TRANSPIRATION FROM FRUITS AND VEGETABLES IN STORAGE

By

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Dedicated to my parents

Paulino Vias Romero

and

Guadalupe Estrada Romero

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LIST OF SYMBOLS

A - cross-sectional area of layer

A_r - surface area of elemental product volume

A_s - product surface area for transpiration

$c_{p,a}$ - specific heat of air

$c_{p,p}$ - specific heat of product

$c_{p,v}$ - specific heat of water vapor

$c_{v,a}$ - specific heat of air at constant volume

$c_{v,v}$ - specific heat of water vapor at constant volume

d - product diameter

D - diffusivity of water vapor through air

D_p - hydraulic radius

g - acceleration of gravity

h - natural convection heat transfer coefficient

H - humidity ratio

k - thermal conductivity of air

k_p - thermal conductivity of product

K - product transpiration coefficient

K_p - permeability

L - latent heat of vaporization

P - water vapor pressure

T - void volume temperature

T_p - product temperature

T_s - product surface temperature

v_i - velocity in layer i

V - volume of layer

V_p - elemental product volume

β - volume expansion coefficient

γ - ratio of specific heats, $c_{p,a}/c_{v,a}$

ε - porosity

μ - air dynamic viscosity

ρ_a - density of air

ρ_p - density of product

ρ_v - mass of water vapor per unit volume

Δr - thickness of elemental product volume

Δz - thickness of layer in vertical direction

Δt - time increment

<u>Subscripts</u>

i - void node

r - product node

s - surface node

<u>Superscripts</u>

n - at time n

o - at initial time

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Abstract of Dissertation Presented to the Graduate School
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Moisture loss due to transpiration during storage and shipment is a major factor affecting the quality and marketability of perishable fruits and vegetables. A good understanding of the transpiration process and an ability to predict weight loss rates from environmental conditions will help to extend the storage life of the perishable product.

To accurately predict product weight loss rates, a transpiration coefficient must be known or measured experimentally. This study presents an experimental procedure which can be used to accurately determine the transpiration coefficient for fruits and vegetables. The procedure accounts for the effects upon transpiration of air velocity past the product, respiration, evaporative cooling, convective heat and mass transfer, radiation heat transfer and the water vapor pressure lowering effect due to solutes in solution within the product moisture.

Transpiration coefficients for several fruits and vegetables were determined and reported. The coefficients were found to be variable among individual products within a given variety.

The fresh fruit and vegetable industries store their perishable products in bulk. Although the storage atmosphere is replenished, the bulk store itself may not be ventilated. Very few engineering models exist which can accurately predict the heat transfer and moisture removal from unventilated bulk stores of fruits and vegetables.

An explicit finite difference numerical model is presented which can accurately predict the heat and mass transfer from unventilated bulk storages. At conditions tested, experimental and simulation data show that the transpiration rates for Valencia oranges within a bulk store can be as much as 40% less than those of single fruits in storage. Single-product transpiration models are not expected to be able to simulate transpiration from products in storage.

Simulation results indicate that natural convection may have a significant effect on the moisture removal from the bulk store. More research is needed to determine the extent of this effect on transpiration from fruits and vegetables in industrial storage facilities.

INTRODUCTION

Marketing fruits and vegetables often requires storage to extend shelf life beyond the end of the harvest season. Perishable commodities are stored in environments where physiological breakdown, physical damage and attack from pathogens are minimized. Typically the storage environment is controlled to maintain low temperature, high humidity and a predetermined atmospheric composition if required. The effect of low temperature is to slow the biological activities of the product. The effect of high humidity is to minimize product transpiration and resulting dessication by maintaining a low water vapor pressure deficit between the product and the environment. The effect of a controlled atmospheric composition is to slow the biological activity of the product. The goals for commercial storage of perishable horticultural commodities are

1) to slow the biological activity of the product by maintaining the lowest temperature that will not cause injury and by controlling the atmospheric composition of the storage environment,
2) to slow the growth of microorganisms by maintaining low temperature and minimizing surface moisture,
3) to minimize product drying by reducing the water vapor pressure deficit between the product and air.

Moisture loss due to transpiration during storage and shipment is a major factor affecting the quality and marketability of perishable commodities. It also represents profit lost due to salable weight loss. A good understanding of the transpiration process and an ability to predict weight loss rates from environmental conditions will improve storage procedures, help to extend the storage life of horticultural commodities and assist in the proper design of storage facilities.

Much research has been conducted to determine the transpiration rates from fruits and vegetables. Typically this work has involved measuring the transpiration rate from a single product in a controlled environment. To accurately predict or calculate the transpiration rates for products in storage, accurate transpiration coefficients must be known. With the transpiration coefficient known, one can calculate a transpiration rate knowing only product weight and water vapor pressure deficit between the product and the environment. An experimental procedure which can account for the various factors which affect transpiration is needed to accurately determine the transpiration coefficient of perishable commodities.

The fresh fruit and vegetable industries store their perishable commodities in bulk; either in palletized containers or in bulk bins. Although the storage atmosphere is replenished, the bulk itself may not be ventilated. Within unventilated bulk stores, air is simply moved past the pallet instead of through the pallet and product respiratory heat may accumulate within the bulk. This heat accumulation can defeat the first and second storage goals listed above by allowing higher rates of biological and microbial activity.

Very few engineering models exist which can accurately predict the heat transfer and moisture removal from bulk fruits and vegetables and no published models exist which do so for unventilated bulk stores. In addition, produce or containers typically surround an individual product in bulk storage and transpired moisture may leave the bulk store by either diffusion and/or currents created by natural convection in the absence of ventilation. A model to predict the transpiration rates and temperature profile within bulk stores of horticultural commodities would aid in better understanding the process of moisture loss from the bulk store.

With the current interest in modified atmosphere packaging of horticultural commodities, scientists and engineers must study the environment within the bulk store to determine the means of gas transport through the bulk. Simulation models which aid in understanding the environment of the bulk store could be used to better design storage procedures and environments which maintain product quality.

The objectives of this study were to

1) develop an experimental procedure to accurately determine the transpiration coefficient of fruits and vegetables,
2) measure the transpiration coefficient for several fruits and vegetables,
3) develop a numerical model which can predict the weight loss from commodities in bulk storage and
4) validate the numerical model with experiments conducted on Valencia oranges.

REVIEW OF LITERATURE

This chapter begins with a brief discussion of the horticultural and physiological factors important to the successful storage of perishable commodities. The effects of transpiration on the storage quality of fruits and vegetables are also discussed. Previous work to determine the transpiration rates and coefficients of fruits and vegetables is then reviewed. The few models developed to simulate heat and mass transfer from bulk stores of perishable commodities are then discussed.

Storage of Perishable Commodities: Postharvest Physiology and Transpiration During Storage -- An Overview

The goals for successful storage of fruits and vegetables are

1) to slow the biological activity of the commodity,
2) to slow the activity of microflora and
3) to minimize product weight loss due to transpiration (Thompson, 1985).

Slowing the biological activity and deterioration of the product is essential for successful storage of perishable commodities. The rate of deterioration of harvested products is generally proportional to the respiration rate (Kader, 1985). Respiration is the process where stored organic matter is broken into simple end products with a resulting release of energy. Molecular oxygen is consumed to break down organic compounds into the end products of carbon dioxide, water, chemical energy and internal product energy. The released chemical energy is then used to synthesize substances, build cell wall components and maintain cell integrity (Ryall and Pentzer, 1972). The released internal energy results in increased product temperatures within the bulk and becomes important because the increased bulk temperature may affect product quality.

