures were not significantly different. The authors observed that bulk density varied in an erratic manner for all the three hybrids used in their experiment as drying temperature was increased from 27 to 93.3 °C.

Under all the drying, cooling and tempering treatments, the bulk density and hardness characteristics of the "Clint" hybrid indicated that it is significantly heavier and harder than the "Raissa" hybrid. These phenomena could help explain why food maize processors prefer "hard" hybrids.

Both the "Clint" and "Raissa" hybrids had less damage when they were tempered for at least 4 hours and/or cooled inside chilly bin. The most damage occurred to the grain that was cooled by the dryer or was not tempered. These results corroborate with the reports made by Trim and Robinson (1994), de Lucia and Assennato (1994), and Hardacre et al. (1997). These authors suggested that rapid or sudden cooling of grain and temperature fluctuation during storage can also contribute to stress crack development during milling. In Experiment II, the results indicated that tempering might start to have effects earlier than four hours, and therefore, contrasting to the report made by Brooker et al. (1992). These authors suggested that at least 4 hours should be allowed for the moisture redistribution process, and more time, up to 12 hours, is preferred. However, slow cooling and/or tempering the hot grain for some

time, creates a constraint to dryer design and capacity in particular for commercial-scale dryers.

The results in the present study also suggest that the dried grain did not damage much during drying. As drying grain with heated air establishes a temperature and moisture gradient in each kernel (Kunze, 1979), cooling it slowly or tempering it for sometime, especially in an airtight and well-insulated container, could reduce the level of grain damage. In such containers (the vacuum bottle and the sealed chilly bin), no moisture escapes and no heat is conducted out of the grain, and the change in the average temperature and moisture content of the grain is negligible accounting for the lowest incidence of grain damage.

The overall level of damage was small when both hybrids were dried at the ambient air temperature; but the drying took longer time and the dried samples developed other problems with mould or fungus development. Moulds are plants without roots, leaves, or chlorophyll; therefore, they are forced to live off other materials, such as grain. They reproduce chiefly by means of small, light, asexual airborne spores that are easily distributed by the wind. Spores develop into new mould plants whenever the moisture and temperature conditions for their growth are favourable (Brooker et al., 1992). Christensen et al. (1992) also mentioned that at high moisture content (from 18 % upwards for maize), many species of storage fungi can develop quickly in the grain. Therefore, prolonged drying the grain at high moisture content (approx. 20, 25 and 30 %), as conducted in the treatment, was the main reason for the probably fungi invasion.

The Stenvert energy consumption and the Stenvert resistance time showed that "Clint" was overall harder than the "Raissa". These were probably due to the hybrid characters.

7.4 A conceptual framework for optimising dryer performance

Figure 27 demonstrates the main parameters related to optimisation of the operating performance and of the effects on dried grain quality. For instance, if high drying capacity (e.g. 12 kg/h) is required, when using the prototype dryer for both "Clint" and

"Raissa" maize hybrids, either the drying air temperature is to be increased (≥ 80 °C) or the grain initial moisture content is to be decreased (≤ 25 %). If breakage susceptibility of approx. 23 % is the maximum allowable for the dried "Clint ", air temperature of lower than 80 °C must be used. At the same time the initial grain moisture content must be lower than 25 %. At 80 °C drying air temperature, the breakage susceptibility of the "Clint" grain would be smaller than 23 % if they are cooled in air-tight container (either left to cool in chilly bin or in cold room, or tempered for about 4 hours).

Referring to the testing procedures of different grain dryers reported by other researchers (Bakker-Arkema, 1995; ESCAP, 1995; Adeyemo, 1993; Brook, 1992; Chakraverty and More, 1983; and Aguilar and Boyce, 1966), however, further measurements such as exhaust air temperature, relative humidity, uniformity of drying, and air and noise pollution should be made regularly during the test. The environment conditions should be fully monitored. Nellist and Bruce (1992) stated that the main reasons for testing grain dryers are: (a) to aid the development of a prototype, (b) to confirm the specified performance and (c) to provide information for marketing and operator guidance. According to these authors, however, to have the prototype dryer for other purposes or for trade nationally or internationally, there is a need to standardise the evaluation procedures on a nation or a world scale.

Similarly, ESCAP (1995) recommended that to determine dryer performances and compare them with those of other makes or types, testing must be done using a standard code and procedure. A grain dryer can be evaluated properly only after reliable tests have been performed. It can be validly compared with other dryers only if the test procedure is standardised.
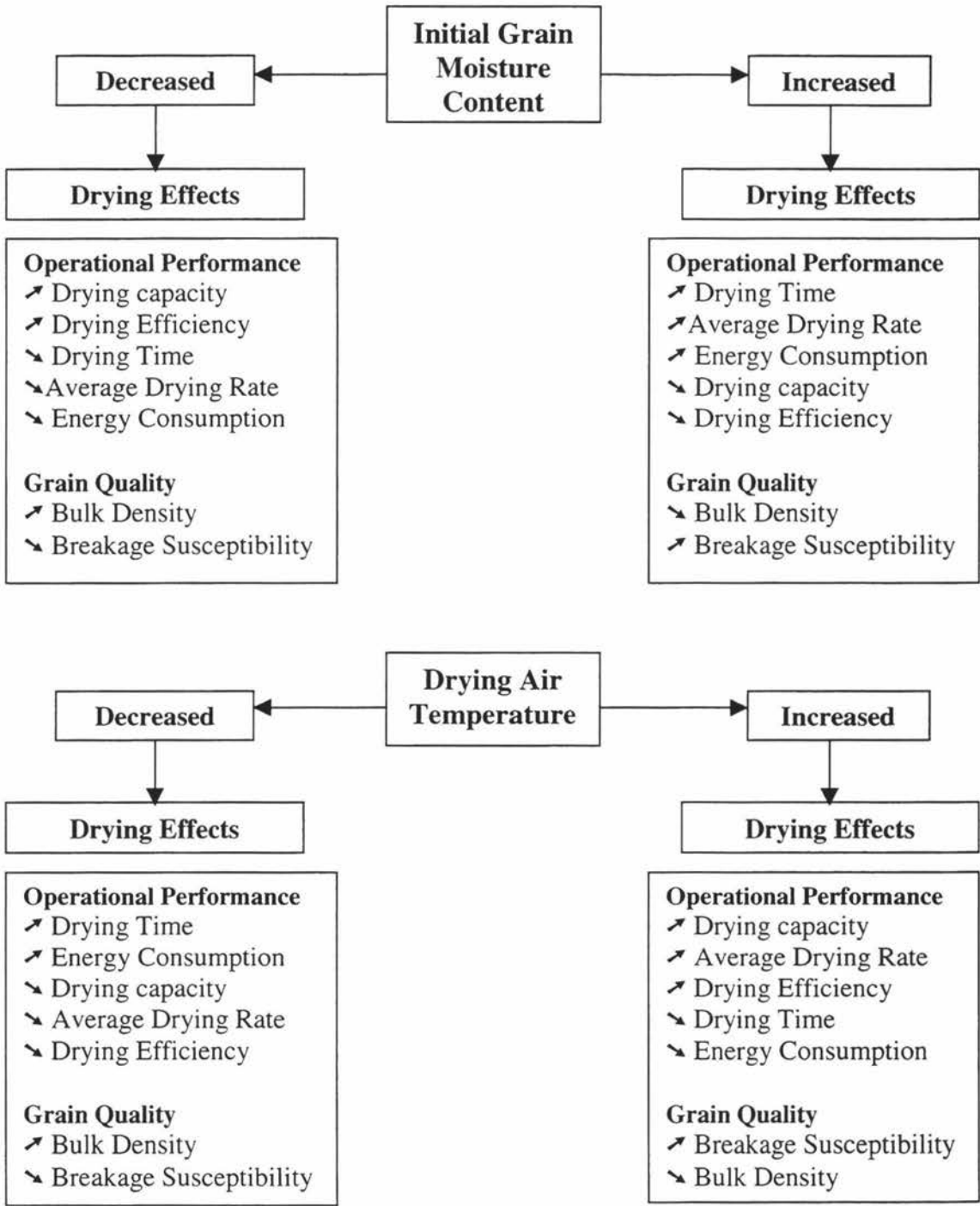
Note : ⤷ Increase; ⤸ Decrease

FIGURE 27 Flow diagram for the effects of grain initial moisture content and drying air temperature on the dryer performance.

Chapter 8

CONCLUSIONS AND FURTHER RESEARCH

8.1 General Conclusions

The results and observations in this study indicate that the prototype dryer performed well in achieving the desired grain moisture content. Its automatic-control systems make the dryer simple and one trained operator is sufficient to operate it, and thus most suitable for research and experimental purposes.

