# MATHEMATICAL MODELLING OF BULK STORED ONIONS IN TRANSPORT CONTAINERS

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# ABSTRACT

Export onion bulbs are predominantly transported from New Zealand loose in sacks which are bulk loaded into intermodal transport containers. Product respiratory heat, water vapour, and volatiles are dispensed of by a fan unit installed in the end of the container, ventilating the stow by forcing ambient air from a false floor up through the crop and exhausting the air from a head space.

The objective of this study was to mathematically model this system with respect to onion bulb temperature and weight loss, and internal container air temperature and relative humidity. These product and flowfield variables were predicted at different locations within the transport vessel. Bulb temperature and weight loss were simulated as dynamic variables using ordinary differential equations, and air temperature and relative humidity were simulated as quasi steady state variables using algebraic equations.

A validation experiment was conducted to evaluate the simulation model by placing temperature and humidity sensors throughout the product and flowfield space measuring the respective properties. Onion and air temperatures were predicted with satisfactory accuracy in almost all measured locations of the container. Prediction of relative humidity varied considerably throughout the container, although excessive sensor errors were identified casting suspicion on some validation measurements. Simulated relative humidity could not therefore be fully verified. Bulb weight loss was predicted with variable levels of accuracy. Significant variability in the validation data was evident in the upper and lower regions of the container preventing complete model validation. Central regions of the container were simulated with satisfactory accuracy.

A model sensitivity analysis revealed that container ventilation rate strongly influenced model performance with respect to temperature and relative humidity. The mass transfer coefficient, as expected, was most influential over product weight loss.

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# LIST OF SYMBOLS

| Symbol in Text | Symbol in Model | Description | Units |
|---|---|---|---|
| A | As | surface area of onion bulb | $m^2$ |
| $A_z$ | - | total surface area of onions in zone | $m^2$ |
| AHL | - | absolute humidity lowering effect | - |
| Bi | - | Biot number | - |
| $C_p$ | Cpa | specific heat capacity of air | $J.g^{-1}.°C^{-1}$ |
| $C_{p(on)}$ | Cp | specific heat capacity of onion | $J.g^{-1}.°C^{-1}$ |
| $CO_2^f$ | - | carbon dioxide final concentration | % |
| $CO_2^i$ | - | carbon dioxide initial concentration | % |
| d | - | diameter of average onion | m |
| $dm_C/dt$ | DelMd | mass transfer of carbon | $g.s^{-1}$ |
| $dm_{H2O}/dt$ | DelMw | mass transfer of water vapour | $g.s^{-1}$ |
| $dT_{on}/dt$ | DelT | temperature change of onion | $°C.s^{-1}$ |
| $D_{AB}$ | - | binary mass diffusion coefficient | $m^2.s^{-1}$ |
| g | - | gravitational acceleration | $m.s^{-2}$ |
| Gr | - | Grashof number | - |
| $h_c$ | htc[] | convective heat transfer coefficient | $W.m^{-2}.°C^{-1}$ |
| $j_h$ | - | Colburn $j$ factor for heat transfer | - |
| $j_m$ | - | Colburn $j$ factor for mass transfer | - |
| k | - | thermal conductivity of onion | $W.m^{-1}.°C^{-1}$ |
| $k_a$ | - | convective air mass transfer coefficient | $g.m^{-2}.s^{-1}.Pa^{-1}$ |
| $k_{a(r)}$ | - | convective air mass transfer coefficient | $m.s^{-1}$ |
| $k_s$ | - | skin mass transfer coefficient | $g.m^{-2}.s^{-1}.Pa^{-1}$ |
| $k_t$ | - | mass transfer coefficient | $g.m^{-2}.s^{-1}.Pa^{-1}$ |
| $k_{t(r)}$ | mtc[] | mass transfer coefficient | $m.s^{-1}$ |
| L | - | characteristic dimension | m |
| m | - | mass of onion bulb | kg |
| $\dot{m}_{a(z)}$ | - | mass flow of air in zone | g |
| $\dot{m}_{H2O}$ | fevap | mass flow rate of water vapour | $g.s^{-1}$ |
| $m_s$ | - | mass of onion sample | kg |
| $m_z$ | - | mass of onions in zone | kg |

| $M_C$ | - | molecular mass of carbon | g.mol$^{-1}$ |
| $P_a$ | pa[] | vapour pressure of air | Pa |
| $P'_a$ | pasat | saturated vapour pressure of air | Pa |
| $P_{ATM}$ | - | atmospheric pressure | Pa |
| $P_{PDS}$ | - | air pressure in pressure drop system | Pa |
| $P_s$ | - | vapour pressure of onion surface | Pa |
| Pr | - | Prandtl number | - |
| $\Delta P_{z11}$ | - | air pressure difference across zone column | Pa |
| $r_h$ | - | heat of respiration | W.kg$^{-1}$ |
| $\pi_C$ | - | relative respiratory carbon mass depletion | g.kg$^{-1}$.s$^{-1}$ |
| $\pi_{CO_2}$ | - | relative respiratory carbon dioxide production | mol.kg$^{-1}$.s$^{-1}$ |
| Re | - | Reynolds number | - |
| RH | RH[] | relative humidity of air | % |
| Sc | - | Schmidt number | - |
| St | - | Stanton number | - |
| $St_m$ | - | Stanton number for mass transfer | - |
| t | - | time | s |
| $T_a$ | Ta[] | temperature of air | °C |
| $\Delta T_a$ | - | temperature change of zone air | °C |
| $T_{a(i)}$ | Tai | temperature of air entering zone | °C |
| $T_{a(o)}$ | Tao | temperature of air exiting zone | °C |
| $\Delta T_m$ | lmtd | onion/flowfield log mean temperature difference | °C |
| $T_{on}$ | Ton[] | temperature of onion | °C |
| $T_s$ | - | temperature of onion surface | °C |
| u | - | air velocity | m.s$^{-1}$ |
| $u_\infty$ | - | upstream air velocity | m.s$^{-1}$ |
| v | v[] | volumetric air flow rate through zone | m$^3$.s$^{-1}$ |
| V | - | volume of onion bulb | m$^3$ |
| $V_j$ | - | volume of jar | m$^3$ |
| $V_s$ | - | volume of onion sample | m$^3$ |
| W | wtfrac | onion water content fraction | - |
| $\dot{\alpha}$ | - | thermal diffusivity of air | m$^2$.s$^{-1}$ |
| $\beta$ | - | volumetric thermal expansion coefficient | K$^{-1}$ |
| $\varepsilon$ | - | packed bed volumetric void fraction | - |

| | | | |
|---|---|---|---|
| $\lambda$ | Lambda | latent heat of vaporization of water | $J.g^{-1}$ |
| $\rho$ | rho[] | density of air | $g.m^{-3}$ |
| $\rho_{on}$ | - | density of onion | $kg.m^{-3}$ |
| $\nu$ | - | kinematic viscosity of air | $m^2.s^{-1}$ |
| $\phi_{conv}$ | Qc | convective heat transfer from onion to zone air | W |
| $\phi_{evap}$ | Qevap | latent heat transfer from onion to zone air | W |
| $\phi_{resp}$ | Qresp | heat generation from respiration | W |
| $\chi$ | Xa[] | absolute humidity of air | $g.m^{-3}$ |
| $\Delta\chi$ | - | absolute humidity change of zone air | $g.m^{-3}$ |
| $\chi_i$ | Xai | absolute humidity of air entering zone | $g.m^{-3}$ |
| $\Delta\chi_m$ | lmXd | onion/flowfield log mean absolute humidity diff. | $g.m^{-3}$ |
| $\chi_o$ | Xao | absolute humidity of air exiting zone | $g.m^{-3}$ |
| $\chi_{on}$ | Xonsat | absolute humidity of onion surface | $g.m^{-3}$ |

**Additional symbols used in model not used in text**

| | | |
|---|---|---|
| Asav | surface area of average onion bulb | $m^2$ |
| fresp | mass transfer rate of carbon | $g.s^{-1}$ |
| massav | mass of average onion bulb | kg |
| masst | total mass of onions in container | kg |
| Mdon[] | mass of onion dry fraction | g |
| Mon[] | mass of onions in zone | g |
| Mwon[] | mass of onion wet fraction | g |
| number | number of onion in container | - |
| pin | vapour pressure of air entering container | Pa |
| psatin | saturated vapour pressure of air entering container | Pa |
| rhoin | density of air entering container | $g.m^{-3}$ |
| RHin | relative humidity of air entering container | % |
| simtime | simulation step length | s |
| step | simulation step length | s |
| Tin | temperature of air entering container | °C |
| vent | total container ventilation rate | $m^3.s^{-1}$ |
| Xin | absolute humidity of air entering container | $g.m^{-3}$ |

where:

[] = array of zone positions

# CHAPTER 1

# INTRODUCTION

Onion (*Allium cepa* L.) is an important crop constituting a significant proportion of New Zealand's horticultural export trade. The year to March 1994 saw an increased consignment of approximately 100,000 tonnes of fresh onion bulbs exported at a value exceeding 55 million dollars to 36 countries. This represented the fourth most valuable horticultural export crop produced in this country.

An important consideration in the exportation of horticultural items is the issue of product quality. This is of particular importance to New Zealand due to the vast distances that produce typically travel and the associated implications transit storage has on quality. Long sea voyages are experienced by much of New Zealand's export onion crop with approximately 50% sent to Europe, 25% sent to Asia, 15% sent to North America, and the bulk of the remainder sold to the Pacific Islands.

## 1.1 ONION STORAGE POTENTIAL

Onions have been reported to have good storage potential which is dependant on a number of factors: variety, cultural practices during production, maturity, and postharvest handling (Thompson et al. 1972; Singer 1980). Postharvest losses in bulb quality are largely attributed to pathogenic diseases, sprouting, and weight loss (Woodman and Barnell 1937; Ward 1976; Thompson 1982; Bisbrown et al. 1991).

On a weight basis onion bulbs can be regarded as a relatively low value product. Packaging and transportation is therefore important as one means of retaining profitability in the crop. The industry has accommodated these issues by developing

low maintenance postharvest procedures for packaging and transportation. Much of the exported crop is packaged into 20 kg fibre woven bags and bulk loaded into fan ventilated intermodal transport containers.

The use of refrigeration is important to New Zealand and is not typically neglected for most agricultural and horticultural products. Robinson et al. (1975) and Miedema (1994) commented that the optimum storage temperature for onion bulbs is 0°C and deviation from this temperature would inhibit storage potential. However, compromises due to economic factors means that almost all the crop is transported in unrefrigerated vessels.

Respiratory processes are enhanced by warmer conditions (Platenius 1942), creating possibilities for the increased incidence of bulb weight loss particularly through carbon depletion (Ward 1976). Consequently, higher temperatures, in conjunction with high relative humidity, can be responsible for significant bulb losses through disease (Van den Berg and Lentz 1973). Lowering relative humidity has been found to have the effect of increasing transpiration and hence weight loss (Van den Berg and Lentz 1973). It is apparent that relative humidity is an important factor governing product quality and that a compromise is required between the excess of either weight loss or disease infection. Sprouting was generally found to occur later during storage and was inhibited at specific minimum and maximum temperatures (Karmarkar and Joshi 1941; Thompson et al. 1972).

Onion quality losses can be significant, particularly after prolonged periods of storage. Stow (1975) reported that onions stored after 5 months under various relative humidity regimes at 30°C suffered weight losses from 12-16%. Ward (1976) reported total weight loss after 9 months storage at 70% relative humidity and 15-25°C to be 13-16%. Weight loss of this magnitude can represent serious loss of saleable commodity.

## 1.2 THERMOPHYSICAL VARIATION WITHIN PRODUCT STOWS

Product respiration and transpiration occur continuously throughout all areas of a stored onion lot. The respective heat and evaporative processes of respiration and transpiration obviously influence internal container atmosphere. Reports have indicated that relative humidity and air temperature within packed beds of biological products are spatially irregular and that this in turn has an effect on product temperature and moisture content consistency (Boyce 1965; Boyce 1966; Bakker-Arkema et al. 1967).

Unrefrigerated fan ventilation is commonly utilized in transport containers holding onions. It is operationally inexpensive and an easily maintained mechanism available to counter excessive environmental heat and moisture build up. Air ventilation also aids in the reduction of spatial irregularity of temperature and relative humidity throughout the onion stow.

## 1.3 PREDICTING PRODUCT TEMPERATURE AND WEIGHT LOSS

Stored product lots subjected to forced ambient air ventilation experience a constant change in their thermal and mass status due to the dynamic nature of the atmospheric environment. Predicting product temperature and moisture content under variable temperature and relative humidity regimes is demanding, particularly when the crop is stored in a deep bed where the processes of product metabolism and transpiration can be influential on adjacent product. Mathematical models have been developed by some researchers for various biological storage lots predicting the product and product void area status (Ofoli and Burgess 1986; Romero and Chau 1987; Gan and Woods 1989). Description of the respiratory and evaporative responses of onion bulbs in various environments has been relatively well documented, particularly as single product items. Research related to the modelling of bulb responses in deep beds is considerably less extensive, particularly those beds positioned within intermodal transport containers.

# CHAPTER 2

# LITERATURE REVIEW

This literature review encompasses various topics of particular importance to the research. It consists of the areas of: general principles of mathematical modelling; intermodal transport containers, the types of vessels and their performance; mathematical models of transport containers; models of heat and mass (water vapour) transfer from commodities, particularly bulk stacked product; and physiology of the onion bulb, emphasising the respiratory and evaporative processes as influenced by environmental conditions. These respiratory and evaporative processes are considered with respect to the release of metabolic heat and water vapour from the product.

## 2.1 PRINCIPLES OF MATHEMATICAL MODELLING

Quantitative description of an occurrence in the real-world can be denoted as a model of that particular system or process. If the system or process is described by working equations then it can be referred to as a mathematical model. Giordano and Weir (1985) defined a mathematical model as a mathematical construct designed to study a particular real-world system or phenomenon.

### 2.1.1 Model Classification and Infrastructure

Mathematical models describing a system concerning the storage of biological products can be categorized according to various factors. Touber (1984) suggested a basic method of classification linked to model building based on the degree of inductivity. An inductive model, referred to as a behaviour level, black box or empirical model is formulated from experimental data constituting observations of

system inputs and outputs. A deductive model, described as a structure level, white box or mechanistic model is formulated from knowledge or insight regarding the structure of the system.

Deductive models are considered to have unique solutions of the modelling problem as they are based on fundamental physical laws and principles, such as the First Law of Thermodynamics (Law of Conservation of Energy) and the Continuity Equation (Law of Conservation of Mass). Inductive modelling typically require the introduction of assumptions as boundaries and parameters which exist when utilizing experimental data. Mathematical relationships determine output variables as functions of input variables from such data.

The fundamental approach of deductive modelling avoids the constraints of inductivity. Thus, researchers should endeavour to exploit the deductive approach where possible; however as with almost all modelled systems, some degree of inductivity is usually necessary.

### 2.1.2 Model Development Strategy

In the realm of product storage technology a system under study will usually behave in a dynamic manner. Such systems are more than often prohibitively complex to be modelled in their entirety with exacting precision. Reducing model complexity is possible by omitting factors which have a negligible effect on the system. The extent to which simplification should occur is dependent on the accuracy required of the model and the resources available to develop it. Operational simplicity must also bear some consequence as to the appropriate degree of model complexity. Cleland (1990) suggested that the important consideration in evaluating a model is one of appropriateness, not whether all known physical effects are included. Similarly, Wang and Touber (1990) believed that a good balance is required between model complexity, the cost of computation, and the benefit of use obtained from it.

The complexity of a model representing the behaviour of stored biological products is largely governed by model development with respect to the time and space domain.

### 2.1.2.1 *Time domain*

Modelling with respect to the time domain is typically identified as either "steady-state" or "dynamic".

Steady-state models have been popular in the past due to their relative ease of design and computation, particularly in the pre-computer era (Touber 1984). They assume there is no change in the state of a system as a function of time. Thus, a system's output is predicted to occur instantaneously in response to a step input change.

Dynamic models predict the rate of change in the state of a system with time. They offer greater accuracy in predicting outputs from such problems involving unsteady heat and mass flow (Touber 1984). Such models are typically defined by a set of differential equations.

### 2.1.2.2 *Space domain*

This component of modelling considers spatial variability of a system. Mathematical models discriminating with respect to position are referred to as either "lumped" or "distributed" (Wang and Touber 1990).

Lumped models essentially divide the system's space into zones (lumps). Each zone is considered to be perfectly air mixed or homogeneous from which ordinary differential equations suffice in predicting temperature and water vapour concentration.

Distributed models consider one volume which is imperfectly mixed or inhomogeneous. Therefore, temperature or water vapour concentration is predicted

with respect to time and position within the control volume. Solving for the dependent variable when incorporating a second independent variable (position) requires the use of partial differential equations.

## 2.2   ISO INTERMODAL TRANSPORT CONTAINERS

It was estimated in 1993 that approximately 7 million International Standardization Organisation (ISO) freight containers were in existence world-wide. A relatively small proportion of these, approximately 3-4%, are suitable for the carriage of perishable agricultural products which are temperature and often moisture sensitive. Insulated and refrigerated containers, some fitted with dehumidifying capabilities, are extensively utilized for such product transportation. To a lesser extent other containers employing natural ventilation or fan ventilation are utilized for transporting products typically of lower bulk value that may also be somewhat temperature or moisture sensitive.

In general, the more complex the container the better the internal control of environmental conditions. Costs related to purchasing, leasing and operating such containers typically increase accordingly. It is therefore important to place the appropriate products in the appropriate containers (Heap and Pryor 1993).

New Zealand onion bulb exports have steadily increased over recent years and they are now a major horticultural commodity dispatched in transport containers. Refrigerated containers are occasionally used but a majority of the crop is consigned in fan ventilated 6 or 12 m long containers. The product is maintained loose in either bins, which may or may not be loaded into containers, or more commonly in 20 kg fibre woven sacks which are bulk stacked into ventilated containers.

## 2.2.1 Ventilated Containers

Airflow circulation is a basic requirement for good thermal protection in product storage facilities, particularly for medium or long term storage. In many instances it is also important for removing by-products of the respiratory and evaporative processes. Ventilation can occur naturally by heat generated through product respiration; a film of air encircling the product experiences a drop in density through heating, thus forcing the air to slowly rise. Ventilation of this type is only reasonable if the low air velocities can deal with the expected heat flow. This would require the presence of air channels of significant volume between relatively small batches of product (Meffert and Van Beek 1983), a circumstance which is usually uneconomical particularly when transporting product of low bulk value. Forced internal airflow is required to attain suitable ventilation when air channels are reduced.

Various types of ventilated container utilizing electric fans systems are currently in use. Some systems are of commercial design where containers have been specifically manufactured with fan systems installed, or designed for the adaption of fan systems to be fitted. Furthermore, standard freight containers can be modified and/or fitted with custom made fan ventilation systems.

### 2.2.1.1 *Refrigerated containers*

Refrigerated containers incorporate refrigeration and air handling equipment and are the most common design of standardised container specialising in forced internal airflow. They function by circulating air through the loadspace to collect heat from the cargo and from the container walls. Modern units deliver air to the base of the container under a false floor after which the air rises up through the cargo and is extracted from ceiling level back to the evaporator coils to be recirculated (Sharp and Irving 1991a).

### 2.2.1.2 *Insulated containers*

Fans and refrigeration equipment are not incorporated in insulated containers. However, thermal insulation is utilized to an extent that would typically be found in refrigerated containers. Porthole apertures at the inlet and outlet areas of the cargo space at one end of the container can be fitted with a clip-on refrigeration machine or an external air circulation system (Heap 1989).

### 2.2.1.3 *Purpose built Fantainers*

Fantainers are freight containers that are fan ventilated with ambient air. Purpose built Fantainers are a recent development, being permanently modified standard freight containers. They have provisions for the outlet and inlet vent openings to be sealed with covers when cargoes not requiring ventilation are transported. Air is usually distributed beneath a false floor or, in a palletised stow, through the pallets, and exhausted out through the headspace. Sharp and Irving (1991b) referred to a design of P&O purpose built Fantainer which had a perforated bottom rail at the rear of the container as an air entry point, and a fan mounted high in the left hand door as the air exit point. Air is distributed beneath the stow by pallets or a slatted wooden floor.

### 2.2.1.4 *Temporarily modified containers*

Ventilation by temporary modification to standard freight containers has become a popular option, consequently many different designs have evolved. Sharp and Irving (1991b) stated that, with a supply of old freight containers shipping companies were prepared to cut openings in standard containers for fans and vents. After the voyage the containers were sold, or more usually, the fan and floor were removed, the openings repaired, and the containers returned to general duty. The authors also referred to these modified units as Fantainers and mentioned three popular designs:

*Side-inlet Fantainers* - Air enters through side vents (usually four each side) located at floor level, is distributed beneath a slatted wooden floor, and exhausted by a fan mounted high in the end wall.

*End-inlet Fantainers* - Air enters through a single vent low in the end wall, is directed to floor level by a bulkhead, and distributed beneath a wooden slatted or palletized floor. The air is exhausted by a fan mounted in the end wall above the inlet vent.

*Porthole containers (Insulated containers)* - Intended for refrigerated cargo carried on ducted-air ships; these containers have also been used as Fantainers. Air enters through a lower porthole, is distributed by a plenum to slotted T-bar floor channels, and exhausted after rising through the stow to a fan mounted in the upper porthole.

Other temporary designs of modified container may feature fan units placed at floor level in the inlet opening, along with various designs of plenum chambers and false floors. Container doors may be temporarily replaced with false doors for housing fans and vents, thus preventing damage or modification to the original doors.

### 2.2.2 Container Performance

Evaluating the performance of containers designed for transporting agricultural product has involved studying air circulation in ambient air ventilated containers; analysing air circulation, overall refrigeration capacity, and controllability in refrigerated containers (Heap 1989). Most research has focused on the later because of the widespread use of these units, and significance for transporting perishable products of high value. The performance of a container with respect to the interests of this study would be sufficiently judged by, internal air circulation, and air or product temperature distribution.

### 2.2.2.1 *Internal air circulation*

Where respiring product is stowed tightly air circulation caused by reductions in air density, being a factor of the heat of product respiration, would be negligible. Under forced high ventilation regimes of about 0.4 $m^3.s^{-1}$ typically found with containers stowed with onions (Sharp and Irving 1991b) displacement of such volumes would dominate air circulation. Thus, forced ventilation can be considered responsible for air volume displacement and distribution within containers.

The pattern of airflow inside a container is governed by the design of the container and ventilation system, and by the method the stow is packed or configured. Published material on airflow distribution in ambient air ventilated and refrigerated containers is scarce, particularly quantitative data on the influence of the stowage on the distribution of airflow.

Risse (1986) reported on two trial shipments of tomato transplants which where conducted in refrigerated trailers during each of 1985 and 1986. One trailer was equipped with conventionally over-the-load air delivery system and the second trailer under-the-load air delivery system; the later being more conventional with modern refrigerated containers for ocean shipment (Lenker et al. 1985). Transit time was approximately 45 hours. Results indicated that the under-the-load air distribution system cooled the load more efficiently and maintained more uniform transit temperatures. The author mainly attributed this finding to the fact that the delivery air was pressurized under the floor channels or T-bar; a consequence of the end floor channels being plugged and the stow completely covering the floor space. The pressurized air was forced uniformly up through the load to the free air negative pressure space above the load.

Heap (1989) remarked that in refrigerated containers airflow across the width of the container was measured by checking velocity in each channel of the T-bar floor. Variations across the channels of ±20-30% were reported as being typical.

Sharp and Irving (1991b) studied air distribution in Side-inlet and End-inlet Fantainers, Porthole containers, and purpose built P&O Fantainers. They examined airflow in each type of container when packed with onions in 20 or 25 kg fibre woven bags, or when stowed loose in the container behind a bulkhead positioned near the door. They commented that onion sweating, caused by the dewpoint of the ambient air rising above the temperature of the product, produced an environment conducive to the development of Penicillium and other organisms. It was therefore important that ventilation rates were high, particularly when the product travelled through tropical regions. Equally important was uniform air distribution within the containers. The authors found that air resistance through bagged onions was more than double that of the loose bulk stowed onions. Uniform air distribution in Side-inlet Fantainers was obtained when vents were equally positioned along both sides of the container; End-inlet Fantainers distributed air uniformly; fan end of the stow in Porthole containers was ventilated at twice the rate of the door end; and P&O Fantainers distributed air uniformly with a palletised stow, but in a loose bulk stow the first fifth of the cargo was less well ventilated.

Nordtvedt (1993) observed deficiencies of air circulation inside refrigerated trailers used by Norwegian fish exporters. The research assessed a very tightly stacked consignment of boxed frozen fish which was in transit for 96 hours. The effect of poor air circulation resulted in relatively large fluctuations in fish temperature between floor and ceiling, and front and rear of the unit. A computer programme was utilized to simulate air distribution for different product loading alternatives. The conclusions of the simulations revealed that a significantly improved air velocity profile in the hold resulted as a consequence of minor modifications to the product stack configuration. The research did not evaluate air circulation within the stow as air spaces between boxes of fish were essentially non existent. The simulations altered dimensions of the air spaces between the perimeters of the product and the trailer's walls, creating a more uniform curtain of cold air to protect the stow. Nevertheless, the research demonstrated the importance of good air circulation.

### 2.2.2.2 *Internal temperature distribution*

An important approach in evaluating one component of container performance has been to survey temperature distribution throughout the unit. For units ventilated with ambient air, the only cause of a temperature differential between the internal and external environment, under steady state conditions, is heat released by the stow. Assuming the respiration rate is uniform throughout a stow, air circulation must be responsible for the respiratory heat distribution. Heap (1989) stated that for refrigerated units other factors are also responsible for temperature distribution:

*Ambient temperature* - The higher the difference between ambient temperature and cargo temperature, the greater the heat flow through the container walls. Hence, under steady state conditions cargo nearer the walls would be expected to have a higher temperature.

*Air circulation rate* - All other factors being equal, the range of temperature in a cargo under refrigeration will be inversely proportional to the air circulation rate, once steady conditions have become established. Hence, for a narrower range of product temperatures a higher circulation rate is required.

*Refrigeration control system* - Short term air temperature changes exist due to the refrigeration system modulating. This factor would have less of an effect on product temperature distribution as the thermal capacity of the cargo would act as a buffer.

*Loading temperature* - Refrigerated containers are not designed to cool down produce, but to hold temperatures at a steady level. If produce is loaded above the carriage temperature, there will be an increase in the temperature range for a period of time whilst the stow cools. Additionally, if respiratory heat released from the produce is high, combined with poor product packing and configuration, desired carriage temperature for the cargo may not be attained.

Temperature differentials inside containers are necessary if respiratory heat and heat conducted through the unit's walls is to be removed. Narrow temperature ranges are sometimes important when circumstances such as cold treatment sterilization of fruits in transit is required. Therefore, airflow distribution and the other above mentioned factors are important considerations under such requirements.

Product temperature in 12 metre long refrigerated trailers equipped with under-the-load air delivery systems, stowed with tomato seedlings, were found by Risse (1986) to vary in separate trials by up to 4°C and 2°C at the end of a 45 hour journey. The warmer stow was detected in the higher regions of the trailer.

Irving (1988) noted that product temperature distribution in refrigerated units was more variable then the difference between the delivery and return air. This was attributed to airflow not being distributed in proportion to the amount of heat it had to absorb.

Heap (1989) reported that in an experiment conducted on a refrigerated container packed with chilled cartoned meat in an ambient temperature of 15°C, temperature distribution vertically varied by 0.6°C at the front and by 1.0°C at the rear end of the container, and the front to rear gradient was about 1.0°C. The difference between delivery and return air temperature was 0.8°C and the range of cargo temperature was 1.9°C.

Heap and Pryor (1993) illustrated a number of examples where product, both perishable and semi-perishable, were transported in refrigerated and standard containers by ocean shipment. Temperature variation appeared more dramatic within standard containers with thermal differentials as high as 10°C. Temperature differentials within refrigerated vessels appeared to be about 2°C or less, with the headspace sustaining the higher temperatures. It was also commented by the authors that when stowing fruit and vegetables in transport containers with a typical air circulation rate of 90 air changes per hour, every 1000 W of respiratory heat will add about 1.1°C to the temperature increase across the cargo. Heats of respiration at 0°C

vary from 3 W.tonne$^{-1}$ for grapes to 60 W.tonne$^{-1}$ for asparagus; nominal loads of 10 tonnes could amount to an increase in temperature of up to 0.7°C. Respiratory heat production increases rapidly when fruit is stored at warmer temperatures.

Part of an investigation by Irving and Sharp (1993) revealed from chilled cartoned meat stored in refrigerated containers, that the distribution of product temperature increased from 2°C to 3°C as ambient temperature increased from 20°C to 40°C. It was also stated, as is generally the case with refrigerated containers, that under steady state conditions a relatively consistent temperature gradient existed between the front and rear of the container, and top and bottom. Warmer product was monitored nearer the front or doors of the unit, and closer to the ceiling.

## 2.3 MATHEMATICAL MODELS OF TRANSPORT CONTAINERS

Although research focusing on measured performance (air circulation and temperature distribution) of fan ventilated containers is scarce, work directed at modelling these parameters, as anticipated, was found to be more limited. This is also largely applicable to refrigerated and insulated containers, although because of their ubiquitous presence world-wide some details of such studies would be expected with these vessels. The extent to which the performance of refrigerated transport containers and other refrigerated facilities have been modelled is unclear, as much work carried out in this field by industrial research organisations is not communicated through public papers (Touber 1984).

Models can be conveniently illustrated with respect to the time domain.

### 2.3.1 Steady State Models

Meffert and Van Beek (1983) developed a model for predicting air distribution in transport containers. Air circulation was considered only to occur through pre-determined pathways; circulation through the product was ignored. The air

circulatory pathways were expressed as a network of connections in parallel and in series with the stow an object of resistance. The model was solved using an electrical resistance analogy, and was revealed to be in general agreement with measured data given by Irving and Sharp (1976).

A model predicting air circulation and temperature distribution within refrigerated containers was reported by Meffert and Van Beek (1988). The component of the simulation estimating air circulation was based on their earlier model (Meffert and Van Beek 1983). Output from the simulation detailed airflow per channel, final air temperatures at the end of channels, and mixing temperatures where channels joined. Validation of the predicted temperature distribution by measured data was not reported.