This released internal energy is commonly referred to as the respiratory heat evolution. The loss of stored energy reserves from the product inevitably results in loss of food value, quality, dry salable weight and senescence.

The respiration rate of perishable commodities is affected by the temperature of the product and the availability of molecular oxygen in the storage environment. Respiration rate increases significantly (Figure 1) with increasing product temperature and lowering the product temperature is one method to slow the biological activity of perishable commodities. Technologies including hydrocooling, top-icing, in-package icing, vacuum cooling and forced-air cooling are used to quickly lower the temperature of perishable commodities (Mitchell, 1985).

An objective of the storage environment is to maintain low temperatures to minimize product respiration rate and maintain product quality at the highest possible level. Mechanical refrigeration is the technology typically used to maintain low storage temperatures although evaporative cooling and naturally formed ice are alternate forms of refrigeration (Thompson, 1985). Hardenburg et al. (1986) lists recommended storage temperatures and humidities for horticultural products (Table 1). It is also important to recognize that control of the storage temperature is essential to extend the shelf life of perishable products. Too low a storage temperature may result in freezing or chilling injury. Too high a temperature may result in accelerated deterioration, senescence and possibly high-temperature injury

Controlling or modifying the storage atmosphere composition is a second method used to lower the biological activity of fruits and vegetables (Thompson,1985). Lowering the amount of molecular oxygen and/or raising the amount of carbon dioxide or other gases in the atmosphere reduces the respiration rate and slows the biological activity of the product. Much research has been conducted in this area and interest exists today in the marketing of fresh fruits and vegetables in modified atmosphere packages. Recent published results include the following

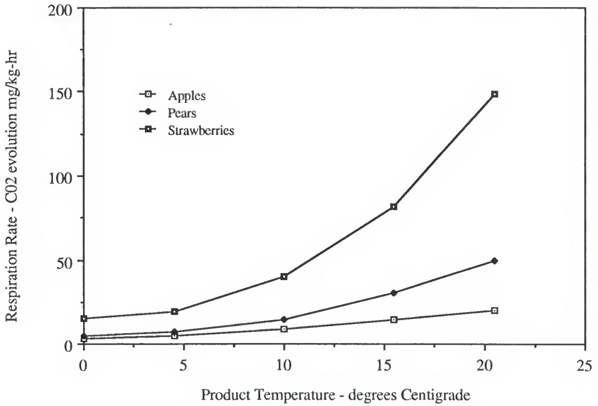

Figure 1. Respiration Rates of Apples, Pears and Strawberries

TABLE 1

Recommended Storage Temperature and Relative Humidity for Several Fresh Fruits and Vegetables

Commodity	Temperature C	Relative Humidity %
Apples	-1-4	90
Blueberries	-0.5-0	90-95
Brussels Sprouts	0	90-95
Cabbage	0	90-95
Grapefruit	10-15.5	85-90
Green Peppers	7-13	90-95
Lemons	10	85-90
Lima Beans	3-5	90
Limes	9-10	85-90
Oranges	0-9	85-90
Peaches	-0.5-0	90
Pears	-1.5 to -0.5	90-95
Snap Beans	4-7	90-95
Strawberries	0	90-95
Tomatoes	13-21	90-95

1) Lipton and Mackey (1987) studied the physiological and quality responses of brussels sprouts to storage in controlled atmospheres. They concluded that high CO_2 concentration (10%) and low O_2 concentration (1%-4%) could be used to maintain the quality of brussels sprouts in less than optimum temperature storage conditions. High CO_2 in combination with low O_2 concentrations helped to reduce the development of decay and helped to reduce the rate of ethylene production, yielding a higher percentage of salable buds.
2) Chen et al. (1985) studied the effect of low oxygen atmosphere on the surface scalding and quality preservation of "Delicious" apples. They found a combination of 1% O_2 and 1% CO_2 would control the amount of surface scalding and provide preservation of quality for "Delicious" apples grown in Oregon.
3) Hobson (1987) studied the low temperature injury and storage of ripening tomatoes. Various types of chilling injury were described and a number of storage regimes involving modified atmospheres were tested. It was found that the most satisfactory modified atmosphere system was to overwrap the tomato with PVC film. Concentrations of 5 % CO_2 were found to be not harmful to fruit quality and may be beneficial to counteract the spread of disease. This study also indicated that the use of modified atmospheres may help to alleviate chilling injury in low temperature storage.
4) Reyes and Smith (1987) found that celery stored for 11 weeks at 0 °C- 1 °C in 1.5% O_2 and 2.5 - 7.5% CO had better marketable quality than celery stored for 11 weeks at 0 °C - 1 °C air.

The magnitude of the effects of controlled and modified atmospheres depends upon many factors including the cultivar, physiological commodity age, O_2, CO_2 and CO atmospheric concentration, temperature and duration of holding (Kader, 1985).

The second objective for storage of perishable commodities is to slow or mimimize the growth of microorganisms which may infect the commodity. Infection of perishable commodities by bacteria and fungi may result in losses from a reduction in quality grade to complete loss of the product (Lund, 1983). Fungal organisms typically attack fruit and both fungi and bacteria attack vegetables. In addition, fungal nesting in adjacent fruits can result in large losses of perishable commodities during bulk storage. The presence of microbes in storage is dependent on intrinsic properties of the perishable commodity such as

1) the extent of damage at harvest,
2) the maturity of the commodity,
3) the turgidity of the commodity tissue,
4) the structure of the cell wall and its vulnerability to pathogens,
5) the concentration in the commodity of pathogen nutrients and anti-pathogen compounds, and
6) the ability of the commodity tissue to form barriers to pathogen infection (Lund, 1983).

The storage environment may be used to slow or delay the activity of fungal organisms but not to completely stop the activity. The minimum temperature for growth of most of the molds that cause rotting in storage is below $0^{o}C$, so their development cannot be prevented by the use of refrigeration (Edney, 1983). Low temperatures reduce the rate of rotting by retarding the activity of causal organisms, maintaining the firmness of soft fruits (Scott and Lawrence, 1975) and reducing the rate of ripening of the fruit (Edney, 1983). Soft fruits which have lost tissue firmness and fruits which have ripened are highly susceptible to attack by fungal organisms. Also at low temperatures, $0\text{-}1^{o}C$, the growth of spoilage bacteria may be effectively retarded.

Small fluctuations in temperature of high humidity stores can result in condensation on the surface of stored vegetables, leading to an increased risk of bacterial soft rot (Lund, 1983).

Lund (1983) stated relative humidities in the range of 90%-95% are low enough to prevent the growth of spoilage bacteria on the surfaces of fruit and vegetables stored in conventional storage facilities.

Chemical treatments of the perishable product are used during storage to prevent spoilage caused by fungal and bacterial pathogens. Wounds are also an important avenue for invasion by pathogens of many perishable commodities including carrots, potatoes and other root crops. During curing, root crops are able to produce a periderm which prevents pathogenic invasion of surface wounds. Lewis et al. (1983) found that treatment for carrots at high temperature and a humidity approaching saturation dramatically reduced infection of wounds by M. acerina. Lewis and Garrod (1983) thought the short term treatment of root crops at high temperature and at high humidity allows the healing of wounds and a higher resistance to pathogenic attack during storage.