The dryer operational performance was affected by the grain initial moisture content and the drying air temperature. Most of the grain quality attributes were affected by the grain initial moisture content, the drying air temperature, and the cooling and tempering treatments:

1. On the whole, the dryer had fairly low heat utilisation efficiencies (Max. HUF = 45 %). Depending on the grain initial moisture content and the drying air temperature: drying time varied from approx. 45 to 270 min, the dryer capacity varied from 3.5 to 20 kg/h, the average drying rate varied from 0.58 to 2.93 kg/h, the energy consumed by the dryer varied from 1 to 5 kWh. The drying time increased as the moisture content was increased and/or the air temperature was decreased. The capacity varied inversely with the drying time. The drying rate increased as the air temperature and the moisture increased. The energy consumption increased as the air temperature was decreased and/or the moisture content was increased.

2. A maximum amount of grain that the dryer could dry by consuming least time and energy would be obtained by using high air temperature (approx. 110 °C) and low grain initial moisture content (approx. 20 %). However, grain damage was found generally to be associated with high moisture content, rapid drying with high drying air temperature followed by rapid cooling or non-tempering process. Breakage and bulk density of the dried grain were affected more badly as the air temperature and the moisture content increased. When grain was dried too rapidly, it became more brittle and thus more susceptible to physical damage. Extremely rapid drying resulted in grain

of reduced bulk density with kernels that were enlarged or puffed. This study confirmed that the grain did not damage much during drying and the reduction of the overall damage could be attained by slow cooling or tempering it for a period of time.

3. It is, therefore, very important to find the proper balance between drying too fast or too slowly to ensure the maintenance of high quality for the dried grain. Slow cooling could surely help reduced the damage of dried grain. For instance, cooling the dried grain by the dryer caused the two maize hybrids to break over 30 % and cooling it in the vacuum bottle and chilly bin lowered the level of the damage to below 14 %. The best cooling treatment based on minimum grain damage was the chilly bin, followed by the cold room and the ambient-air treatments. The worst treatment was cooling the grain in the dryer.

4. The results suggest that tempering the maize appeared to be a suitable strategy to reduce grain brittleness and increase its bulk density. Tempering appeared to reduce the grain hardness although the extent of this effect varied slightly between the hard and soft maize hybrids. Tempering the dried grain for 4 hours reduced the breakage susceptibility from approx. 28 % by about 7 to 8 times and increased the bulk density by about 3.3 kg/hl. Tempering the grain beyond 4 hours did not confer additional benefits on its quality. Therefore, tempering the dried grain for 4 hours would be the most appropriate.

5. Under all the drying conditions as well as cooling and tempering treatments, "Clint" hybrid had higher bulk density than "Raissa" hybrid. The grain hardness characteristics, on the other hand, seemed to decrease as the grain was dried at higher air temperature and/or from higher moisture content. However, the analysis did not indicate these effects substantially and clearly. The cooling treatments did not affect grain hardness characteristics. The non-tempered grain seemed to be harder than the tempered one but the differences in values for the two hardness measurements (within each of the two hybrids) tempered differently were relatively small and inconsistent. Under all the applied treatments, the only absolutely clear indication was that "Clint" grain is harder than "Raissa" grain. These were probably due to the hybrid characters.

6. Using the thin-layer drying model, there was not good agreement between the experimental and predicted moisture ratios based on general form of drying constant. However, there was good agreement between the two moisture ratios when the specific drying constants (determined in this study) were used. Characteristics of maize hybrids and the inconsistency of the ambient air were the main suspecting factors.

8.2 Recommendation for further research

Based on the work done in this study, the following areas for further research are recommended to optimise the operational characteristics of the dryer and the grain quality:

1. Thickness of grain layer in the drying bins would need to be differentiated to find out the optimum dryer capacity, drying rate and efficiencies.

2. Effects of drying on other grain quality attributes (such as biochemical properties, including starch, protein, oil and ash) should be considered.

3. Tempering the dried grain for shorter time, from 0 to 4 hours, would be important to find out the tempering effects on the quality of the dried grain while maintaining the same drying conditions.

4. The same cooling and tempering treatments should be applied on the grain dried at higher air temperature (for example, 110 °C). If the quality of the cooled and tempered grain will be still high, as affected by the treatments, the high temperature drying would be the most recommended.

5. Other maize hybrids should be tested under the same cooling and tempering treatments to find out if the effects on them will be similar to those obtained for "Clint" and "Raissa" in this study.

6. Assessment of the economic performance of the dryer.

REFERENCES

1. American Association of Cereal Chemists (AACC), 1983. *Approved Methods of the AACC, Method 55-20. Corn Breakage Susceptibility.* St. Paul, Minn, USA.

2. Abe T. and Afzal T.M., 1997. *Thin-Layer Infrared Radiation Drying of Rough Rice.* Journal of Agricultural Engineering Research 67 : 289 - 297.

3. Abe T., Otoche C.E., Hikida Y. and Yamashita J., 1992. *Effects of Drying Parameters on Quality of Artificially Dried Rough Rice.* Journal of Agricultural Mechanisation in Asia, Africa and Latin America 23 (4) : 42 - 46.

4. Adeyemo L.T., 1993. *Modification of a Natural Air Convection Dryer.* Journal of Agricultural Mechanisation in Asia, Africa and Latin America 24 (2) : 33 - 36.

5. Aguilar S.C. and Boyce S.D., 1966. *Temperature Ratios for Measuring Efficiency and for the Control of Dryers.* Journal of Agricultural Engineering research 11 (1) : 19 - 23.

6. Allen J R., 1960. *Application of Grain Drying Theory to the Drying of Maize and Rice.* Journal of Agricultural Engineering research 5 (4) : 363 - 385.

7. Almeida-Dominguez H D; Ordonez-Duran G G; Almeida N G, 1998. *Influence of Kernel Damage on Corn Nutrient Composition, Dry Matter Losses, and Processability during Alkaline Cooking.* Cereal chemistry, 75 (1) : 124 - 128.

8. Arinze E.A., Sokhansanj S., Schoenau G.J. and Trauttmansdorff F.G., 1996. *Experimental Evaluation, Simulation and Optimisation of a Commercial Heated-Air Batch Hay Drier: Part 1, Drier Functional Performance, Product Quality, and Economic Analysis of Drying.* Journal of Agricultural Engineering Research 63 : 301-314.

9. Bakker-Arkema W.F., Montross D.M., Qiang L. and Maier E.D., 1995. *Analysis of continuous-flow grain dryers.* Proceeding of an international conference held at the FAO regional office for Asia and the Pacific, Edited by Champ R.B., Highley E. and Johnson I.G., 123 – 131.

10. Bakker-Arkema, F.W. and Salleh, H.M. 1985. *In-store Drying of Grain : The State of the Art.* Proceedings of an International Seminar on Preserving Grain Quality by Aeration and In-store Drying, held in Kuala Lumpur, Malaysia. Edited by Champ, B.R. and Highley, E.

11. Barker G.L. and Laird J.W., 1996. *Effect of Temperature on the Drying Rate of Gin Run Cotton Seed.* Transactions of the American Society of Agricultural Engineers 40 (2) : 289 - 294.

12. Basu R.N., 1994. *An Appraisal of Research on Wet and Dry Physiological Seed Treatments and their Applicability with Special Reference to Tropical and Sub-tropical Countries.* Seed Science and Technology, 22: 107-126.

13. Brenton-RuleJ.R., Hardacre K.A. and Clark M.S., 1998. *Testing Procedures for Maize Grain Quality in New Zealand.* Foundation for Arable Research (FAR) Arable Update No. 8.

14. Brook C.R., 1992. *Drying cereal grains.* In : Storage of cereal grains and their products. American Association of Cereal Chemists Inc., Minnesota, USA.

15. Brooker, B.D., Bakker-Arkema, W.F. and Hall, W.C., 1974. *Drying Cereal Grains.*Westport, Connecticut, The Avi Publishing Company, Inc.

16. Brooker, B.D., Bakker-Arkema, W.F. and Hall, W.C., 1992. *Drying and Storage of Grains and Oilseeds.* New York, Van Nostrand Reinhold.

17. Brown R.B., Fulford G.N., Daynard T.B., Meiering A.G. and Otten L., 1979. *Effects of Drying Method on Grain Quality.* Cereal Chemistry 56 (6): 529-532.

18. Bruce D.M., 1985. *Exposed-Layer Barley Drying : Three Models Fitted to New Data up to 150 °C.* Journal of Agricultural Engineering Research 32 : 337-347.

19. Chakraverty A. and More H.G., 1983. *Development and Testing of a Simple Baffle Type Grain Dryer.* Agricultural Mechanisation in Asia, Africa and Latin America 14 (4) : 41 - 44.

20. Chinnan M.S., 1984. *Evaluation of Selected Mathematical Models for Describing Thin-Layer Drying of In-Shell Pecans.* Transactions of the American Society of Agricultural Engineers : 610-615.

21. Christensen M.C., Miller S.B. and Johnston A.J, 1992. *Moisture and its Measurement.* In : Storage of Cereal Grains and their Products. American Association of Cereal Chemists Inc., Minnesota, USA.