Heap (1989) presented a simple mathematical model for predicting temperature rise in 6 m long refrigerated containers. The model was designed for non-respiring product as provisions for metabolic heat release was not made; heat conducted through the container walls was the only thermal source accounted for. The model was based on the concept that if heat input to a given flow of air is known, the temperature rise can be calculated from the flow rate, specific heat capacity, and density. Input variables for the model were: container heat leakage; ambient temperature; air delivery temperature; and air circulation rate (changes per hour). Output estimated the delivery/return air temperature difference. Measured temperatures collated from 21 separate trials on cargoes of cheese, butter, lamb, and a respiring cargo of apples, showed reasonable agreement with predicted temperatures. Cargo temperatures were also measured in each trial but these deviated dramatically from predicted values by approximately twice the delivery/return air temperature range. The author attributed this circumstance to the effects of increased heating at the edges and corners of the stow and to non-uniformities in airflow. Further results from tests on empty refrigerated containers at a number of ambient and internal temperatures have shown the delivery/return air temperature variation to be consistently predictable to within ±0.5°C, as long as air delivery temperature is an average over a representative number of locations.

### 2.3.2 Dynamic Models

Few comprehensive dynamic models of product transport units or storage facilities have been developed. Amos (1994) commented that most dynamic models of refrigerated facilities have concentrated on the refrigeration system, not the application. The majority of dynamic models have simulated conditions within freezer and chilled storage rooms (Marshall and James 1975; Szczechowiak and Rainczak 1987; Wang and Touber 1988), and have typically been specific to their application making their utility somewhat limited. Some packages have been developed for more general use and are applicable to a wider array of refrigerated facilities (Cleland 1983; Amos 1994).

Van de Ree et al. (1974) illustrated a dynamic model of a refrigerated container utilizing the finite element method through a computer programme termed BERTEM. The programme simulated the transients of air temperature, and revealed that the rate of air circulation and stacking pattern of the stow significantly affected temperature distribution throughout the vessel. The author noted that the programme was highly universal in scope and can be applied to those areas where the transport of heat plays a role, but was particularly suited to calculating temperature distributions in stacks of products. Extensive input data and computational time was required to run the simulation. Verification of the model by measured data from experimentation was not reported.

## 2.4 PRODUCT HEAT AND MASS TRANSFER

When modelling stored product it is often of interest to acquire knowledge of rates of heat and mass (water vapour) transfer across the surface of the product. Important factors to consider when investigating transients of heat from product are the effects of convective heat transfer with the air, conductive heat transfer both within the product and with other surfaces in contact with the product, latent heat transfer through evaporation as a consequence of transpiration, and product metabolic heat

generation. Important components of product mass transfer are water loss through transpiration, and for some products carbon loss via respiration.

### 2.4.1 Modelling Heat Transfer

Cleland (1990) gave a comprehensive summary on studies of heat transfer from products whilst subjected to the cooling process or maintained under cold storage conditions. Models of both single and bulk stacked product were reviewed.

#### 2.4.1.1 *Single product*

Heat transfer models for single products were illustrated, where temperature was predicted with respect to time, or time and position within the product; and for determining the product heat load on the refrigeration system. Methods for predicting transient heat were classified according to their solution procedure of which 3 operations were noted (Cleland 1990):

*Analytical solution* - Exact solutions are possible for various simple regular shapes. This requires that the object obey the following conditions:

- Be composed of homogeneous material.
- Maintain constant thermal properties.
- Internal and external heat transfer by the respective conductive and convective processes only.
- No internal heat generation.
- Uniform initial conditions.

In addition to the above requirements, constant external conditions must prevail. Where one or more of these requirements is not met then approximate analytical techniques can be used. In such cases average values must be used as approximations with a consequential introduction of errors.

*Empirical solution* - For irregular shapes and for thermal factors other then conduction and convection occurring, a common approach for modelling heat transfer has been to adopt methods of empiricism. Analysis of product thermal conditions derived from experimental results can be extended to analytically derived models from which simplifying assumptions have been made. The temperature status at specific locations, typically the slowest cooling position in the body and the thermal mass average position, are usually predicted.

*Numerical solution* - Techniques of this nature such as finite difference and finite element methods are useful for solving problems of heat conduction where conditions stipulated for analytical solutions do not hold. They are particularly applicable to irregular shapes; the finite element method can be applied to shapes lacking any kind of symmetry. Differential forms of analytical formulae can also be solved with numerical integration.

### 2.4.1.2   Bulk stacked product

Commercial products in storage are usually bulk stacked. They can be stored as separated units which are individually packaged, or as multiple units specifically positioned in a single package, and in both instances the packages themselves are configured into a bulk stack. The product can also be treated as a non-packaged or loosely packaged agglomerate usually contained within a relatively large volume which is referred to by some as a "bed" or "porous bed". The later is more common with low value robust product where intensive packaging is not economically feasible or required for protection. Heat transfer associated with bulk stacked product is of particular relevance to this study.

Models developed by numerous researchers describing heat transfer from products within porous beds have utilized both finite difference and lumped capacitance approaches. The former approach considers a temperature gradient within the product with respect to time, hence requires partial differentiation for solving. The

later considers no temperature gradient within the product (Biot number = 0) with respect to time, hence can be solved using ordinary differential equations.

The beds are divided into layers (or zones) in the direction of the airflow. A volume of air travelling through the bed is treated as a parcel of which its dimension is usually related to the size of the zone. Each air parcel enters the bed and travels from one zone to the next in a plug flow process.

A model developed by Bakker-Arkema and Bickert (1966) utilized a product lumped capacitance approach to predict temperature status of vegetables during cooling. The model was tested against a bulk load of sugarbeets but was found to overestimate product temperature. The authors attributed this circumstance to the model's lack of accounting for evaporative cooling. The effects of respiratory heat generation was also omitted from the model.

Bakker-Arkema et al. (1967) modelled heat and mass transfer in a porous bed of high moisture content cherry pits. The product bed was treated as an infinite slab, hence the temperature gradient was only realized vertically in the direction of the airflow. The individual pits were considered to have a negligible internal temperature gradient, and conductive heat transfer by particle-to-particle contact was considered insignificant. The simulated heat transfer values were tested against experimentally measured values and showed good agreement.

Yavuzkurt et al. (1976) detailed a product lumped capacitance model in a porous body of apples within sealed zones (no ventilation). Vertical temperature variation across the zone was solved by the explicit finite difference method. The product temperature at every point in the zone was considered to be equal to the temperature of the air in the same region. Both respiratory and evaporative processes were considered in the model. The simulation was tested against a controlled experimental set-up and agreed well with measured data.

Baird and Gaffney (1976) illustrated a model for predicting heat transfer in bulk loads of fruits and vegetables. Temperature gradients within the products were acknowledged and modelled using the finite difference method. Important assumptions reported by the authors were that no conduction heat transfer occurred between products, and no mass transfer occurred between product and air. The model was tested against a bed of oranges undergoing forced cooling. The numerically derived predictions agreed well with the experimentally measured temperatures.

An investigation of the thermal conditions within a bed of sugarbeets was conducted by Holdredge and Wyse (1982). Experimental tests were performed on a small pile of product that simulated a section of a larger pile. It was subjected to inlet air temperature variations of -5°C to 16°C. Some important observations from the trial revealed that:

- A cooling front passed through the pile.
- Unless the beet was heated or cooled at a rapid rate the temperature variation within the product was small.
- Most combinations of pile and air temperature gave no observable difference between the temperature of the beet and the adjacent air.
- Essentially no temperature variation occurred in any horizontal plane.

The model by Holdredge and Wyse (1982) was developed based on the above observations. The first observation led the authors to conclude that convection was strongly dominant over conduction resulting from product-to-product contact, hence the later was eliminated from the model; second observation implied a product lumped capacitance model was suitable; third observation was the basis for the assumption that the sugarbeet and air temperature differential at the same point in the zone was negligible; last observation indicated the temperature was a function only of vertical position and time. Numerically predicted temperatures were in good agreement with measured temperatures from a commercial sugarbeet pile of typical size.

Ofoli and Burgess (1986) derived relationships for heat and mass transfer from the laws of equilibrium and non-equilibrium in a bed of agricultural products subjected to cooling by forced air convection. The bed was divided into layers and the ventilated air treated as a plug flow. The product was treated thermodynamically as a lumped capacitance with both respiratory and evaporative processes considered. The model yielded predictions of air temperature at various depths in the stack which compared favourably with 2 sources of measured data from beds of potatoes.

Gan and Woods (1989) presented a deep bed model for the cooling of vegetables by a cold air stream, which also incorporated a thin layer description of moisture loss. Energy balances for the air stream and the crop were derived with the later stated in terms of the local mass average temperature. The temperature distribution within the product was described in relation to that which would be expected within a sphere, a shape the authors considered a suitable analogy to a swede (the modelled crop). This was achieved by the finite difference solution of the transient heat conduction equation in spherical coordinates for each layer of the bed. The model was reported to be in good agreement with measured results.

MacKinnon and Bilanski (1992) modelled heat and mass transfer through beds of fruits and vegetables. They stated that the model was particularly suitable for thin leafy vegetables as it assumed there was no temperature gradient within the commodity. A product lumped capacitance model was therefore suitable. The finite difference method was utilized to predict temperature with respect to time and vertical position within the bed. The model was verified against an experimental bed of leaf lettuce.

A model by Marchant et al. (1994) was derived to predict heat and mass transfer within a bed of potatoes. The bed was divided into layers with one-dimensional airflow considered to occur in the form of a plug flow. Air in each zone was treated as homogeneous in composition and described with linear equations. The authors assumed the effects of airflow by natural convection to be negligible under fan ventilation but accountable between intervals of fan operation; that continuous

thermal equilibrium existed between crop and air; and heat transfer between individual crop components was insignificant. The product was treated as a lumped capacitance with the effects of evaporation and respiration considered. The simulation was compared with data acquired from potato stores monitored in 3 locations. Model predictions were evaluated under 2 control regimes; that of a sudden and significant temperature change, either a pulldown or increase in temperature; and steady state conditions. The authors considered the model to be in good agreement with measured data.

### 2.4.2 Modelling Mass Transfer

Transfers of mass from the product to the environment occur by means of product transpiration and respiration. The former consists of weight loss by water depletion due to the process of evaporation as a consequence of a difference between the water vapour pressure of the evaporating surface (immediately beneath the skin) and that of the surrounding air. Gaffney (1978) stated that this moisture loss is directly proportional to the differential (an implicit function of concentration). Sastry (1985) and Woods (1990) reviewed studies by numerous researchers discussing in detail factors affecting this differential, specifically the water vapour pressure at the product surface. Respiration consists of weight loss by carbon depletion due to metabolic processes. Both transpiration and respiration have an effect on product temperature through evaporative cooling and metabolic heat generation, respectively.

Amongst researchers, it has been common to make a number of standard assumptions when modelling mass transfer from stored products:

- Evaporation of moisture has been considered the only cause of weight loss.
- Mass transfer coefficient is dependent only upon properties of the product surface.
- Vapour pressure at the evaporating surface of the product is the saturation vapour pressure of pure water at the same temperature as the surrounding air.

Gaffney et al. (1985) reported that under certain conditions the above assumptions result in some error, and factors which could be important under some conditions were:

- Carbon depletion as a second source of weight loss.
- Air film resistance as it affects the overall mass transfer coefficient.
- Respiratory heat generation and evaporative cooling as these affect the temperature of the evaporating surface.
- Vapour pressure lowering due to dissolved substances.

For a basic model considering only transpiration as responsible for weight reduction, rate of water loss per unit surface area of commodity is the product of the differential between the water vapour pressure at the commodity surface and that of the surrounding air, and the transpiration coefficient specific to the particular commodity.

### 2.4.2.1 *Single product*

Lentz and Rooke (1964) studied rates of moisture loss in various varieties of apples under refrigerated storage conditions. They assumed the vapour pressure of the apples at their surface to be equal to that of water at the same temperature. It was noted that weight loss was not linearly related to vapour pressure difference; transpiration coefficient decreased as the vapour pressure difference increased, a finding supported by the work of Pieniazek (1944). However, the departure from linearity was small, and Lentz and Rooke (1964) attributed this phenomenon to the skin and surface layers of the fruit drying out. They considered this process to be reversible if the drying was not severe. An additional finding from the research determined that air flowfield velocity, within the limits of the test (10 to 33 m.min$^{-1}$), did not affect rate of weight loss appreciably.

Fockens and Meffert (1972) defined a model predicting moisture loss during product cooling. They assumed product surface temperature to correspond with ambient air temperature, and to behave as a free water surface, hence, evaporative cooling,

respiratory heat generation and vapour pressure lowering were neglected. The authors detailed a modified transpiration coefficient which accounted for the effects of variable skin permeability and air flowfield velocity.

Sastry et al. (1978) presented an extensive list of mass transfer coefficients for various fruits and vegetables. The coefficients did not consider the effects of water vapour pressure differentials, water activity, or air flowfield velocity. A simplified model presented by the author did not include factors such as evaporative cooling and water vapour pressure lowering at the commodity surface.

Sastry and Buffington (1983) numerically modelled the transpiration rate of tomatoes, but specified that the model was applicable to any commodity of approximate spherical shape possessing uniform and largely impervious skins (vapour transfer only through pores). Evaporative cooling, respiratory heat, the properties and flow rate of the surrounding air, and dissolved solids inside the product were considered. The authors offered details on quantifying the transpiration coefficient by a description of the relationship between the fraction of fruit surface area covered by pores, skin thickness, and the diffusion coefficient of water vapour in air. Transpiration coefficient was considered to be stable with variable product surface/air vapour pressure differentials, contradicting Fockens and Meffert (1972). However, Sastry and Buffington (1983) acknowledged a variable coefficient but only under high vapour pressure deficits which were considered an unlikely event in storage facilities maintaining perishable products. The model was found to predicted transpiration rates with close agreement to those rates derived experimentally from samples of tomatoes.

Gaffney et al. (1985) modelled weight loss in apples, peaches, and brussels sprouts which are products representing low, medium, and high skin mass transfer coefficients, respectively. The model was based on that given by Chau et al. (1984). Both processes of evaporative cooling and respiratory heat generation were considered to affect product surface skin temperature and hence, produce a differential between product surface temperature and air flow field temperature.

Vapour pressure lowering due to dissolved substances in the commodity was also considered in their model. An important finding from the research revealed that velocity of the air flowfield had a significant effect on moisture transfer if the product had a relatively high skin transfer coefficient.

Equations presented by Chau et al. (1988a) were utilized for predicting transpiration rates of fruits and vegetables having shapes analogous to spheres, cylinders, or slabs. The model was of a steady state formulation that considered internal heat of respiration, the convective and radiative heat transfers at the surface, the evaporative cooling effect and the vapour pressure lowering effect. The authors suggested that it was possible to determine this vapour pressure lowering effect of dissolved substances by measuring the freezing point depression of the product. It was stated that for most horticultural products this effect was quantified at about 0.98 or 0.99.

### 2.4.2.2  Bulk stacked product

A study to predict heat and mass transfer in a porous bed of potatoes was performed by Ofoli and Burgess (1986) as stated under section 2.4.1.2, and briefly detailed with respect to the heat transfer component. Mass transfer rate, and the status of the moisture content in the ventilated air stream and in the product were predicted with respect to time and vertical position within the bed. The procedure required that the skin transfer coefficient used in the mass loss equation be determined from experimental data. Simulations agreed well with weight loss data recorded from 2 sources of product each under 2 different environmental conditions. The authors used only one skin transfer coefficient in their research which was found suitable for the simulation for both sources of crop. They suggested it might only be necessary to determine one coefficient for a class of agricultural product (i.e. potatoes) rather than for each different storage situation of the same product.

Romero and Chau (1987) developed a simulation for predicting transpiration from Valencia oranges in bulk storage. The fruit was contained in boxes which were configured onto a pallet to allow the presence of slots to facilitate heat and moisture

removal. Important effects considered for the simulation included evaporative cooling, respiratory heat generation, water vapour transfer through the air and from the bulk by diffusion and natural convection currents only, and carbon loss as a source of weight loss. The stack was divided into horizontal zones or layers with the air properties in each zone treated as a homogeneous element. Energy and mass balances were derived for each zone. The numerical predictions compared well with experimental data for the transpiration rates and moisture removal from a bulk store of oranges.

## 2.5 PHYSIOLOGY OF ONION BULB STORAGE

During storage the onion bulb is in a state of rest or dormancy. Distinction between the definitions of rest and dormancy, and if or when one subdues or succeeds to the other, is conflicting in the literature (Komochi 1990). In either eventuality the bulb is subjected to a state of growth inhibition. Rest or dormancy results from environmental conditions which are not conducive to observable growth, and in the other instance, environmental conditions which are suitable for observable growth but the bulb response is arrested due to endogenous inhibitors. During these periods important physiological processes of particular interest to this study continue.

### 2.5.1 Product Respiration

Respiration, being one such continuous process involves the oxidation of compounds to $CO_2$ and the reduction of absorbed $O_2$ to $H_2O$. Some respiratory substrates include starch, fructans, sucrose and other sugars, fats, organic acids, and under some conditions proteins. The process is a series of 50 or more component reactions but is often expressed as a summary equation for the common respiration of glucose (Salisbury and Ross 1992):

$$C_6 H_{12} O_6 + 6 O_2 \rightarrow 6 CO_2 + 6 H_2O + \text{energy} \tag{2.1}$$

28
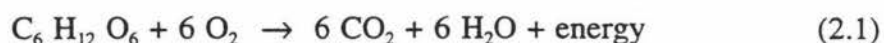
Respiration is necessary in order to generate energy to maintain the living status of the product. Most of the energy is eventually converted into heat, approximately 2870 kJ.mol$^{-1}$ of glucose, and dissipated to the environment. Glucose depletion and the heat of respiration are important respiratory processes that need consideration when modelling weight loss and temperature of stored product.

### 2.5.1.1 *Carbon weight loss*

For a stored product it is revealed from equation 2.1 that carbohydrate is oxidised to $CO_2$ and the net weight loss from the reaction is the carbon component. The by-product of $H_2O$ observed in equation 2.1 is considered to remain within the product thereby not contributing to weight loss (Gaffney et al. 1985). The authors stated that the rate of carbon depletion was directly proportional to the respiration rate which is a function of product temperature. Carbon loss is usually an insignificant portion of total product weight loss, and was reported not to be affected by relative humidity. Consequently, under humid environments when transpiration rates are low, and depending on temperature, the carbon weight loss component can become significant.

Ward (1976) determined weight loss in onion bulbs by $CO_2$ evolution assuming the substrate depletion to be that of glucose and the $H_2O$ produced by the reduction reaction to remain in the tissues. Every 1 g of $CO_2$ evolved resulted in a net loss of weight of 0.273 g of dry bulb material.

### 2.5.1.2 *Effect of temperature on respiration*

Robinson et al. (1975), Ward and Tucker (1976), Komochi (1990), and Brewster (1994) reported that the respiration rate of onion bulbs is remarkably low when compared to other vegetables. In an environment of 10°C the respiration rate of carrot roots, parsnip roots and cauliflower heads were about four times greater than onion bulbs. It has been well documented that the respiration rate in horticultural products generally increases when exposed to higher temperatures. Thompson et al. (1972) and Robinson et al. (1975) noted that the respiration rate of onion bulbs

increased more slowly as temperature increased when compared to most other stored products.

Ogata (1952) researched the change in respiration rate of bulbs at a number of low temperatures from harvest to sprouting. After drying of the foliage leaves the release of $CO_2$ remained at a constant and low level for a certain period of time then slowly increased. The author suggested that this corresponded to the entry, experience, and exit of the rest phase. Similarly, Van den Berg and Lentz (1972) Ward and Tucker (1976) expressed that the respiration rate was directly controlled by the depth of dormancy.

Ward and Tucker (1976) studied respiration rates of a popular cultivar of onion grown in the United Kingdom. Respiration rates of maleic hydrazide (sprouting suppressant) treated and untreated bulbs were compared. In both samples little change in respiration rate was observed for the first 5 to 6 months of storage when exposed to environments of 3, 8, and 15°C. $CO_2$ output from the bulbs increased significantly after this period, but less so from the treated sample. The authors commented that it was well established that rates of respiration increased approximately exponentially with temperature rise in the region 0-30°C, referring to the work of Platenius (1942). However, they stated that a 15°C range of temperatures used in their study revealed a small increase in respiration rate, with both an exponential relationship and a linear regression fitting their data equally well.

Ward (1976) and Tanaka et al. (1985) took continuous measurements of bulb respiration rates when stored at temperatures between 0 and 25°C. At lower temperatures $CO_2$ evolution was low and stable for 5 months or longer. At higher temperatures respiration was relatively stable for 2 or 3 months then increased with time.

Salama and Hicks (1987) studied the effect that maleic hydrazide had on the respiratory quotient of stored onion bulbs. No effect on $CO_2$ evolution at low temperatures was evident although a minor effect at higher temperatures was noticed.

However, an important finding from their research revealed that for bulbs stored at 0 and 15°C no change in the respiration rate with time was observed through the entire storage period of 5 months. At 30°C $CO_2$ production was stable for 7 weeks but increased thereafter.

## 2.5.2  Product Transpiration

Transpiration from stored product, an important physiological and largely continuous process, involves the evaporation of water from the product to the environment. It is governed by the differential between product water vapour pressure and that of the atmosphere beyond the boundary layer. The resistance to transpiration is that of the boundary layer (Gaffney et al. 1985). As referred to under section 2.4.2, manuscripts have detailed factors affecting product water vapour pressure, such as product water activity and solutes concentration (Sastry 1985; Woods 1990).

### 2.5.2.1  *Moisture weight loss*

Rate of transpiration of water from bulbs can be relatively variable but is usually the major factor responsible for product weight loss (Apeland 1971; Komochi 1990).

Woodman and Barnell (1937) examined water loss in 8 cultivars of onion and discovered that long storage type cultivars transpired less than in other types throughout the storage period. They noted that the rates of water loss were highest immediately after harvest and thereafter tended to stabilize at lower levels as a consequence of the outer scales drying and thereby offering resistance to water vapour transfer.

Apeland (1971) asserted that the loss of skins led to a doubling of weight loss by bulbs due to enhanced desiccation. Similarly, Karmarkar and Joshi (1941) also noted a role of the skin in protection against moisture weight loss.

Rajapakse et al. (1992) researched weight loss in 10 cultivars of onion. The authors considered net weight loss of onion lots which included losses through water depletion, disease infection, and sprouting. Bulbs that had sprouted and or suffered symptoms of disease were removed which accounted for about 50% of the net weight loss. Water depletion was held accountable for the remainder of the loss.

### 2.5.2.2 *Effect of relative humidity and temperature on weight loss*

General product weight loss, as affected by water and carbon depletion, was discussed under the parent section 2.5.2 (product transpiration) due to the significance of the product water loss component. Much literature referring to general weight loss in onion bulbs has typically attributed those losses only to water depletion, dismissing the effects of respiratory carbon weight loss (Apeland 1971; Stow 1975; Rajapakse et al. 1992; Mikitzel and Fellman 1994).

Thompson et al. (1972) reviewed work relating to bulb weight loss when affected by variable relative humidity (RH). They stated that loss of weight decreased with increasing RH but at over 80% RH the rate of weight loss showed a marked reduction. A component of the research from Stow (1975) demonstrated weight loss through desiccation for 2 cultivars of onion bulb when stored at 30°C and 35, 50, 60, and 70% RH. During the first 3 months of storage the highest rate of desiccation occurred at the lowest humidity, thereafter no trend of decreasing weight loss with increasing humidity was evident.

Apeland (1971), Mikitzel and Fellman (1994), and Wall and Corgan (1994) determined that at constant RH weight loss was linear over time. Apeland (1971) commented that the rate of weight loss increased at the onset of sprouting. Van den Berg and Lentz (1972) and (1973) reported that the rate of weight loss during the curing process directly after harvest was considerably greater then during the following storage period. Curing in circulating air at 20°C and 50-70% RH for 1 week incurred a weight loss of 5-7%.

Many researchers have studied the effects of temperature and RH regimes on weight loss from onion bulbs over various storage periods. Generally, it has been realized that the effects of these environmental factors have been extremely significant as illustrated in Table 2.1. It has also been noted that weight loss varied significantly between cultivars stored under the same environmental regime (Rajapakse et al. 1992).

## Table 2.1

Percentage weight loss from onion bulbs during storage under various environmental regimes.

| Source | Temp (°C) | RH (%) | Storage Length (Months) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
| Karmarkar & Joshi (1941)[2] | 0 | NS | 1.1 | | | | | | | | 17 |
| | 31-35 | NS | 5.1 | | | | | | | | 38 |
| Van den Berg & Lentz (1972)[2] | 0-1.1 | 100 | | | 1.5 | | | | | | |
| Van den Berg & Lentz (1973)[2] | 0-5 | 75-80 | | | | | | | 5.6 | | |
| Stow (1975)[2] | 30 | 35-70 | | | | | 14 | | | | |
| Ward (1976)[2] | 2 | 70 | | | | | | | | | 8.2 |
| | 7.5 | 70 | | | | | | | | | 8.1 |
| | 15 | 70 | | | | | | | | | 13 |
| | 25 | 70 | | | | | | | | | 16 |
| Toledo et al. (1984)[2] | 1 | 80-90 | | | | 1.2 | | | | | |
| Tucker & Morris (1984)[2] | 5 | 80 | | | | | 4.0 | | | | |
| Hurst et al. (1985)[2] | 1 | 65-75 | | | | | | 8.0 | | | |
| | 4 | 65-75 | | | | | | 11 | | | |
| | 21 | 65-75 | | | | | | 17 | | | |
| Salama & Hicks (1987)[1] | 0 | 40 | | | | | 3.0 | | | | |
| | 15 | 40 | | | | | 7.5 | | | | |
| | 30 | 40 | | | | | 30 | | | | |
| | 0 | 60 | | | | | 2.5 | | | | |
| | 15 | 60 | | | | | 6.0 | | | | |
| | 30 | 60 | | | | | 24 | | | | |
| Pike et al. (1989)[1] | 1 | NS | 1.0 | | | | | | | | |
| | 15 | NS | 1.5 | | | | | | | | |
| | 24 | NS | 1.8 | | | | | | | | |
| Rajapakse et al. (1992)[1] | 26 | 60 | 5.7 | | 22 | | | | | | |

| Mikitzel & Fellman (1994)[2] | 22 | 35-40 | 3 | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Wall & Corgan (1994)[2] | 15-34 | 10-76 | 15 | | | | | | | |

1 = Ventilation applied to bulbs during storage
2 = Ventilation not applied to bulbs during storage, or ventilation not stated
NS = Not stated

# CHAPTER 3

# RESEARCH OBJECTIVES

## 3.1 JUSTIFICATION OF THE RESEARCH

An extensive literature search failed to reveal any published material pertaining to methods of predicting temperature distribution of and weight loss from onion bulbs when stored in intermodal transport containers. Justification for such research can be attributed to the need to maintain and provide for export markets optimum quality onion bulbs, which when subjected to high temperature and moisture depletion can suffer from decreased quality. Knowledge of the crop quality status, by prediction of its condition after prolonged periods of storage in transport vessels, is therefore important. Under hypothetical environmental conditions and under conditions where transport containers vary in their performance (e.g. ventilation rate), as a consequence of the use of non-standard units, a mechanism for predicting crop quality responses would be of considerable value.

## 3.2 OBJECTIVES OF THE RESEARCH

Mathematical models will be developed as a mechanism to predict temperature of and weight loss from onion bulbs when bulk stacked for storage or transit into intermodal transport containers. The models, comprising energy and mass (water vapour) balances for the internal container atmosphere and for the product, will predict heat and mass transfers from the bulbs with respect to time and positional variability. Simulations will be conducted, then compared to measured temperature and weight loss data recorded from a fan ventilated container stowed with onions.

# CHAPTER 4

# MEASURING THE ENVIRONMENTAL
# AND PRODUCT STATUS IN A
# TRANSPORT CONTAINER

Environmental and product data were collected from a stationary transport container stowed with onions located at a commercial property in Opiki, Manawatu. Practical constraints prevented data acquisition additional stationary or transient transport vessels. Determination of various bulb physiological processes not attainable at the site, involving precision measurements taken under controlled conditions, occurred in environmental facilities at Massey University, Palmerston North.

## 4.1 PRODUCT SPECIFICATIONS

Onions (*Allium cepa* L.) of the cultivar 'Pukekohe Long Keeper' were harvested at mid commercial harvest from a property in Opiki, Manawatu, at the end of March 1994. The crop sample selected for the research was of typical export quality which had been graded according to bulb diameter, ranging from 45 mm to 65 mm. They were packaged loose in 20 kg synthetic fibre woven sacks, stacked onto pallets and stored under cover.

Prior to export consignment, 15 tonnes of onions comprising of $750 \times 20$ kg sacks were acquired for the research on August 16, 1994. The onions were bulk stacked into a transport container in a customary manner; each sack's longitudinal dimension orientated in parallel with the longest dimension of the floor, roof, and sides of the

container. The bulbs were returned to the owners at completion of the trial work 13 days later on August 29.

## 4.2   CONTAINER SPECIFICATIONS

The product containment vessel was a standard intermodal freight or transport container. Internal dimensional measurements of the unit were 6 m from front to rear, 2.4 m from top to bottom, and 2.4 m across the width. A pair of doors were positioned at one end and were hinged at the sides closing together to form a seal down the centre of the vessel. The container was positioned on a concrete slab and was orientated with the doors or front facing to the north. The western side of the unit was approximately 1.5 m from a building.

Modifications were made to the container in order to prepare it for the transportation and storage of the bulbs. This involved the fitting of a ventilation system, thus the conversion of the unit into what Sharp and Irving (1991b) termed a Fantainer.

### 4.2.1   False Floor Design

A false floor was utilized as a means of distributing ventilation air below the stow prior to its movement up through the crop. Wooden beams running the width of the vessel were covered with planks running lengthways forming a pallet type arrangement. The planks were separated by approximately 10 mm to create a ventilation gap. Distance between the container floor and false floor was approximately 100 mm. A separation in the false floor was created down the length of the container and was slightly off-centre so as to accommodate the plenum and duct. The perimeters of the false floor were sealed with planks to prevent air escaping up through the corrugated sides of the vessel. This would also act to increase air pressure below the stow thereby aiding uniformity of ventilation (Figure 4.1). Risse (1986) reported such a finding when T-bar floor channels were plugged at the perimeters and the stow completely covered the floor space.