The third goal for storage of fruit and vegetables is to minimize product drying resulting from transpiration (Thompson, 1985). Transpiration primarily occurs when a water vapor pressure deficit exists between the commodity evaporating surface and the surrounding air. An efficient storage environment will minimize the water vapor pressure deficit between the product evaporating surface and the surrounding environment. Large water vapor pressure deficits will result in high transpiration rates and excessive loss of product moisture. Kader (1985) stated that for low temperature stores, moisture loss is a main contributor to loss of product quality since it not only results in quantitative losses (loss of salable weight), but also may cause losses in

1) appearance due to wilting and shriveling,
2) textural quality due to softening, flaccidity, limpness, loss of crispness and juiciness and

3) nutritional quality.

Transpiration occurs near or at the surface of the product. Nearly all researchers observe that the transpiration rates of fruits and vegetables have a linear relationship to the water vapor pressure deficit between the evaporating surface and the surrounding environment (Sastry et al., 1978). The deficit can be reduced by maintaining high humidities and low temperatures in the storage room.

Sastry et al. (1978) stated that several factors can affect the transpiration rate from fruits and vegetables. For stored commodities these factors include:

1) water vapor deficit between the product and environment,
2) air movement past the product,
3) product respiration,
4) the amount of moisture loss and its effect on skin and tissue permeability
5) the endothermic effects of evaporation and
6) the condition of the product surface.

Air movement past the commodity affects the transpiration rate by reducing the boundary layer of air film through which vapor must diffuse. With a thinner layer, higher transpiration rates will occur.

The effect of product respiration is to metabolize organic compounds to carbon dioxide, water and energy. Carbon dioxide diffuses to the environment resulting in a loss of salable weight. Water remains within the product tissues and the respiratory heat generated may raise the temperature of the product and cause higher transpiration rates to occur (Sastry et al., 1978).

As transpiration occurs, moisture loss may affect the permeability of the surface skin or tissue. Many researchers have noted this effect and attributed it to a "drying" of the surface tissue. Wardlaw and Leonard (1940) stated that dessication causes an increase in tissue resistance to gas movement. Ben-Yehoshua (1969) reported that the drying of orange peel resulted in an increased resistance to gas diffusion. Lentz and Rooke (1964) found a decrease in the transpiration coefficient of apples at high vapor deficits and attributed this effect to drying of the surface material. Fockens and Meffert (1972) developed a mathematical model to describe transpiration assuming that the surface cells of biological products will be round and turgid at low water vapor pressure deficits and will be flat and cause high resistance to gas diffusion at high water vapor pressure deficits.

Transpiration is a process of evaporation. Diffusion and endothermic effects (evaporative cooling) are parts of the evaporation process. Sastry et al. (1978) postulate that the effect of evaporative cooling is to lower the product evaporative surface temperature which may simultaneously lower the water vapor pressure at the site of evaporation. This effect and the effect of respiration on the temperature of the product may determine the transpiraton rate at the surface of evaporation.

For commercial storage of most perishable products, water vapor pressures resulting in relative humidities of 90%-95% are recommended for storage (Table 1). Lund (1983) stated that relative humidities in the 94%-95% range will minimize transpiration and provide an environment not conducive to microbial action while temperature fluctuations in stores above 95% relative humidity may allow condensation to occur somewhere in storage and microorganisms may sprout and grow.

To successfully store perishable products, low temperatures, high relative humidity and an optimum atmospheric composition must be maintained to minimize product biological and microflora activity and reduce loss of product quality due to transpiration.

Determination of the Transpiration Rates and Coefficients for Products in Storage

Much research has been conducted to determine the transpiration rates and transpiration coefficients of fruits and vegetables. Although extensive research has been conducted on this subject, there exists a wide range of reported transpiration coefficients for any given crop. This variation in reported transpiration rates and coefficients may be due to the experimental procedures used to determine these properties. Some of the early work conducted in this area was done to determine the transpiration rates and the effects of humidity, water vapor pressure deficit, air velocity and surface structure on transpiration from perishable commodities.

Pienieziak (1942) studied factors affecting transpiration rate from apples in cold storage. These factors included water vapor pressure deficit, air velocity, surface structure, respiratory effects and maturity of the product; however, the effects of respiratory heat generation on the transpiration rate of the products were not considered.

Wells (1962) studied the effects of storage temperature and humidity on the transpiration rate from fruits. The effect of water vapor pressure deficit was considered and transpiration was found to vary linearly with change in water vapor pressure deficit.

Gentry et al. (1963) reported the weight loss of grapes and nectarines as affected by humidity and air velocity during storage. They concluded that low airflow rate past the stored product is important to minimize transpiration and the transpiration rate varies linearly with relative humidity (water vapor pressure deficit) at constant airflow rates.

Lentz and Rooke (1964) studied the transpiration rate from apples and reported the weight loss rates for eight varieties. The weight loss rates were found to be variable among varieties, linearly dependent on vapor pressure deficit and independent of airflow rate past the product.

Lentz (1966) reported the moisture loss from carrots in refrigerated storage and determined equations for the effects of airflow on the transpiration coefficient of Nantes and Chantenay varieties. Lentz concluded that carrots are highly susceptible to moisture loss under adverse conditions.

Gentry (1971) developed a procedure for rapidly determining the transpiration rates of fruits. This is an unsteady state procedure and was conducted by placing samples in an airstream, forcing dry air past the sample and measuring the humidification of the air.

Dypolt (1972) experimentally measured the transpiration rates of green peppers by forcing dry air past the products and measuring the increase in humidity using a dewpoint hygrometer. Dypolt reported transpiration rates for green peppers held in various humidity conditions and found the transpiration coefficient to be 2.36×10^{-8} g water per (min mm^2 mmHg). The experimental design was an unsteady-state mass transfer procedure similar to that developed by Gentry (1971) and allowed quick measurement of the transpiration rate and coefficient.

Talbot (1973) also used the above unsteady-state mass transfer procedure to measure the transpiration rates and coefficients of snap green beans. Talbot reported that product variety, airflow rate past the commodity and temperature affect the mean mass transfer coefficient of snap green beans. Results from this study indicate that evaporative cooling has a significant affect on the transpiration rate of snap green beans.

Robinson et al. (1975) reported the storage characteristics for fruits and vegetables placed in a low oxygen (3% O_2) atmosphere and in air. The effects of water vapor pressure deficit and air velocity were also considered. The results were that low oxygen atmosphere could be used to effectively lower the respiration rate of the thirty fruits and vegetables studied. Robinson et al. (1975) reported optimum storage conditions for the commodities studied and suggested low temperature and high humidity as the most optimum storage conditions.

Sastry et al. (1978) reviewed over 400 papers relating to moisture loss from fruits and vegetables. A number of these papers dealt with the calculation of the transpiration coefficient or the skin permeability to water vapor flow for a particular product. Sastry et alnoted that for each particular fruit or vegetable variety values of reported transpiration coefficients varied widely and this variation may be due to the experimental procedure used to determine the transpiration coefficient. Sastry et al. (1978) concluded that since no researcher had considered all the factors affecting transpiration it is important to approach the determination of the transpiration coefficient for fruits and vegetables with all factors accounted for. There exists a definite need for the development of an experimental procedure which accounts for all the factors affecting transpiration from fruits and vegetables in storage.

To accurately measure the transpiration coefficient a number of factors must be considered (Sastry et al., 1978 and Gaffney et al., 1985). These factors include the effects of air velocity on the convective heat transfer, radiation heat transfer, evaporative cooling due to transpiration at the product surface, respiratory heat generation and the vapor pressure lowering effect due to the presence of dissolved solutes in the product moisture. All of these factors must be considered for accurate moisture loss calculations or when calculating the product transpiration coefficients from experimental data.