22. Clarke A.P. and Orchard E.J., 1994. *Quality and Grading of Grain.* In : Grain Storage Techniques – Evolution and Trends in Developing Countries. FAO Agricultural Service Bulletin No. 109, Edited by Proctor L.D.

23. Coker D.R., 1994. *Biodeterioration of Grain and the Risk of Mycotoxins.* In : Grain Storage Techniques – Evolution and Trends in Developing Countries. FAO Agricultural Service Bulletin No. 109, Edited by Proctor L.D.

24. de Lucia M. and Assennato D., 1994. *Agricultural Engineering in Development.* FAO Agriculture Services Bulletin No. 93.

25. DiMattia D.G., Amyotte P.R. and Hamdullahpur F., 1996. *Fluidized Bed Drying of Large Particles.* Transactions of the American Society of Agricultural Engineers 39 (5) : 1745 - 1750.

26. Driscoll, R. and Srzednicki, G., 1995. *In-bin Grain Drying Systems.* Proceedings of an International Conference on Grain Drying in Asia, held at the FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. Edited by Champ, B.R., Highley, E. and Johnson, G.I.

27. Economic and Social Commission for Asia and the Pacific, Regional Network for Agricultural Machinery (ESCAP), 1995. *RNAM Test Codes and Procedures for Farm Machinery.* Technical Series No. 12.

28. Emam A., Okos R.M., Foster H.G. and Fortes M., 1979. *Effect of Tempering Time on Quality Dried Corn.* Paper presented at the 1979 Winter Meeting American Society of Agricultural Engineers. New Qrleans, LA, U.S.A.

29. Food and Agriculture Organisation of the United Nations (FAO), 1984. *Post-harvest Losses in Quality of Food Grains.* Food and Nutrient Paper No. 29.

30. Food and Agriculture Organisation of the United Nations (FAO), 1992. *Maize in Human Nutrition.* Rome, Italy.

31. Fortes M. and Okos M.R., 1980. *Changes in Physical Properties of Corn During Drying.* Transactions of the American Society of Agricultural Engineers:1004-1008.

32. Foster H.G., 1973. *Dryeration : Heated Air Drying and Corn Quality.* Annales de Technologie Agricole 22 (3) : 233 – 244.

33. Freeman E.J., 1973. *Quality Factors Affecting Value of Corn for Wet Milling.* Transactions of the American Society of Agricultural Engineers 16 : 671 - 678

34. Ganesh S., 1998. *Analysis of Experiments for Researchers.* Study guides I and II. Department of Statistics, Massey University, Palmerston North, New Zealand.

35. Gunasekaran S., 1988. *Evaluation and Comparison of Wisconsin and Stein Breakage Testers of Corn.* Cereal Chemistry 65 (4) : 287 - 291.

36. Gunasekaren, S., Deshpande, S.S., Paulsen, R.M. and Shove, C.G., 1985. *Size Characterisation of Stress Cracks.* Transactions of the American Society of Agricultural Engineers 28 (5) : 1668 - 1672.

37. Gunasekaran S. and Paulsen M.R., 1985. *Breakage Resistance of Corn as a Function of Drying Rates.* Transactions of the American Society of Agricultural Engineers 28 : 2071.

38. Gustafson J.R., Mahmoud Y.A. and Hall E.G., 1982. *Breakage Susceptibility Reduction by Short-Term Tempering of Corn.* Paper presented at the 1982 Winter Meeting American Society of Agricultural Engineers. Chicago, U.S.A.

39. Gustafson R.J., Morey R.V, Christensen C.M. and Meronuck R.A., 1978. *Quality Changes During High-Low Temperature Drying.* ASAE Paper No. 76-3523. Scientific Journal Series No. 9747 of the Minnesota Agricultural Experiment Station, St. Paul, MN.

40. Gustafson J.R. and Morey V.R., 1979. *Study of Factorss Affecting Quality Changes During High-Temperature Drying*. Transactions of the American Society of Agricultural Engineers 22 (4) : 926 – 932.

41. Hall C.W., 1980. *Drying and Storage of Agricultural Crops*. AVI Publishing Company, Westport, Connecticut.

42. Hall G.E., 1972. *Test-Weight Changes of Shelled Corn During Drying*. Transactions of the American Society of Agricultural Engineers 15 : 320 - 323.

43. Hampton J., 1994. *Seed Quality*. Lecture notes and readings. Department of Plant Science. Massey University, Palmerston North, New Zealand.

44. Handerson M.S., 1974. *Progress in Developing the Thin Layer Drying Equation*. Transactions of the American Society of Agricultural Engineers 17 (6) : 1167-1168, 1172.

45. Hardacre K.A., 1997. *Maize Grain Attributes, 1997 Results*. Fundation for Arable Research (FAR) Arable Update No. 9.

46. Hardacre K.A, Brenton-Rule R. and Clark M.S., 1997. *The Analysis of Maize Grain Quality in New Zealand and Calibration of Testing Methods*. Report No. 367 prepared for the Maize Grain Quality Committee, New Zealand Manufacturers Association. New Zealand Institute for Crop and Food Research Ltd., Christchurch, New Zealand.

47. Hardacre K.A. and Pyke N., 1998. *Influence of Commercial Drying on Maize Grain Attributes – 1997*. Fundation for Arable Research (FAR) Arable Update No. 10.

48. Hill, M.J., 1997. *Seed Moisture and Drying*. Teaching Material. Seed Technology Centre, Massey University, Palmerston North, New Zealand.

49. Hoseney C.R., 1994. *Principles of Cereal Science and Technology*. Second edition. American Association of Cereal Chemists, Inc. St. Paul, Minnesota, USA.

50. Hukill V.W., 1947. *Basic Principles in Drying Corn and Grain Sorghum*. Agricultural Engineering (The Journal of the American Society of Agricultural Engineers) 28 (8) : 335 – 338.

51. Hukill V.W., 1974. *Grain Drying*. In : Storage of Cereal Grains and Their Products, Edited by Christensen M.C. American Association of Cereal Chemists, Paul, Minnesota, U.S.A.

52. Hummeida A.M. and Sheikh E.A., 1989. *Determination of Drying Curves of Two Varieties of Peanuts*. Agricultural Mechanisation in Asia, Africa and Latin America 20 (4) : 47 - 51, 58.

53. Jain R.K. and Bal S., 1997. *Properties of Pearl Millet.* Journal of Agricultural Engineering Research 66, 85 - 91.

54. Joshi D.C., Das S.K. and Mukherjee R.K., 1993. *Physical Properties of Pumpkin Seeds.* Journal of Agricultural Engineering Research 54 : 219 - 229.

55. Kirleis A.W. and Stroshine, R.L., 1990. *Effects of Hardness and Drying Air Temperature on Breakage Susceptibility and Dry-Milling Characteristics of Yellow Dent Corn.* Cereal Chemistry 67 (6) : 523 - 528.

56. Kunze R.O., 1979. *Fissuring of the Rice Grain After Heated Air Drying.* Transactions of the American Society of Agricultural Engineers 1979, 22 : 1197 – 1201, 1207.

57. Li P.X.-P, Hardacre A.K, Campanella O.H. and Kirkpatrick K.J., 1996. *Determination of Endosperm Characteristics of 38 Corn Hybrids Using the Stenvert Hardness Test.* Cereal Chemistry 73 (4) : 466 - 471.

58. Li H. and Morey R.V., 1984. *Thin Layer Drying of Yellow Dent Corn.* Transactions of the American Society of Agricultural Engineers 27 (2) : 581-585.

59. Litchfield B.J. and Fortes M., 1982. *Design of Corn Drying Systems to Minimise Kernel Stress.* Paper presented at the 1982 Winter Meeting American Society of Agricultural Engineers. Chicago, U.S.A.

60. Litchfield B.J and Okos R.M., 1988. *Prediction of Corn Kernel Stress and Breakage Induced by Drying, Tempering and Cooling.* Transactions of the American Society of Agricultural Engineers 31 (2) : 585 - 594.

61. Liu Q., Cao C.W. and Bakker-Arkema F.W., 1998. *Grain Drying.* In CIGR Agricultural Engineering Hand Book Vol. IV. St. Joseph, U.S.A.

62. Lorenz J.K. and Kulp K., 1991. *Handbook of Cereal Science and Technology.* Marcel Dekker, Inc. New York, U.S.A.

63. Maier D.E, 1994. *Chilled Aeration and Storage of U.S. Crops-a review.* Proceeding of the 6th International Working Conference on Stored-product Protection, Canberra, Australia. Edited by Highley, E., Banks, E,J. and Champ, B.R.

64. Martin C.R., Converse H.H., Czuchajowska Z., Lai F.S. and Pomeranz Y., 1987. *Breakage Susceptibility and Hardness of Corn Kernels of Various Sizes and Shapes.* Applied Engineering in Agriculture 3 (1) : 104 – 113.