38
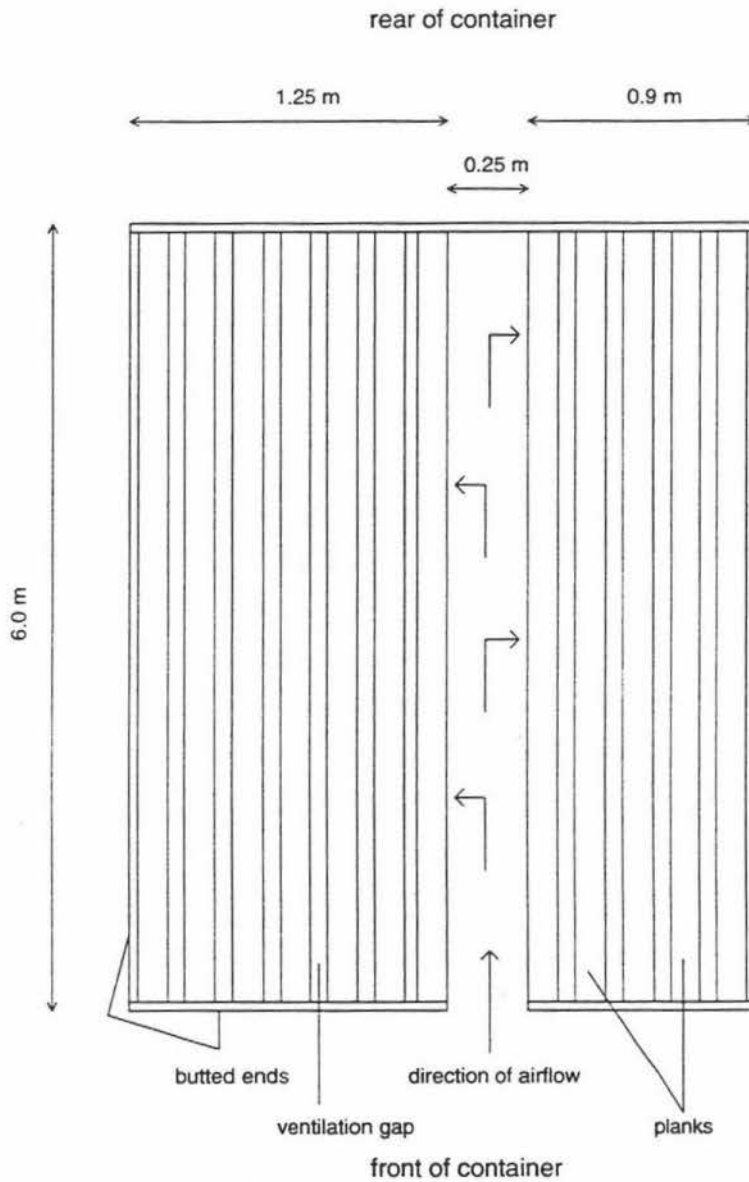


**Figure 4.1**    Plan view of false floor with dimensions given. Sealed perimeters and air delivery channel illustrated. Supporting beams for planks not shown. Not drawn to scale.

### 4.2.2 Plenum and Duct Design

Delivery air from the fan was directed into the 0.2 $m^2$ aperture of the plenum. It was then directed into a duct which was positioned over the 0.25 m wide separation in the false floor that extended to the rear of the container. The duct and plenum had an open base thereby allowing air to escape into the false floor separation vent, then on to be distributed beneath the stow. The roof of the duct was planked with approximately 5 mm separation between planks. Positioned on top of the duct but not extending to the full length of the vessel was a pallet. It was placed on its side to enhance ventilation in the region obstructed by the duct (Figure 4.2).
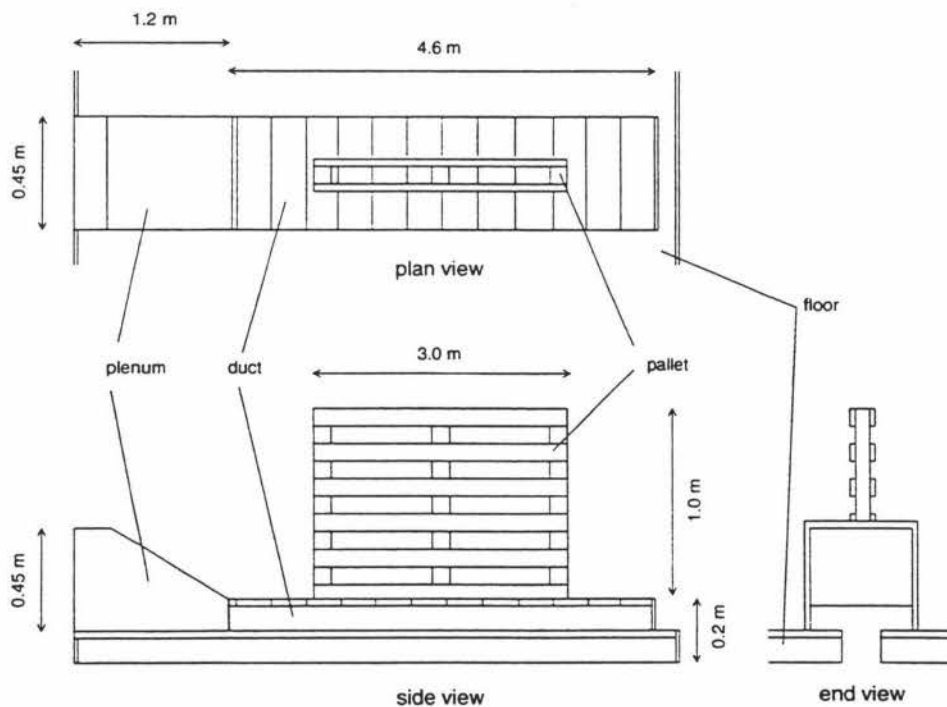


**Figure 4.2**   Views of plenum and duct with dimensional measurements given. Ventilation gaps on the roof of the duct not detailed. Not drawn to scale.
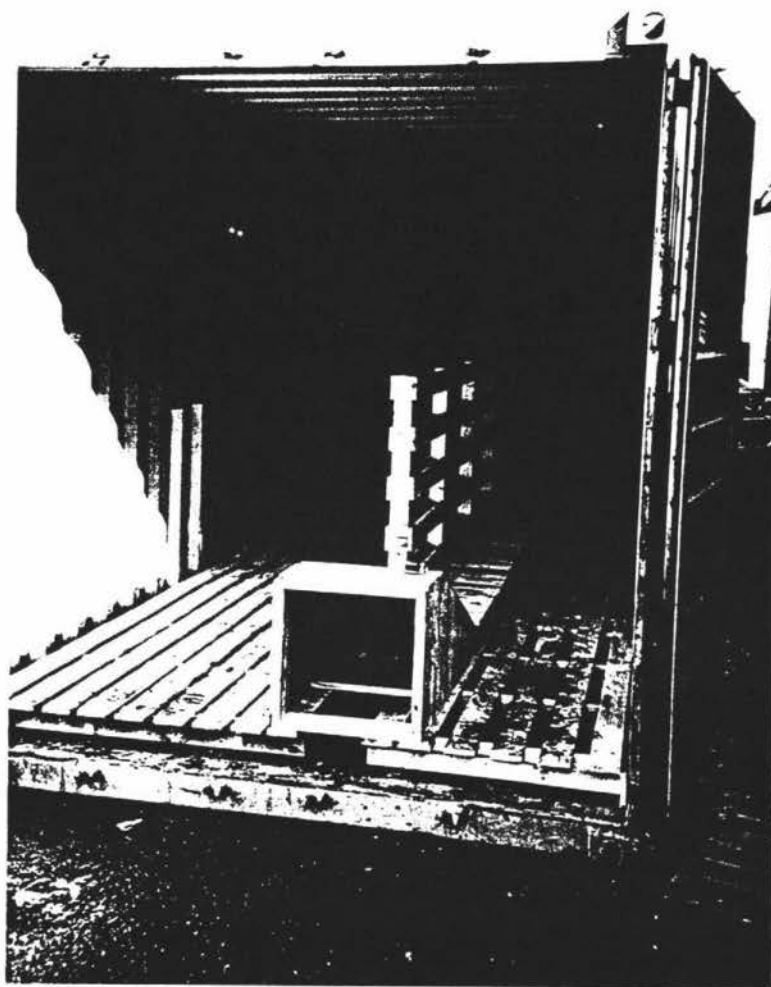
**Figure 4.3**    Plenum, duct, and false floor configuration viewed through open doors of the transport container.

### 4.2.3  False Door Design

Modifications to the container were necessary in order to provide an air inlet port to house the ducted fan unit and to provide for exhaust ports.  Positioning of the plenum, duct, and floor separation vent off the centre line of the vessel by 0.18 m reduced the necessity for alterations to one door only.  To prevent modification and/or damage to the container door a false door of plywood construction was employed which was secured permanently into position after the vessel was loaded. The original right hand side container door was fastened back to the side of the vessel.  The air inlet port was located in the lower left hand side of the door, and the exhaust ports were situated at the top and across the width of the door (Figure 4.4).
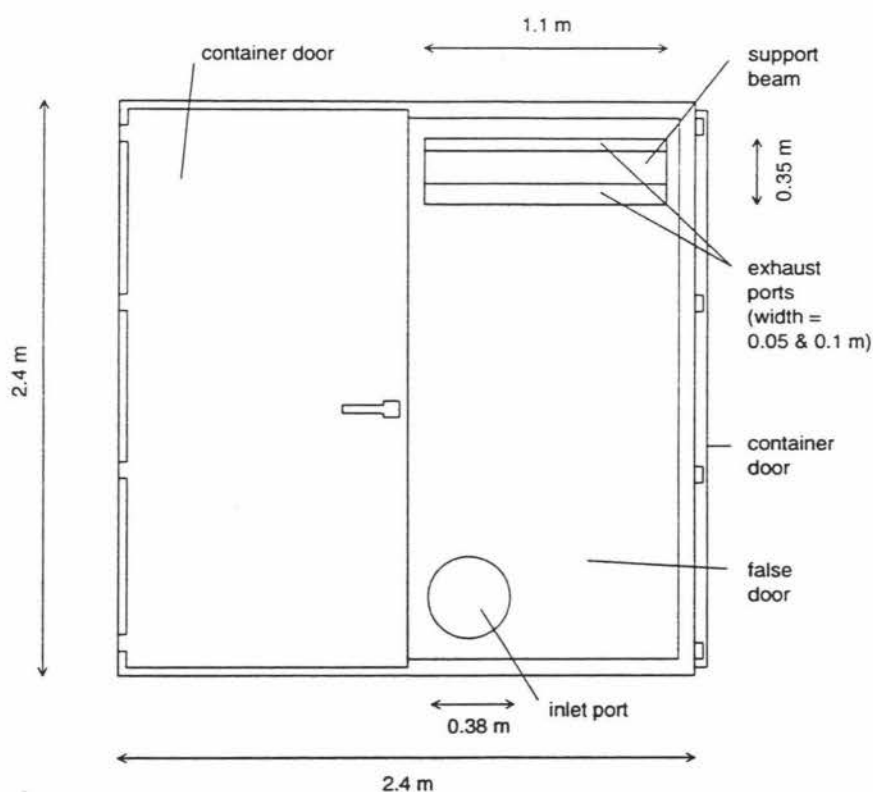


**Figure 4.4**    End view of doors with dimensions given.  Inlet and exhaust ports illustrated.  Not drawn to scale.

### 4.2.4  Fan Unit

Air to the container was delivered by a Hison 105 W axial flow ducted fan mounted into both the inlet port of the false door and the plenum. Flow rate under a steady static pressure was measured at 0.726 $m^3.s^{-1}$ (refer to section 4.3.3.4). Operational time for the fan was continuous.

### 4.3  ENVIRONMENTAL AND PRODUCT MEASUREMENTS

Atmospheric conditions throughout the void space within the onion packed bed were monitored. Similarly, measurements were collected of various bulb parameters at a number of localities. Collection of such information was necessary as a means to evaluate the performance of any derived mathematical model.

Modelling of the crop in the spatial domain, or with respect to its position within the vessel was a major objective of the research. Therefore, positioning of the various probes and sensors throughout the stow was an important consideration if thorough model testing was to occur. It was considered rational that measurements, where possible, should be taken at consistent intervals across the horizontal and vertical planes of the packed onion bed. Constraints associated with the availability of required measuring instruments limited the extent to which the number of locations probes and sensors could be positioned.

### 4.3.1  Measurement Localities

Volume of the packed onion bed including areas containing the plenum, duct, and pallet equated to 32.4 $m^3$. The above ventilation components only contributed 0.15, 0.21, and 0.30 $m^3$, respectively. Volume of the false floor was determined at 1.44 $m^3$, and that of the approximate 50 mm headspace equated to 0.72 $m^3$. The later two ventilation spaces were omitted from the total volume of the packed bed.

To determine measurement localities at consistent intervals for the probes and sensors the total packed bed volume was divided into multiple volumes of equal size, termed zones. The product storage space in the container was separated into 27 zones configured by the division of the length, width, and height of the bed by 3. Dimensional measurements of each zone equated to 2.00, 0.80, and 0.75 m, respectively; volume equalled 1.2 $m^3$. Sensors and probes were positioned at the centre of the zones. Zones were identified by numeration using a cartesian coordinate system with container dimensions represented by $i,j,k$; $i$ are zones across the container, $j$ are zones down the container length, and $k$ are layers within the container (Figure 4.5).

rear of container



front of container
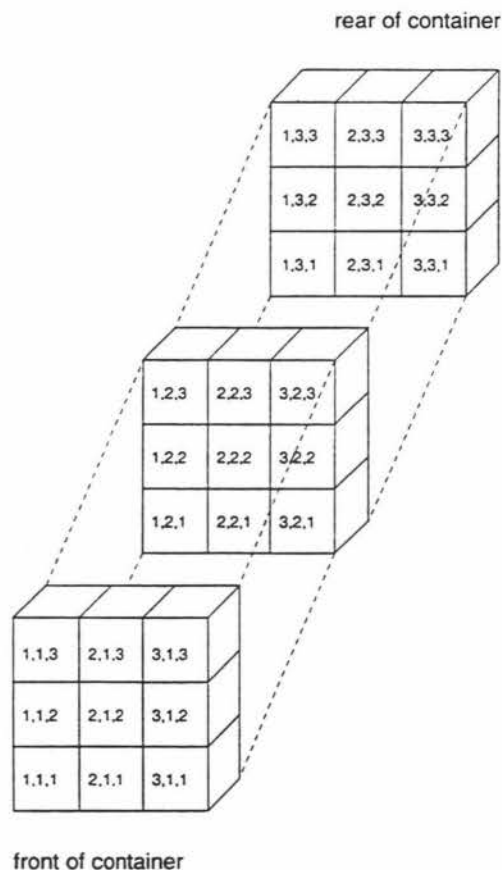
**Figure 4.5** Labelling of onion bed zones throughout the transport container. Viewed with horizontal expansion along the length between adjacent zones.

the false floor, in the headspace, at the inlet and exhaust ports, and at the container walls.

Multiplexers with emanating temperature and relative humidity sensors were buried within the product bed on the boundary of zones 2,2,2 and 2,1,2 (Figure 4.6). The data-logger was positioned outside the vessel.
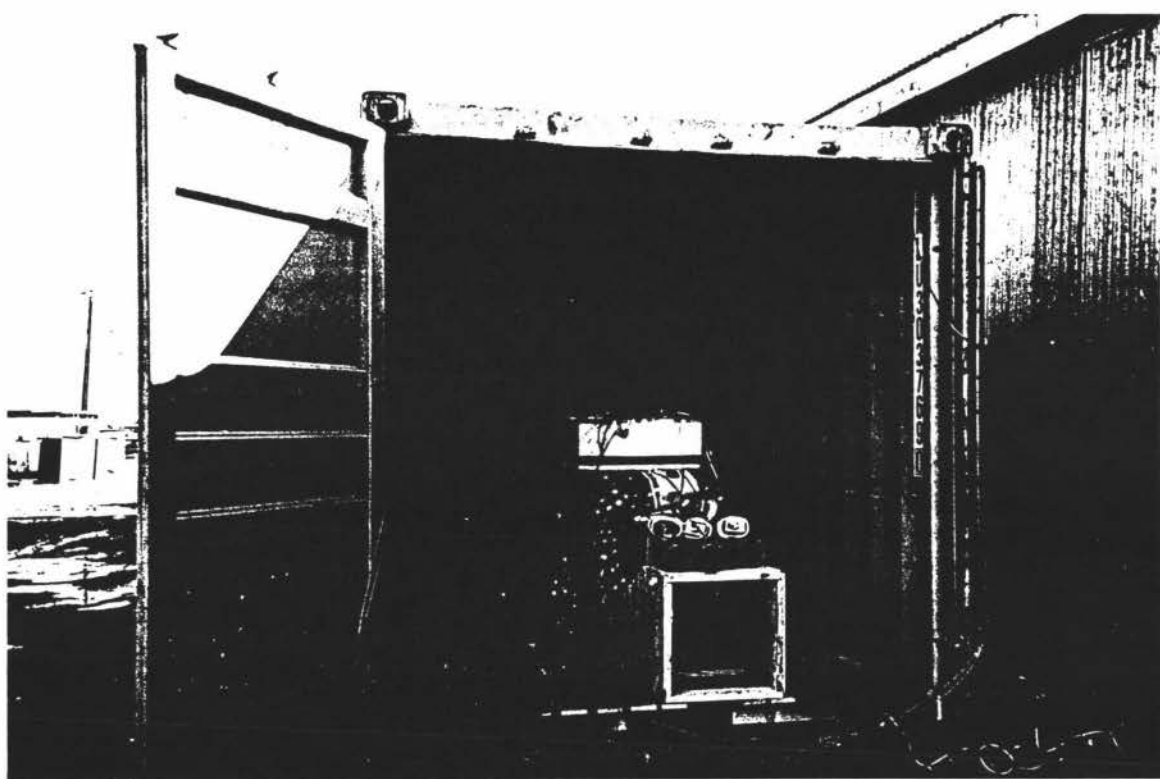


**Figure 4.6** Transport container partially filled with onions. Protective polystyrene housing for multiplexers viewed with probes and sensors emanating.

### 4.3.3.1 *Temperature*

Numerous temperatures were measured throughout all zones of the container of both the product and atmosphere. Additional temperatures were collected of the eastern wall, western wall, and roof of the vessel; and of the ambient conditions just outside the unit, and of the inlet air temperature inside the plenum downwind of the fan.

Centre temperatures and some surface temperatures were collected from a single onion in each zone. This was possible by carefully forcing a thermocouple into the central bulb region whilst ensuring a tight seal remained at the point of insertion. A second thermocouple was located immediately below the outermost moist scale of the same bulb to determine product surface temperature. Air temperature was monitored immediately adjacent to the measured bulb in each zone. Thermocouples were adhered to the specified internal sides of the vessel to establish surface temperature, and to the plenum and exhaust ports to determine air temperature at these locations. Zones monitored for air, bulb centre, and bulb surface temperatures are specified in Table 4.1.

Recording of temperatures commenced at 1200 hours on Julian day 229 (August 17). Temperatures were monitored at 30 second intervals and then averaged over 5 minute periods. The data was then automatically downloaded onto magnetic tape. Monitoring of temperatures ceased at 0800 hours on Julian day 241 (August 29).

### 4.3.3.2 *Relative humidity*

A limited supply of probes enabled only void areas of selected zones to be measured for relative humidity (Table 4.1). Probes were positioned adjacent to the thermocouple sensors in the centre of the selected zones. Probes were also positioned at the inlet and exhaust ports of the container. Logging of relative humidity occurred during the same period and at the same frequency as stated for the temperature measurements.

## Table 4.1

Measurement positions for various parameters monitored throughout the transport container.

| Zones | Temperature (°C) | | | Relative humidity (%) | Weight loss (kg) |
|---|---|---|---|---|---|
| | Air | Bulb centre | Bulb surface | | |
| 1,1,1 | √ | √ | | √ | √ |
| 2,1,1 | √ | √ | | | √ |
| 3,1,1 | √ | √ | | √ | √ |
| 1,2,1 | √ | √ | | | √ |
| 2,2,1 | √ | √ | | | √ |
| 3,2,1 | √ | √ | | | √ |
| 1,3,1 | √ | √ | √ | √ | √ |
| 2,3,1 | √ | √ | | | √ |
| 3,3,1 | √ | √ | √ | √ | √ |
| 1,1,2 | √ | √ | | | √ |
| 2,1,2 | √ | √ | | | √ |
| 3,1,2 | √ | √ | | | √ |
| 1,2,2 | √ | √ | | | √ |
| 2,2,2 | √ | √ | √ | √ | √ |
| 3,2,2 | √ | √ | | | √ |
| 1,3,2 | √ | √ | | | √ |
| 2,3,2 | √ | √ | | | √ |
| 3,3,2 | √ | √ | | | √ |
| 1,1,3 | √ | √ | | √ | √ |
| 2,1,3 | √ | √ | | | √ |
| 3,1,3 | √ | √ | √ | √ | √ |
| 1,2,3 | √ | √ | | | √ |
| 2,2,3 | √ | √ | | | √ |
| 3,2,3 | √ | √ | | | √ |
| 1,3,3 | √ | √ | √ | √ | √ |
| 2,3,3 | √ | √ | | | √ |
| 3,3,3 | √ | √ | √ | √ | √ |
| Inlet port | √ | | | √ | |
| Exhaust port | √ | | | √ | |

√ = Position measured

**4.3.3.3** *Weight loss*

A sack of onions from each zone was weighed as the container was loaded on Julian day 228. Weight loss experienced by the bulbs from each zone was determined by re-weighing the sacks at the completion of the trial on Julian day 241.

**4.3.3.4** *Ventilation rate*

Measurement of air velocities collected at the exhaust ports of the container provided means of determining ventilation rate through the unit. Total air flow rate was calculated by ascertaining air velocity passing through known portions of cross sectional area of each port (Figure 4.7). Ventilation was continuous and remained constant, thus continuous measurement of this parameter was unnecessary. Two samples of measurements (Appendix A1) revealed that the ventilation rate through the container equated $0.726$ $m^3.s^{-1}$.
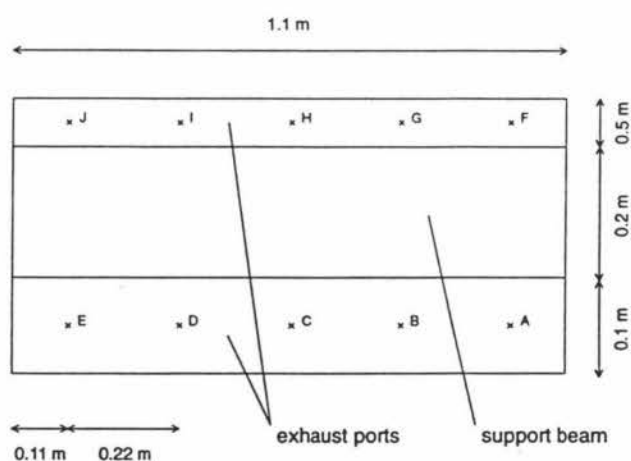


**Figure 4.7** View of exhaust ports with air velocity measurement locations marked with crosses. Not drawn to scale.

### 4.3.3.5 *Air pressure*

Distribution of ventilation air through the product bed was evaluated by measuring air pressure at specific locations. Strips of plastic tubing were positioned with an open end either below or above each zone column with the remaining end extended out an exhaust port. Air pressure could then be determined at these locations after the container was sealed. Measurements were taken on 2 occasions with good agreement between samples. Air pressure was found to be relatively consistent between zone columns with the exception of 1 column which experienced significantly higher pressures (Appendix A2).

# CHAPTER 5

# THERMOPHYSICAL PROPERTIES
# AND PARAMETERS

A precursor to any calculation of heat and mass transfer requires various thermal and physical properties and parameters to be defined. Synthesis of such information is required from both product and flowfield. Thermophysical properties and parameters have been derived from reference material where possible, or obtained specifically for this study through computation or laboratory experimentation.

## 5.1 ONION BULB

For calculation of heat and mass transfer from product to flowfield, thermophysical properties to be determined for the product are specific heat capacity, thermal conductivity, convective heat transfer, convective mass transfer, surface area and volume, and bulb water content. Other parameters to be quantified which influence product heat and mass transfer include respiration rate through its effects of metabolic heat generation and carbon depletion, and transpiration rate through evaporative cooling effects and mass loss by water depletion.

### 5.1.1 Specific Heat Capacity

Specific heat capacity of foodstuffs is related to their moisture content. Rapusas and Driscoll (1995) studied the effect of moisture content on the specific heat capacity of fresh and dried white onion slices. Eight moisture levels ranging from 69.2 to 0%

wet basis were evaluated. Specific heat decreased linearly with decreasing moisture content and was best explained by the following equation:

$$C_{p(on)} = 1.84 + 2.34\,W \qquad (5.1)$$

where:

$C_{p(on)}$ = specific heat capacity of onion $(J.g^{-1}.{}^{\circ}C^{-1})$

W = moisture content of onion (fraction wet basis)

The coefficient of determination $(R^2)$ and standard error of Equation 5.1 was 0.998 and 0.9%, respectively. The authors compared their predicted values with published specific heat data for onions with moisture contents ranging from 80% to 90% weight basis and found that the maximum difference between predicted and published values was 3.0%.

### 5.1.2 Thermal Conductivity

Thermal conductivity of foodstuffs is also related to moisture content. Rapusas and Driscoll (1995) established a strong empirical relationship between these properties for white onion. The correlation was best explained by a linear equation:

$$k = 0.18 + 0.41\,W \qquad (5.2)$$

where:

k = thermal conductivity of onion $(W.m^{-1}.{}^{\circ}C^{-1})$

The $R^2$ and standard error for Equation 5.2 was 0.991 and 2%, respectively. The authors commented that no significant effects of temperature fluctuation ($\pm6^{\circ}C$) and substrate porosity on the effective thermal conductivity were detected.

### 5.1.3  Convective Heat Transfer

The irregular flow that exists in the voids of a packed bed enhances convective heat transfer through turbulent mixing.  Incropera and De Witt (1985) recommended an equation for predicting the convective heat transfer coefficient for a packed bed of spheres in a gaseous flowfield using the Reynolds-Colburn $j$ factor, and Prandtl-Stanton-Colburn $j$ factor correlations:

$$\varepsilon\, j_h = 2.06\ Re^{-0.575} \tag{5.3}$$

$$j_h = St\ Pr^{2/3} \tag{5.4}$$

$$St = \frac{h_c}{\rho\, u_\infty\, C_p} \tag{5.5}$$

$$Pr = \frac{\nu}{\alpha} \tag{5.6}$$

$$Re = \frac{u_\infty\, d}{\nu} \tag{5.7}$$

where:

| | | |
|---|---|---|
| $j_h$ | = | Colburn $j$ factor (dimensionless) |
| St | = | Stanton number "modified Nusselt number" (dimensionless) |
| Pr | = | Prandtl number (dimensionless) |
| Re | = | Reynolds number (dimensionless) |
| $\varepsilon$ | = | volumetric void fraction |
| $C_p$ | = | specific heat capacity of air ($J.g^{-1}.°C^{-1}$) |
| $u_\infty$ | = | upstream velocity ($m.s^{-1}$) |
| d | = | spherical diameter (m) |
| $\nu$ | = | kinematic viscosity ($m^2.s^{-1}$) |
| $h_c$ | = | convective heat transfer coefficient ($W.m^{-2}.°C^{-1}$) |
| $\rho$ | = | flowfield density ($g.m^{-3}$) |
| $\alpha$ | = | thermal diffusivity ($m^2.s^{-1}$) |

### 5.1.4  Surface Area and Volume

Bulb surface area must be defined when calculating heat and water vapour transfer between product and flowfield. Product volume is required to determine the fraction of void space present in the container when stowed with bulbs. With a known ventilation flow rate and void space, average air velocity can be determined.

#### 5.1.4.1  *Experiment introduction*

Given product mass, surface area and volume can be estimated by establishing a correlation between these physical parameters. Various researchers have utilized such relationships for estimating surface area for a number of products with high degrees of correlation attained (Sastry and Buffington 1983; Banks 1985; Clayton et al. 1995). The objective of this component of the research was to predict bulb surface area and volume by relating these parameters to bulb mass.

#### 5.1.4.2  *Method and materials*

Immediately following the collection of data from the containerized onion storage trials a random sample of 25 onion bulbs from the container were selected, and various physical parameters determined. Mass was measured to ±0.01 g using Mettler Model PM6100 scales. Bulb volume was determined by immersing the product in water and weighing the water displaced (Mohsenin 1986), and calculating the appropriate value from the relationship between mass and volume of water. Volume was measured to the nearest 10 mm$^3$.

Actual surface area was estimated by covering each bulb with 0.15 mm thick electrical insulation tape which was then sectioned and removed from the product surface, mounted onto acetate sheet and its area determined using a LI-COR Model LI-3100 area meter to the nearest 1 mm$^2$. Area measurement of actual bulb scale was dismissed due to difficulties associated with the separation and discrimination of underlying scales from the surface scale, and the flattening of dried scales

necessary for area measurement. Accuracy of the tape technique was verified by Clayton et al. (1995).