Recently, Gaffney et al. (1985) discussed the influence of the various factors affecting weight loss of fruits and vegetables. They concluded that considerable error can occur when making moisture loss calculations from fruits and vegetables without considering all of the variables that influence the total mass transfer. For example, most researchers have considered that the liquid at the evaporating surface is pure water at a temperature the same as the temperature of the surrounding air. Therefore they have calculated the product surface water vapor pressure at the temperature of the surrounding air. Gaffney et al. (1985) calculated that under very special conditions these assumptions result in little error, however, measurement of the transpiration coefficient for a horticultural commodity in typical storage conditions can lead to substantial errors if the above assumption is used.

Chau et al. (1985) developed a mathematical model which can be used to determine the transpiration from individual fruits and vegetables. The overall transpiration coefficient is considered to be influenced by two factors, a K_s coefficient dependent upon the surface characteristics of the commodity and a K_a coefficient dependent upon the properties of the air next to the product.

An experimental procedure which can account for the factors affecting transpiration from fruits and vegetables is definitely needed. This procedure can then be used to accurately calculate the transpiration rates and coefficients of perishable commodities.

Modeling of the Heat and Mass Transfer from Unventilated Stored Perishable Commodities

The modeling of the heat and mass transfer from stored perishable commodities has been treated by various researchers. The majority of work conducted has been to model the heat and mass transfer from single or bulk products in a forced stream of air or within ventilated storages.

Villa (1973) developed a model to simulate single particle convective moisture loss from products in ventilated storage. This model was based on the assumption that transpiration at the product surface is dependent on the water vapor pressure deficit between the surface and the environment. At high water vapor pressure deficits, the product surface was assumed to have high diffusional resistance to transpiration and at low water vapor pressure deficits the product surface was assumed to have low diffusional resistance to transpiration. The model was found to predict well the transpiration rates of perishables commodities.

Lerew (1978) wrote a model to simulate the ventilated storage of potatoes. The model accounts for the effects of transpiration, respiration, airflow rate on the convective and diffusive heat and mass transfer from the bulk store. Lerew concluded that simulation of the bulk store during unventilated periods is needed and that natural convection may have a role in the heat and mass transfer from the bulk store.

Sastry and Buffington (1982) developed a model to simulate transpiration from single tomatoes in a forced steady-state stream of air. The model accounted for the effects of evaporative cooling and respiration on the transpiration rate of the product. However product surface temperature was assumed to be at the air temperature resulting in unusually large temperature gradients between the product surface and the site of water evaporation within the product.

Chau et al. (1985) developed a model to simulate transpiration from regularly shaped horticultural commodities. The model assumes steady-state heat and mass transfer between the product and environment and accounts for the effects of respiratory heat generation, the convective and radiative heat transfer at the product surface, evaporative cooling and the water vapor pressure lowering effect due to solutes in solution within the product moisture. The model can be used to calculate the transpiration rate from fruits and vegetables if the transpiration coefficient of the product is known.

The above models all assumed transpiration to occur during periods of ventilation or from single commodities surrounded by a uniform and unchanging storage atmosphere. Within the bulk industrial store, an individual product is surrounded by other products or a container. These individual products may not be directly exposed to the storage environment and ventilation may not reach the interior of the bulk store. It is within these stores that natural convection heat transfer may have a significant role in the transpiration from products and removal of moisture from the bulk store. Few studies have been concerned with the simulation of unventilated stores and the possibility of natural convection currents occurring within the bulk storage configuration.

Burton et al. (1955) studied unventilated piles of potatoes and developed an empirical algebraic relationship for the temperature difference between the average potato temperature and the average air temperature. This relationship was a function of respiratory heat generation, resistance to airflow, conduction heat transfer and porosity. However weight loss and evaporative cooling of the product surfaces were not considered.

Beukema et al. (1983) successfully simulated bulk-stored agricultural commodities as a porous medium. The model simulates three-dimensional natural convection in a confined porous medium with internal generation. Natural convection is found to significantly affect heat transfer from the products with the location of the maximum temperature of the bulk being moved upward from the center of the bulk. This model did not account for the effects of transpiration and evaporative cooling which would typically be found in stored agricultural commodities.

In closely related research, Prat (1986) analyzed water loss from a sandy soil using a two-dimensional numerical simulation for moisture migration in unsaturated porous media. The effects of temperature differences and gravity on the rate of moisture migration from a porous medium were discussed. The moisture migration was considered to be due to the variation of interfacial tension with temperature (governing fluid water flow) and due to water vapor partial pressure variations with temperature (governing water vapor flow). The results presented indicate that moisture migration due to temperature gradient can be significant even in the presence of a dominating gravity force.

Other studies have been concerned with the natural convection heat transfer from porous media. Although these studies have not incorporated moisture migration within their simulations, the approaches used to solve the heat transfer problem are important to review.

Close (1983) proposed a method for storing thermal energy in packed beds where the transport of heat would be enhanced by natural convection of a gas/vapor mixture where heat was used to evaporate liquid into vapor. This method involved using a wetted bed where a liquid pool at the base of the bed was heated, causing evaporation and natural convection currents to occur through the packed bed. Natural convection of gas and vapor within heated packed medium may also occur in agricultural situations such as the underground heating of soils or as a result of respiratory heat generation and evaporative cooling within packed beds of fruits and vegetables in storage. Close's method, however, involved temperature gradients which would not be typically found within packed beds of fruits and vegetables.

Stewart and Dona (1986) presented a numerical analysis for the steady-state temperature and stream function distribution within a short cylinder containing heat-generating porous medium. Darcy's equation and the Boussinesq approximation were used to analyze the momentum and natural convection respectively within the heat-generating porous medium. The rates of heat generation used during this study were an order of magnitude higher than those rates found in stores of fruits and vegetables. This research, however, successfully incorporates porous medium, natural convection heat transfer and Darcy's flow assumptions to discuss the heat transfer within a porous medium.

Within unventilated bulk stores of fruits and vegetables, natural convection, diffusion and heat generation may dominate the heat transfer from the bulk store while natural convection currents, diffusion and transpiration may dominate the moisture (water vapor) migration from the bulk store. No numerical model or simulation was found in the literature which discusses this problem and it is desired to develop a computer simulation which may help to understand the physics of transpiration within bulk stores of fruits and vegetables.

PROCEDURE FOR CALCULATION OF THE OVERALL MASS TRANSFER COEFFICIENT K AND THE K_S TRANSPIRATION COEFFICIENT

The transpiration rate is affected by the size and shape of the product, the skin characteristic of the product, the conditions of the surrounding atmosphere, the heat of respiration, the heat transfer by convection and radiation at the product surface and the vapor pressure lowering effect due to the presence of solutes in the product moisture. All of these factors must be taken into account when calculating a transpiration coefficient.

The type of surface and underlying tissues of fruits and vegetables can have a marked effect on the rate of water loss (Wills et. al., 1981). The surface of leafy perishable products consists of a cuticle which may or may not have stomata. The most important function of the cuticle is to supplement the action of the stomata in regulation of the passage of water and gases from within the plant to its environment (Martin and Juniper, 1970). The stomata are pore openings in the epidermal surface and are regulated by the turgidity within the leaf and humidity in the environment (Schulze, 1986). Typically, the stomata of harvested leafy produce close after a small amount of water is transpired (Wills et. al., 1981), but can remain open when the leafy surface is in contact with cold air during cold storage. Thus it may be assumed that the transpiration from leafy produce in storage will predominantly occur through the cuticle when the stomata close. Other perishable products have cuticles with no stomata. These products have lenticels and not stomates (Wills et. al., 1981). The function of the lenticel is to provide a pore opening for gas exchange with the environment. This pore opening has no mechanism for closure and cannot be regulated.