65. McLean A.K., 1989. *Drying and Storing Combinable Crops.* Second Edition. Farming Press, Ipswich, United Kingdom.

66. Meas P., 1998. *Preliminary Evaluation of a Prototype Flat-Bed Grain Dryer.* Research Project Report presented in partial fulfilment of the requirements for the Postgraduate Diploma at Massey University, Palmerston North, New Zealand.

67. Meiering A.G., Daynard T.B., Brown R. and Otten L., 1977. *Drier Performance and Energy Use in Corn Drying.* Canadian Agricultural Engineering 19 No. 1.

68. Michael M.A. and Ojha P.D., 1978. *Principles of Agricultural Engineering*, Vol. 1. Jain Brothers, Jodhpur, India.

69. Miller B.S., Hughes J.W., Rousser R. and Pomeranz Y., 1981. *Measuring the Breakage Susceptibility of Shelled Corn.* Cereal Foods World, February 26 (2) : 75 - 80.

70. Misra M.K. and Brooker D.B., 1980. *Thin-Layer Drying and Rewetting Equations for Shelled Yellow Corn.* Transactions of the American Society of Agricultural Engineers 23 (5) : 1254 - 1260.

71. Nellist E.M. and Bruce M.D., 1992. *Grain Dryer Testing, Calcilation and Adjustment of Results, and Effect of Errors.* Journal of Agricultural Engineering Research 52 : 35 - 49.

72. Ofoche E.C., Abe T. and Hikida Y., 1991. *Accelerating Design and Performance Test Evaluation of Cross-flow Tempering Drier Using Computer Simulation Model.* Agricultural Mechanisation in Asia, Africa and Latin America 22 (4): 54 - 60.

73. Omar J.S. and Yamashita R., 1987. *Rice Drying, Husking and Milling,* Part I – Drying. Agricultural Mechanisation in Asia, Africa and Latin America 18 (2): 43 - 49.

74. Patil G.B. and Ward T.G., 1989. *Heated air Drying of Rapeseed.* Journal of Agricultural Mechanisation in Asia, Africa and Latin America 20 (4) : 52 – 58.

75. Paulsen M.R. and Hill L.D., 1985. *Corn Quality Factors Affecting Dry, Milling Performance.* Journal of Agricultural Engineering Research. 31: 255 - 263.

76. Peplinski, J.A., Paulis, W.J., Bietz, A.J. and Pratt, C.R., 1994. *Drying of High-Moisture Corn : Changes in Properties and Physical Quality.* Cereal Chemistry 71 (2) : 129 - 133.

77. Peplinski J.A., Paulsen R.M., Anderson A.R. and Kwolek F.W., 1989. *Physical, chemical, and dry-milling characteristics of corn hybrids from various genotypes.* Cereal chemistry 66 (2) : 117 – 120.

78. Picard J. and Proctor L.D., 1994. *Storage at Farm/Village Level and in Warehouses.* In : Grain Storage Techniques, Evolution and Trends in Developing Countries. Edited by Proctor L.D. Food and Agriculture Organization of the United Nations. Agricultural Services Bulletin No. 109.

79. Pomeranz Y., 1992. *Biochemical, functional, and nutritive changes during storage.* In : Storage of cereal grains and their products, edited by Sauer B.D. American Association of Cereal Chemists, Inc. St. Paul, Minnesota, USA.

80. Pomeranz Y., Czuchajovska Z., Martin C.R. and Lai F.S., 1985. *Determination of Corn Hardness by Stenvert Hardness Tester.* Cereal Chemistry 62:108 - 112.

81. Pomeranz Y., Martin C.R., Traylor D.D. and Lai F.S., 1984. *Corn Hardness Determination.* Cereal Chemistry 61(2) : 147-150.

82. Radajewski W., Jolly P. and Abawi Y.G., 1988. *Grain Drying in a Continuous Flow Drier Supplemented with a Microwave Heating System.* Journal of Agricultural Engineering Research 41 : 211-225.

83. Ranhotra S.G., 1991. *Nutritional Quality of Cereals and Cereal-Based Foods.* In : Handbook of cereal science and technology, edited by Lorenz J.K. and Kulp K. Marcel Dekker, Inc. New York, Basel, Hong Kong.

84. Ross I.J. and White G.M., 1972. *Thin Layer Drying Characteristics of White Corn.* Transactions of the American Society of Agricultural Engineers 15 (1) : 175 -176, 179.

85. Sabbah A.M., Foster H.G., Haugh G.C. and Peart M.R., 1972. *Effect of tempering after drying on cooling shelled corn.* Transactions of the American Society of Agricultural Engineers : 763 - 765

86. Shivhare U.S., Raghavan G.S.V. and Bosisio R.G., 1992. *Microwave Drying of Corn, II. Constant Power, Continuous Operation.* Transactions of the American Society of Agricultural Engineers 35 (3): 951 - 957.

87. Shukla D.B. and Patil T.R., 1988. *Overview of Grain Drying and Storage Problem in India.* In : Research and development issues in grain postharvest problems in Asia, edited by Group for Assistance on Systems relating to Grain After harvest (GASGA). GASGA Executive Seminar Series No. 2. Deutsche Gesellschaft für Technische, Zusammenarbeit (GTZ) GmbH , Eschborn, Federal Republic of Germany.

88. Steel R.G.D. and Torrie J.H., 1980. *Principles and Procedures of Statistics, a Biometrical Approach.* McGraw-Hill book, Coy., New York, USA.

89. Steffee J.F. and Singh R. P., 1982. *Diffusion Coefficients Predicting Thin Layer Drying Behaviour.* Journal of Agricultural Engineering Research 1982, 27 : 489-493.

90. Stroshine L.R., Kirleiss W.A., Tuite F.J., Bauman F.L. and Emam A., 1986. *Differences in Grain Quality Among Selected Corn Hybrids.* Cereal Food World, 31 : 311 – 316.

91. Tagawa A., Kitamura Y. and Murata S., 1996. *Thin Layer Drying Characteristics of Adzuki Beans.* Transactions of the American Society of Agricultural Engineers 39 (2) : 605 - 609.

92. Teter N., 1987. *Paddy Drying Manual*. Food and Agriculture Organization of the United Nations. Agricultural Services Bulletin No. 70.

93. Thompson R.A. and Foster G.H., 1963. *Stress Cracks and Breakage in Artificially Dried Corn*. United States Department of Agriculture. Marketing Res. Report No. 631.24 pp.

94. Trim, D.S. and Robinson, A.P., 1994. *Drying Methods*. In : Grain Storage Techniques, Evolution and Trends in Developing Countries. Edited by Proctor L.D. Food and Agriculture Organization of the United Nations. Agricultural Services Bulletin 1994 No. 109.

95. Tumambing, A.J.,1995. *Small-scale Grain Dryers*. Proceedings of an International Conference on *Grain Drying in Asia*, held at the FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. Edited by Champ, B.R., Highley, E. and Johnson, G.I.

96. Verma, R.L., 1993. *New Methods for On-The-Farm Rice Drying: Solar and Biomass*. In : Rice Science and Technology. Edited By Marshall, W.E. and Wadsworth, J.I. New York : Marcel Dekker.

97. Watson s.a., 1987. *Corn : Chemistry and Technology*. American Association of Cereal Chemists. St. Paul, Minn., U.S.A.

98. Watson, S.A., 1991. *Measurement and Maintenance of Quality*. In Corn : Chemistry and Technology. Edited by Watson, S.A. and Ramstat P.E. American Association of Cereal Chemists : St. Paul, Minnesota, USA.

99. Weller C.L., Paulsen M.R. and Steinberg M.P., 1990. *Stress Cracking and Breakage Susceptibility as Affected by Moisture Content at Harvest for Four Yellow Dent Corn Hybrids*. Transactions of the American Society of Agricultural Engineers 33 (3) : May-Jun..

100. Westerman P.W., White G.M., Ross I.J.,1973. *Relative Humidity Effect on the High Temperature Drying of Shelled Corn*. Transactions of the American Society of Agricultural Engineers 16 (6) : 1136 - 1139.

101. White G M and Ross I J, 1972. *Discoloration and Stress-Cracking in White Corn as Affected by Drying Temperature and Cooling Rate*. Transactions of the American Society of Agricultural Engineers 15 (3) : 504 - 507.

102. White G M, Ross I J and Poneleit C G, 1982. *Stress Crack Development in Popcorn as Influenced by Drying and Rehydration Processes*. Transactions of the American Society of Agricultural Engineers 25 (3) : 768 - 772.

103. Wilson M.D. and Abramson D., 1992. *Mycotoxins*. In : Storage of cereal grains and their products, edited by Sauer B.D. American Association of Cereal Chemists, Inc. St. Paul, Minnesota, USA.