### 5.1.4.3 *Results and discussion*

Strong correlations were found between surface area and volume with mass. The relationship between product volume and mass was linear and a least squares regression analysis yielded the following linear equation with an $R^2$ of 0.989:

$$V = -1.430 \times 10^{-7} + m\,0.001063 \qquad (5.8)$$

where:

V   =   volume of onion $(m^3)$

m   =   mass of onion (kg)

The relationship between product surface area and mass was non-linear. A least squares regression analysis revealed that the most appropriate equation with an $R^2$ of 0.973 was:

$$A = -0.003753 + 0.04131\,m^{0.4668} \qquad (5.9)$$

where:

A   =   surface area of onion $(m^2)$

Figures 5.1 and 5.2 illustrate the correlations between volume and surface area with mass, and show fitted regression Equations 5.8 and 5.9, respectively.
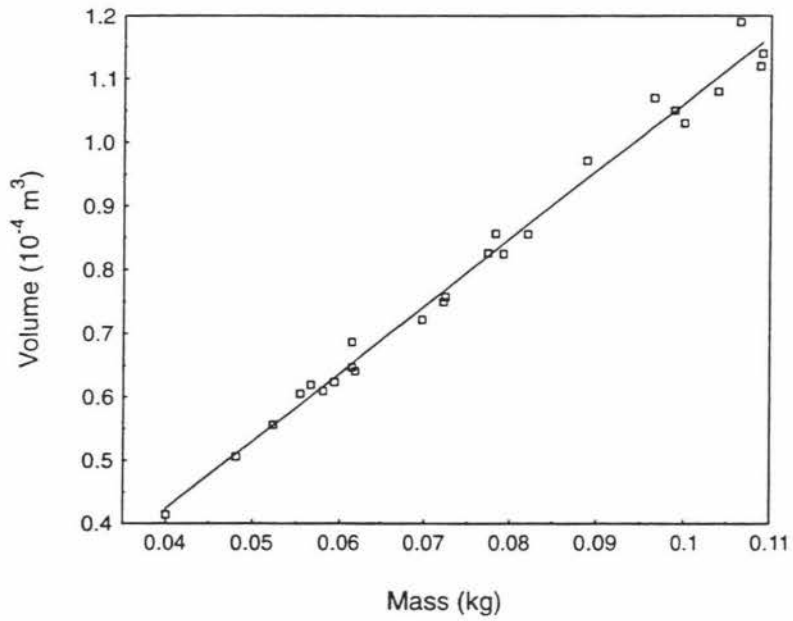
**Figure 5.1**    Relationship between volume and mass of onion bulbs.
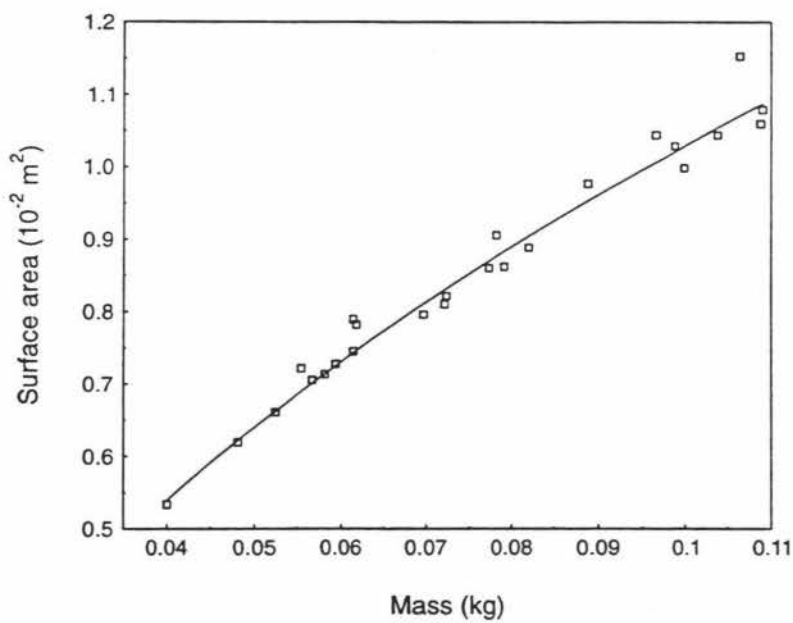


**Figure 5.2**    Relationship between surface area and mass of onion bulbs.

The non-linear relationship of surface area with mass of onions was consistent with findings of Sastry and Buffington (1983) with tomatoes, Banks (1985) with potatoes, and Clayton et al. (1995) with apples. Distribution about the correlation of volume with mass demonstrates the degree of variability of onion bulb density and/or bulb shape.

### 5.1.5  Respiration

The process of respiratory heat generation required quantification in order to establish its effects on increasing bulb temperature. Dissipation of such heat can occur directly to the environment, or indirectly through latent means by evaporation of product moisture. Oxidation of carbon compounds also required quantification as this contributes to bulb weight loss; although usually a minor contributor for most products it may be significant under some environmental conditions.

Literature pertaining to the respiration of onion bulbs mainly discussed trends and general responses of this parameter to environment conditions. The scarcity of detailed information on white onion bulb respiration strengthened the need to investigate this process.

#### 5.1.5.1  *Experiment introduction*

As stated under section 2.5.1 product respiration rate is not noticeably influenced by relative humidity but is controlled by product temperature. Quantification of the process can be derived by measuring the evolution of $CO_2$ at various bulb temperatures. Utilizing molecular weights, the carbon mass component can be separated from the oxygen component to give the loss of dry matter. From Equation 2.1 respiratory heat generation can be determined based on its relationship established with $CO_2$ evolution.

The objective of this work was to measure respiration rate of bulbs used in the container storage trial, and to predict carbon weight loss and respiratory heat generation from product temperature.

### 5.1.5.2   *Method and materials*

Three samples of onion bulbs were obtained from the transport container. Each sample consisted of 11 or 12 randomly chosen bulbs. Total mass of each sample was measured to $\pm 0.01$ g using Mettler Model PM6100 scales. The volume of 3 jars required to accommodate the samples at various stages of the experiment was determined by weighing the water each could contain. Volume was measured to the nearest 10 $mm^3$.

Temperatures utilized for the experiment ranged from 0-35°C at 5°C intervals. Initially temperatures were randomly selected from 0-25°C to decide the order of respiration rate analysis; bulb response to the higher temperatures of 30 and 35°C was evaluated last due to the possibility of permanent bulb injury through high temperature denaturation of cellular compounds.

The 3 samples were exposed to the selected temperature in an environmental room for a minimum period of 48 hours, thereby attaining thermal equilibrium. Each sample was then fan ventilated to disperse localized respiratory gas concentrations, and sealed into a gas tight jar. The atmosphere within each jar was immediately analyzed for $CO_2$ concentration by withdrawing a sample of air through a septum with a syringe and injecting the contents into a minute infra-red $CO_2$ transducer with $N_2$ as the carrier gas. Results of the analysis were presented through a Hewlett Packard Model HP3394A Integrator. Exactly 20 minutes later a second air sample was collected from each jar and analyzed for $CO_2$ concentration.

### 5.1.5.3 *Results and discussion*

The concentration of $CO_2$ presented by the Hewlett Packard Integrator was given in percentage. Measurement differential over the 20 minute intervals was the percentage increase in $CO_2$ concentration. Conversion to units of molecular $CO_2$ production was given by the following equation:

$$rr_{CO_2} = (V_j \times 10^6 - V_s \times 10^6)(CO_2^f - CO_2^i)\left(\frac{(1 \times 10^{-5})P_{ATM}}{8.3143\,(m_s \times 10^3)(T_{on} + 273.15)t}\right)$$

$$(5.10)$$

where:

$rr_{CO_2}$ = relative respiratory $CO_2$ production ($mol.kg^{-1}.s^{-1}$)

$V_j$ = jar volume ($m^3$)

$V_s$ = volume of onion sample ($m^3$)

$CO_2^f$ = final $CO_2$ concentration (%)

$CO_2^i$ = initial $CO_2$ concentration (%)

$P_{ATM}$ = atmospheric pressure (Pa)

$T_{on}$ = temperature of onion (°C)

$m_s$ = mass of onion sample (kg)

$t$ = time (s)

To determine the rate of loss of carbon mass from the onion bulbs, the following relationship applies:

$$rr_C = M_C\, rr_{CO_2} \qquad\qquad (5.11)$$

where:

$rr_C$ = relative respiratory carbon mass depletion ($g.kg^{-1}.s^{-1}$)

$M_C$ = molecular mass of carbon ($g.mol^{-1}$)

The plot of relative respiratory carbon mass depletion against bulb temperature showed a non-linear relationship between the 2 variables. A third-order polynomial equation was found to explain well the experimental data with an $R^2$ of 0.984:

$$rr_C = (3.201 \times 10^{-7}) + (5.261 \times 10^{-9})T_{on} + (4.513 \times 10^{-9})T_{on}^2 - (9.750 \times 10^{-11})T_{on}^3$$

$$(5.12)$$

Figure 5.3 illustrates carbon depletion as a function of bulb temperature with the polynomial Equation 5.12 fitted.

Generation of respiratory heat was stated in section 2.5.1 as being 2870 kJ.mol$^{-1}$ of glucose (Salisbury and Ross 1992). From the oxidation/reduction processes of Equation 2.1 it can be noted that 1 glucose molecule and 6 oxygen molecules are converted into 6 carbon dioxide molecules and 6 water molecules with the release of energy. Quantification of respiratory heat output for the onion bulbs on a product mass basis can be obtained by finding the product of glucose consumption based on the rate of $CO_2$ production in moles given by Equation 5.10, and the energy released by respiration on a glucose molar basis:

$$r_h = \frac{rr_{CO_2}(2870 \times 10^3)}{6} \qquad (5.13)$$

where:

$r_h$ = heat of respiration (W.kg$^{-1}$)

The relationship between respiratory heat generation and relative respiratory carbon depletion is constant. Therefore, a polynomial equation of the same order correlating carbon depletion against onion bulb temperature would equally well describe respiratory heat:

$$r_h = (1.278 \times 10^{-2}) + (2.029 \times 10^{-4}) T_{on} + (1.800 \times 10^{-4}) T_{on}^2 - (3.882 \times 10^{-6}) T_{on}^3$$

$$(5.14)$$

Depiction of respiratory heat generation plotted against temperature with Equation 5.14 fitted is given in Figure 5.3.
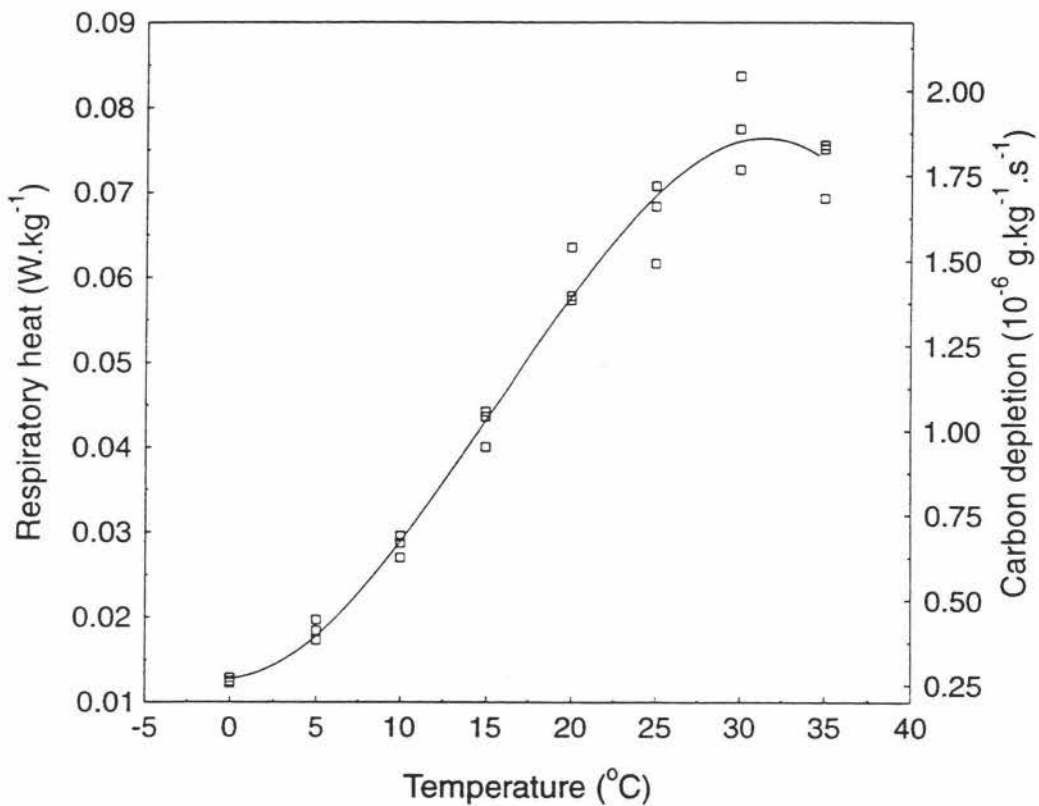


**Figure 5.3**   Heat of respiration and rate of carbon mass depletion as a function of onion bulb temperature.

### 5.1.6  Transpiration

The major factor responsible for weight loss in onion bulbs is water depletion through the process of transpiration.  This can diminish quality attributes and reduce

saleable product weight. Bulb temperature is also responsive to transpiration rate through the effects of evaporative cooling.

Use of empirical relationships between onion transpiration rate and environmental conditions from the literature was considered unsuitable. As with respiration, information primarily focused on trends and general responses of this parameter with little information detailing specific environmental conditions. Variability of transpiration rate between cultivars was also reported. An investigation into this parameter was considered necessary due to these factors.

### 5.1.6.1  *Experiment introduction*

As discussed in Chapter 2 product transpiration rate is influenced by relative humidity and temperature, or the vapour pressure of the air as evident from Fick's law of diffusion:

$$\dot{m}_{H_2O} = A \; k_t \; (P_s - P_a) \qquad (5.15)$$

where:

$\dot{m}_{H2O}$ =  mass flow rate of water vapour $(g.s^{-1})$

$k_t$  =  mass transfer coefficient $(g.m^{-2}.s^{-1}.Pa^{-1})$

$P_s$  =  vapour pressure of product surface (Pa)

$P_a$  =  vapour pressure of air (Pa)

The mass transfer coefficient is specific to a product and to some properties of the flowfield. It can be separated into 2 components; the product surface transpiration coefficient, and the convective air transpiration coefficient. The former is related to the properties of the product skin and is usually determined experimentally, while the later is largely related to product shape and flowfield velocity (Gaffney et al. 1985; Chau et al. 1988a; Chau et al. 1988b). They form the following relationship:

$$k_t = \cfrac{1}{\cfrac{1}{k_a} + \cfrac{1}{k_s}} \tag{5.16}$$

where:

$k_a$ = convective air mass transfer coefficient ($g.m^{-2}.s^{-1}.Pa^{-1}$)

$k_s$ = product skin mass transfer coefficient ($g.m^{-2}.s^{-1}.Pa^{-1}$)

Formulation of a computer simulation predicting the rate of water loss from a product requires all the related parameters in Equation 5.15 to be defined. Chau et al. (1988b) and Becker et al. (1995) detailed a procedure for estimating the mass transfer coefficient for a particular product. It was based on experimentally determining $k_s$, and mathematically calculating $k_a$ from known dimensional relationships.

Objectives for this section were to use experimental procedures suggested by the above authors to estimate $k_s$ (a constant property under variable flowfield velocities) through deriving values for $k_t$ and $k_a$. To then predict a suitable mass transfer coefficient for the onion bulbs during the transport container storage trial by recalculation of $k_a$ at the appropriate container air ventilation velocity rate.

### 5.1.6.2  *Method and materials*

Three samples each of 15 randomly selected onion bulbs were obtained from the container at the completion of the storage trial. Total weight loss from each sample was determined under relative humidity regimes of 45, 60, 75, and 90%, in a laboratory maintained at 20°C. Prior to the experiment a fourth sample of onions was used to determine the effects of bulb water activity over the range of selected RH. At transfer from one RH to another the sample mass was measured regularly to establish the time period necessary for the rate of weight loss to reach equilibrium. In all instances equilibrium was reached with 24 hours.

Each sample was placed in a randomly selected controlled RH environment for 24 hours, then removed and each bulb immediately weighed using Mettler Model AE200 scales to a resolution of 0.0001 g, then returned to the same environment. Total weight loss was determined after reweighing the sample 24 hours later.

Control of RH was possible using a flow through pressure drop system, where pressurized air was saturated by being bubbled through a number of water-baths then brought to atmospheric pressure and directed into a tin foil bag containing the onion sample (Figure 5.4). Manipulation of water-bath system pressure allowed for means of accurate control of RH ($\pm 2\%$):

$$RH(\%) = \frac{P_{ATM}}{P_{PDS}} \tag{5.17}$$

where:

$P_{PDS}$ =   air pressure in pressure drop system (Pa)

Bag RH was monitored throughout the experiment using Monolithic IC Model IH-3602 humidity sensors, resolution to 2% RH. Air velocity through the bag, assuming plug flow, was maintained at 0.0024 m.s$^{-1}$ for all RH regimes.

### 5.1.6.3  *Results and discussion*

Differentiation of weight loss between water and carbon depletion was necessary. Loss of water was calculated utilizing Equation 5.12 to subtract estimated carbon mass loss from the total weight loss of each sample at all RH regimes. From Fick's law of diffusion (Equation 5.15) water loss should exhibit a linear relationship at variable vapour pressure deficits between product and air, assuming factors such as product water activity to be negligible over the range of vapour pressures studied. Such a relationship was found from the results of this study with an $R^2$ of 0.955 (Figure 5.5). The mass transfer coefficient for the sample bulbs could be estimated
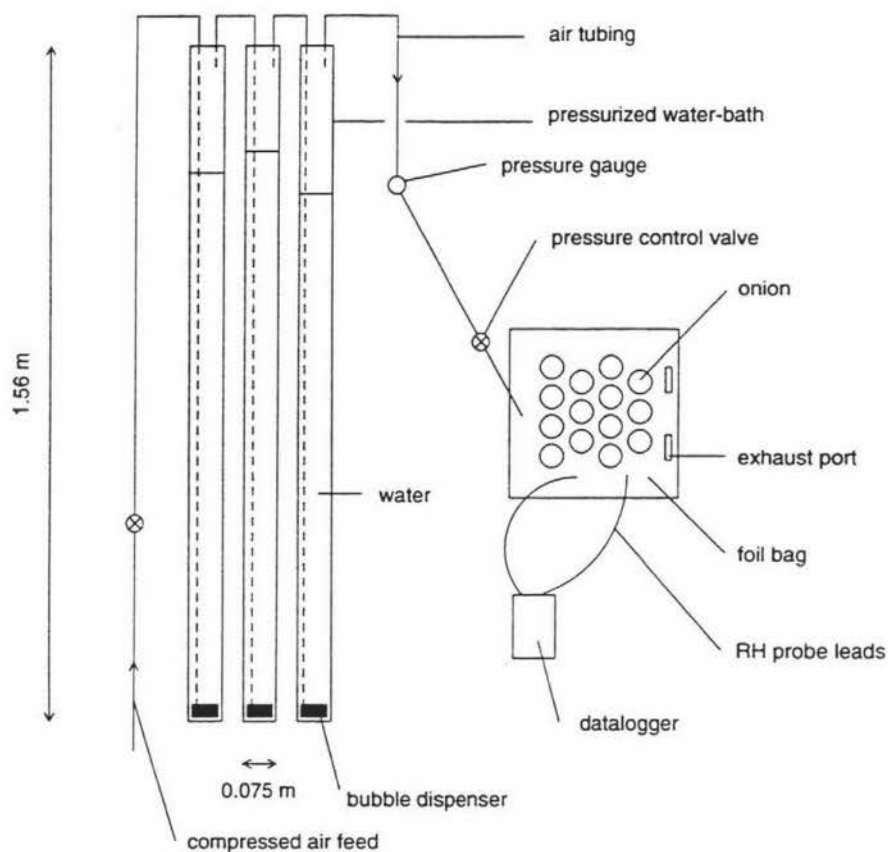
**Figure 5.4**   View of pressure drop system with relative humidity controlled crop containment bag.  Not drawn to scale.

now that all other parameters in Equation 5.15 can be defined.

Vapour pressure at the product surface was calculated according to the procedure of Chau et al. (1988b) and Becker et al. (1995).  Bulb surface temperature was adjusted to account for internal heat generation due to respiration (Equation 5.14), and evaporative cooling.  Chau et al. (1988b) gave the following relationship to calculate temperature at the surface of a sphere:
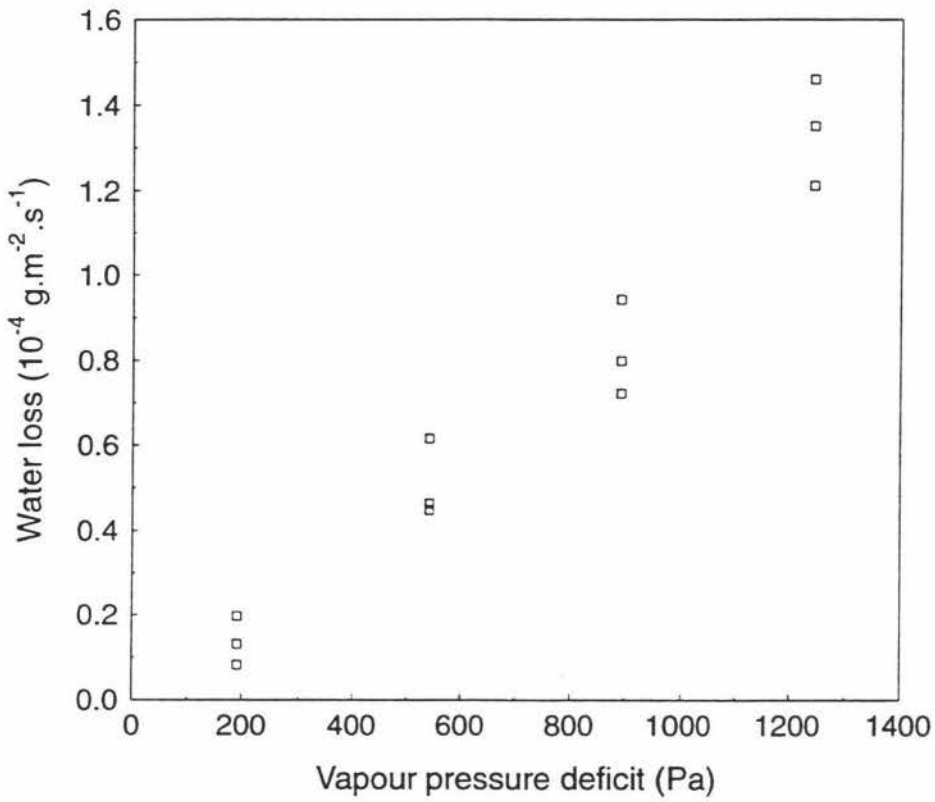
**Figure 5.5**    Onion bulb water loss as a function of vapour pressure deficit.

$$T_s = T_a + \frac{r_h \, \rho_{on} \, d}{3 \, h_c} - \frac{\lambda \, (\dot{m}_{H_2O} \times 10^3)}{A \, h_c} \qquad (5.18)$$

where:

$T_a$ = temperature of air (°C)

$T_s$ = temperature of onion surface (°C)

$\rho_{on}$ = density of onion (kg.m$^{-3}$)

$\lambda$ = latent heat of vaporization of water (J.g$^{-1}$)

A further adjustment to product surface vapour pressure was necessary due to the presence of dissolved solutes. Vapour pressure lowering effect for onion due to solutes was quantified by experimentation from Chau et al. (1987) to be 0.98.

Mass transfer coefficients ($k_a$) were determined for each sample when exposed to each environmental regime. Skin mass transfer coefficient was estimated by solving Equation 5.16 with respect to $k_t$ and $k_a$. Incropera and De Witt (1985) offered an analogous mathematical expression to their recommended heat transfer coefficient equation for predicting the convective air mass transfer coefficient for a packed bed of spheres in a gaseous flowfield. The Reynolds-Colburn $j$ factor, and Stanton-Schmidt-Colburn $j$ factor dimensionless relationships were applied:

$$\varepsilon \, j_m = 2.06 \, Re^{-0.575} \tag{5.19}$$

$$j_m = St_m \, Sc^{2/3} \tag{5.20}$$

$$St_m = \frac{k_{a(r)}}{u_\infty} \tag{5.21}$$

$$Sc = \frac{\nu}{D_{AB}} \tag{5.22}$$

where:

$j_m$ = Colburn $j$ factor for mass transfer (dimensionless)

$St_m$ = Stanton mass transfer number "modified Sherwood number" (dimensionless)

$Sc$ = Schmidt number (dimensionless)

$k_{a(r)}$ = convective air mass transfer coefficient ($m.s^{-1}$)

$D_{AB}$ = binary mass diffusion coefficient for air and water ($m^2.s^{-1}$)

The mass transfer Stanton number yields $k_{a(r)}$ in inverse units of resistance. The driving force can be converted into units of vapour pressure using the perfect gas law. Average skin mass transfer coefficient ($k_s$) was $9.570 \times 10^{-8}$ $g.m^{-2}.s^{-1}.Pa^{-1}$ with

a standard deviation of $1.479 \times 10^{-8}$. Total mass transfer coefficient suitable for the bulbs contained in the transport vessel during the storage trial was estimated from $k_s$, and a recalculated $k_a$ from Equation 5.19. Conversion of total mass transfer coefficient, $k_t$, from units of vapour pressure to inverse units of resistance, $k_{t(r)}$, was again possible using the perfect gas law.

### 5.1.7 Water Content

The solution to Equations 5.1 and 5.2 require the defining of onion bulb moisture content as a fraction of product mass. Rapusas and Driscoll (1995) established a correlation between white onion bulb density and moisture content, and fitted a third-order polynomial equation with an $R^2$ and standard error of 0.998 and 0.8%, respectively:

$$\rho_{on} = 1192 - 412\,W + 1068\,W^2 - 1065\,W^3 \qquad (5.23)$$

From results obtained for estimating surface area and volume from bulb mass (section 5.1.4) average bulb density was calculated. Solving Equation 5.23 for moisture content from a known density was possible by deriving the cubic root of the equation when in its homogeneous form.

### 5.2 FLOWFIELD

As with the onion bulb, various flowfield properties of interest to this study which would be significantly variable within a computer simulation predicting heat and mass transfer require defining. These properties include saturated water vapour pressure from which the vapour pressure of a sample of air can be determined if RH is known, absolute humidity, air density, and the latent heat of vaporization. Some properties such as the binary mass diffusion coefficient and the specific heat capacity

of air were held constant as variation of these parameters were either small or had an insignificant effect on the solution to equations they appeared in.

### 5.2.1 Saturated Water Vapour Pressure

This property is variable depending on temperature and is a parameter utilized for calculating the rate of water loss from a product after being adjusted according to the relative humidity. Saturated water vapour pressure has been determined using Tetens equation (Tetens 1930):

$$P_a' = 611 \exp\left(17.27 \; \frac{T_a}{(T_a + 237.3)}\right) \qquad (5.24)$$

where:

$P_a'$  =  saturated water vapour pressure of air (Pa)

The vapour pressure under the product skin is considered to be saturated and is determined from the product surface temperature. Vapour pressure lowering of the product is required to account for dissolved solutes.

### 5.2.2 Absolute Humidity

Absolute humidity is the ratio of the mass of water vapour to the total volume of the sample; the water vapour concentration of the air. It is useful for adjusting the water content of the air due to evaporation of moisture from the product. Absolute humidity is derived from the following:

$$\chi = \frac{P_a \; 2.17}{(T_a + 273.15)} \qquad (5.25)$$

where:

$\chi$    =    absolute humidity of air (g.m$^{-3}$)

### 5.2.3   Air Density

The density of air is a function of atmospheric pressure, water vapour pressure, and temperature. This property of the flowfield can be calculated from the following relationship:

$$\rho = 3.49 \; \frac{(P_{ATM} - P_a)}{(T_a + 273.15)} \qquad (5.26)$$

### 5.2.4   Latent Heat of Vaporization

As water changes phase from liquid to vapour, energy is absorbed from the evaporating surface. Transpiration is a process where such an event occurs producing a cooling effect at the surface of the product. The amount of latent heat absorbed by this process is a function of temperature:

$$\lambda = 2500.83 - 2.36 T_a \qquad (5.27)$$

### 5.3   PARAMETER VALUES

Parameter values expected to vary with some significance within the simulation, or requiring calculation due to specific features of the crop or flowfield were detailed in sections 5.1 and 5.2. Other necessary parameter values were treated as constants. Features of the crop requiring recalculation would include onion surface area when modelling different bulb sizes, or re-estimation of initial bulb water content which is dependent on the bulb's history of water loss. Features of the flowfield would

include predicting new convective heat and mass transfer coefficients if air velocity through the containment vessel differed from that experienced during the bulb storage trial.

Thermophysical parameter values suitable for utilization in a model specific to the crop and flowfield conditions experienced during the transport container storage trial are listed in Table 5.1. Derivation of such values has occurred from the literature, experimentation, or a combination of both sources.

## Table 5.1

Onion bulb and flowfield thermophysical values suitable for a computer algorithm of the transport container storage trial.

| Bulb parameters | Value used |
|---|---|
| [I]Mass[*] | 0.07593 kg |
| [C]Diameter[*] | 0.055 m |
| [C]Volume[*] | $8.0568 \times 10^{-5}$ m$^3$ |
| [C]Surface area[*] | 0.008647 m$^2$ |
| [I]Density[*] | 943.506 kg.m$^{-3}$ |
| [I]Water content fraction | 0.867 |
| [I]Specific heat capacity | 3869 J.kg$^{-1}$.°C$^{-1}$ |
| [I]Thermal conductivity | 0.5355 W.m$^{-1}$.°C$^{-1}$ |
| [C]Heat transfer coefficient | 14.81 W.m$^{-2}$.°C$^{-1}$ |
| [C]Mass transfer coefficient | $1.294 \times 10^{-5}$ m.s$^{-1}$ |
| [C]Skin mass transfer coefficient | $1.295 \times 10^{-5}$ m.s$^{-1}$ |
| [V]Water vapour pressure | Pa |
| [V]Respiration | Pa |
| [V]Transpiration | Pa |
| **Flowfield parameters** | **Value used** |
| [C]Container volumetric void fraction | 0.499 |
| [C]Velocity | 0.1008 m.s$^{-1}$ |
| [C]Upstream velocity | 0.0504 m.s$^{-1}$ |
| [V]Density | kg.m$^{-3}$ |
| [V]Saturated water vapour pressure | Pa |
| [V]Water vapour pressure | Pa |
| [V]Absolute humidity | g.m$^{-3}$ |
| [V]Latent heat of vaporization of water | J.g$^{-1}$ |
| [C]Convective air mass transfer coefficient | 0.01499 m.s$^{-1}$ |
| [C]Specific heat capacity | 1007 J.kg$^{-1}$.°C$^{-1}$ |
| [C]Thermal diffusivity | $2.0 \times 10^{-5}$ m$^2$.s$^{-1}$ |
| [C]Kinematic viscosity | $1.40 \times 10^{-5}$ m$^2$.s$^{-1}$ |
| [C]Binary mass diffusion coefficient | $2.60 \times 10^{-5}$ m$^2$.s$^{-1}$ |

I = Initial simulation value
C = Constant simulation value
V = Variable simulation value
* = Mean estimated value

# CHAPTER 6

# MODEL DEVELOPMENT

To expect a high degree of utility a model predicting temperature and weight loss of stored product requires a reasonable level of accuracy associated with a sufficient degree of operational simplicity. As stated in the literature review an important consideration in developing a model is to consider its appropriateness, not whether all effects are included (Cleland 1990). With these concepts in mind it was considered appropriate that only the important effects governing bulb temperature and weight loss be modelled.

## 6.1 HEAT AND MASS TRANSFER PATHWAYS

Various potentially important pathways exist which need to be considered when modelling heat and mass transfer of onion bulbs in an ambient air ventilated porus bed. Such factors include: convection between onions and flowfield, convection between flowfield and container walls, evaporation of water from onions to flowfield, loss of onion carbon content, conduction within onions, conduction between onions at points of contact, and forced and free convection through the bed. The most important of these effects will have to be included in the model if a reasonable level of accuracy is to be obtained.