The cuticle lies over and merges into the outer wall of the epidermal cell. It is multilayered and composed of an outer layer of wax, a cuticular membrane consisting of cutin and tannin-like material above the epidermal cell of the plant part. The waxy layer appears to be the main resistance to vapor diffusion through the cuticle. Pieniezak (1944) studied the physical characteristics of the skin of apples in relation to moisture loss. No correlation was found between the thickness of the cuticle and the transpiration rate, but surface russeting increased water loss. Wills et al. (1981) stated that the structure of the wax coating is more important than its thickness. Waxy coatings consisting of a complex, well-ordered structure of overlapping platelets provide more resistance to the permeation of water than coatings which are thicker but flat and structureless. Movement of moisture from within the product and through the cuticle was described by Chambers and Possingham (1963). They described water movement through the cuticle as the diffusion of liquid water from within the product through the cuticular membrane to just below the waxy layer of the cuticle. At this point water moves through the wax platelet layer as a vapor since water droplets or films cannot form in this space due to the hydrophobic nature of the waxy surfaces.

Within storage environments the action of the stomata and function of the cuticle and lenticels may be limited. The stomata of leafy product may close with small losses in moisture perhaps due to insufficient turgidity to keep stomata open. The waxy layer of the cuticle may naturally increase with length of storage or decrease due to poor handling practices. Typically, the cuticle will remain intact if proper storage and handling are practiced. The lenticels may eventually be covered by the waxy layer of the cuticle, resulting in lower rates of transpiration.

The surface of some tubers and roots contain periderm cells comprised of several layers of suberized cells. The suberin deposited in the cell walls of the periderm is a hydrophobic substance chemically similar to the cutin in the cuticle of other products.

It is evident from the studies of the surfaces of perishable commodities that the condition of the cuticle and the number of pore openings affect the resistance to transpiration and, presumably, the transpiration coefficient. The experimental procedure for determination of the transpiration coefficient must be general enough to account for the various surfaces found on perishable commodities. The procedure must be able to, at least qualitatively, account for the effect of product surface on the transpiration coefficient.

Procedure

Transpiration rate (m) from horticultural commodities is typically expressed by an equation of the following form:

$$m = KA_s(P_s - P_a) \tag{1}$$

where

K is the overall mass transfer coefficient,

A_s is the surface area of the product,

P_s is the water vapor pressure at the evaporating surface,

P_a is the water vapor pressure of the surrounding atmosphere.

The water vapor pressure at the evaporating surface P_s is affected by the temperature of the evaporating surface and the water vapor pressure lowering effect (VPL) due to solutes within the product moisture (Gaffney et al., 1985). The water vapor pressure P_s can be expressed as

$$P_s = VPL \times P_{sat} \tag{2}$$

where

P_{sat} is the saturation water vapor pressure at the temperature of the evaporating surface.

The coefficient K is an overall mass transfer coefficient that is dependent on the product and air properties. Chau et al. (1985) defined the coefficient K to be dependent on a skin transpiration coefficient K_s and an air film mass transfer coefficient K_a. They are related by the following equation

$$\frac{1}{K} = \frac{1}{K_s} + \frac{1}{K_a} \qquad (3)$$

This equation represents the resistance (1/K) to transpiration from the evaporating surface to the surrounding environment. The resistance to transpiration of the air film boundary layer adjacent to the surface of the commodity is represented by $1/K_a$. The resistance to transpiration of the product surface is represented by $1/K_s$.

It is important to recognize that K is composed of two variables, K_s and K_a. Different values of K would be obtained for the same identical product under different air temperature and flowrate conditions because K_a would not remain constant. The product transpiration coefficient K_s of the commodity depends only on the characteristics of the product. The coefficients K and K_s were calculated by this using equations (1), (2) and (3). K_a was calculated from equations available in the literature.

Combining equations (1), (2) and (3), the K_s coefficient can be calculated by using the following equation:

$$K_s = \frac{1}{\dfrac{A_s\,(\mathrm{VPL} \times P_{sat} - P_a)}{m} - \dfrac{1}{K_a}} \qquad (4)$$

To calculate the K_s transpiration coefficient from equation (4), product transpiration rates must be accurately measured from commodities placed in steady state forced-air. Gaffney et al. (1985) described the effects of various environmental and physiological factors upon the rates of transpiration from horticultural commodities. Based on this work an experimental procedure for measurement of product transpiration rates and coefficients (K_s) was designed to minimize the effects of the heat of respiration, air film resistance to mass transfer, radiation heat transfer and the water vapor pressure lowering effect due to solutes in solution within the commodity. The experimental procedure included airflow rates in the 2.5-5.0 m/sec range, relative humidities in the 45%-65% range and air temperatures in the 15.5-24.0 °C range to minimize the effects of the above factors on the weight loss of the commodities monitored.

Environmental steady state conditions were achieved by maintaining constant air drybulb and dewpoint temperatures during experimentation. The environmental chamber (Figure 2) was used to establish and control the drybulb and dewpoint temperatures of air. Two separate chambers were used to run experiments at various humidity levels. Within each room an experimental apparatus was placed to house sample commodities in two different velocity air streams.

To determine the K_S transpiration coefficient from equation (4), the following data were collected:

1) product weight loss rates to determine m,
2) product surface area (A_s), volume and dimensions,
3) air drybulb and dewpoint temperatures to obtain P_a,
4) air velocities and flowrates past the products to calculate K_a,
5) using the Chau et al. (1985) model to calculate the evaporating surface temperature and P_{sat}, and
6) the freezing point depression of the evaporating surface material to determine VPL.

This procedure was also used to calculate the overall mass transfer coefficient K for products stored in still air. The products were placed into an environmental chamber (Figure 2) where little or no air flow occured. The environmental chamber was maintained at constant conditions ranging from 5-20 °C drybulb and 45-95% relative humidity. Using equation (1), the overall mass transfer coefficient K can be calculated if the product transpiration rate, product surface area and the water vapor pressure deficit are known.

The overall mass transfer coefficient K for products stored in still air and the K_s transpiration coefficient were determined for seventeen common fruits and vegetables. The seventeen products, their varieties and stages of development are listed in Table 2. All products tested were either harvested from commercial fields or selected from

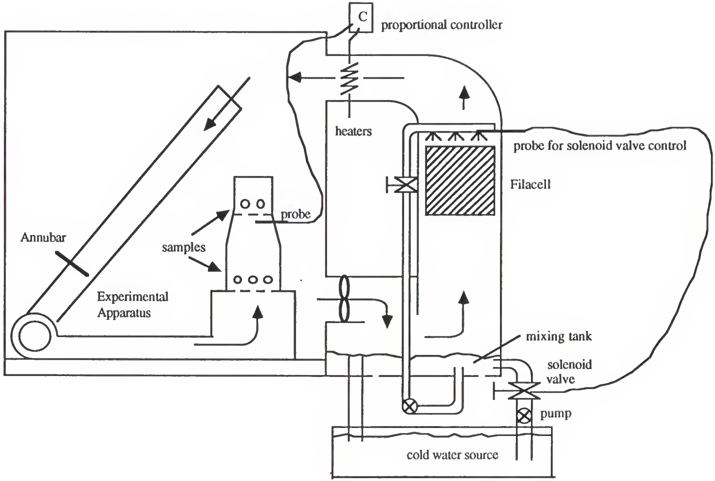

Figure 2. Environmental Chamber and Apparatus used to Experimentally Determine the K and Ks Coefficients