APPENDIX A

Determination of average drying rate

Based on the formulae for determination of grain moisture content dry basis (Brooker et al., 1992; McLean, 1989) :

$$MC_o = \frac{W_o}{M} \times 100 \qquad\qquad \text{............................. (A.1)}$$

$$MC_f = \frac{W_f}{M} \times 100 \qquad\qquad \text{............................. (A.2)}$$

$$(A.1) \Rightarrow W_o = \frac{M}{100} \times MC_o \qquad\qquad \text{............................. (A.3)}$$

$$(A.2) \Rightarrow W_f = \frac{M}{100} \times MC_f \qquad\qquad \text{............................. (A.4)}$$

Water removed from one bin (W) :

$$W = W_o - W_f = \frac{M}{100} \times (MC_o - MC_f) \qquad\qquad \text{............................. (A.5)}$$

Thus, the average drying rate (ADR) of the whole system with 3 drying bins :

$$ADR = \frac{W}{T} \times 60 \times 3 = \frac{M}{100 \times T} \times (MC_o - MC_f) \times 60 \times 3 \quad \text{................... (A.6)}$$

Where

W_o = initial amount of water in the grain (kg)

W_f = amount of water in the grain at the end of drying (kg)

M = dry matter of grain in one drying bin (kg)

MC_o = grain initial moisture content (% d.b)

MC_f = moisture content of the grain at the end of drying (% d.b.)

T = drying time (min)

APPENDIX B

Comparison of the observed grain moisture ratio with the thin-layer model recommended by Liu et al. (1998)

The experimental moisture ratio (MR_e) was determined based the observed data during the experiment using the following equation:

$$MR_e = \frac{MC_t - MC_e}{MC_o - MC_e}$$ .... (B.1)

Where

MC_t = observed moisture content at time t (decimal d.b.)

MC_o = initial moisture content (decimal d.b.)

MC_e = equilibrium moisture content (decimal d.b.)

According to Liu et al. (1998), the equilibrium moisture content (MC_e) and the predicted moisture ratio (MR_p) were determined using the following equations:

$$MC_e = 0.339 - 0.059 \ln [-(T + 30.205) \ln RH]$$ ......…..………… (B.2)

$$MR_p = exp (-kt^n)$$ ………........ (B.3)

$$k = 1.091 \times 10^{-2} + 2.767 \times 10^{-6} T^2 + 7.286 \times 10^{-6} T.MC_o$$ ………......…..... (B.4)

$$n = 0.5375 + 1.141 \times 10^{-5}MC_o^2 + 5.183 \times 10^{-5}T^2$$ …........................ (B.5)

Where

RH = relative humidity of the drying air (decimal)

K and n = drying constants

t = time (min)

T = air temperature ($27 - 116\,^\circ$C)

MC_o = grain initial moisture content ($23 - 36$ % d.b.)

Note : According to the authors, MR_p can be determined using Equation (B3) when the air relative humidity and airflow ranged from $5 - 40$ % and from $0.1 - 0.5$ m^3/s.m^2, respectively.

The higher grain initial moisture content (approx. 30 %) and air temperatures (80 and 110 °C) were excluded from the analysis due to they are not within the ranges of conditions:

- As air is heated, the changes of its properties occur on a horizontal line on the psychrometric chart (Brooker et al., 1992 and Hall, 1980). When the ambient air of approx. 18 °C and 80 % relative humidity is heated to 80 and 110 °C, its relative humidity would become smaller than 3.5 %. Such value of the relative humidity is out of the range (5 – 40 %) and therefore, the drying air temperatures of 80 and 110 °C were discarded from the analysis;

- Table B.1 listed the grain initial moisture contents dry basis (MC_d) as converted from the moisture contents wet basis (MC_w) using Equation (B.6) (McLean, 1989) :

$$ MC_d = \frac{100 \times MC_w}{100 - MC_w} \qquad\qquad\qquad\qquad (B.6) $$

According to Table B.1, the grain initial moisture contents of "Clint" and "Raissa" maize hybrids of 31.42 and 32.15 %, which are equivalent to 45.82 and 47.38 % d.b., respectively, can not be included in the analysis, because Liu et al' s model is limited to the grain moisture content in the range of 23 to 26 % d.b (Liu et al., 1998).

TABLE B.1 Grain initial moisture contents as dry basis converted from wet basis

Hybrid	Grain initial moisture content, %		
	Approximate (wet basis)	Measured (wet basis)	Converted (dry basis)
Clint	20	18.67	22.96
Clint	25	25.69	34.57
Clint	30	31.42	45.82
Raissa	20	19.73	24.58
Raissa	25	25.96	35.06
Raissa	30	32.15	47.38

Therefore, the following analysis was focusing only on both maize hybrids dried from approx. 20 and 25 % moisture contents at 58 °C drying air temperature:

1. For "Clint"

1.a/ MC_o= 25.69 % w.b. = 34.57 % d.b. :

While the relative humidity and the dry-bulb temperature of the ambient air RH_a = 73.23 % and T_a= 18.59 °C, respectively, according to the Psychrometric chart, the air of 58 °C temperature would result in RH = 8.7 % (Hall, 1980 and Brooker et al., 1992). Applications of Equations (B.2), (B.4), and (B.5):

$MC_e = 0.339 - 0.059 \ln [-(58 + 30.205) \ln 0.087] = 2.2027$ % d.b.

$k = (1.091 \times 10^{-2}) + (2.767 \times 10^{-6} \times (58)^2) + (7.286 \times 10^{-6} \times 58 \times 34.57) = 0.0348$

$n = 0.5375 + [1.141 \times 10^{-5} \times (34.57)^2] + [5.183 \times 10^{-5} (58)^2] = 0.7255$

1.b/ MC_o= 18.67 % w.b. = 22.96 % d.b. :

While the relative humidity and the dry-bulb temperature of the ambient air RH_a = 80.85 % and T_a= 16.66 °C, respectively, according to the Psychrometric chart, the air of 58 °C temperature would result in RH = 8.5 %. Applications of Equations (B.2), (B.4), and (B.5):

$MC_e = 0.339 - 0.059 \ln [-(58 + 30.205) \ln 0.085] = 2.1468$ % d.b.

$k = (1.091 \times 10^{-2}) + (2.767 \times 10^{-6} \times (58)^2) + (7.286 \times 10^{-6} \times 58 \times 22.96) = 0.0299$

$n = 0.5375 + [1.141 \times 10^{-5} \times (22.96)^2] + [5.183 \times 10^{-5} (58)^2] = 0.7179$

2. For "Raissa"

2.a/ MC_o= 25.96 % w.b. = 35.06 % d.b. :

While the relative humidity and the dry-bulb temperature of the ambient air RH_a = 73.23 % and T_a= 18.59 °C, respectively, according to the Psychrometric chart, the air of 58 °C temperature would result in RH = 8.7 %. Applications of Equations (B.2), (B.4), and (B.5):

$MC_e = 0.339 - 0.059 \ln [-(58 + 30.205) \ln 0.087] = 2.2027$ % d.b.

$k = (1.091 \times 10^{-2}) + (2.767 \times 10^{-6} \times (58)^2) + (7.286 \times 10^{-6} \times 58 \times 35.06) = 0.0811$

$n = 0.5375 + [1.141 \times 10^{-5} \times (35.06)^2] + [5.183 \times 10^{-5} (58)^2] = 0.7259$

2.b/ MC$_o$= 19.73 % w.b. = 24.58 % d.b. :

While the relative humidity and the dry-bulb temperature of the ambient air RH$_a$ = 80.85 % and T$_a$= 16.66 °C, respectively, according to the Psychrometric chart, the air of 58 °C temperature would result in RH = 8.7 %. Applications of Equations (B.2), (B.4), and (B.5):

$$MC_e = 0.339 - 0.059 \ln [-(58 + 30.205) \ln 0.087] = 2.203 \% \text{ d.b.}$$
$$k = (1.091 \times 10^{-2}) + (2.767 \times 10^{-6} \times (58)^2) + (7.286 \times 10^{-6} \times 58 \times 24.58) = 0.0306$$
$$n = 0.5375 + [1.141 \times 10^{-5} \times (24.58)^2] + [5.183 \times 10^{-5} (58)^2] = 0.7188$$

Results :

The experimental (MR$_e$) and predicted (MR$_p$) moisture ratios calculated from Equations (B.1) and (B.3), respectively, are listed in the Table B.2 below:

TABLE B.2 Comparison of the resulted MR$_e$ with MR$_p$ of both maize hybrids dried at 58 °C