### 6.1.1 Convection Between Flowfield and Walls

Models of transport containers have mainly focused on refrigerated vessels where significant temperature gradients exist between internal and ambient air conditions (Van de Ree et al. 1974; Meffert and Van Beek 1988; Heap 1989). Subsequently,

transients of heat through container walls has classically been treated as the most important pathway influencing air temperature distribution, and hence the stow temperature.

Researchers modelling packed or porous bed product of low weight value, either ventilated with ambient air or non-ventilated but stored under ambient conditions have focused on product respiratory heat generation and/or evaporative product cooling as the most important pathway influencing temperature distribution (Bakker-Arkema et al. 1967; Marchant et al. 1994). Historically, models of these porous beds have not described stored product fully enclosed by a containment unit although many beds have been modelled whilst confined in storage bins or larger open-ended storage facilities. Temperature gradients between the bed void area and the surrounding air or confinement wall have not been considered significant enough to be modelled in many of these situations.

This research has endeavoured to model onion temperature and weight loss whilst the bulbs were stored or transported in a porous bed within an intermodal transport container. Ventilation was with ambient air at $0.726 \text{ m}^3.\text{s}^{-1}$ or approximately 160 air changes per hour; an expected flow rate for onions stored in such vessels. Under such a regime convection between the inner walls of the container and the product bed as a consequence of temperature differentials between the bed void area and ambient air, including solar energy gains on the walls, would be relatively small. A plugflow of air originating below the stow in the false floor and exiting into the headspace travels vertically through the packed bed in approximately 22 seconds, leaving little opportunity for horizontal transient heat to diffuse a significant distance between the unit's walls and the onion bed.

### 6.1.2 Conduction Between Onions

When product is supported by packaging the contact area between the 2 objects is relatively large in many situations. New Zealand export apples are typically transported in approximately 20 kg cartons where layers of apples are supported in

cupped trays termed "Friday trays". The cups are designed to support and protect the product by creating a large contact surface with the apple thereby distributing the load and any potentially damaging impact forces over a relatively large area (Heap 1994). This circumstance possibly offers a significant pathway for energy conduction between the apple and tray. Amos (1995) considered the pathway between apple and Friday tray important and modelled the conductive process accordingly.

A spherical product in a porous bed is supported by a number of contact points with adjacent products. Ofoli and Burgess (1986) modelling potato tubers, asserted that when assuming agricultural product are arranged in a bin in such a manner that only point-to-point contacts occur between adjacent pieces of product, the contact area is very small and the thermal conduction pathway between product is negligible. Similarly, Bakker-Arkema et al. (1967) considered conductive heat transfer through particle-to-particle contact in a porous bed of cherry pits to be insignificant. Contact area between onion bulbs in a porous bed was thus considered small with conduction between product therefore negligible.

### 6.1.3 Conduction Within Onions

Two basic approaches exist for describing the temperature response of an onion bulb to the temperature flux of the environment and evaporative flux of the product. Ideally, temperature should be predicted with respect to position within the bulb under dynamic condition. Partial differentiation is required to solve for temperature under such circumstances using finite difference or finite element approximation methods. These techniques are computationally intensive particularly if the added requirement of modelling the bulbs with respect to position within the porous bed is necessary.

A second approach which is less prohibitively complex is to consider the bulb as a lumped capacitance volume. This treats the product temperature as homogeneous throughout all positions within the bulb. Although open to inaccuracy this approach can be justified with result of minimal error if a relationship between various

thermophysical properties of the bulb and flowfield is met. If a low Biot number is calculated (transients of heat by conduction is dominant over convection between bulb and flowfield) then a low temperature gradient throughout the bulb can be assumed and a lumped capacitance approach justified. A low Biot number of 0.25 was calculated for onion bulbs during the storage trial from the following relationship:

$$Bi = \frac{h_c L}{k} \qquad (6.1)$$

$$L = \frac{V}{A} \qquad (6.2)$$

where:

Bi   =   Biot number (dimensionless)

L   =   characteristic dimension (m)

$h_c$   =   heat transfer coefficient ($W.m^{-2}.°C^{-1}$)

k   =   thermal conductivity of onion ($W.m^{-1}.°C^{-1}$)

A   =   surface area of onion ($m^2$)

V   =   volume of onion ($m^3$)

Duffie and Beckman (1980), Incropera and De Witt (1985), and Holman (1986) proposed that a lumped capacitance technique was appropriate when $Bi \leq 0.1$. Although not meeting these requirements, this approach was utilized due to the relatively close agreement with the conditions proposed by the above authors, and after measurements revealed that only small differences existed between onion centre and surface temperatures (Figure 6.1).

### 6.1.4   Forced and Free Convection

Convection from a solid material to a fluid occurs by molecular diffusion and by gross molecular motion caused by an external driving force. Fluid adjacent to an
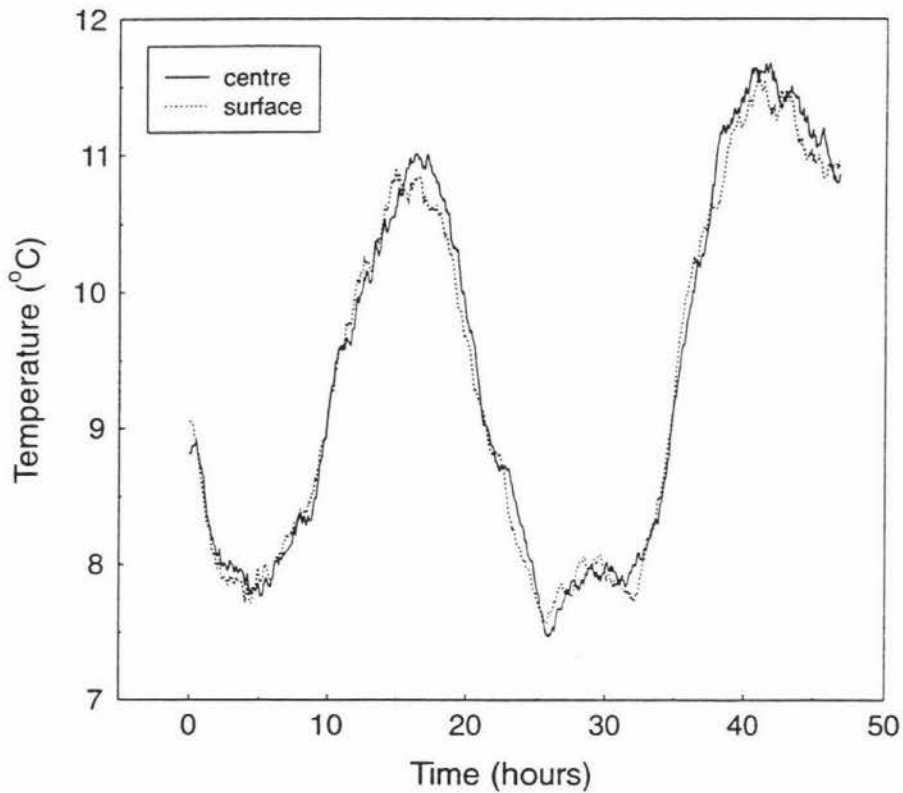
**Figure 6.1**    Measured centre and surface temperatures of an onion bulb stowed in a porous bed within a transport container.

object can be heated thus becoming less dense or buoyant carrying the heated molecules away from the object. This driving force is known as free convection. A fluid can be forced past an object by such mechanisms as fans, carrying heated molecules with it. This driving agent is termed forced convection. These driving forces enhance both heat and mass transfer by decreasing the diffusion resistance.

The relationship between the Grashof number (Gr; ratio of the buoyancy to viscous force acting on a fluid) and Reynolds number (Re; ratio of inertial to viscous force acting on a fluid element) squared, can be used as a criterion for determining the significance of both convective driving forces to each other (Monteith and Unsworth

1990). When Gr is considerably larger than $Re^2$, heat transfer is governed by free convection. Conversely, a much larger $Re^2$ implies free convection is negligible and forced convection is the predominant driving force. $Gr/Re^2 \approx 1$ dictates both free and forced convection are important. Gr can be numerically determined from the following relationship (Incropera and De Witt 1985):

$$Gr = \frac{g \; \beta \; (T_s - T_a) \; L^3}{v^2} \qquad (6.3)$$

$$\beta = \frac{1}{(T_a + 273.15)} \qquad (6.4)$$

where:

Gr  =  Grashof number (dimensionless)

$\beta$  =  volumetric thermal expansion coefficient ($K^{-1}$)

$T_s$  =  temperature of onion surface (°C)

$T_a$  =  temperature of air (°C)

g  =  gravitational acceleration ($m.s^{-2}$)

v  =  kinematic viscosity ($m^2.s^{-1}$)

The ratio of Gr to $Re^2$ was determined at $6.89 \times 10^{-4}$, indicating that free convection was negligible and forced convection was strongly predominant. Heat and mass transfer coefficients for forced convection were detailed in sections 5.13 and 5.16, respectively.

### 6.1.5  Remaining Pathways

Experience suggests that the product temperature and mass status responds dramatically to differentials in flowfield conditions, and under a steady state regime the response is proportional as evident from Newton's law of cooling and Fick's law of diffusion, respectively. Convective heat and mass transfer between onion and flowfield are therefore important pathways as discussed in the previous section.

Evaporative water loss, and respiratory carbon depletion and heat production are additional pathways considered important processes for the formulation of a containerized onion storage model in this study. The appropriateness of such a model has been a compromise between the unimportant pathways discussed and model complexity.

## 6.2 ONION AND FLOWFIELD MODEL FORMULATION

### 6.2.1 Methodology

An important factor to consider during model development is the description of the thermal and mass status of product and flowfield with respect to spatial distribution throughout the container. These properties can be treated as being variable at every location in the direction of heat and mass flow (fully distributed), or as being a single homogeneous volume (lumped). The later approach would treat the container as a large single perfectly mixed zone whereby spatial variation of bulb and flowfield thermophysical properties are not considered. A circumstance possibly leading to unacceptably high errors in some localities of the vessel. For these reasons this approach was rejected. A fully distributed model, although appealing, became an unfavourable option due to the intensive computational requirements necessary; involved solving simultaneous partial differential equations for heat and mass transfer and possibly fluid hydrodynamics if variable airflows throughout the vessel were to be considered.

A compromise between potential inaccuracies associated with a single lumped zone and the computational complexity of a fully distributed model were met by utilizing a multiple zoned lumped parameter approach. The container volume was divided into discrete zones. In each zone the state of the onions was assumed to be spatially constant. Whereas the assumptions of plugflow leads to the properties of the air varying vertically within each zone. Mathematically simulating various

thermophysical processes with respect to positional discretisation throughout numerous locations was therefore possible.

The transport container was modelled as 27 zones so as to remain consistent with those zones defined in section 4.3.1 as localities for positioning of probes and sensors during the containerised onion storage trial. Identification of each modelled zone remained as given in section 4.3.1 using $i,j,k$ as cartesian coordinates (Figure 4.5).

Air flow through the porous bed was modelled as moving "air parcels" or "plugflows" travelling vertically up each zone column ($i,j,1 \rightarrow i,j,2 \rightarrow i,j,3$). The 9 columns throughout the product bed were modelled separately with respect to ventilation rate, thereby allowing for variable air flow which were dependent on the ventilation system employed. Heat and mass transfer coefficients (determined as functions of air velocity; sections 5.1.3 and 5.1.6, respectively) were specific to each zonal column. Air pressure measurements from the bulb storage trial collected in each zone indicated that flowfield velocities were generally higher towards the rear of the container with the ventilation system used in the trial (section 4.3.3.5).

The model commences with a specified air temperature and relative humidity entering through the plenum. Fresh air parcels move into zones $i,j,1$ simultaneously as other parcels move to $i,j,k+1$. At each time step the product absolute humidity and air plug absolute humidity are determined based on the product temperature, air plug temperature, and existing mass of plug water vapour. Transpiration rate for the time step is then established based on the absolute humidity deficit. The mass of water vapour in each zone is then updated. Similarly within each zone, carbon mass loss and heat generation from product respiration is established, along with evaporative cooling due to transpiration, and convective heat transfer between onion and flowfield. Bulb temperature, air plug temperature, and mass of onions in each zone from water vapour and carbon depletion are then also updated, completing the calculations for the time step.

### 6.2.2 Onion Temperature

A dynamic approach was used to model bulb temperature. As the single product was treated as a lumped capacitance the only independent variable was time, hence an ordinary differential equation sufficed for predicting temperature in each zone:

$$m_z \ C_{p(on)} \ \frac{dT_{on}}{dt} = \phi_{resp} - \phi_{conv} - \phi_{evap} \qquad (6.5)$$

where:

$m_z$   =   total mass of onions in zone (kg)

$C_{p(on)}$   =   specific heat capacity of onion $(J.kg^{-1}.°C^{-1})$

$dT_{on}/dt =$    temperature change of onions $(°C.s^{-1})$

$\phi_{conv}$   =   convective heat transfer from onions to zone air (W)

$\phi_{evap}$   =   latent heat transfer by evaporation from onions to zone air (W)

$\phi_{resp}$   =   respiratory heat generation (W)

Definition of energy transfer components in Equation 6.5 are:

$$\phi_{conv} = h_c \ A_z \ (T_{on} - T_a) \qquad (6.6)$$

$$\phi_{evap} = \lambda \ k_{t(r)} \ A_z \ (AHL\chi_{on} - \chi) \qquad (6.7)$$

$$\phi_{resp} = m_z \ r_h \qquad (6.8)$$

where:

$h_c$   =   convective heat transfer coefficient $(W.m^{-2}.°C^{-1})$

$A_z$   =   total surface area of onions in zone $(m^2)$

$\lambda$   =   latent heat of vaporization of water $(J.g^{-1})$

$k_{t(r)}$   =   mass transfer coefficient $(m.s^{-1})$

$\chi_{on}$ = absolute humidity of onions (g.m⁻³)

$\chi$ = absolute humidity of zone air (g.m⁻³)

$r_h$ = heat of respiration (W.kg⁻¹)

AHL= absolute humidity lowering effect (fraction)

Absolute humidity at the product surface is considered to be saturated but was adjusted by an absolute humidity lowering effect (often referred to in the literature under alternative units as vapour pressure lowering (VPL) effect (section 2.4.2)) to account for the presence of dissolved solutes in the product's wet fraction. Derivation of the AHL or VPL value for onion bulbs is specified in section 5.1.6.3.

Respiratory heat generation illustrated in Equation 6.8 is fully defined by Equation 5.14.

### 6.2.3 Onion Weight Loss

Product water vapour and carbon loss were also modelled dynamically with ordinary differential equations. Water loss was predicted from the following relationship:

$$\frac{dm_{H_2O}}{dt} = k_{t(r)} A_z (AHL\chi_{on} - \chi) \tag{6.9}$$

where:

$dm_{H_2O}/dt$ = mass transfer of water vapour (g.s⁻¹)

Carbon mass loss was calculated using:

$$\frac{dm_C}{dt} = m_z\, rr_C \tag{6.10}$$

where:

$dm_c/dt$   =   mass transfer of carbon (g.s$^{-1}$)

$rr_c$      =   respiratory carbon mass depletion (g.kg$^{-1}$.s$^{-1}$)

Carbon mass depletion from bulb respiration rate required for Equation 6.10 is given by Equation 5.12.

### 6.2.4 Air Temperature

The flowfield was modelled as plugflow within zonal columns. Air temperature within each zone was considered dimensionally homogeneous and stable over the time step with respect to the onions, but was based on an average temperature as the plug traversed the zone. Thus, air temperature was essentially treated as quasi steady state. A requirement under this approach was that for each simulation time step onion temperature is considered stable; a reasonable assumption as bulb temperature fluctuation over typically 5 or 10 second simulation time steps was expected to be small.

The log mean temperature difference based on plug entry and exit temperature from each zone was used as an average zone air temperature. This was appropriate due to the exponential temperature profile typically experienced by a fluid approaching the temperature of another object or fluid under steady state conditions.

Newton's law of cooling described convective energy exchanges between bulbs and flowfield. Equation 6.6 was the basis for such calculation but was modified to account for onion/flowfield log mean temperature difference. Air temperature change for each zone was determined from the following:

$$\dot{m}_{a(z)} \, C_p \, \Delta T_a = h_c \, A_z \, \Delta T_m \qquad (6.11)$$

where:

$\Delta T_a$ = temperature change of zone air (°C)

$\Delta T_m$ = onion/flowfield log mean temperature difference (°C)

$\dot{m}_{a(z)}$ = mass flow of air in zone (g)

$C_p$ = specific heat capacity of air (J.g$^{-1}$.°C$^{-1}$)

Derivation of log mean temperature difference between flowfield and onions is:

$$\Delta T_m = \frac{(T_{on} - T_{a(i)}) - (T_{on} - T_{a(o)})}{Ln\left(\dfrac{T_{on} - T_{a(i)}}{T_{on} - T_{a(o)}}\right)} \qquad (6.12)$$

where:

$T_{a(i)}$ = temperature of air entering zone (°C)

$T_{a(o)}$ = temperature of air exiting zone (°C)

### 6.2.5 Air Humidity

Zone air absolute humidity was determined in a similar manner to zone air temperature where Equation 6.9 was modified to predict water vapour transfer between bulbs and air under a steady state regime:

$$v \, \Delta \chi = k_{t(r)} \, A_z \, \Delta \chi_m \qquad (6.13)$$

where:

$\Delta \chi$ = absolute humidity change of zone air (g.m$^{-3}$)

$\Delta \chi_m$ = onion/flowfield log mean absolute humidity difference (g.m$^{-3}$)

$v$ = volumetric air flow rate (m$^3$.s$^{-1}$)

Derivation of log mean absolute humidity difference between flowfield and onions is:

$$\Delta\chi_m = \frac{(AHL\chi_{on} - \chi_i) - (AHL\chi_{on} - \chi_o)}{Ln\left(\dfrac{AHL\chi_{on} - \chi_i}{AHL\chi_{on} - \chi_o}\right)}$$

(6.14)

where:

$\chi_i$   =   absolute humidity of air entering zone (g.m$^{-3}$)

$\chi_o$   =   absolute humidity of air exiting zone (g.m$^{-3}$)

Absolute humidity was converted to units of vapour pressure by the following relationship:

$$\Delta P_a = \frac{\Delta\chi \ (T_a + 273.15)}{2.17}$$

(6.15)

where:

$\Delta P_a$   =   vapour pressure change of air in zone (Pa)

The change in relative humidity can be derived from the relationship between the change in vapour pressure and the saturated vapour pressure of air in the zone at the appropriate temperature:

$$\Delta RH = \frac{\Delta P_a}{P_a'}$$

(6.16)

where:

$\Delta RH$ = relative humidity change of zone air (fraction)

$P_a'$  =  saturate vapour pressure of zone air (Pa)

Saturated vapour pressure at the appropriate temperature can be determined from Tetens equation (Equation 5.24).

### 6.2.6  Model Programming

The computer simulation was written in Borland Pascal Version 7 and consisted of 81 ordinary differential equations solving for onion temperature, onion water loss, and onion carbon loss for each of 27 zones; and approximately 500 algebraic equations solving for the flowfield conditions, and various input data. The ordinary differential equations were solved using the fourth order Runge-Kutta numerical technique, estimating each of the above parameters for each zone per time step using the mean of 6 predictor extrapolations. Illustration of the model is given in Appendix B1.

### 6.2.7  Model Operational Details

The model can operate on a personal computer with Borland Pascal Version 7 software installed. Pascal access to execution and input files, and writing to output files has been specified through an "ONION" directory in the computer "C" drive. Execution and input files should be installed in this directory.

#### 6.2.7.1  *Input parameter requirements*

An input file labelled "INPUT.TXT" specifying the necessary parameter values in plain ASCII text arranged in columns in the following order needs to be constructed: Julian day, time (24 hr), container western wall temperature, container eastern wall temperature, container roof temperature, plenum inlet air temperature, exhaust port outlet air temperature, outside ambient air temperature, solar radiation, exhaust port outlet air RH, and plenum inlet air RH. Of the above parameters required for the input file, only the plenum input temperature and RH were eventually utilized for the

simulation. The model reads in each line as a new input value at each 5 minute interval of ventilated container operation. Hence, time, input temperature, and input RH values to be simulated by the model should be values representative of 5 minute intervals experienced during the time period of container operation. An example format of an INPUT.TXT file is given in Appendix B2.

### 6.2.7.2 *Initialization parameter requirements*

The model provides convenient access through the file labelled "INITIAL.TXT" to important onion and flowfield parameter values which may require alteration in compliance to crop and container specifications. Provisions have been made for adjustments to: total mass of onions in container, average onion mass, onion moisture content, volumetric ventilation rate up each zonal column, specific heat and mass transfer coefficients for each zonal column, estimated initial onion bulb temperature in each zone, and simulation time step. An example format of an INITIAL.TXT file is given in Appendix B3.

# CHAPTER 7

# MODEL EVALUATION AND DISCUSSION

Evaluation of the simulation model was possible by comparing predicted values for bulb temperature, air temperature, air RH, and weight loss against measured data collected from an onion stowed transport container as detailed in Chapter 4.

The demands of the model were to predict the required flowfield and bulb properties throughout all 27 zones. Thermal exchanges between flowfield and stored crop were significant which stressed the importance of identifying the interactive processes. Temperature differences between inlet and outlet container ventilation air of typically 2 to 3°C demonstrated the significance of these processes (Figure 7.1).

## 7.1 EVALUATION PROCEDURE

The influence of crop and flowfield parameters on the performance of the model, particularly those contained in the initialization file that may require adjustment depending on the crop and container specifications were evaluated for sensitivity. A potentially important parameter not accessible through the initialization file, namely bulb respiration rate, was also tested for sensitivity through modifications made to the simulation programme.

A sensitivity analysis was important as this indicates the robustness and utility of the model. There is no doubt that a degree of error exists when determining model parameter values, when either obtained by mathematical relationships, from the
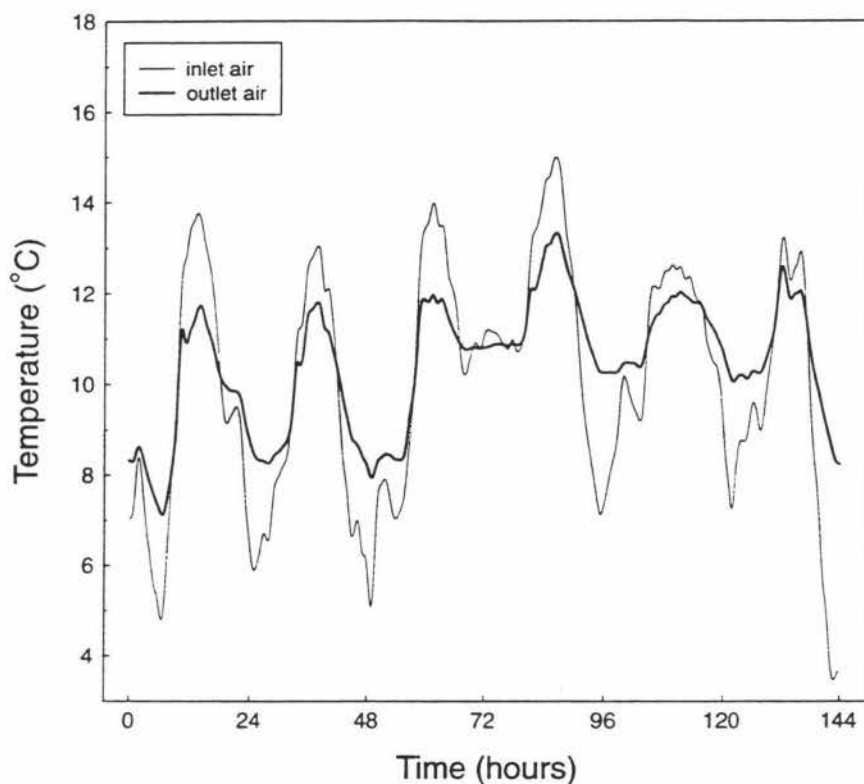
**Figure 7.1**    Inlet and outlet temperature of container ventilation air measured from Julian day 233 to 239.

literature, or when derived by experimentation.  It is therefore of benefit to any user of such a model that parameters which are sensitive to model predictions are acknowledged.  Time, effort, and expense of collecting appropriate thermophysical data could be weighted accordingly.

Evaluation of general model performance is best illustrated graphically.  Simulated temperature, RH, and weight loss data plotted against measured values obtained from the containerized onion storage trial could be compared in this manner.  In addition, a number of statistical procedures can reveal the degree of simulation fit to measured data and the response of model sensitivity to parameter changes.

## 7.2   STANDARD MODEL SIMULATION

### 7.2.1   Introduction

The model input file was loaded with the plenum entry air temperature and relative humidity measured at 5 minute intervals during the onion storage trial. The initialization file had the appropriate thermophysical data entered into it from Table 5.1.

An important flowfield parameter to be specified was volumetric flow rate up each zone column. Upon examination of container ventilation system design and consultation with its users, it was apparent that the intensions were to disperse ventilation air evenly across the entire floor area of the unit. The circumference of the false floor was butted to prevent air escaping up the corrugated sides of the container which also had a secondary effect of increasing air pressure throughout the floor region thereby enhancing uniformity of air distribution (Risse 1986). Air flow through the plenum was therefore distributed evenly between zone columns.

Attention was also directed at product respiration rate. Laboratory experimentation to quantify this parameter was only possible approximately 3 months after completion of the onion storage trial. During this period the crop samples were maintained under cold storage. Immediately prior to experimentation early signs of bulb sprouting became evident; an indication of the stored crop exiting the dormancy phase. Evidence of accentuated respiration rate close to or at the break of dormancy has been reported in the literature (Ward and Tucker 1976; Tanaka et al. 1985). A preliminary run of the model indicated that simulated bulb temperatures were consistently higher during the entire simulation period in all zones of the product bed. Elevated respiratory heat generation was assumed to be responsible for the anomaly. Respiration rate was corrected accordingly based on the observations of Tanaka et al. (1985), to a rate of 20% of that determined from the laboratory experiment. This is discussed in more detail in section 7.2.3. At this level of

refinement the model was considered to be standard and was then fully prepared for statistical and graphical analysis, and modification if required.

### 7.2.2 Results

The standard model performance was evaluated by graphical comparison of measured property values plotted against simulation predicted values, and by sensitivity analysis.

#### 7.2.2.1 *Graphical evaluation*

Due to the relatively large number of zones present and the 4 flowfield and bulb properties being modelled it was considered appropriate that graphical depiction of model performance of each property be illustrated by 2 zones. One of the zones reflected either typical or good model performance, and the second zone reflected unusually poor model performance. A typical simulated prediction of onion bulb and air temperature was evident in zone column $3,3,k$ (Figures 7.2 and 7.3, respectively). An unusually poor simulated prediction for bulb and air temperature was found in zone column $2,2,k$ which happened to predominantly containing the upright pallet utilized as a component of the ventilation system (Figures 7.4 and 7.5, respectively).

Relative humidity of the air was measured in the 8 corner zones and central zone of the porous bed. It was therefore not possible to evaluate graphically a full zone column. However, the top and bottom zones of some columns can be illustrated. Columns $1,3,k$ and $1,1,k$ contained zones representing relatively good model performance and unusually poor model performance (Figures 7.6 and 7.7, respectively).