TABLE 2

Commodities Tested and Their Stage of Development when Harvested

Commodity	Variety	Stage of Development when Harvested
Apples	Red Delicious	Mature, not ripe
Blueberries	Tifblue	Mature, ripe
Brussels Sprouts	Ranpac	Mature
Cabbage	unknown	Mature
Carrots	Pacmore	Mature
Grapefruit	Marsh	Mature
Green Peppers	Jupiter	Mature
Lemons	Eureka	Mature
Lima Beans	Speckled	Mature
Limes	Persian	Mature
Oranges	Valencia	Mature
Peaches	Red Globe	Mature, not ripe
Pears	D'Anjou	Mature, not ripe
Snap Beans	Contender	Mature
Strawberries	Pajaro	Mature, ripe
Sugarbeets	unknown	Mature
Tomatoes	Sunny	Mature-Green

industrial storage. The samples were transported as quickly as possible to Gainesville, Florida, and either placed immediately into a controlled environmental chamber (Figure 2) or stored at 4 °C until testing could be conducted. All samples were inspected to separate damaged individuals and to separate the test samples into sizes. All samples were placed into the environmental chamber and allowed to reach a uniform temperature prior to experimentation.

The following section will describe the methodologies used to establish and control the required environmental conditions and to measure or calculate the properties of air and product required to determine K_s and K.

Methodology

Control of Drybulb and Dewpoint Temperatures

Accurate calculation of the K_s transpiration coefficient requires that the air flowing past the products be maintained at steady state conditions during measurement of the product weight loss rate. Two environmental chambers were used to establish and control the dry bulb and dewpoint temperatures of air at two humidity levels. Each environmental chamber was a 2.4m x 1.3m x 1.1m walk-in room (Figure 2).

To control the dewpoint temperature of the room air, a Humi-Fresh model 1.8E36 air handler was attached to the rooms. The air handler housing consisted of two 0.32 cm fiberglass skins, spray bonded to each side of a rigid polyurethane insulation. Within the housing, a 0.61m x 0.61m x 0.91m filacell unit was used. The filacell consists of polypropylene monofilament wrapped horizontally around a wooden structure. A spray tree made up with polypropylene nozzles and PVC pipe and fittings was used to evenly distribute water onto the monofilament. When water is sprayed onto the monofilament, small water droplets hang on to the filacell and create a large area for heat and mass transfer. A Dayton model 1C791 blower was then used to move room air through the filacell and to saturate the air at the temperature of the water spray. By maintaining a constant spray temperature, the dewpoint of the room air was controlled.

Control of the spray temperature was achieved by placing a YSI series 600 temperature probe in-line from a mixing-tank located at the base of the filacell housing (Figure 2). The YSI in-line temperature probe was connected to a YSI model 63RC thermistor controller which powered a 1.9 cm solenoid valve located in-line from a cold water tank. When the solenoid valve was opened, 4 °C water was pumped into the mixing tank from the cold water tank and a constant temperature (± 0.1 °C) was maintained at the spray tree. Overflow from the mixing tank was returned to the cold water tank.

Control of the air drybulb temperature was achieved by blowing the saturated air past a series of resistance heaters. The heaters raised the temperature of the air to achieve proper relative humidity for experimentation. A YSI series 600 air temperature probe was placed into the experimental apparatus to maintain a constant drybulb temperature at the location of the test samples (Figure 2). The probe was connected to a YSI model 72 proportional controller which powered the resistance heaters.

The resulting control achieved by the filacell unit and resistance heaters was excellent; dewpoint and air drybulb temperatures were controlled to ± 0.1 °C.

Product Weight Loss Rates

To calculate the transpiration rate (m) of the products, product weight loss rates were measured by monitoring the product weight during experimentation. Product weight loss was periodically measured by placing the products on top-loading digital scales having accuracies of 1 mg for samples under 160 g and 10 mg for samples over 160 g. The frequency of measurement was based on either a 1% product weight loss or a magnitude of weight loss which could be accurately measured by the digital scales. All products were tested until at least 4% of the total product weight was lost.

Product weight loss rate is a combination of the rate of moisture loss and the rate of carbon loss due to the evolution of carbon dioxide during respiration. Carbon dioxide rates of evolution were estimated from the respiration data listed in Hardenberg et al.

(1986). At the test conditions described the amount of CO_2 evolved from the commodities was nearly negligible when compared to the total weight loss measured (Table 3). In a typical test carbon loss rates were calculated at 0.01%-0.1% of total product weight. Therefore, the rate of moisture loss (m) from the commodities was calculated directly from the measured weight loss data minus the nearly negligible carbon loss calculated from the data listed in Hardenburg et al. (1986).

To measure the product weight loss under forced air conditions, an experimental apparatus was built (Figure 2). The apparatus was constructed so that

1) forced-air could be blown past experimental products at two different velocities and
2) air flowrates could be monitored.

A Dayton model 47525A blower and a Dayton model 2C864 DC motor with a variable speed controller were used to blow air through a wooden duct and past the experimental products. The products were placed into a wooden structure (Figure 2) which was constructed so that the forced-air was blown through a 0.10 m^2 cross-section and a 0.05 m^2 cross-section, achieving two velocities past the experimental products. During experimentation, the amount of product transpiration within the lower section of the apparatus did not the signigicantly affect the humidity of the air flowing through the upper section of the apparatus.

Product Surface Area, Volume and Dimensions

Product surface areas (A) were determined by tracing the axi-symmetrical cross sections of the product with a digitizer and using a computer program to calculate the surface of revolution generated by the cross-section. For non-axisymmetrical products, a cross-section was created by carefully slicing the products into halves determined by the major axis, tracing the border of the half-slice and computing the surface of revolution created by the half slices. This procedure for non-axisymmetrical products was used only

TABLE 3

Total Product Weight Loss and Calculated Carbon Loss at 21 °C and 50% Relative Humidity Storage

Product	Weight Loss grams	Weight Loss %	Carbon Loss grams	Carbon Loss of Total Product Weight %
Red Delicious Apples	9.15	5	0.119	0.065
Tifblue Bluberries	0.0825	5	0.00197	0.118
Ranpac Brussels Sprouts	0.940	5	0.0183	0.102
Cabbage	57.5	5	1.00	0.0811
Carrots	5.20	5	0.000946	0.0096
Marsh Grapefruit	23.6	5	0.932	0.191
Jupiter Green Peppers	7.75	5	0.245	0.158
Eureka Lemons	5.90	5	0.153	0.130
Speckled Lima Beans	0.150	5	0.00150	0.050
Persian Limes	7.35	5	0.141	0.00636
Valencia Oranges	11.7	5	0.59	0.140
Red Globe Peaches	10.3	5	0.11304	0.0865
D' Anjou Pears	11.25	5	0.245	0.109
Contender Snap Beans	0.50	5	0.0112	0.112
Pajaro Strawberries	0.550	5	0.00552	0.055
Sunny Tomatoes	10.15	5	0.353	0.114

for the determination of the sugarbeets surface area. Axisymmetrical products were found for the other sixteen products.

Product volumes were measured using the water displacement technique described in Moshenin (1986). A 250 ml beaker was used to submerge products in 150 - 200 ml of distilled water. The water displacement caused by holding the product submerged was measured using a Mettler 3000 digital balance (Figure 3).

To determine the K_a coefficient for air film resistance to mass transfer, product dimensions and shape were needed. Product dimensions (length and widths) were measured using a dial caliper.