Drying time (min)	Clint				Raissa			
	MC$_o$ = 25 %		MC$_o$ = 20 %		MC$_o$ = 25 %		MC$_o$ = 20 %	
	MR$_e$	MR$_p$	MR$_e$	MR$_p$	MR$_e$	MR$_p$	MR$_e$	MR$_p$
0	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
10	0.935	0.831	0.950	0.855	0.936	0.830	0.932	0.852
20	0.868	0.736	0.885	0.773	0.857	0.735	0.862	0.768
30	0.818	0.663	0.840	0.709	0.798	0.661	0.808	0.703
40	0.767	0.603	0.805	0.655	0.748	0.601	0.768	0.648
50	0.730	0.552	0.774	0.609	0.704	0.549	0.732	0.601
60	0.695	0.507	0.749	0.568	0.665	0.504	0.703	0.560
70	0.665	0.468	0.726	0.532	0.633	0.465		
80	0.639	0.433			0.603	0.430		
90	0.612	0.402			0.575	0.399		
100	0.590	0.374			0.552	0.371		
110	0.564	0.348			0.527	0.346		
120	0.545	0.325			0.506	0.322		
130	0.528	0.304			0.487	0.301		
140	0.508	0.285			0.469	0.282		
150	0.493	0.267						
160	0.479	0.251						

APPENDIX C

Determination of the specific coefficients k and n
of thin-layer drying model

Following the steps made by Misra and Brooker (1980) and Li and Morey (1984), the drying constants k and n of thin-layer drying (Page model) were determined for each initial moisture content and drying temperature using linear regression on the transformed equation:

$$Ln\ (-lnMR) = ln\ k + n\ (ln\ t) \qquad \text{...} (C.1)$$

The experimental (MR_e) and predicted (MR_p) moisture ratios were calculated using the following equations :

$$MR_e = \frac{MC_t - MC_e}{MC_o - MC_e} \qquad \text{...} (C.2)$$

$$MR_p = exp\ (-kt^n) \qquad \text{...} (C.3)$$

Where

t = drying time (min)

T = drying air temperature (^oC)

MC_t = grain moisture content at time t (%)

MC_o = grain initial moisture content (%)

MC_e = grain equilibrium moisture content (%)

According to Liu et al. (1998), grain equilibrium moisture content is determined as :

$$MC_e = 0.339 - 0.059\ ln\ [-(T + 30.205)\ ln\ RH] \qquad \text{...........................} (C.4)$$

Where RH is relative humidity of the drying air (decimal)

Publication Arising from this Thesis

Meas P., Opara U.L. and Hardacre K.A., 1998. Performance evaluation of a prototype flat-bed grain dryer and drying characteristics of soft and hard maize hybrids*. Proceeding of the 5th Annual New Zealand Engineering and Technology Postgraduate Conference, 26 – 29 November, pp. 366 – 371.

* Paper awarded the Overall First Prize at the conference.

Performance Evaluation of a Prototype Flat-bed Grain Dryer and Drying Characteristics of Soft and Hard Maize Hybrids

Meas Pyseth
Institute of Technology and Engineering, Massey University
Pyseth.Meas.1@uni.massey.ac.nz

Opara U. Linus
Institute of Technology and Engineering, Massey University

Hardacre K. Allan
Crop and Food Research Ltd., Palmerston North New Zealand

Abstract

The increasing emphasis on grain quality and energy conservation during drying has created a need to develop drying systems that will deliver a better quality product with lower energy consumption. A new prototype flat-bed grain dryer was evaluated using maize grain of two hybrids (soft and hard). Dryer performance parameters such as capacity and drying rate were determined and the dried grains were tested for their quality attributes. Preliminary results showed that grain bulk density and breakage susceptibility correlated well with the drying air temperatures and the initial grain moisture content. Low initial grain moisture content and high drying temperatures increased dryer capacity and reduced total energy consumption for drying. However, both high drying air temperature and high initial grain moisture content increased the incidence of grain damage. The implication of these results for optimizing dryer performance and dried grain quality will be discussed.

1. Introduction

Evaluation of performance of grain dryers and understanding the effects on grain properties are still important to satisfy the need of grain producers, grain traders, grain processors and grain users. Drying operation must not be considered as merely the removal of moisture since there are many quality factors that can be adversely affected by incorrect selection of drying conditions and equipment [17].

Research studies have shown that grain initial moisture content and drying temperature have substantial effects on dryer performance and dried grain quality such as bulk density, breakage, stress cracking, and milling quality [6, 7, and 12].

The specific objectives of this experiment were to conduct performance evaluation of the prototype flat-bed grain dryer by :

• Determining the effects of grain moisture content and air temperature on dryer capacity, drying efficiency and energy consumed by the dryer
• Quantifying the same effects on grain quality attributes.

2. Materials and methodology

2.1 Grain

Two hybrids of yellow maize grains (250 kg each) named "Clint" and "Raissa", which are hard and soft, respectively, were used in this study. The Clint was planted in October 1997, on the experimental site of the Crop and Food Research Ltd. in Palmerston North, New Zealand; manually harvested on May 21 and June 15, 1998; and shelled by a husker-sheller (Haban, USA) at the moisture content of around 22 %. (Note : All the grain moisture contents cited in this report are in wet basis). The Raissa was planted on October 24, 1997, in Aorangi, Kairanga region, Manawatu, New Zealand; and harvested and shelled by a commercial combine harvester (John Deer, USA) in May 29, 1998, at the moisture content of around 24 %. In order to carry out the experimental work in the time available, it was necessary to artificially dry or wet the grains to obtain three different moisture contents (approx. 20, 25 and 30 %).

2.2 The prototype flat-bed grain dryer

The prototype flat-bed grain dryer (Figure 1), constructed by the Crop and Food Research has four main parts : a centrifugal fan powered by an electric motor; a heating section consisting of 8 two-kilowatt electric heaters; a central plenum chamber and three removable rectangular boxes used as drying bins. Each of the bins is vertical column of 40 x 40 cm (cross section) and 40 cm (height). The sides of the bins are made of sheet metal and the bottoms are made of metal mesh.
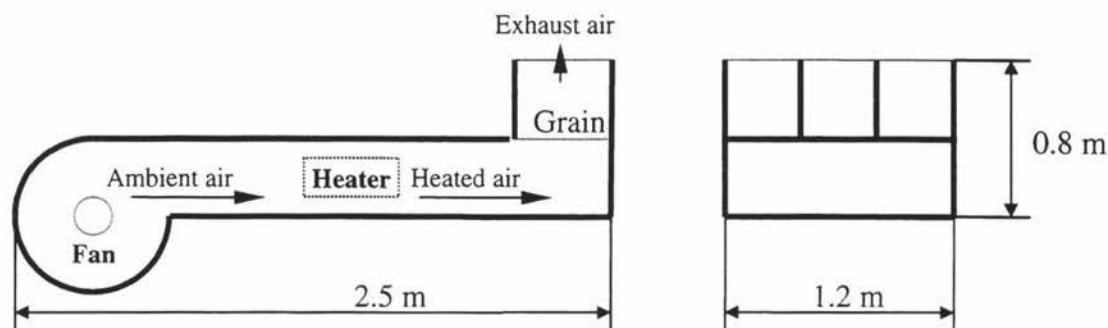
Figure 1 Schematic diagram of the prototype flat-bed grain dryer

The heating section and the plenum chamber are made of the sheet metal and insulated with 2.5 cm thick expanded polystyrene to minimize the effect of heat loss to the surroundings. Drying air temperature (max. 130 °C) and flow can be set using an electric-relay system (Grain Dryer Controller, Gewiss GW46006, Electro-engineering Ltd., Palmerston North, New Zealand).

When operating, the fan propels drying air into the plenum chamber. It passes through heaters in the heating section and, then to drying grain in the bins through the perforated metal floors.

2.3 Methodology

Grain of both hybrids were dried from the three initial moisture contents, using the dryer, at three drying air temperatures (58, 80 and 110 °C) in three replications. Each time, 5-kg sample was dried in one of the three drying bins. Approx. 100 to 150 g of grains in each drying bin was put in a small metal-mesh bag and left to dry all together in the bin. The small bags were taken out of the drying bins every 10 minutes to weight in order to detect moisture reduction of the dried samples.

Sample was no longer dried when its weight reduced to a predetermined value, which is related to the moisture content of : 16 % at 110 °C, 15.4 % at 80 °C and 14.6 % at 58 °C. These target moisture contents have been used by the Crop and Food Research, as moisture content of dried grain usually drops further during cooling process, in accordance to their experiences. Apart from drying with the dryer, grain of both hybrids were dried at ambient air temperature from all the three initial moisture contents.

Other parameters were also measured every 10 minutes during the drying process. Temperature and the humidity of the ambient air were measured and recorded by Cambell Scientific CR10 data logger. Temperature of the heated air was read from the dryer control system. Flow and temperature of

the air exhausted from the grain were measured and recorded using a wind speed indicator (Davis Instruments, California, USA) and thermocouple immersion probe (model 80PK-2A, type K, John Fluke Mfg. Co., Inc., USA), respectively. Electric power consumed by dryer was read from power meter located at the power source.

Grain Moisture contents were measured using the oven method (72 hours at 103 °C) before drying. Moisture meter (GAC2000, DICKEY-John Corp., USA) was used to measure moisture content and bulk density after drying.