A sack of approximately 20 kg of onions was weighed and positioned in the centre of each zone as the container was loaded on August 16. Loading of the vessel took approximately 6 hours occurring from 9 am to 3 pm. Unloading and re-weighing of each sample occurred between 9 am and 3 pm on August 29. Weight loss
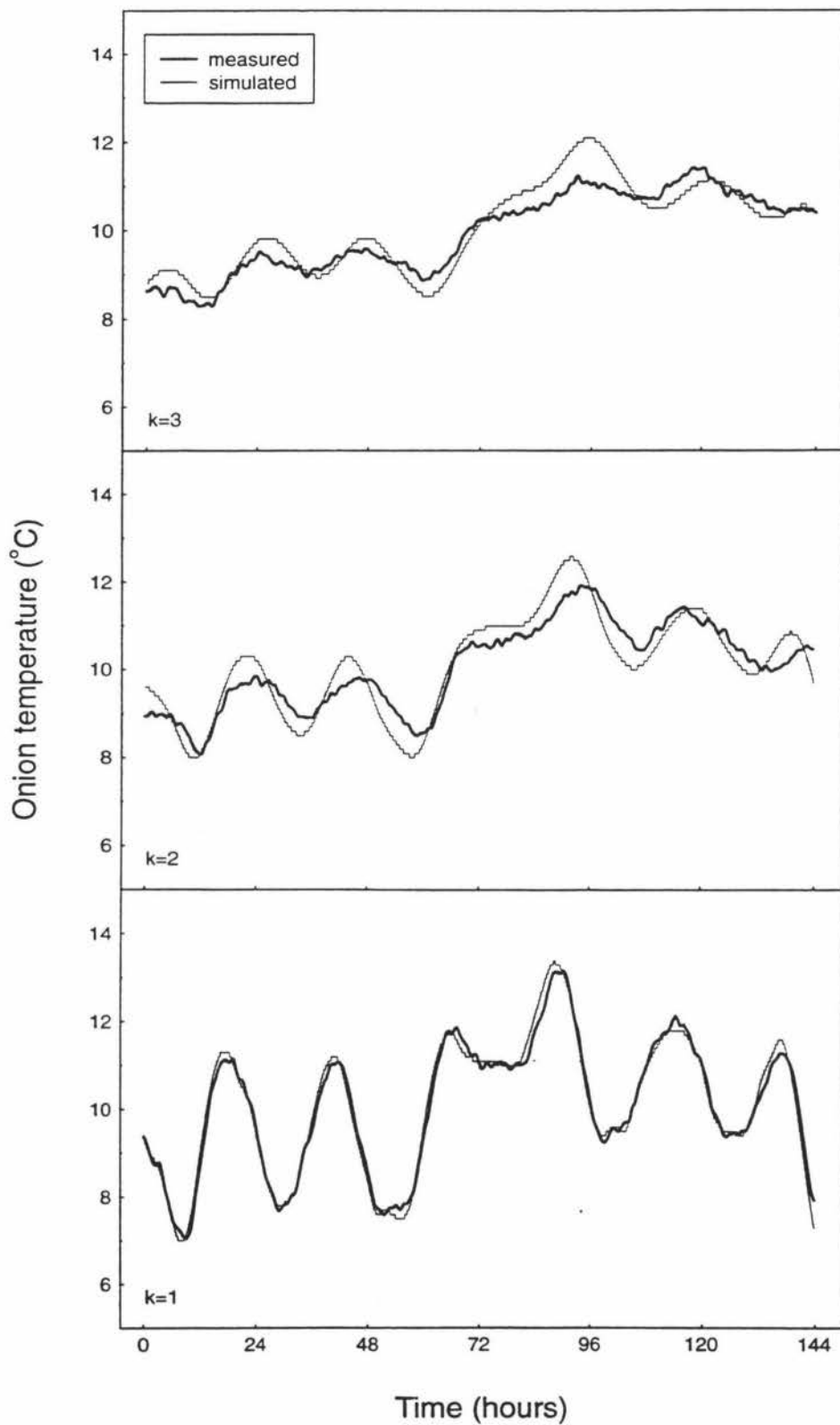
**Figure 7.2** Measured and typical standard model simulation of onion bulb temperature in zone column *3,3,k* from Julian day 233 to 239.
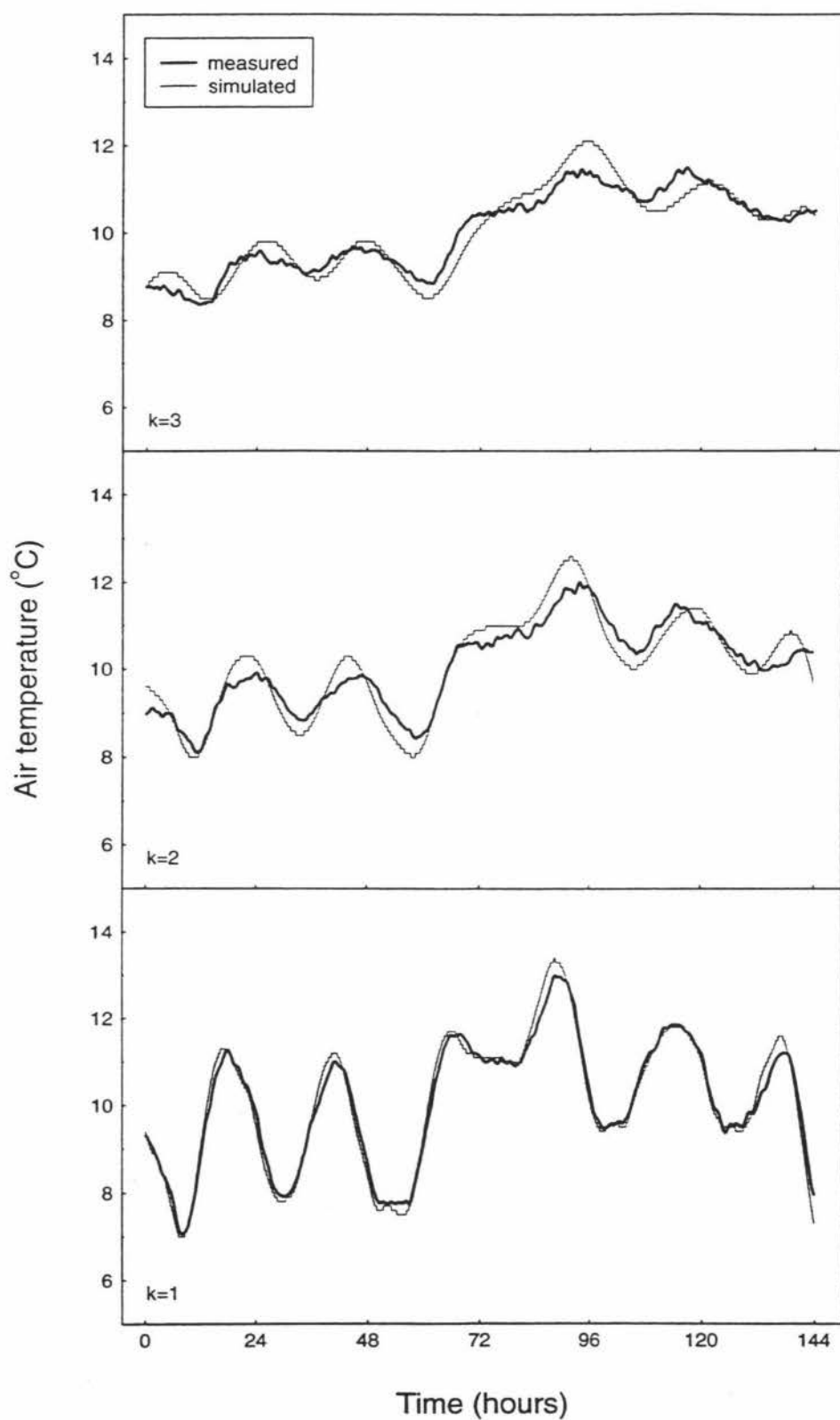
**Figure 7.3** Measured and typical standard model simulation of air temperature in zone column *3,3,k* from Julian day 233 to 239.
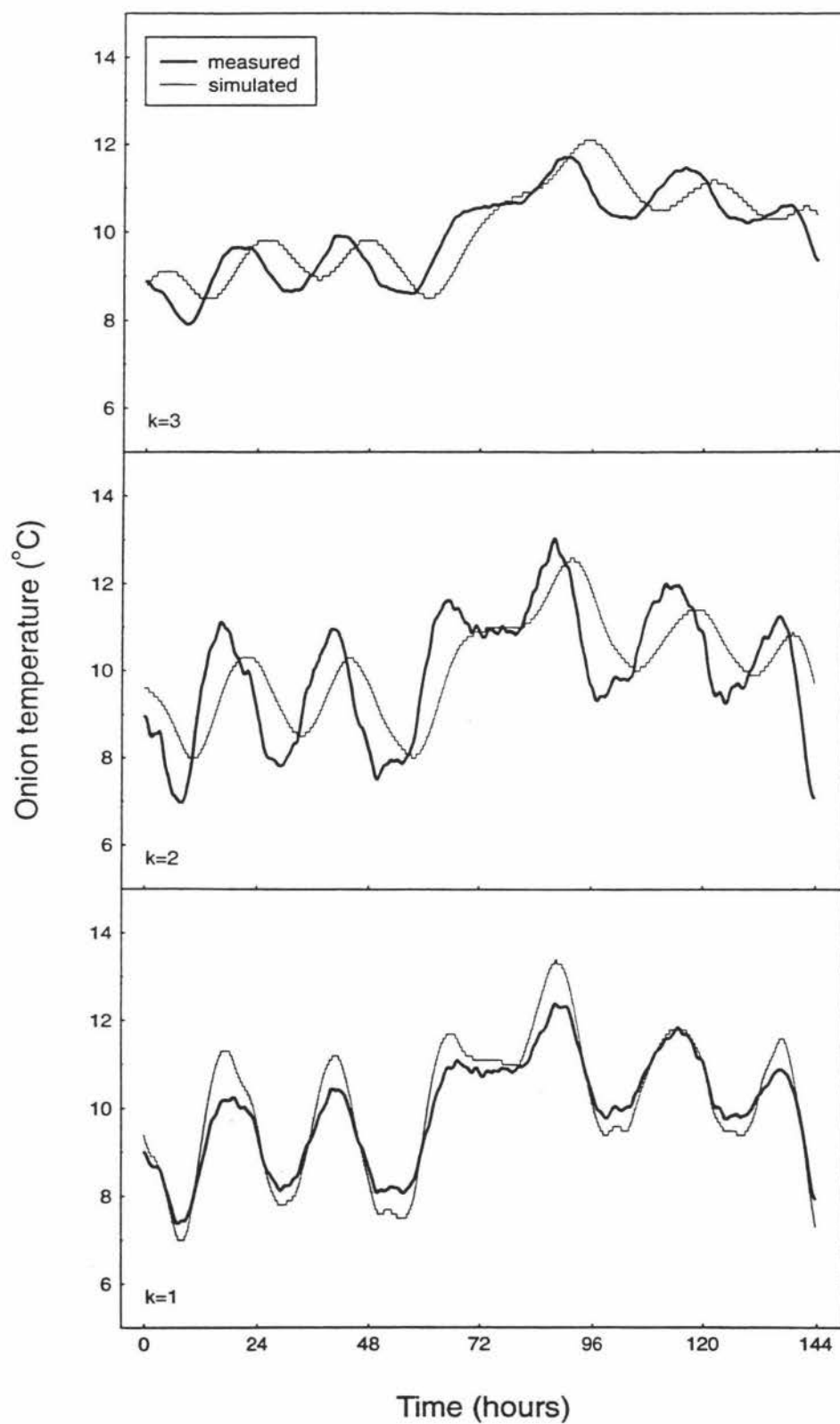
**Figure 7.4** Measured and poor standard model simulation of onion bulb temperature in zone column 2,2,$k$ from Julian day 233 to 239.
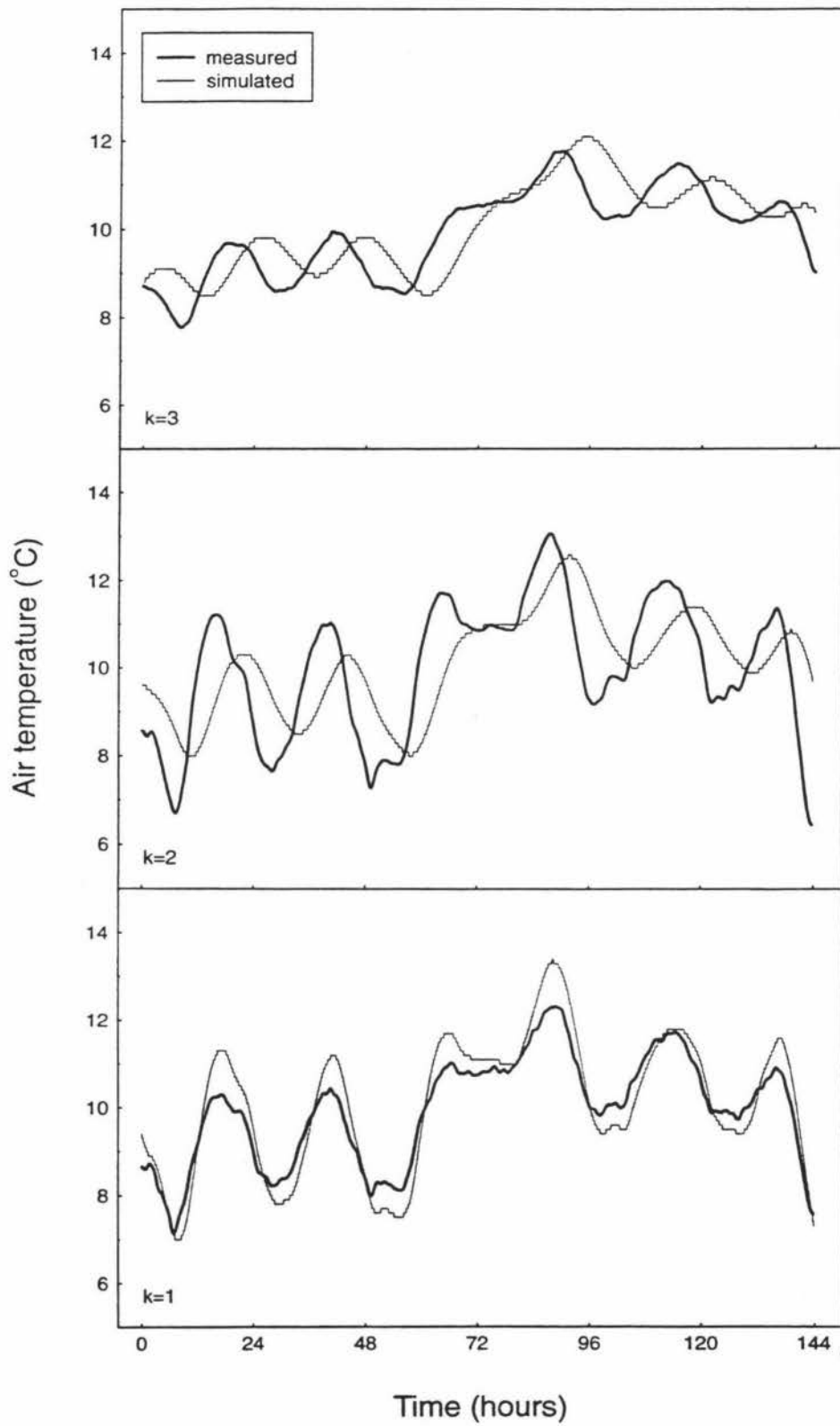
**Figure 7.5** Measured and poor standard model simulation of air temperature in zone column 2,2,k from Julian day 233 to 239.
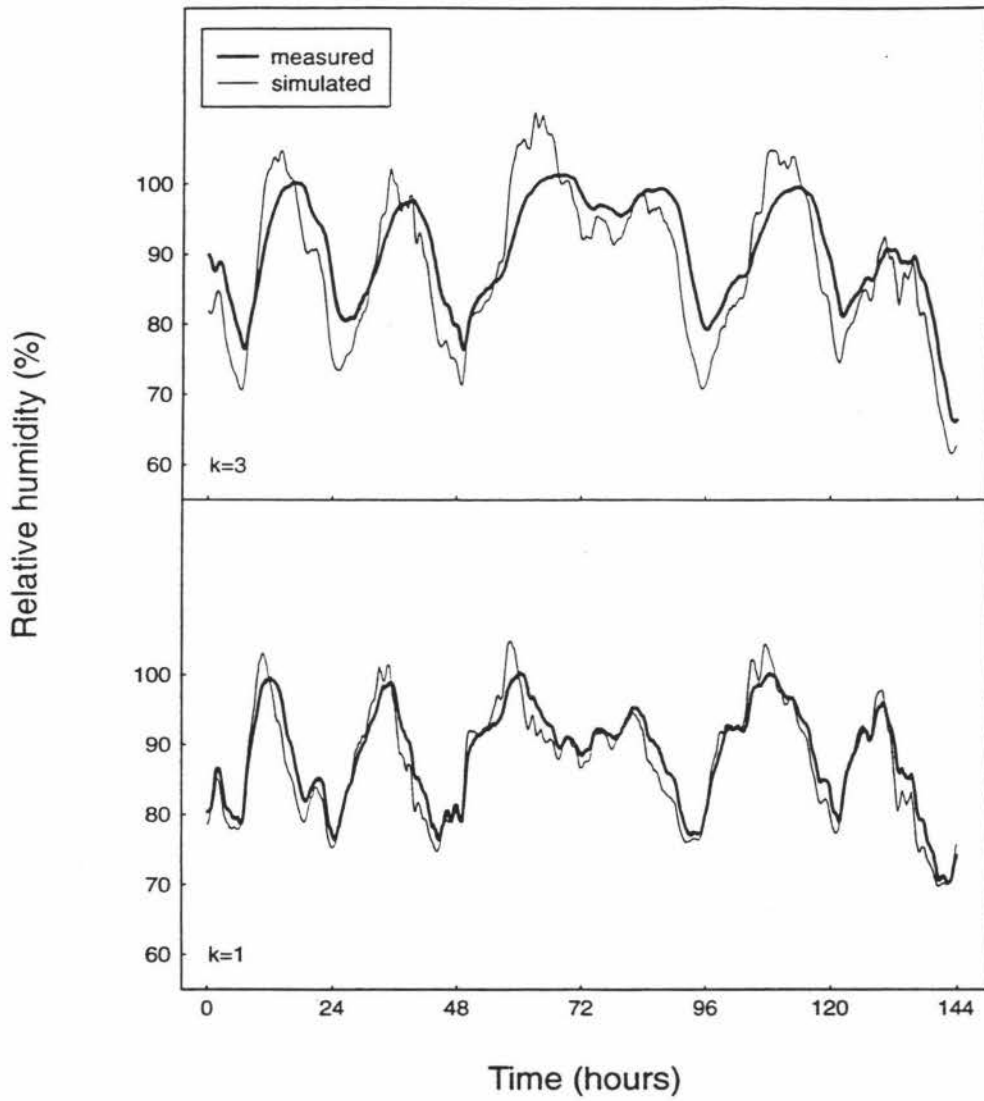
**Figure 7.6** Measured and well predicted standard model simulation of air relative humidity in zone column *1,3,k* from Julian day 233 to 239.
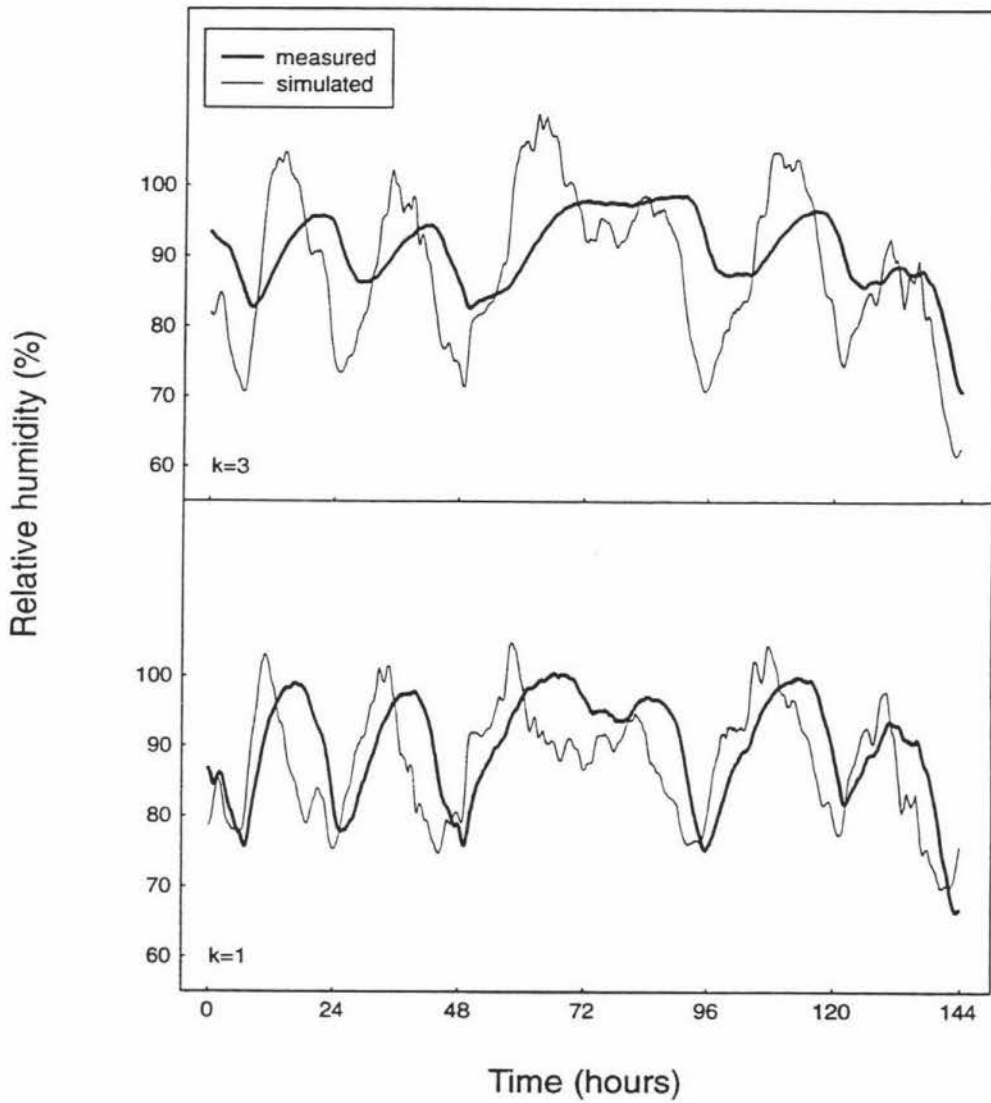
**Figure 7.7** Measured and poor standard model simulation of air relative humidity in zone column *1,1,k* from Julian day 233 to 239.

measurements thus occurred over approximately 312 hours. Collection of model input data commenced after the container was filled and sealed (August 17, 12 pm) and completed prior to its unloading (August 29, 8 am). It was therefore necessary to extrapolate predicted weight loss, which was simulated over 284 hours, in order to coincide with the measured weight loss period. The extent of weight loss extrapolation required was an additional 9.86%. The extrapolation was linear and based on the whole simulation period. This was appropriate as discontinuity between the measured and simulation periods occurred predominantly during a 24 hour period prior to simulation commencement.

Measured weight loss from each sack was used as a basis for estimating weight loss throughout the entire zone. Mass of product in each zone was assumed to be equal. Total loss per zone was calculated based on the fraction of sack weight loss to total sack mass. Measured and simulated weight loss in all zones are illustrated in Figure 7.8.

### 7.2.2.2 *Sensitivity analysis*

Parameters investigated for model performance sensitivity were: heat transfer coefficient, mass transfer coefficient, initial bulb moisture content, respiration rate, and ventilation rate. Model sensitivity due to the rate of energy exchange between bulbs and flowfield as a consequence of a temperature differential was investigated by reduction of the heat transfer coefficient by 10%. Initial bulb moisture content is an input value required in the model initialization file and was a parameter used for determining the mass of the bulb wet and dry fraction, and for calculation of bulb specific heat capacity; model sensitivity to this parameter was measured by reducing its value 10%. The mass transfer coefficient was important not only with respect to its direct and proportional effects on bulb water loss, but also with its effects on bulb temperature as a consequence of evaporative cooling; model sensitivity was evaluated when this parameter was reduced 10%. Respiration rate, affecting bulb temperature and weight loss, was evaluated for sensitivity also using a 10% reduction in this parameter. Finally, the ventilation rate, an important parameter affecting flowfield
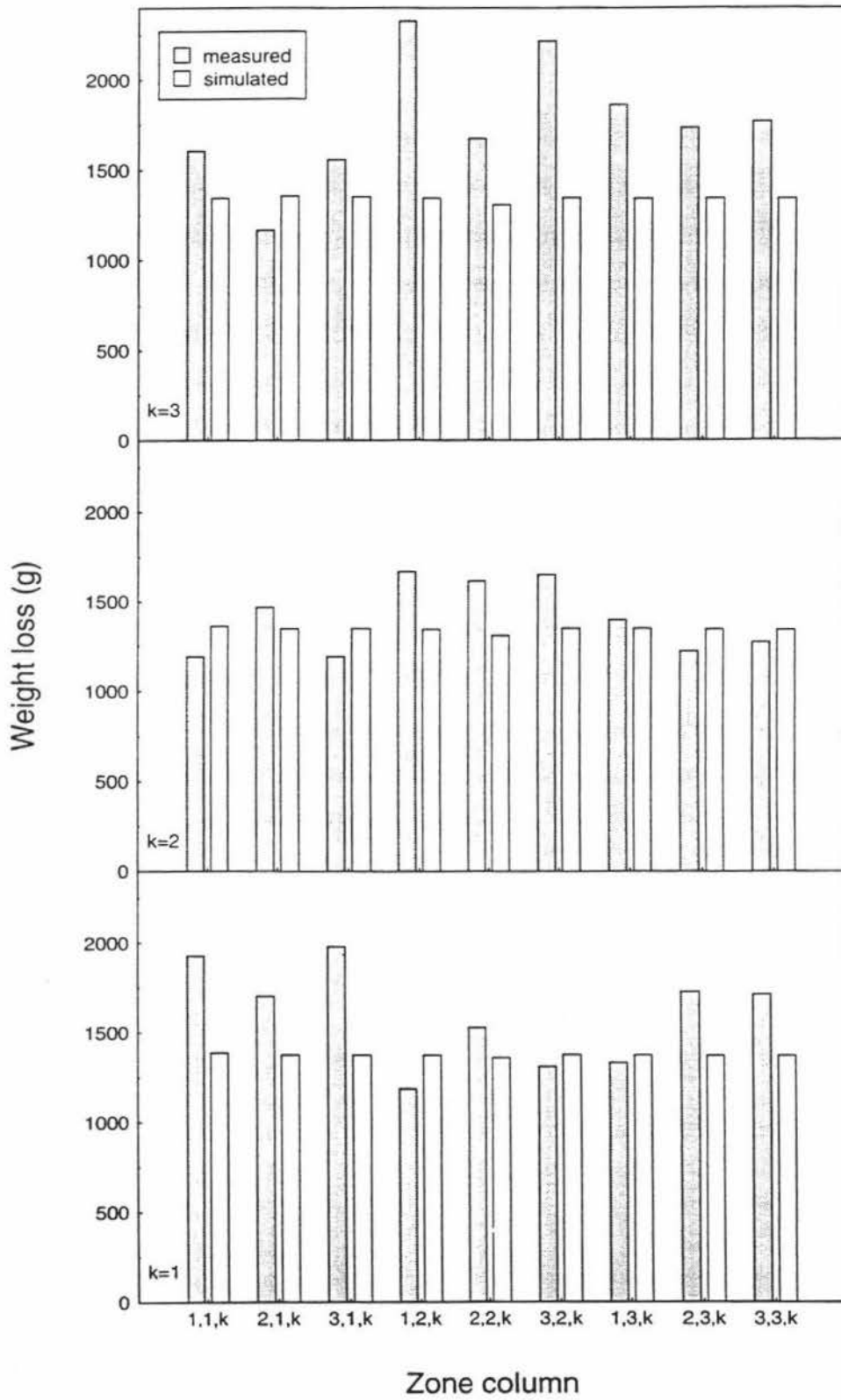
**Figure 7.8** Measured and standard model simulation of onion bulb weight loss in zone $i,j,k$ from Julian day 228 to 241.

velocity was similarly dropped 10% to measure the sensitivity of the model to this factor.

The above parameter modifications were evaluated for model sensitivity using 3 statistics. Firstly, the effect of the parameter on the mean error (ME) between measured and simulated predictions, indicating the mean offset of the model simulation. Secondly, the effect of the parameter on the root mean squared error (RMS) or standard deviation of simulated prediction about measured values. Finally, the effect of the parameter on the correlation coefficient (r), a measure of the degree to which measured and simulated data vary together or a measure of their intensity of association. The errors and correlations between measured data from the container and the standard model simulation for each zone are given in Table 7.1. The degree of sensitivity of the standard model to modifications made to the above mentioned parameters are summarised in Table 7.2. A negative solution to the change in ME and RMS statistic in Table 7.2 represented a reduction of error as a consequence of the parameter modification. The inverse is true for a positive solution. A negative solution to the change in r represented a reduced correlation coefficient as a consequence of the parameter modification.

## Table 7.1

Standard model statistical results for prediction of zone: air temperature, air RH, onion temperature, and onion weight loss, from Julian day 233 to 239.

| Zone | Air temperature | | | Air RH | | | Onion temperature | | | Wt loss |
|------|-----------|------------|-------|-----------|------------|-------|-----------|------------|-------|-----------|
| | ME (°C) | RMS (°C) | r | ME (%) | RMS (%) | r | ME (°C) | RMS (°C) | r | ME (g) |
| 1,1,1 | -0.014 | 0.933 | 0.792 | -2.345 | 8.132 | 0.522 | -0.025 | 0.964 | 0.773 | -540.8 |
| 2,1,1 | -0.023 | 0.833 | 0.842 | - | - | - | -0.026 | 0.384 | 0.968 | -329.8 |
| 3,1,1 | -0.033 | 0.479 | 0.971 | -2.106 | 9.455 | 0.518 | -0.057 | 0.406 | 0.987 | -606.8 |
| 1,2,1 | 0.172 | 1.143 | 0.663 | - | - | - | 0.177 | 1.204 | 0.616 | 187.7 |
| 2,2,1 | 0.135 | 0.551 | 0.946 | - | - | - | 0.125 | 0.503 | 0.958 | -169.1 |
| 3,2,1 | 0.074 | 0.972 | 0.775 | - | - | - | 0.123 | 1.157 | 0.647 | 66.0 |
| 1,3,1 | -0.001 | 0.442 | 0.960 | -0.834 | 2.719 | 0.951 | -0.002 | 0.424 | 0.960 | 40.9 |
| 2,3,1 | 0.002 | 0.280 | 0.983 | - | - | - | -0.033 | 0.328 | 0.982 | -358.5 |
| 3,3,1 | -0.007 | 0.308 | 0.979 | -0.586 | 3.264 | 0.933 | 0.004 | 0.326 | 0.976 | -345.6 |
| 1,1,2 | 0.209 | 0.728 | 0.782 | - | - | - | 0.168 | 0.774 | 0.746 | 170.7 |
| 2,1,2 | 0.148 | 0.490 | 0.911 | - | - | - | 0.100 | 0.542 | 0.881 | -120.4 |
| 3,1,2 | 0.048 | 0.541 | 0.878 | - | - | - | 0.088 | 0.613 | 0.840 | 154.3 |
| 1,2,2 | 0.320 | 0.745 | 0.801 | - | - | - | 0.245 | 0.747 | 0.782 | -325.4 |
| 2,2,2 | 0.099 | 1.329 | 0.535 | 0.565 | 7.725 | 0.867 | 0.093 | 1.139 | 0.642 | -307.6 |
| 3,2,2 | 0.208 | 0.662 | 0.827 | - | - | - | 0.254 | 0.731 | 0.792 | -301.1 |
| 1,3,2 | 0.094 | 0.529 | 0.885 | - | - | - | 0.039 | 0.519 | 0.886 | -49.4 |
| 2,3,2 | 0.059 | 0.617 | 0.835 | - | - | - | 0.054 | 0.611 | 0.839 | 121.9 |
| 3,3,2 | 0.029 | 0.412 | 0.931 | - | - | - | 0.033 | 0.476 | 0.906 | 67.8 |
| 1,1,3 | 0.163 | 0.572 | 0.833 | -2.312 | 9.594 | 0.511 | 0.144 | 0.603 | 0.815 | -261.8 |
| 2,1,3 | 0.001 | 0.751 | 0.698 | - | - | - | -0.034 | 0.763 | 0.696 | 186.8 |
| 3,1,3 | 0.063 | 0.482 | 0.876 | -0.498 | 4.536 | 0.944 | 0.049 | 0.553 | 0.837 | -206.3 |
| 1,2,3 | 0.288 | 0.539 | 0.889 | - | - | - | 0.259 | 0.527 | 0.886 | -983.7 |
| 2,2,3 | 0.121 | 0.712 | 0.749 | - | - | - | 0.098 | 0.615 | 0.811 | -367.2 |
| 3,2,3 | 0.361 | 0.600 | 0.876 | - | - | - | 0.315 | 0.636 | 0.839 | -870.4 |
| 1,3,3 | 0.007 | 0.413 | 0.910 | -1.902 | 5.559 | 0.896 | 0.025 | 0.421 | 0.907 | -518.2 |
| 2,3,3 | 0.122 | 0.433 | 0.908 | - | - | - | 0.093 | 0.428 | 0.907 | -389.8 |
| 3,3,3 | 0.026 | 0.374 | 0.926 | -2.631 | 10.634 | 0.313 | 0.115 | 0.429 | 0.909 | -427.4 |
| x̄ | 0.099 | 0.625 | 0.850 | -1.741 | 7.547 | 0.649 | 0.090 | 0.623 | 0.844 | -240.1 |

**Table 7.2**

Model sensitivity (mean of all zones) to a 10% reduction ($\downarrow$) of: heat transfer coefficient ($h_c$), mass transfer coefficient ($k_{t(r)}$), initial bulb moisture content (W), respiration rate ($r_h$ & $rr_C$), and ventilation rate (v).

| Parameter | Air temperature | | | Air RH | | | Onion temperature | | | Wt loss |
|---|---|---|---|---|---|---|---|---|---|---|
| | $\Delta$ME (°C) | $\Delta$RMS (°C) | $\Delta$r | $\Delta$ME (%) | $\Delta$RMS (%) | $\Delta$r | $\Delta$ME (°C) | $\Delta$RMS (°C) | $\Delta$r | $\Delta$ME (g) |
| $\downarrow h_c$ | 0.000 | 0.000 | 0.000 | 0.000 | -0.001 | 0.000 | 0.000 | 0.000 | 0.000 | 0.0 |
| $\downarrow k_{t(r)}$ | 0.004 | 0.001 | 0.000 | 0.039 | 0.023 | 0.000 | 0.004 | 0.000 | 0.000 | 87.8 |
| $\downarrow$ W | 0.007 | 0.032 | -0.011 | 0.038 | 0.149 | -0.013 | 0.009 | 0.031 | -0.011 | 1.9 |
| $\downarrow r_h$ & $rr_C$ | -0.006 | -0.002 | 0.000 | -0.003 | -0.006 | 0.000 | -0.006 | -0.001 | 0.000 | 47.5 |
| $\downarrow$ v | -0.013 | -0.055 | 0.019 | -0.096 | -0.281 | 0.022 | -0.013 | -0.052 | 0.019 | -2.8 |

### 7.2.3 Discussion

#### 7.2.3.1 *Respiration rate*

Lowering of simulated respiration rate was required due to signs of sprouting at the time of experimental evaluation of this parameter; evidence that the crop was exiting the dormancy phase (hence respiring at elevated levels). This occurrence was an oversight in light of the crop samples being maintained in cold storage at approximately 1-3°C. Preliminary model simulations revealed overestimated bulb and air temperatures of approximately 0.5°C in all zones, a likely consequence of increased bulb respiratory processes. Tanaka et al. (1985) reported that at the break of dormancy, bulbs stored at 15 and 25°C, respectively exhibited enhanced respiration rates of approximately 6 and 4 times that experienced during mid dormancy. Bulbs stored at 0 and 5°C, showed accentuated respiration rates of 2 and 3 times that previously experienced at mid dormancy, respectively. Similarly, Ward

and Tucker (1976) commented that onion bulb respiration rate was significantly elevated after approximately 5 months storage.