Measurement of Air Drybulb and Dewpoint Temperatures

To determine the water vapor pressure (P_a) in the surrounding air, air drybulb and dewpoint temperatures were measured. Measurement of air stream drybulb temperature was done using 30-gage copper-constantan thermocouple wire. An Esterline Angus model PD2064 datalogger and Texas Instraments Silent 700 ASR were used to record the data to paper and tape cassette. The data were then transferred to a minicomputer for analysis and file manipulation.

Measurement of air dewpoint temperature was done by using a General Eastern System 1100DP dewpoint hygrometer. The dewpoint data were also recorded by the Esterline Angus datalogger to cassette and sent to a minicomputer for analysis and file manipulation.

Measurement of the Air Flowrates and Velocities Past the Products

To calculate the K_a coefficient for air film resistance to mass transfer, air velocity or air flowrates past the product must be known. The air flowrate past the products was measured using a 0.203m Annubar installed in a 0.203m PVC pipe located upstream from the experimental products (Figure 2). Uniform airflow was achieved by placing perforated sheet metal in the apparatus duct.

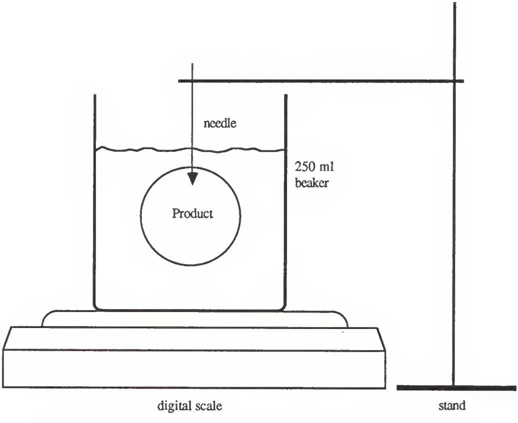

Figure 3. Experimental Apparatus Used to Determine Product Volumes

Calculation of the Vapor Pressure Lowering Effect (VPL) and Measurement of the Freezing Point Depression of the Evaporating Surface

The magnitude of the water vapor pressure lowering effect on Ps was determined by measuring the freezing point depression ΔT_f of the product surface material and using Raoult's law defined as

$$VPL = \frac{1}{1 + \frac{0.018(\Delta T_f)}{1.86}} \tag{5}$$

To determine the magnitude of vapor pressure lowering effect (VPL) at the surface of the products, the freezing point depression of the evaporating surface material was measured. The freezing point depression of the evaporating surface was measured by placing a 2cm x 1cm x 1cm sample of the surface material in a -12.2 °C freezer. Figure 4 shows the placement of a thermocouple into the sample and reference to 0 °C . The reference temperature was held constant by a Kaye Instruments Ice Point reference. The thermocouple junctions were wired into a Honeywell Elektronik 194 strip chart recorder and a typical freezing curve and freezing point depression is shown in Figure 5.

Calculation of P_s

To calculate the water vapor pressure at the evaporating surface it is necessary to know the surface temperature and vapor pressure lowering effect due to solutes in solution. The vapor pressure lowering effect can be calculated knowing the freezing point depression of the evaporating surface material. The temperature of the evaporating surface was calculated using the Chau et al. (1985) model

$$T_s = T_a + \frac{WV}{h_e A_s} - \frac{Lm}{h_e} \tag{6}$$

where W is the rate of heat generation per unit volume,

V is the product volume,

h_e is the effective heat transfer coefficient and

L is the heat of vaporization,

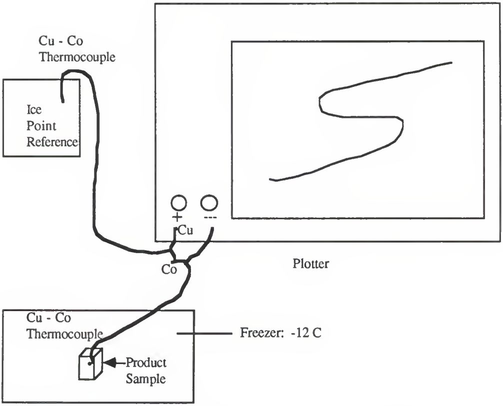

Figure 4. Experimental Setup for Determination of the Freezing Point Depression for Fruits and Vegetables

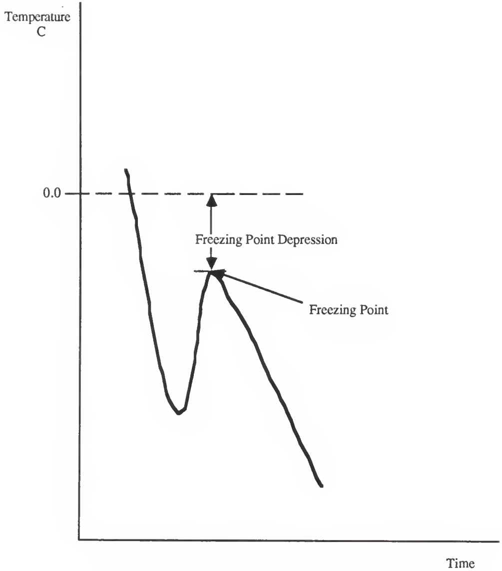

Figure 5. Typical Freezing Curve for Fruits and Vegetables

A_s is the product surface area.

Chau et al. (1985) derived an equation for the product mass average temperature

$$T_{ma} = T_s + \left(1 + \frac{r_{ma}^2}{R^2}\right)\frac{W\,R\,V}{2k_pA_s} \qquad (7)$$

where r_{ma} is the location where the mass average temperature occurs,

R is the characteristic product dimension and

k_p is the product thermal conductivity.

For this study W was expressed as a function of the mass average temperature (Table 4) by performing regressions on the data available in Hardenburg et al. (1986). These regressions resulted in coefficients a and b for the equation

$$W = a(T_{ma})^b \qquad (8)$$

An iterative computer procedure was written to iterate equations (6), (7) and (8) to determine T_s.

Knowing the surface temperature and vapor pressure lowering effect (VPL), Ps was calculated from the equation

$$P_s = VPL\ (P_{sat}(T_s)) \qquad (9)$$

where $P_{sat}(T_s)$ is the water vapor pressure for saturated air at Ts.

Calculation of K_a

The air film mass transfer coefficient K_a was calculated using the Sherwood-Reynolds-Schmidt correlation for spheres described by Geankoplis(1978)

$$Sh = 2.0 + 0.552\ Re^{0.50}Sc^{0.33}\ \ (1 < Re < 48000) \qquad (10)$$

where

$$K_a = \frac{Sh\ D}{d}$$

$$Re = \frac{\rho\ v\ d}{\mu}$$

TABLE 4

Regression of Heat of Evolution Data

Equation:[1] $W = a(1.8T + 32)^b$

Product	a	b	r^2
Apples	4.57 x 10-7	2.8691	0.9873
Blueberries	2.52 x 10-7	3.2143	0.9924
Brussels Sprouts	1.05 x 10-5	2.4909	0.9968
Cabbage	2.20 x 10-6	2.5623	0.9918
Carrots	4.66 x 10-5	1.9516	0.9600
Grapefruit	4.98 x 10-7	2.7609	0.9959
Green Peppers	1.32 x 10-5	2.1777	0.9664
Lemons	2.51 x 10-6	2.3859	0.9862
Lima Beans	4.51 x 10-6	2.7222	0.9629
Limes	1.63 x 10-7	2.9640	0.9244
Oranges	8.91 x 10-7	2.6795	0.9904
Peaches	5.49 x 10-8	3.5677	0.9806
Pears	1.82 x 10-7	3.2249	0.9772
Snap Beans	8.56 x 10-6	2.6660	0.9801
Strawberries	1.43 x 10-8	4.2226	0.9375
Tomatoes	4.30 x 10-7	2.9076	0.9907

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1 - W in W/kg, T in °C

$$Sc = \frac{\mu}{\rho D}$$

D = diffusivity

d = product diameter

V = air velocity

μ = air dynamic viscosity

Note that K_a is dependent upon V, ρ, μ, D and d. V, ρ, μ and D are properties of the air flowing past the product and d is the diameter (or size) of the product.