Breakage susceptibility of the grains dried under particular drying condition was determined in three replications using the Stein breakage tester developed by the Crop and Food Research. Each time, 50-g sample of clean and sound grain kernels was subjected to breakage in the tester for 6 minutes and then manually sieved using a 4.75 mm-aperture sieve (Pattern No. 667924, Endecotts Ltd., London, England) to separate the fine material and broken kernels from sound kernels. Breakage susceptibility was determined as the sum of weight percent of the fine material and the broken grain to the sample weight. Similar method has been used by many researchers [5, 9, 11 and 18]

The hardness test, based on the method used by Li et al. [10] and Pomeranz et al [13], was applied for all the dried samples using the Stenvert Hardness Tester at the Crop and Food Research. The speed of the tester mill was set for 3,600 rpm, when unloaded. Each time, a 20 g-sample of sound kernels was ground and the resistance time and milling energy consumption were recorded by a computerized data logging system attached to the tester. The dried maize samples ranged in moisture content from 12.53 to 14.27 %, therefore, the quality test results had to be corrected to 14 % moisture content using models developed in the Crop and Food research. The models are commercially confidential and not allowed to be published.

3. Results

Preliminary results are listed in the Table below. Some of them are illustrated in the following Figures.

Variety	Initial Moisture Content, %	Drying Temperature, °C	Drying Time, min	Energy Consumption, kW	Dryer Capacity, kg/h	Bulk Density, kg/hl	Breakage Susceptibility, %	Milling Energy Consumption, kJ	Resistance Time, s
Clint	20	Ambient	-	-	-	77.58	1.86	9.34	29.80
		58	95.33	1.80	9.50	77.09	13.37	10.50	34.83
		80	50.67	1.22	17.91	76.24	15.68	10.43	33.73
		110	45.33	1.11	19.89	75.74	19.28	10.76	36.07
	25	Ambient	-	-	-	77.91	1.24	9.26	28.67
		58	196.33	3.31	4.60	75.31	22.19	10.05	33.30
		80	97.00	2.56	9.38	73.92	23.11	10.20	32.33
		110	72.33	1.93	12.46	72.57	28.83	9.19	29.47
	30	Ambient	-	-	-	76.44	1.20	9.68	28.83
		58	270.67	4.82	3.35	72.63	25.21	10.40	33.07
		80	139.67	3.80	6.50	71.46	28.23	10.27	31.47
		110	87.33	2.96	10.31	69.83	31.17	9.18	27.43
Raissa	20	Ambient	-	-	-	76.00	1.21	7.51	18.87
		58	97.33	1.53	9.31	74.49	13.18	7.96	19.17
		80	54.33	1.27	16.64	73.41	14.23	7.74	19.07
		110	48.67	1.06	18.50	72.46	18.29	8.15	19.37
	25	Ambient	-	-	-	74.57	1.96	7.99	20.30
		58	173.67	3.09	5.21	72.11	20.62	7.77	17.20
		80	94.00	2.48	9.63	70.61	28.57	7.53	16.43
		110	70.67	1.93	12.77	68.90	30.14	7.81	17.07
	30	Ambient	-	-	-	72.85	1.24	7.81	18.40
		58	236.67	4.07	3.82	69.60	23.24	7.59	16.87
		80	134.67	3.56	6.71	67.83	33.95	7.63	15.43
		110	5.33	3.00	10.72	66.28	33.94	7.38	14.43

3.1 Drying time, capacity and energy used

With the same size of the drying sample, capacity of the dryer was related only on the drying time. Figure 2 indicates that drying time varied apparently with the grain initial moisture content and the drying air temperature. For both hybrids, the time was shown the same trends. The higher the moisture content, the longer the drying took time. The grain could be dried from any moisture content to the predetermined level in shorter time by increasing the drying temperature. The longest drying time was approx. 4 h and 30 min for drying the Clint from the highest moisture content (30 %) at the lowest temperature (58°C). The shortest time was about 45 min when both hybrids were dried from the lowest moisture content (20 %) at the highest temperature (110 °C).

The data in the Table above show that the dryer could dry grain of up to approx. 20 kg/h at 110 °C when the moisture content was 20 %. This capacity decreased with lower temperature and higher moisture content.

The energy consumed by the dryer was affected also by the drying conditions (Figure 3). More energy was used for both hybrids of higher moisture content. Within each moisture content, the energy was reduced when higher temperature was used. The dryer used most energy (almost 5 kWh) when drying the Clint from 30 % at 58 °C. The minimum energy (approx. 1 kWh) was used for the lowest moisture when the highest temperature was applied.
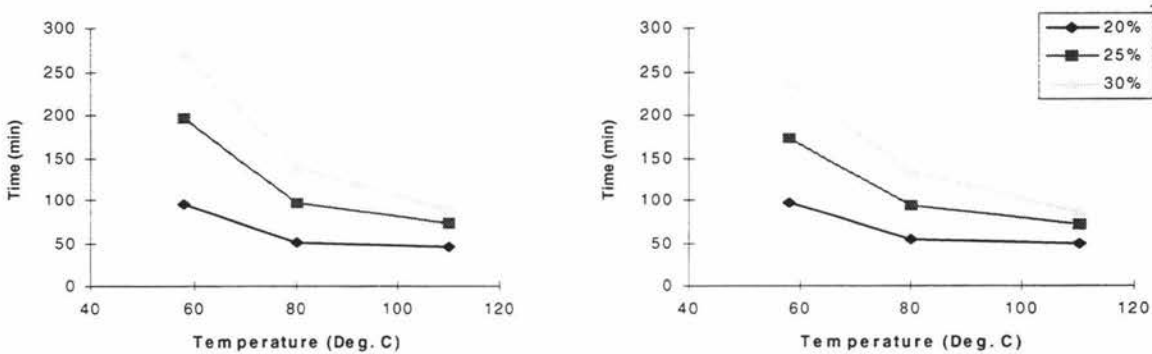

Figure 2 Dryer time as affected by the moisture content and temperature (Clint - left and Raissa - right)
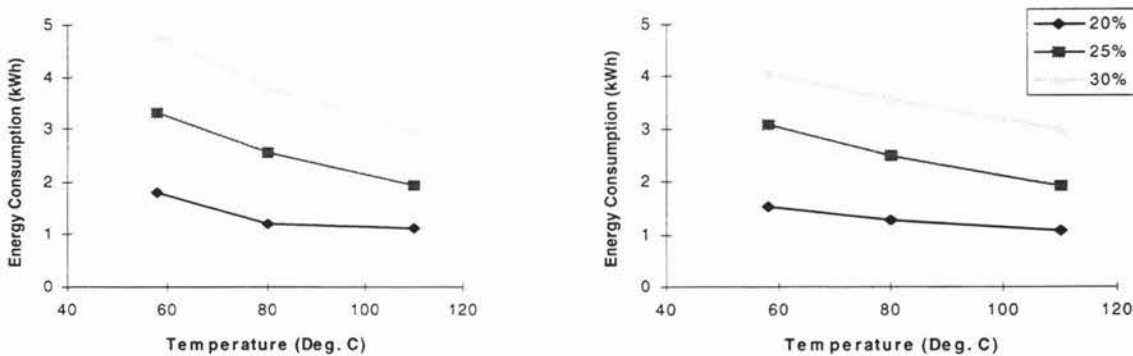

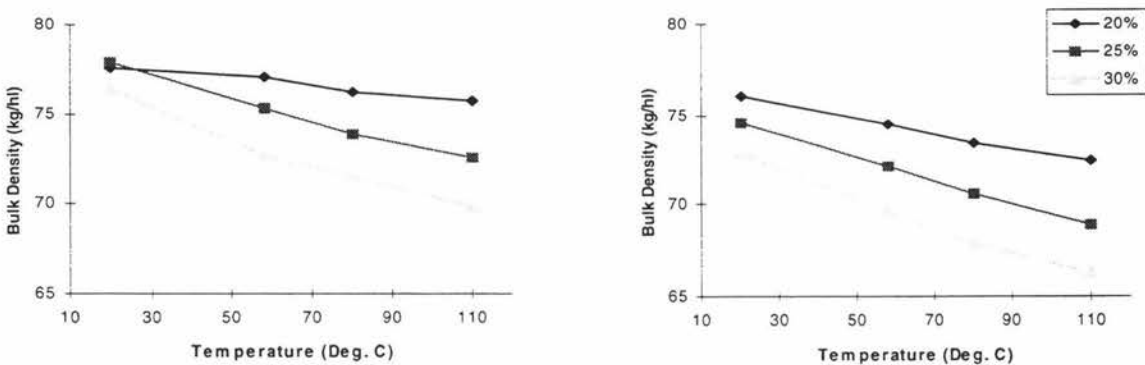*Figure 3* Dryer energy consumption as affected by the moisture content and temperature