The onion samples were assessed for $CO_2$ production approximately 3 months after the container trial at 8 temperatures between 0 and 35°C. Onions exhibiting signs of sprouting were omitted from the experiment, nevertheless it could be assumed that bulb respiration rate had significantly increased from the time of the storage trial. Respiration rate was therefore reduced to 20% of that measured during the experimental period, consistent with that suggested by Tanaka et al. (1985). The response of simulated onion and air temperature improved reducing temperature offset.

Another check on respiration rate was made by considering the air temperature rise through the container. Measured container inlet and outlet temperatures averaged over the storage trial period were within 0.1°C of each other. With the mean temperature during this period of 10°C, respiratory heat generation according to Equation 5.14 for 15000 kg of onions would be 434 W. From the following relationship the increase in mean outlet air temperature due to respiratory heat can be estimated:

$$\Delta T_a = \frac{r_h\ 15000}{\rho\ v\ C_p} \qquad (7.1)$$

where:

$\Delta T_a$ = temperature change of air (°C)

$r_h$ = heat of respiration (W.kg$^{-1}$)

$\rho$ = density of air (g.m$^{-3}$)

v = volumetric air flow rate (m$^3$.s$^{-1}$)

$C_p$ = specific heat capacity of air (J.g$^{-1}$.°C$^{-1}$)

Equation 7.1 predicts mean outlet air temperature increase to be 0.49°C, considerably higher than the measured outlet temperature difference. This further supports the assumption that respiratory heat generation at the time of the containerized onion storage trial was about 20% of that occurring during the time of experimental respiratory heat determination.

### 7.2.3.2 *Onion and air temperature*

Figures 7.2 and 7.3 illustrate relatively consistent symmetry between measured and predicted temperature data. Poorly predicted zones shown in Figures 7.4 and 7.5 illustrated consistency of over and underestimation of onion and air temperature with all 6 zones registering small ME. More suitable statistics for evaluating the degree of overall model fit is RMS error and r, the former representing the standard deviation of predicted about measured data. These are given for each zone in Table 7.1. Averaged across all zones onion and air temperature RMS equated to 0.623 and 0.625°C. The RMS statistic for zones in column $3,3,k$ for onion and air temperature is relatively small indicating a good model fit (Figures 7.2 and 7.3). Zones in column $2,2,k$ demonstrated some of the highest RMS errors indicating an unusually poor model fit (Figures 7.4 and 7.5).

An explanation for the poor model fit in zone column $2,2,k$ can most likely be attributed to a disturbance in porous bed ventilation. From Figures 7.4 and 7.5 observation of measured temperatures in the upper zones of the columns reveal a quicker response with increased sensitivity to temperature fluctuations. Enhanced ventilation in this area of the bed would explain such an occurrence.

### 7.2.3.3 *Relative humidity*

Relative humidity was simulated with less accuracy than was temperature. This occurrence was expected as RH is considerably more difficult to measure accurately. Simulated ME was relatively small with a maximum discrepancy of -3.5% measured in zone $3,1,3$ and an average discrepancy across all measured zones of only -1.7%

(Table 7.1). The average RMS error across all measured zones was 7.5%. Figure 7.6 illustrates zones *1,3,1* and *1,3,3* as having reasonably good RH simulations with RMS errors of 2.7 and 5.6%. respectively, and r values of 0.951 and 0.896, respectively. Figure 7.7 illustrates exceptionally poor predicted zones *1,1,1* and *1,1,3* with RMS errors of 8.1 and 9.6%, respectively, and r values of 0.522 and 0.511, respectively.

Absolute humidity of the air was simulated without consideration of saturated absolute humidity. This was a shortcoming of the model as transformation of this property to RH revealed predictions in excess of 100%. The model did not consider the condensation of super saturated air on the container walls and product. For the later the driving force for mass transfer would be the air/product surface differential, as apposed to the air/product sub-surface differential for transpiration. The product skin mass transfer coefficient given in Equation 5.16 would not be applicable, hence resistance to water vapour transfer would be considerably less causing a relatively rapid response of condensation of super saturated air. This may have prevented RH predictions exceeding 100%, or if not, would certainly have reduced the error significantly.

RMS errors and correlation coefficients revealed dramatic variability in predicted RH across zones, contrasting with simulated temperature statistics. Prediction of RH in column *1,3,k* shows from Table 7.1 that the bottom zone $(3,3,1)$ is simulated with the second highest level of accuracy whilst the top zone $(3,3,3)$ is simulated with the lowest degree of accuracy. Measured RH from a number of probes were found to exceed 100%, occasionally registering up to 110%. Probe anomalies were also discovered during the transpiration experiment where the devices used in the container bulb storage trial were used to monitor the RH generating pressure drop system (section 5.1.6). A number of probes were found to respond slowly to changes in RH. This circumstance would explain inconsistencies between response times of measured and simulated RH in Figure 7.7. Examination of r and RMS error in Table 7.1 for RH indicate a general trend where both statistics are either reasonably good

or very poor between zones, possibly a consequence of quick and slow responding probes.

### 7.2.3.4  *Weight loss*

Weight loss from each zone over the entire bulb storage period (312 hours) is given in Figure 7.8. An analysis of variance statistic was utilized for the evaluation of a significant difference between measured and simulated weight loss in each layer.

The simulation predicted bulb weight loss in the central zone layer $(i,j,2)$ relatively well. An analysis of variance at the 5% level revealed that no significant difference existed between measured and simulated weight loss in this layer. Simulated bulb weight losses in the top and bottom layers $(i,j,1)$ and $(i,j,3)$ show a general underprediction which was supported by an analysis of variance revealing a significant difference between measured and simulated weight loss, at the 5% level. Mean zone weight loss in the bottom layer $(i,j,1)$ for measured and simulated bulbs was 1603.2 and 1374.8 g, respectively. Mean zone weight loss in the top layer $(i,j,3)$ for measured and simulated bulbs was 1768.2 and 1341.9 g, respectively. The reason for such discrepancy between measured and simulated bulb weight loss in these layers is unclear. A possible hypothesis for underprediction of weight loss could be attributed to a change in the skin mass transfer coefficient. The transpiration experiment quantifying bulb moisture loss for the simulation was conducted 3 months after the container storage trial. Although the bulb samples were maintained in cold storage and under a relatively high humidity, water loss during this period, causing some skin shrinkage, may have increased skin resistance to moisture transfer. Pieniazek (1944) and Lentz and Rooke (1964) reported this circumstance occurring at high vapour pressure deficits. The same occurrence at low vapour pressure deficits could be possible over long periods of time. However, this hypothesis fails to explain why the discrepancy was not evident in the central layer.

In Figure 7.8 a large variability in measured weight loss between zones in the upper and lower layers can be observed. Biological factors such as disease infection and

sprouting have been noted as enhancing weight loss and causing variable rates of moisture loss under steady environmental conditions (Rajapakse et al. 1992), but signs of these factors were not evident during loading and unloading of the container. Alternatively, sacks containing bulbs with damaged skins placed in the upper and lower layers may have been responsible for the high degree of measured weight loss variability. Damaged or loose skins have been reported to dramatically increase onion moisture loss (Karmarker and Joshi 1941; Apeland 1971).

As it is difficult to ascertain a reason for such variability in measured onion weight loss between zones, the model simulation of weight loss performed as expected. Mean simulated weight loss from zones in the bottom layer was highest at 1374.8 g and found by analysis of variance to be significantly different from weight loss experienced in other layers at the 5% level. A decrease of vapour pressure deficit in the upper layers would be expected as moisture is transferred from bulbs to air in zone $i,j,k$, then travels on to zone $i,j,k+1$. Mean zone simulated weight loss for layers $i,j,2$ and $i,j,3$ were 1345.2 and 1341.9 g, respectively. Although an analysis of variance indicated no significant difference between these layers, it was possible that enhanced carbon weight loss, as a consequence of steady bulb temperatures, compensated for a reduction in moisture weight loss in the top layer. Unexplained variability in the measured data presents difficulties concerning the verification of simulated results, particularly when weight loss was modelled with respect to position. As discussed above, the simulation did predict weight loss as significantly different between the bottom layer, and weight loss in the centre and top layers. However, it was apparent that measured weight loss was not sufficiently stable enough to support this result. It was considered that overall weight loss was simulated reasonably well considering the unpredictable behaviour and response of the bulbs. Simulated zone weight loss underpredicted measured weight loss in layers $i,j,1$, $i,j,2$, and $i,j,3$ on average by 14.2, 4.6, and 24.1%, respectively.

### 7.2.3.5 *Sensitivity analysis*

Summarized results of simulation sensitivity are presented in Table 7.2. The mean error, root mean squared error, and correlation coefficient were determined for the standard model output for zone air temperature, zone air RH, and zone onion temperature. Only the mean error was suitable for weight loss output. Modifications were made to the standard model, separately reducing by 10% each of the thermophysical parameters listed in Table 7.2 and regenerating new statistics with respect to the measured data. The difference or change ($\Delta$) between the standard model statistic and modified standard model statistic are listed indicating the degree of model sensitivity. A negative statistic for ME and RMS is interpreted as a reduction in error or improvement in model fit; a negative change for r is given as a reduction in correlation or a poorer model fit. As previously discussed the RMS and r statistic are more appropriate measures of general model fit or performance.

The sensitivity analysis revealed that a reduction of the heat transfer coefficient by 10% had virtually no effect on the bulb and flowfield properties. Model sensitivity to a reduction in the mass transfer coefficient by 10% was minimal for general fit of air and onion temperature although a relatively minor shift in mean air and onion temperature and RH was registered. As expected onion weight loss was very sensitive to this parameter with a change in mean error of 87.8 g equating to 6.5%. Bulb weight loss was also sensitive to respiration rate with a change in mean error of 47.5 g or 3.5%. Minor improvements from reduced respiration rate were evident with all temperature predictions although not enough to register an improvement in r. Initial bulb moisture content was the next sensitive parameter for general temperature and RH. A reduction of this parameter by 10% registered a relatively large change in RMS and r statistic.

Table 7.2 revealed that the most sensitive parameter to model simulation performance for air and onion temperature and air RH was the ventilation rate. Sensitivity was almost double that of initial bulb moisture content, and in general many times more

sensitive than the other evaluated parameters. A minor change in mean error for bulb weight loss was also noted.

## 7.3 MODIFIED MODEL SIMULATION

### 7.3.1 Introduction

The sensitivity analysis identified that ventilation rate was a critical factor influencing model performance. The standard model assumed air velocity up each zone to be equal, meeting the design criteria of the ventilation system. Air pressure measurements taken below and above each zone column during the container storage trial indicated some irregularity in ventilation rate between zone columns. With respect to the sensitivity of this flowfield property, air flow up each zone column was adjusted in accordance with measured air pressure data given in Appendix A2. The following relationship of proportionality was used to establish flow rate up each column:

$$v \propto \sqrt{\Delta P_{z11}} \qquad (7.2)$$

where:

v        =        volumetric air flow of zone air ($m^3.s^{-1}$)

$\Delta P_{z11}$   =        air pressure difference vertically across zone column (Pa)

Although pressures taken on August 18 and 26 were in good agreement, the later measurements were utilized due to poor weather conditions during data collection on August 18. With adjustments made to the ventilation rate (Appendix A3), the new simulation was referred to as the modified model.

## 7.3.2  Results

The modified model performance was evaluated in a similar manner to the standard model using graphical evaluation and a sensitivity analysis.

### 7.3.2.1  *Graphical evaluation*

To avoid unnecessary repetition only a few selective zones of the modified model simulation were illustrated graphically, namely typical or well predicted zones presented for the standard model.  Visual comparison between both models was therefore possible.

Modified model simulation of onion bulb and air temperature for zone column $3,3,k$ are illustrated in Figure 7.9 and 7.10, respectively.  Predicted RH for zone column $1,3,k$ for the modified model is given in Figure 7.11.  Poorly simulated zone columns $2,2,k$ and $1,1,k$ illustrated for the standard model for temperature (onion and air) and RH, respectively, were not presented for the modified model as simulated improvement was difficult to detect graphically.  Weight loss was also omitted from graphical presentation as only relatively minor responses were evident for this bulb property as revealed from the sensitivity analysis (Table 7.2).

### 7.3.2.2  *Statistical analysis*

The modified simulation was analyzed utilising the ME, RMS, and r statistics.  Table 7.3 details each statistic for each zone with respect to onion temperature, air temperature, and air RH; weight loss was analyzed with the ME statistic.  Results of the simulation in Table 7.3 are presented as a change or deviation of the statistic from the standard model.  As with the sensitivity analysis, a negative solution to the change in ME and RMS statistic is interpreted as a reduction in error; positive solution is an increased error.  A negative change in the r statistic represents a reduction in correlation; positive change indicates an improved correlation.
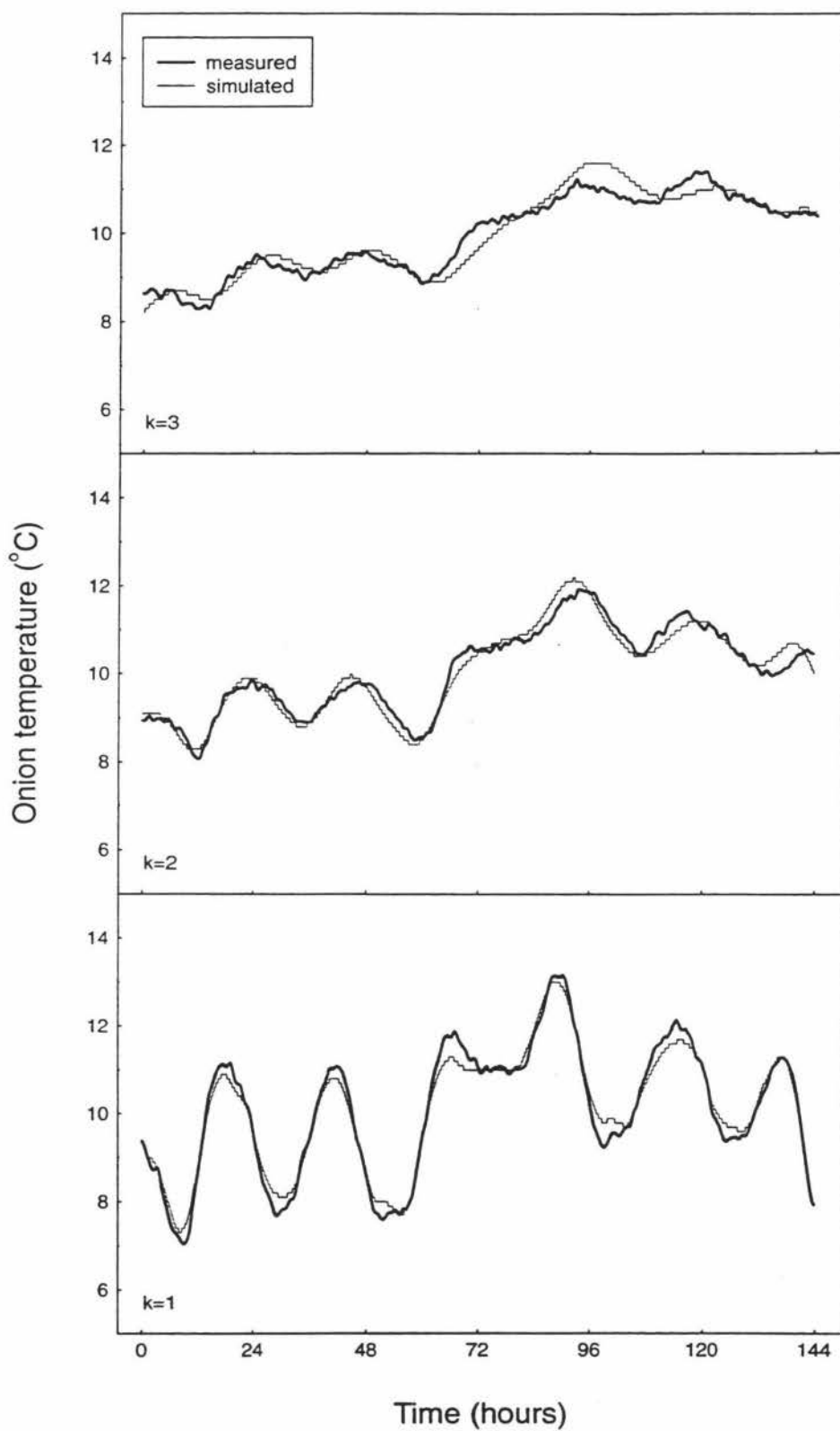
**Figure 7.9** Measured and typical modified model simulation of onion bulb temperature in zone column *3,3,k* from Julian day 233 to 239.
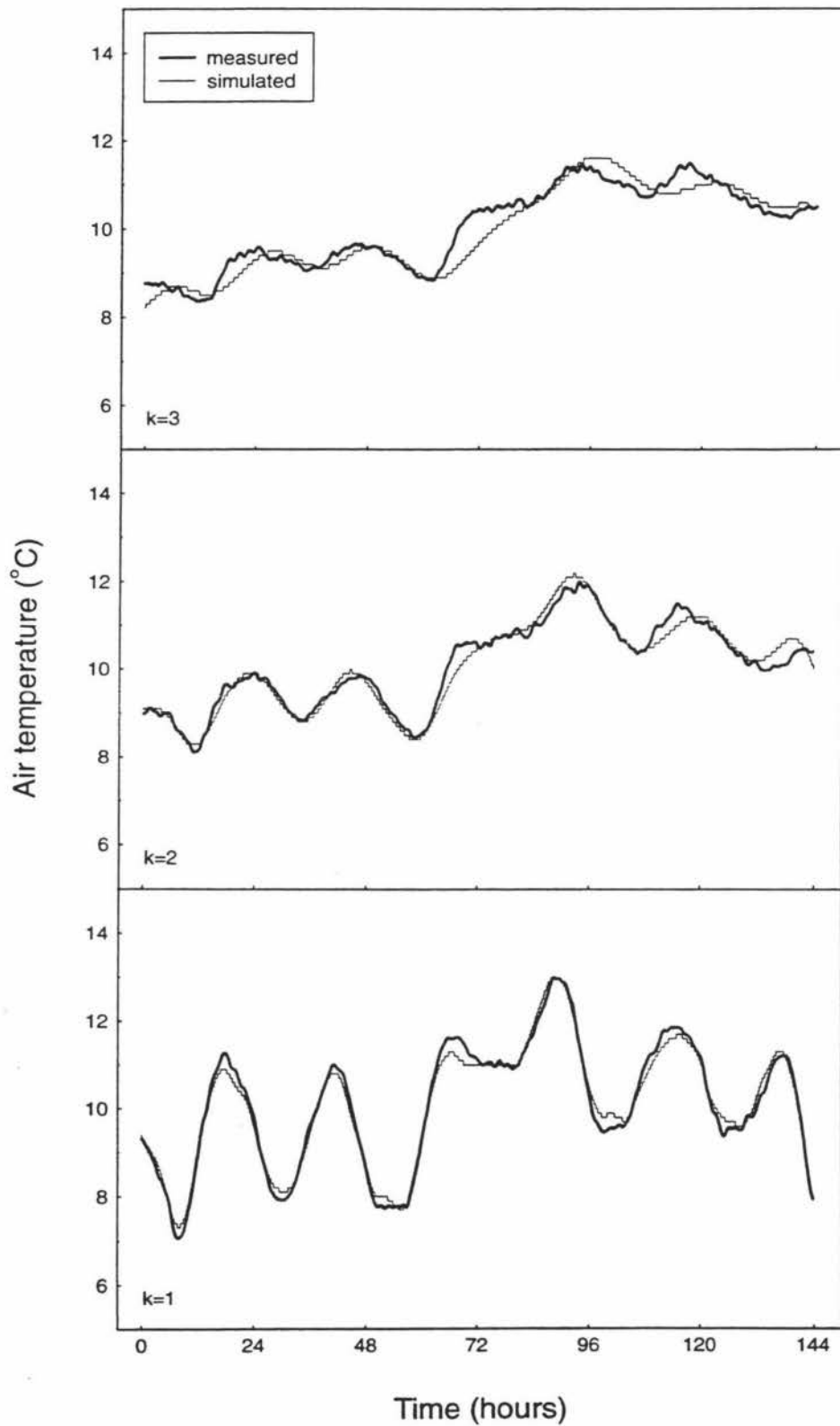
**Figure 7.10** Measured and typical modified model simulation of air temperature in zone column *3,3,k* from Julian day 233 to 239.
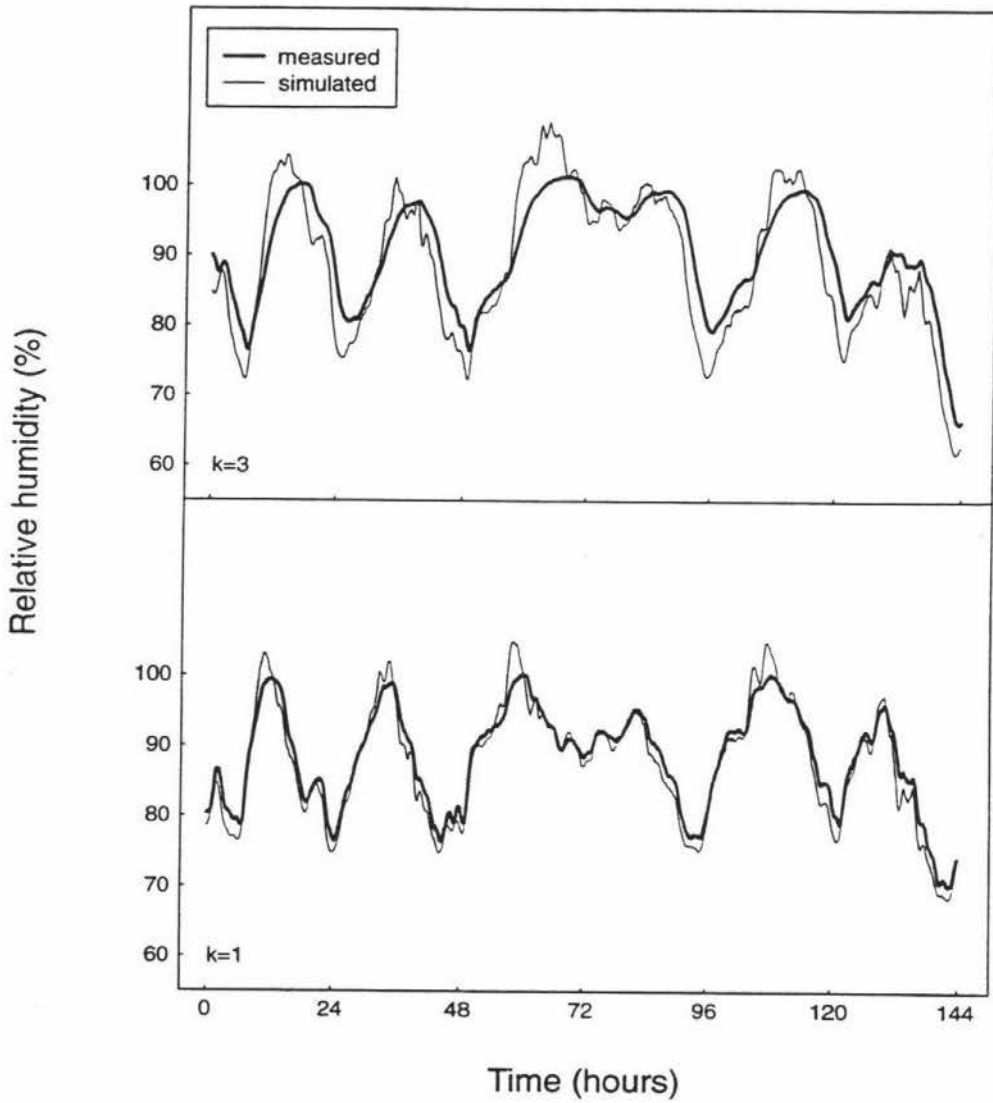
**Figure 7.11** Measured and well predicted modified model simulation of air relative humidity in zone column *1,3,k* from Julian day 233 239.

## Table 7.3

Modified model statistical results specifying degree of improved or unimproved prediction of zone: air temperature, air RH, onion temperature, and onion weight loss, from Julian day 233 to 239.

| Zone | Air temperature | | | Air RH | | | Onion temperature | | | Wt loss |
|---|---|---|---|---|---|---|---|---|---|---|
| | ΔME (°C) | ΔRMS (°C) | Δr | ΔME (%) | ΔRMS (%) | Δr | ΔME (°C) | ΔRMS (°C) | Δr | ΔME (g) |
| 1,1,1 | 0.001 | -0.163 | 0.048 | -0.037 | -0.580 | 0.080 | 0.001 | -0.163 | 0.049 | 9.1 |
| 2,1,1 | 0.012 | -0.397 | 0.095 | - | - | - | 0.013 | -0.008 | 0.000 | 26.7 |
| 3,1,1 | 0.005 | -0.347 | 0.027 | 0.018 | -0.252 | 0.014 | 0.005 | -0.044 | -0.004 | -31.3 |
| 1,2,1 | -0.006 | -0.310 | 0.109 | - | - | - | -0.007 | -0.308 | 0.114 | -23.0 |
| 2,2,1 | -0.009 | -0.107 | 0.005 | - | - | - | -0.009 | -0.206 | 0.018 | 33.5 |
| 3,2,1 | -0.009 | -0.369 | 0.106 | - | - | - | -0.009 | -0.363 | 0.131 | -49.6 |
| 1,3,1 | 0.001 | -0.147 | 0.016 | -0.061 | -0.539 | 0.046 | 0.001 | -0.097 | 0.012 | -23.1 |
| 2,3,1 | 0.000 | 0.153 | -0.019 | - | - | - | 0.004 | 0.170 | -0.017 | 13.9 |
| 3,3,1 | 0.005 | -0.024 | 0.002 | -0.077 | -0.335 | 0.030 | -0.003 | 0.031 | -0.002 | 19.8 |
| 1,1,2 | -0.021 | -0.127 | 0.055 | - | - | - | -0.020 | -0.120 | 0.055 | -2.2 |
| 2,1,2 | -0.083 | -0.177 | 0.038 | - | - | - | -0.082 | -0.251 | 0.073 | 2.9 |
| 3,1,2 | 0.023 | 0.408 | -0.128 | - | - | - | 0.023 | 0.410 | -0.144 | 26.3 |
| 1,2,2 | -0.059 | -0.268 | 0.015 | - | - | - | -0.059 | -0.259 | 0.113 | 6.6 |
| 2,2,2 | -0.075 | 0.071 | -0.091 | 0.482 | -0.182 | -0.023 | -0.075 | 0.109 | -0.106 | 23.6 |
| 3,2,2 | -0.075 | -0.319 | 0.119 | - | - | - | -0.075 | -0.309 | 0.129 | 3.0 |
| 1,3,2 | -0.032 | -0.183 | 0.057 | - | - | - | -0.031 | -0.167 | 0.053 | 5.2 |
| 2,3,2 | -0.037 | -0.209 | 0.080 | - | - | - | -0.038 | -0.199 | 0.028 | -6.8 |
| 3,3,2 | -0.014 | -0.124 | 0.027 | - | - | - | -0.023 | -0.172 | 0.047 | -7.5 |
| 1,1,3 | -0.053 | -0.087 | 0.040 | -0.295 | -0.717 | 0.057 | -0.052 | -0.079 | 0.038 | -5.5 |
| 2,1,3 | 0.164 | -0.146 | 0.116 | - | - | - | 0.165 | -0.133 | 0.113 | 33.2 |
| 3,1,3 | 0.072 | 0.354 | -0.154 | 0.377 | 1.755 | -0.178 | 0.073 | 0.331 | -0.151 | -8.9 |
| 1,2,3 | -0.126 | -0.188 | 0.059 | - | - | - | -0.126 | -0.174 | 0.056 | -18.5 |
| 2,2,3 | -0.090 | -0.027 | 0.008 | - | - | - | -0.044 | 0.012 | -0.015 | -6.1 |
| 3,2,3 | -0.152 | -0.219 | 0.069 | - | - | - | -0.152 | -0.186 | 0.066 | -24.5 |
| 1,3,3 | 0.065 | 0.019 | -0.009 | -0.454 | -0.949 | 0.029 | 0.029 | 0.018 | -0.010 | -9.4 |
| 2,3,3 | -0.084 | -0.112 | 0.036 | - | - | - | -0.085 | -0.104 | 0.035 | -11.1 |
| 3,3,3 | 0.042 | -0.020 | 0.007 | -0.551 | -0.999 | 0.092 | -0.094 | -0.097 | 0.030 | -11.9 |
| x̄ | -0.020 | -0.114 | 0.027 | -0.066 | -0.311 | 0.016 | -0.025 | -0.087 | 0.026 | -1.3 |

### 7.3.3 Discussion

Results of the statistical analysis for the modified model given in Table 7.3 show a general improvement in simulation performance over the standard model. Visual comparison of predicted onion bulb temperature for zone column *3,3,k* between standard and modified models (Figures 7.2 and 7.9, respectively) illustrate an improved model fit, supported by a reduced RMS error and improved r statistic. Air temperature for this column improved in middle and upper layers but the statistical analysis revealed a minor reduced fit in the bottom layer (Figure 7.10). An improved modified model fit for predicted RH in zone column *1,3,k* is evident by comparison of Figures 7.6 and 7.11, and from Table 7.3.

A reduction in the error statistic for the modified model for most zones generally demonstrates enhanced model performance, as does the increase in correlation coefficient. Mean statistical results across all zones for the modified model are given in Table 7.3.

### 7.4 OVERALL DISCUSSION

Model simulations were evaluated over 6 of the 13 days that bulb and flowfield properties were monitored during the storage trial. Computing limitations due to large data acquisitions recorded over the storage period prevented the full graphical and statistical analysis of the simulations. However, diurnal responses of temperature and RH over 6 days offered sufficient variability to test model performance.

As discussed previously, an important preliminary adjustment made to the standard model was necessary. Bulb respiration rate was reduced to 20% of its measured value due to suspected increases in this property between the period of the storage trial and that of respiration rate evaluation. Adjustments to this parameter were consistent with the findings of Ward and Tucker (1976) and Tanaka et al. (1985), and in accordance with the analysis of container ventilated inlet and outlet air

temperatures with respect to energy gains from product respiratory heat (Equation 7.1).

Generally, onion and air temperatures were predicted with an acceptable degree of accuracy with exception to one particularly poor predicted zone column (Figures 7.4 and 7.5). Temperatures in this column were found to respond more quickly and dramatically in the upper layers than the simulation predicted, most likely as a consequence of a pallet stationed upright in this column acting as a ventilation aid. With the model performance established as being sensitive to ventilation rate, further evidence was obtained that the pallet was responsible for predicted temperature anomalies.

Model prediction of RH was very variable. The modified model predicted this parameter in zone _1,3,1_ with a high degree of accuracy; RMS of 2.18% and r of 0.997. Yet in zone _3,3,3_, where temperature was predicted well, simulation fit for RH was extremely poor; RMS of 9.64% and r of 0.405. Some probes at high RH were found to register significantly larger errors than specified by their manufacturers. This combined with the discovery of variable probe response time to RH fluctuation casts suspicion on measured data in some zones. However, the high correlations for RH obtained in 4 of the 9 measured zones, whilst also considering probe error, suggested that simulation accuracy is relatively high although this can not be fully verified.

Measured weight loss from the storage trial was extremely variable particularly in the top and bottom zone layers. Verification of simulated weight loss was marginal under such circumstances. Top and bottom zone layers were on average underpredicted for weight loss, possibly due to an increase in skin diffusivity resistance to water vapour during the transpiration experiment (Pieniazek 1944; Lentz and Rooke 1964), bulb sprouting or disease infection during the storage trial (Rajapakse et al. 1992) although this was unlikely, or damaged or loose bulb skins during the storage trial (Karmarker and Joshi 1941; Apeland 1971). Simulated weight loss data was extended an additional 9.86% by linear extrapolation to coincide

with the measured weight loss period, presenting some degree of error although this was considered to be small. However, the above hypotheses failed to explain the relatively well predicted weight loss in the central zone layer. Obviously, unidentified biological processes or bulb quality factors were responsible for the large fluctuations in measured weight loss, and possibly the poor agreement between measured and predicted weight loss.

Due to the variable thermophysical status of stored biological product it was necessary to allow provisions for modification to be made to important bulb and flowfield parameters. This has been provided through the INITIAL.TXT file (Appendix B3). Sensitivity of various thermophysical parameters on model performance was an important analysis. Quantification of these parameters can be time consuming and/or expensive, often relating to the degree in establishing their accuracy. Identification of the most sensitive model parameters gives some basis to the allocation of time, effort, and expense to their deduction. For prediction of onion and air temperature, ventilation rate throughout the porous bed was the most sensitive parameter affecting model performance, followed by initial bulb moisture content, respiration rate, mass transfer coefficient, and heat transfer coefficient, For prediction of RH the most sensitive parameter was again ventilation rate, followed by initial bulb moisture content, mass transfer coefficient, respiration rate, and heat transfer coefficient. Mass transfer coefficient was the most influential parameter over bulb weight loss, followed by respiration rate, ventilation rate, initial bulb moisture content, and heat transfer coefficient (Table 7.2).

In accordance with the significance of ventilation rate sensitivity, the standard model which assumed even flow rate up each zone column, was adjusted with respect to air pressure measurements collected above and below the containerized stow. Overall improvements eventuated in all 4 bulb and flowfield properties as discussed under the modified model simulation (section 7.3).

# CHAPTER 8

# CONCLUSIONS AND RECOMMENDATIONS

## 8.1 CONCLUSIONS

The aim of this study was to mathematically model the state of onion bulbs, and the surrounding environment, whilst transported or stored in fan ventilated intermodal transport containers. Onion temperature, air temperature, air relative humidity, and onion weight loss have been predicted throughout the transport vessel with respect to position. An extensive literature search failed to reveal any published material pertaining to the simulation of bulk stored onion bulbs in fan ventilated beds, particularly beds confined in transport containers.

In developing a suitable mathematical model it is desirable to obtain a balance between model complexity, accuracy, and operational simplicity, therefore only the important heat and mass transfer pathways have been modelled. Pathways included were convective heat exchanges between onions and flowfield, bulb respiratory heat generation along with the associated product mass loss of carbon, and evaporative cooling effects with mass loss from desiccation. Required thermophysical parameters for the model have been obtained either directly from the literature, through mathematical derivation, or estimated through empirical relationships. Experimental investigations have been conducted to derive three important parameters; bulb surface area, bulb respiration rate, and a coefficient related to bulb transpiration rate. Strong empirical relationships have been established for each of the above parameters.

The model has been evaluated against measured data obtained from an onion stowed transport container. Onion and air temperatures have been predicted with acceptable accuracy. Mean errors between measured and simulated temperatures were on

average 0.06 and 0.08°C, respectively. Average RMS errors were 0.54 and 0.51°C, respectively, and average correlation coefficients were 0.87 and 0.88, respectively.

Prediction of relative humidity was less accurate, possibly due to greater inconsistencies in the measured data. Mean error, RMS error, and correlation coefficient were on average 1.68%, 7.24%, and 0.67, respectively. Greater degrees of correlation between measured and simulated data have been obtained in a number of positions, suggesting good overall model performance. However, some humidity probe errors, generating data to be evaluated against the simulation, obviously contributed to poor model performance in other locations in the container.

Acceptable weight loss predictions were evident in some positions of the container, whilst in others significant discrepancies existed between measured and simulated data. Weight loss on average was underpredicted in bottom, centre, and top zone layers by 14.2, 4.6, and 24.1%, respectively. Measured weight loss data was found to be extremely variable between some adjacent positions in the container. Responsibility for such anomalies was unclear.

Overall, the model was considered sufficiently accurate to be of commercial benefit to onion exporters in particular, although its performance was somewhat disappointing with respect to weight loss prediction.

## 8.2 RECOMMENDATIONS

Further investigation into components of this research would be warranted. Due to time constraints bulb respiration rate was unable to be evaluated during the containerized onion storage trial. Samples of the crop were maintained in cold storage to be evaluated at a later date. Development of enhanced bulb respiration rate whilst in storage was a serious oversight in the study. Evidence from the literature and from analysis of container temperature distribution revealed that estimated respiration rate determined three months after the storage trial had risen by

approximately five times. Although such an occurrence was initially suspected, the extent of enhanced respiration rate was severely underestimated. This was due to the bulb samples being maintained in storage at 0-3°C where development of metabolic processes were thought to be adequately subdued. Re-evaluation of onion respiration rate as a function of temperature and length of time in storage would be justified.

Performance of various relative humidity probes was disappointing. Measurement errors were found to exceed manufacturers specifications particularly at high relative humidity. Sensitivity or response time of some probes to changing relative humidity was also unacceptable. Although a number of probes appeared to operate satisfactorily verifying simulated relative humidity in a number of locations, the overall storage trial measurements failed to fully verify this flowfield property. Measurement of relative humidity in a containerised onion stow with reliable devices, and a re-analysis of measured and simulated data would be warranted.

Further investigation into bulb weight loss would be advantageous to identify the causes of the significant variability measured between the various zones during the container storage trial. As stated earlier such variability would be difficult to model accurately but identification of such causes may reflect on the postharvest treatment and/or handling of the crop. Stabilization and consistency of onion weight loss would allow a fuller evaluation of this aspect of the model.

The sensitivity analysis revealed that definition of the ventilation rate up each zone column was critical. Ventilation rate was defined for the modified model based on air pressure differences measured throughout the container. It is recommended that direct measurements of air flow rate up each zone column be obtained and appropriately specified in the simulation programme. Evaluation of increased model performance would then be possible.

Environmental conditions experienced by the crop during the storage trial, over which evaluation of the model occurred, were for mid winter conditions with temperatures ranging from 4-15°C and RH of 70 to near 100%. With the majority of New

Zealand onion export consignments destined for northern hemisphere markets, temperature and RH conditions experienced by the crop would contrast dramatically to those during the container storage trial. Summer conditions would enhance both respiration and transpiration processes increasing the extent of crop and flowfield variability throughout the transport vessel. Under such environmental regimes simulation performance could be further tested to give an extensive overall evaluation of the model.

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# APPENDIX A

## MEASURED FLOWFIELD PROPERTIES

### A1  Transport Container Ventilation Rate

### Table A.1

Air velocity measurements taken at transport container exhaust port.

| Measurement position | Air velocity (m.s$^{-1}$) | |
|:---:|:---:|:---:|
| | 18-8-94 | 26-8-94 |
| A | 4.6 | 4.3 |
| B | 4.3 | 4.0 |
| C | 4.8 | 4.6 |
| D | 4.8 | 4.6 |
| E | 5.0 | 4.8 |
| F | 3.8 | 4.0 |
| G | 4.1 | 4.0 |
| H | 4.0 | 4.0 |
| I | 4.1 | 4.0 |
| J | 4.2 | 4.2 |

## A2  Transport Container Air Pressures

### Table A.2

Static air pressures (Pa) measured at locations above and below each zone column, and corresponding static pressure differences.

| Zone column | 18-8-94 | | | 26-8-94 | | |
|---|---|---|---|---|---|---|
| | Below column | Above column | ΔPressure | Below column | Above column | ΔPressure |
| 1,3,k | 22 | 17 | 5 | 22 | 16 | 6 |
| 2,3,k | 20 | 17 | 3 | 19 | 16 | 3 |
| 3,3,k | 19 | 19 | 0 | 21 | 17 | 4 |
| 1,2,k | 18 | 17 | 1 | 19 | 15 | 4 |
| 2,2,k | 17 | 17 | 0 | 18 | 16 | 2 |
| 3,2,k | 20 | 15 | 5 | 17 | 16 | 1 |
| 1,1,k | 23 | 16 | 7 | 25 | 15 | 10 |
| 2,1,k | 15 | 15 | 0 | 17 | 15 | 2 |
| 3,1,k | 40 | 14 | 26 | 38 | 15 | 23 |

## A3  Modified Model Ventilation Rate

### Table A.3

Modified model flow rate ($m^3.s^{-1}$) up each zone column estimated from measured pressures within an onion stowed transport container

| Zone column | Ventilation rate |
|---|---|
| 1,1,k | 0.1149 |
| 2,1,k | 0.0514 |
| 3,1,k | 0.1742 |
| 1,2,k | 0.0726 |
| 2,2,k | 0.0514 |
| 3,2,k | 0.0363 |
| 1,3,k | 0.0889 |
| 2,3,k | 0.0629 |
| 3,3,k | 0.0726 |

## APPENDIX B

## MODEL PROGRAMMING AND DATA FILES

### B1   Model Simulation

The model simulation ONION.PAS is listed below.

---

```pascal
programme onion;

uses
    Crt;

Type
    Contain = array[1..3,1..3,0..4] of extended;

Const
    Cpa = 1.007;

var
    Infile,Datafile,Outfile1,Outfile2,Outfile3,Outfile4: text;
    i,j,k,Jday,time : integer;
    Ton,Mon,Mwon,Mdon,Ta,pa,Xa,RH,rho : Contain;
    Twest,Teast,Troof,Tin,Tout,Tamb,Solar,RHout,RHin: extended;
    wtfrac,masst,massav,As,Asav,vent,ponsat,step : extended;
    v,M,htc,mtc : array [1..3,1..3] of extended;

function satvap (T: extended) : extended;
{ Calculates saturated vapour pressure of air in Pa (Tetens, 1930) }
BEGIN
  SatVap := 611 * EXP(17.27*T/(T+237.30))
END;
```

```
FUNCTION Power(B,E: extended): extended;


  FUNCTION Pow(B,E: extended): extended;
  BEGIN
    Pow := EXP(E * Ln(B));
  END;


BEGIN
  IF B > 0 THEN
    Power := Pow(B,E)
  ELSE IF B < 0 THEN BEGIN
    IF Frac(E) = 0 THEN
      IF ODD(TRUNC(E)) then
        Power := -Pow(-B, E)
      ELSE
        Power := Pow(-B, E)
    ELSE
      RunError(207)
  END
  ELSE BEGIN
    IF E = 0 THEN
      Power := 1
    ELSE IF E < 1 THEN
      RunError(207)
    ELSE
      Power := 0
  END;
END;



procedure initialise;
```

```
Var

   Check,Number : extended;


Begin
      { open input and output files }
      Assign(Infile,'C:\ONION\INITIAL.TXT');
      Reset(Infile);
      Assign(Datafile,'C:\ONION\INPUT.TXT');
      Reset(Datafile);
      Assign(Outfile1,'C:\ONION\ONIONT.TXT');
      Rewrite(Outfile1);
      Assign(Outfile2,'C:\ONION\ONIONM.TXT');
      Rewrite(Outfile2);
      Assign(Outfile3,'C:\ONION\AIRT.TXT');
      Rewrite(Outfile3);
      Assign(Outfile4,'C:\ONION\AIRRH.TXT');
      Rewrite(Outfile4);
      { read in simulation step length in seconds }
      readln(Infile,step);
      { read in total mass of onions in container, average mass
        of individual bulbs, initial wet fraction }
      readln(Infile,masst,massav,wtfrac);
      { calculate total number of onions in container }
      Number := masst/massav;
      { calculate surface area of individual bulbs }
      Asav := -0.003753+ 0.04131*POWER(massav,0.4668);
      { calculate surface area in each zone }
      As := Asav* Number/27.0;
      { read in total ventilation rate and split between columns }
      readln(Infile,vent);
      check := 0.0;
      { read in heat and mass transfer coefficients }
```

```pascal
      for j := 1 to 3 do
      begin
        for i := 1 to 3 do
        begin
          readln(infile,v[i,j],htc[i,j],mtc[i,j]); { in m3/s,W/m2C,m/s }
          Check := check + v[i,j];
        end;
      end;
      if check > vent then
      begin
        write('Error in specifying ventilation rates');
        HALT;
      end;
      { read in initial temperature in each zone }
      { i is across container, j is along container, k is up container }
      for k := 1 to 3 do
      begin
        for j := 1 to 3 do
        begin
          for i := 1 to 3 do
          begin
            { read in initial onion temperature }
            readln(Infile,Ton[i,j,k]);
            { calculate total mass of onions in each zone }
            Mon[i,j,k] := masst*1000.0/27.0; { in g }
            { calculate mass of onion wet and dry matter }
            Mwon[i,j,k] := wtfrac*Mon[i,j,k]; { in gH2O }
            Mdon[i,j,k] := Mon[i,j,k] - Mwon[i,j,k]; { in gDM }
          end;
        end;
      end;
end;
```

procedure simulate;

Var

   psatin,pin,Xin,rhoin,pasat,Lambda,Qc,Qevap,Qresp,fresp,fevap : extended;

   Qc1,Qc2,Qc3,Qc4,fevap1,fevap2,fevap3,fevap4 : extended;

DelT1,DelT2,DelT3,DelT4,DelMw1,DelMw2,DelMw3,DelMw4,DelMd1,DelMd2,
DelMd3,

   DelMd4 : extended;

   simtime : extended;

procedure ODES(var DelT,DelMw,DelMd : extended; var Qc,fevap : extended;

      Mwon,Mdon,Ton,Tai,Xai,v,rhoa,htc,mtc,step : extended);

Var

   Cp,Mon,lmtd,lmXd,Tao,Xao,Xonsat : extended;

begin

 Mon := Mwon + Mdon;

 Cp := 1.840 + 2.340*Mwon/Mon; { in J/gC }

 Tao := Ton + (Tai - Ton)*exp(-htc*As/(v*rhoa*Cpa));

 if Tai = Ton then lmtd := 0.0

 else  lmtd := -(Tai - Tao)/ln((Tai-Ton)/(Tao-Ton));

 { convection from onions }

 Qc := htc*As*lmtd; { in W }

 { transpiration from onions }

 Xonsat:=0.98*satvap(Ton)*2.17/(Ton+273.15); { in gH2O/m3 }

 Xao := Xonsat - (Xonsat - Xai)*exp(-mtc*As/v);

 if Xai = Xonsat then lmXd := 0.0

 else lmXd := (Xao - Xai)/ln((Xonsat-Xai)/(Xonsat-Xao));

 fevap := mtc*As*lmXd; { in gH20/s }

 Qevap := Lambda*fevap; { in W }

{ respiration from onions }

Qresp := (Mon/1000.0)*(1.278e-2 + 2.029e-4*Ton

+ 1.8e-4*Ton*Ton - 3.882e-6*Ton*Ton*Ton)*0.2; { in W }

fresp := (Mon/1000.0)*(3.201e-7 + 5.261e-9*Ton

+ 4.513e-9*Ton*Ton - 9.75e-11*Ton*Ton*Ton)*0.2; { gDM/s }

{ differential equations }

DelT := (-Qc - Qevap + Qresp)*step/(Mon*Cp); { in C }

DelMw := -fevap*step; { in gH2O }

DelMd := -fresp*step; { in gDM }

end;


begin

  repeat

    readln(Datafile,Jday,Time,Twest,Teast,Troof,Tin,Tout,Tamb,

      Solar,RHout,RHin);

    writeln(JDay:5,Time:6);

    { calculate saturation vapour pressure of in coming air }

    psatin := satvap(Tin);

    { calculate actual vapour pressure }

    pin := psatin * RHin/100.0; { Pa }

    { calculate absolute humidity of incoming air }

    Xin := pin*2.17/(Tin + 273.15); { in gH2O/m3 }

    { calculate density of incoming air }

    rhoin := 3.49*(101325.0 - pin)/(Tin + 273.15); { in gDA/m3 }

    { set up initial conditions at bottom of each zone column in plenum }

    for i := 1 to 3 do

    begin

      for j := 1 to 3 do

      begin

        pa[i,j,0] := pin;

        Ta[i,j,0] := Tin;

        Xa[i,j,0] := Xin;

```
    RH[i,j,0] := RHin;

    rho[i,j,0] := rhoin;

  end;

end;

{ start of 5 minute initial value problem }

simtime := 0.0;

repeat

  for k := 1 to 3 do

  begin

    for j := 1 to 3 do

    begin

      for i := 1 to 3 do

      begin

        { latent heat of vaporisation }

        Lambda := 2500.833 - 2.35627*Ta[i,j,k-1]; { J/g }

        { solve DE's }

        ODES(DelT1,DelMw1,DelMd1,Qc1,fevap1,Mwon[i,j,k],

            Mdon[i,j,k],Ton[i,j,k],Ta[i,j,k-1],Xa[i,j,k-1],

            v[i,j],rho[i,j,k-1],htc[i,j],mtc[i,j],step);

        ODES(DelT2,DelMw2,DelMd2,Qc2,fevap2,Mwon[i,j,k]+DelMw1/2.0,

            Mdon[i,j,k]+DelMd1/2.0,Ton[i,j,k]+DelT1/2.0,

            Ta[i,j,k-1],Xa[i,j,k-1],v[i,j],rho[i,j,k-1],htc[i,j],

            mtc[i,j],step);

        ODES(DelT3,DelMw3,DelMd3,Qc3,fevap3,Mwon[i,j,k]+DelMw2/2.0,

            Mdon[i,j,k]+DelMd2/2.0,Ton[i,j,k]+DelT2/2.0,

            Ta[i,j,k-1],Xa[i,j,k-1],v[i,j],rho[i,j,k-1],htc[i,j],

            mtc[i,j],step);

        ODES(DelT4,DelMw4,DelMd4,Qc4,fevap4,Mwon[i,j,k]+DelMw3,

            Mdon[i,j,k]+DelMd3,Ton[i,j,k]+DelT3,

            Ta[i,j,k-1],Xa[i,j,k-1],v[i,j],rho[i,j,k-1],htc[i,j],

            mtc[i,j],step);

        { calculate new onion zone temperature and total mass }
```

```
        Ton[i,j,k] := Ton[i,j,k] + (DelT1 + 2.0*DelT2
                    + 2.0*DelT3 + DelT4)/6.0;
        Mdon[i,j,k] := Mdon[i,j,k] + (DelMd1 + 2.0*DelMd2
                    + 2.0*DelMd3 + DelMd4)/6.0;
        Mwon[i,j,k] := Mwon[i,j,k] + (DelMw1 + 2.0*DelMw2
                    + 2.0*DelMw3 + DelMw4)/6.0;
        Mon[i,j,k] := Mdon[i,j,k] + Mwon[i,j,k];
        { solve algebraic equations for outlet conditions from zone }
        Qc := (Qc1 + 2.0*Qc2 + 2.0*Qc3 + Qc4)/6.0;
        fevap := (fevap1 + 2.0*fevap2 + 2.0*fevap3 + fevap4)/6.0;
        Ta[i,j,k] := Ta[i,j,k-1] + Qc/(v[i,j]*rho[i,j,k-1]*Cpa);
        Xa[i,j,k] := Xa[i,j,k-1] + fevap/v[i,j];
        pa[i,j,k] := Xa[i,j,k]*(Ta[i,j,k]+273.15)/2.17;
        pasat := satvap(Ta[i,j,k]);
        RH[i,j,k] := pa[i,j,k]*100.0/pasat;
        rho[i,j,k] := 3.49*(101325 - pa[i,j,k])/(Ta[i,j,k]+ 273.15);
      end;

    end;

  end;

  simtime := simtime + step;
until simtime > 300;
write(Outfile1,Jday:5,time:8);
write(Outfile2,Jday:5,time:8);
write(Outfile3,Jday:5,time:8);
write(Outfile4,Jday:5,time:8);
for k := 1 to 3 do
begin
  for j := 1 to 3 do
  begin
    for i := 1 to 3 do
    begin
      write(outfile1,Ton[i,j,k]:8:1);
```

```pascal
            write(outfile2,Mon[i,j,k]:16:1);
            write(outfile3,Ta[i,j,k]:8:1);
            write(outfile4,RH[i,j,k]:8:3);
          end;
        end;
      end;
    writeln(Outfile1);
    writeln(Outfile2);
    writeln(Outfile3);
    writeln(Outfile4);
    until eof(Datafile);
end;


procedure Finish;


begin
    close(Infile);
    close(Datafile);
    close(Outfile1);
    close(Outfile2);
    close(Outfile3);
    close(Outfile4);
end;

{ main program }
BEGIN
    Initialise;
    Simulate;
    Finish;
END.
```

## B2 Model Input File

The simulation input file INPUT.TXT is partially listed below.

| J-day | time | westtem | easttem | rooftem | inlettem | outlettem | ambient | solar | outletRH | inletRH |
|---|---|---|---|---|---|---|---|---|---|---|
| 229 | 1200 | 9.99 | 12.13 | 16.18 | 11.63 | 10.84 | 11.45 | 0.00 | 79.58 | 71.51 |
| 229 | 1205 | 10.06 | 12.24 | 16.68 | 11.65 | 10.91 | 11.49 | 0.00 | 79.31 | 71.23 |
| 229 | 1210 | 10.13 | 12.33 | 17.17 | 11.72 | 10.96 | 11.54 | 0.00 | 79.36 | 71.28 |
| 229 | 1215 | 10.18 | 12.37 | 17.08 | 11.74 | 10.97 | 11.56 | 0.00 | 79.11 | 71.16 |
| 229 | 1220 | 10.21 | 12.35 | 16.84 | 11.72 | 10.97 | 11.58 | 0.00 | 79.21 | 71.29 |
| 229 | 1225 | 10.23 | 12.36 | 16.61 | 11.70 | 10.96 | 11.58 | 0.00 | 79.18 | 71.32 |
| 229 | 1230 | 10.31 | 12.39 | 16.82 | 11.74 | 11.02 | 11.66 | 0.00 | 79.32 | 71.32 |
| 229 | 1235 | 10.41 | 12.47 | 16.93 | 11.79 | 11.06 | 11.73 | 0.00 | 79.28 | 71.58 |
| 229 | 1240 | 10.54 | 12.60 | 17.54 | 11.90 | 11.12 | 11.81 | 0.00 | 79.24 | 71.71 |
| 229 | 1245 | 10.64 | 12.74 | 17.88 | 11.93 | 11.18 | 11.84 | 0.00 | 78.93 | 71.70 |
| 229 | 1250 | 10.70 | 12.76 | 17.57 | 11.88 | 11.18 | 11.82 | 0.00 | 78.98 | 71.96 |
| 229 | 1255 | 10.73 | 12.77 | 17.26 | 11.88 | 11.17 | 11.83 | 0.00 | 78.96 | 72.07 |
| 229 | 1300 | 10.77 | 12.76 | 16.81 | 11.86 | 11.16 | 11.82 | 0.00 | 79.00 | 72.19 |
| 229 | 1305 | 10.79 | 12.73 | 16.35 | 11.79 | 11.14 | 11.81 | 0.00 | 78.89 | 72.07 |
| 229 | 1310 | 10.85 | 12.79 | 16.44 | 11.78 | 11.17 | 11.83 | 0.00 | 78.98 | 72.08 |
| 229 | 1315 | 10.90 | 12.88 | 16.70 | 11.83 | 11.21 | 11.85 | 0.00 | 78.77 | 71.80 |
| 229 | 1320 | 10.94 | 12.89 | 16.72 | 11.85 | 11.23 | 11.86 | 0.00 | 78.62 | 71.75 |
| 229 | 1325 | 10.98 | 12.90 | 16.84 | 11.90 | 11.26 | 11.91 | 0.00 | 78.48 | 71.56 |

where:

J-day = Julian day

time = hours (24 hour time)

westtem = western container wall temperature (°C)

easttem = eastern container wall temperature (°C)

rooftem = container roof temperature (°C)

inlettem = container air inlet temperature (°C)

outlettem = container air outlet temperature (°C)

ambient = outside ambient air temperature (°C)

solar = solar radiation on container roof ($W.m^{-2}$)

outletRH = container air outlet relative humidity (%)

inletRH = container air inlet relative humidity (%)

## B3 Model Initialization File

The simulation initialization file INITIAL.TXT is listed below.

---

| | | |
|---|---|---|
| 10 | | |
| 15000 | 0.07593 | 0.867 |
| 0.7264 | | |
| 0.1149 | 17.516 | 1.292E-05 |
| 0.0514 | 12.441 | 1.292E-05 |
| 0.1742 | 20.908 | 1.292E-05 |
| 0.0726 | 14.416 | 1.292E-05 |
| 0.0514 | 12.441 | 1.292E-05 |
| 0.0375 | 10.877 | 1.292E-05 |
| 0.0889 | 15.712 | 1.292E-05 |
| 0.0629 | 13.558 | 1.292E-05 |
| 0.0726 | 14.416 | 1.292E-05 |
| 9.5 | | |
| 9.5 | | |
| 9.5 | | |
| 9.5 | | |
| 9.5 | | |
| 9.5 | | |
| 9.5 | | |
| 9.5 | | |
| 9.5 | | |
| 10 | | |
| 10 | | |
| 10 | | |
| 10 | | |
| 10 | | |
| 10 | | |
| 10 | | |
| 10 | | |
| 10 | | |
| 10.5 | | |
| 10.5 | | |
| 10.5 | | |
| 10.5 | | |
| 10.5 | | |
| 10.5 | | |

10.5

10.5

10.5

---

The model initialization file format consists of 39 lines and 3 columns. Line 1, column 1 specifies the simulation time step (s). Line 2, column 1-3 specifies total mass of onions in container (kg), mass of average onion bulb (kg), and onion water content fraction, respectively. Line 3, column 1 defines total container ventilation rate ($m^3.s^{-1}$). Column 1, lines 4-12 defines respective ventilation rates ($m^3.s^{-1}$) up each zone column in the following order:

*1,1,k*

*2,1,k*

*3,1,k*

*1,2,k*

*2,2,k*

*3,2,k*

*1,3,k*

*2,3,k*

*3,3,k*

Column 2, lines 4-12 specifies heat transfer coefficients associated to each ventilation rate. Column 3, lines 4-12 specifies mass transfer coefficients associated to each ventilation rate. Column 1, lines 13-21 specifies initial estimated bulb temperature in each zone of the bottom layer *(i,j,1)* of zone columns listed in order as given above for ventilation rate. Column 1, lines 22-30 specifies initial estimated bulb temperature for each zone of the central layer *(i,j,2)* in the same order as given for the bottom layer. Column 1, lines 31-39 specifies initial estimated bulb temperature in each zone of the top layer *(i,j,3)* in the same order as given for the bottom layer.