Figure 4 Bulk density as affected by the moisture content and temperature
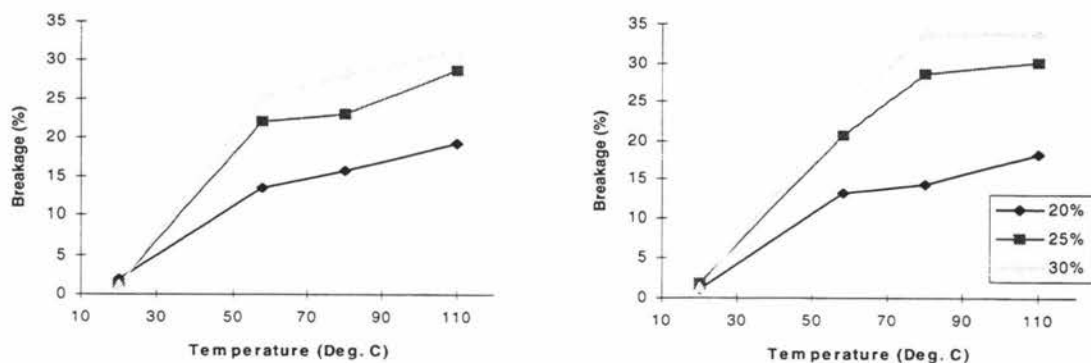
Figure 5. Breakage susceptibility as affected by the moisture content and temperatures

3.2 Bulk Density and breakage susceptibility

The drying temperatures and initial moisture contents were both significant in their effects on the bulk density of the dried grain (Figure 4). The density of all the hybrids tended to decrease as the moisture content and drying temperature increased. The highest bulk density (approx. 78 kg/hl) occurred for the Clint when drying at the ambient air temperature (approx. 20 °C) and from low moisture contents (20 or 25 %). The lowest density (approx. 66 kg/hl) occurred for the Raissa dried at the highest temperature (110 °C) and from the highest moisture content (30 %). Under each drying condition, the Clint bulk density was always higher than the Raissa bulk density.

Breakage of both hybrids was similarly affected by the drying temperature and the moisture content (Figure 5). As the temperature and/or the moisture content increased, the dried grain became somewhat more susceptible to breakage. Level of the damage was very small (approx. 1 %) for both hybrids dried at the ambient air temperature. The highest damage (from approx. 30 to 35 %) occurred for grain dried from the highest moisture content (30 %) at the highest air temperature (110 °C and 80 to 110 °C, for the Clint and Raissa, respectively).

3.3 Stenvert Hardness

Hardness is an important intrinsic property of maize because it is closely related to the ratio of corneous to floury endosperm that affect dry-milling flaking grit yields [9]. The Stenvert results (Table above) did not show clear effects of the moisture content and/or the temperature on hardness properties of the two hybrids. They, however, indicate that the Clint is harder than the Raissa. The Stenvert milling energy and resistance time were around 10 kJ and 34 s, respectively, for the Clint but they were significantly smaller (around 7.8 kJ and 18 s, respectively) for the Raissa.

4. Discussions

A maximum amount of grain that the dryer could dry by consuming least time and energy would be obtained by using as high air temperature and as low grain initial moisture content, as possible. However, the dried grain was more susceptible to damage when being dried at higher air temperature, especially from higher moisture content. The breakage and the bulk density were observed increased and decreased, respectively, as the air temperature and moisture content increased. Similar observations have been made by many other researchers [1, 2, 3, 4, 7, 8,12,14 and 15]

The Stenvert results only showed that there was significant difference between the two hybrids. Kirleis and Stroshine [9] had also found that for each of the tested hybrids, Stenvert hardness test values remained relatively constant for maize dried at temperatures up to 60 °C and then declined only slightly, but not significantly, at the higher drying temperatures.

5. Conclusions

Results of this study suggest that both grain initial moisture content and drying air temperature affect the dryer performance and some of the grain quality attributes :

1. The dryer capacity of approx. 20 kg/h was maximum. It decreased, to the lowest value (approx. 3.5 kg/h), as the air temperature decreased and the moisture content increased for both hybrids.

2. The energy consumed by dryer decreased as the air temperature increased and the moisture content decreased for both hybrids. Its maximum and minimum values were approx. 5 and 1 kWh respectively.

3. Breakage and bulk density of the dried grain were affected more badly as the air temperature and the moisture content increased. The most damage was shown with the highest breakage (35 %) and the lowest bulk density (66 kg/hl).

4. The effects of the moisture content and the air temperature on the grain hardness was not clear. There was only the difference between the hybrids which indicated that the Clint is harder than the Raissa.

5. When drying the Clint, the dryer produced less capacity and consumed more energy than when drying the Raissa.

6. In order to increase the dryer capacity and to decrease the drying energy consumption, therefore, air of high temperature would be needed. However, using higher air temperature for drying would cause more damage to the grain, especially when its initial moisture content is high.

6. Recommendation for future research

Based on the work in this study, the following areas for further research are recommended to optimize the operational characteristics of the dryer and the grain quality :

1. Thickness of grain layer in the drying bins would need to be differentiated to find out the optimum dryer capacity and drying rate.

2. Effects of drying on other grain quality factors (such as biochemical properties, including starch, protein and ash) should be considered.

REFERENCES

[1] Abe T. and Afzal T.M. *"Tin-Layer Infrared Radiation Drying of Rough Rice"*. Journal of Agricultural Engineering Research, (1997) 67, 289 - 297.

[2] Barker G.L. and Laird J.W. "Effect of Temperature on the Drying Rate of Gin Run Cotton Seed". Transactions of the ASAE, 1996 Vol. 40(2): 289 - 294.

[3] Brooker B.D., Bakker-Arkema W.F., and Hall W.C. "Drying and Storage of Grains and Oilseeds". An Avi book Published in 1992 by Van Nostrand Reinhold, New York.

[4] DiMattia D.G., Amyotte P.R. and Hamdullahpur F., 1996 : Fluidized Bed Drying of Large Particles. Transactions of the ASAE, Vol. 39(5): 1745 - 1750.

[5] Fortes M. and Okos M.R. "Changes in Physical Properties of Corn During Drying". Transactions of the ASAE, 1980 : 1004 - 1008.

[6] Gunasekaren, S., Deshpande, S.S., Paulsen, R.M. and Shove, C.G. "Size Characterization of Stress Cracks". Transactions of the ASAE, 1985, 28(5): 1668 - 1672.

[7]. Gunasekaran S. and Paulsen M.R. "Breakage Resistance of Corn as a Function of Drying Rates". Transactions of ASAE, 1985, 28: 2071.

[8] Hall G.E. "Test Weight Changes of Shelled Corn During Drying". Transactions of ASAE, 1972, 15: 320.

[9] Kirleis A.W. and Stroshine, R.L. "Effects of Hardness and Drying Air Temperature on Breakage Susceptibility and Dry-Milling Characteristics of Yellow Dent Corn". Cereal Chemistry, 1990, 67 (6) : 523 - 528.

[10] Li P.X.-P, Hardacre A.K, Campanella O.H. and Kirkpatrick K.J. "Determination of Endosperm Characteristics of 38 Corn Hybrids Using the Stenvert Hardness Test". Cereal Chemistry, 1996, 73 (4) : 466 - 471.

[11] Miller B.S., Hughes J.W., Rousser R. and Pomeranz Y. "Measuring the Breakage Susceptibility of Shelled Corn". Cereal Foods World, February 1981, Vol. 26, No. 2.

[12] Peplinski, J.A., Paulis, W.J., Bietz, A.J. and Pratt, C.R. "Drying of High-Moisture Corn Changes in Properties and Physical Quality". Cereal Chemistry, 1993, Vol. 71, No.2: 129 - 133.

[13] Pomeranz Y., Czuchajovska Z., Martin C.R. and Lai F.S. "Determination of Corn Hardness by Stenvert Hardness Tester". Cereal Chemistry, 1985, 62:108.

[14] Shivhare U.S., Raghavan G.S.V. and Bosisio R.G. "Microwave Drying of Corn. I. Equilibrium Moisture Content". Transactions of the ASAE, Vol. 35(3): May - June 1992.

[15] Tagawa A., Kitamura Y. and Murata S. "Thin Layer Drying Characteristics of Adzuki Beans". Transactions of the ASAE, 1996, Vol 39(2): 605 - 609.

[16] Thompson R.A. and Foster G.H. "Stress Cracks and Breakage in Artificially Dried Corn". United States Department of Agriculture. Marketing Res. Report, 1963, No. 631.24 pp.

[17] Trim, D.S. and Robinson, A.P. "Drying Methods. In : Grain Storage Techniques". FAO Agric. Services Bulletin 1994 (109). Edited by Proctor D.L.

[18] Weller C.L., Paulsen M.R. and Steinberg M.P. "Stress Cracking and Breakage Susceptibility as Affected by Moisture Content at Harvest for Four Yellow Dent Corn Hybrids". Transactions of the ASAE, Vol. 33(3): May-Jun 1990.