Using the above procedure, the K_s transpiration coefficient can be calculated from experimental data.

A MATHEMATICAL MODEL FOR SIMULATION OF TRANSPIRATION FROM FRUITS AND VEGETABLES IN BULK STORAGE

Refrigerated storage of fruits and vegetables has made possible the marketing of these commodities long after their harvest season. The effect of refrigeration is to delay senescence by reducing the respiration and transpiration rates of the products, slowing the rate of microflora activity and reducing the rate of enzymatic action (Wills et. al., 1981). The fruit and vegetable industries store their produce in bulk: either in containers or in piles. Since products in bulk storage are surrounded by other products or containers, diffusion and/or natural convection currents may be the means for moisture removal from the bulk store in the absence of ventilation.

With current interests to extend the marketing of perishable commodities into the modified atmosphere packaging of fresh fruits and vegetables, there is a need to understand the environment within the bulk store. This model is an attempt to determine the air and moisture environment within a bulk store of Valencia oranges and the mechanism for transpiration from within the bulk store. This mathematical model uses explicit finite difference equations to simulate transpiration rates and heat transfer from fruits and vegetables in bulk storage. The purpose of this work was to determine the relative effects of diffusion and natural convection on the removal of moisture from a bulk store of Valencia oranges in the absence of ventilation. Experimental data were collected to validate the model.

Model Development

Valencia oranges were selected as the sample commodity for experimental analysis and model development. Valencia oranges have near-spherical shapes, low transpiration rates and low rates of respiration. These qualities allowed measurement of the transpiration rates from bulk oranges with minimal loss of product quality and allowed assumption of spherical product geometry. In addition, research has been conducted (Gaffney and Baird, 1980) to determine the heat transfer properties of Valencia oranges. For these reasons, Valencia oranges lent themselves readily for experimental analysis and model development.

The Florida citrus industry stores Valencia oranges in either bins such as the one shown in Figure 6. The bin geometry has slots where heat removal and moisture loss are facilitated. Within industrial stores these bins may be stacked and it is hypothesized that near the centers of industrial storage configurations the transfer of heat and moisture may occur by natural convection and/or diffusion in the absence of ventilation.

To facilitate the development of the model, the geometry (Figure 7) found in the packaging of oranges (Size 80, 6.6 cm average diameter) was selected. This geometry consists of 20 near-spherical oranges placed in a horizontal layer. The pattern is staggered from layer-to-layer but the void volume is determinable. This geometry was also selected to facilitate the design of the experimental apparatus which allowed determination of the relative effects of natural convection and diffusion when heat and mass transfer occur predominately in one direction.

For model development the following was assumed:

1) Heat transfer within and from the oranges occurs via conduction and convection respectively. The convective heat transfer coefficient is constant over the product surface,
2) Respiratory heat generation is a function of temperature within the product,
3) Product-to-product heat conduction is negligible,
4) Transpiration occurs at the product surface,
5) Mass loss from the product is due to moisture and carbon loss only. The loss of volatiles is negligible,

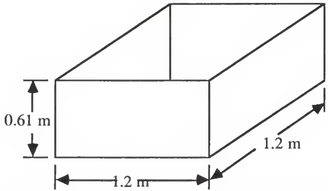

Figure 6. Industrial Bin Configuration for Storage of Valencia Oranges

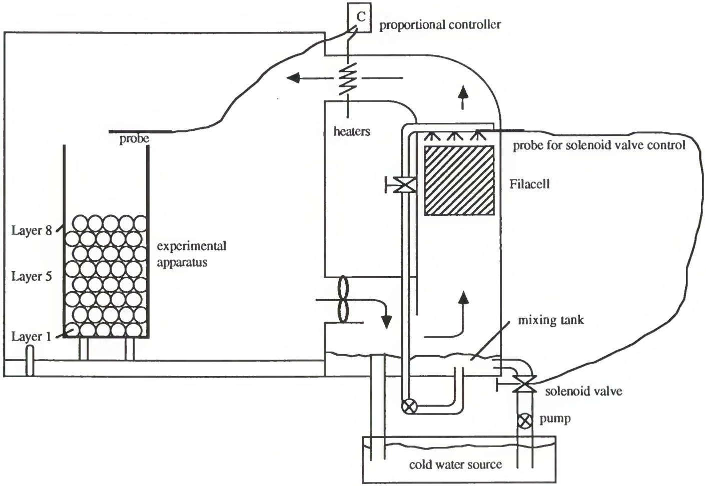

Figure 7. Environmental Chamber and Apparatus used to Experimentally Determine the Transpiration Rates from Valencia Oranges Stored in Bulk.

6) Heat is transferred through the air and from the bulk store by conduction and natural convection only,
7) Natural convection can be described by the Boussinesq approximation. The Boussinesq approximation can be used when air is assumed to behave as an ideal gas and density changes occur due to temperature or concentration gradients. Other researchers, Bejan and Khair (1985) and Beukema et al (1983) have successfully used this approximation in their studies of natural convection in a porous medium,
8) Natural convection can occur between the product surface and air within the void volume and also between adjacent layers within the bulk store,
9) The only significant mass loss from the bulk is water vapor. The mass of dry air within the bulk is assumed to be replenished,
10) Water vapor is transferred through the void and from the bulk by diffusion and natural convection currents only,
11) Heat and mass transfer through the bulk is predominantly in one direction; horizontal heat and mass transfer is negligible,
12) Flow within the bulk can be described by Darcy flow through porous media.

The geometry of the bulk store was divided into layers as shown in Figure 8. For each layer a node was assigned to the air in the void volume and the products were discretized into the elemental volumes shown to determine temperature gradients within the product. It was assumed that the air temperature and product heat and mass transfer characteristics would not vary within a layer at any given time.

Near a surface, the magnitude of velocity induced by natural convection in the vertical direction governed by Darcy's law through a porous medium can be expressed as (Bejan and Khair, 1985)

$$v_{i,s}^{n} = \frac{K_p}{\mu}(\rho_a \beta g(T_{s,i}^{n} - T_{a,i}^{n})) \tag{11}$$

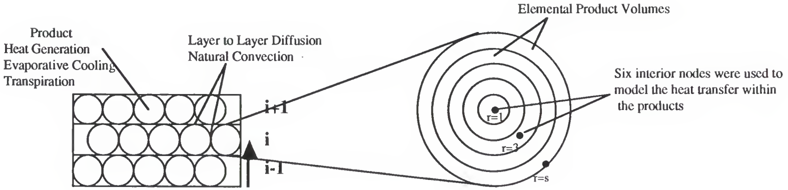

Figure 8. Division of the Bulk into Elemental Product Volumes and Layers within the Bulk

Fahien (1983) presented an equation for the specific permeability K_p based on the Kozeny-Carmen equation

$$K_p = \frac{\varepsilon^3 D_p^2}{180(1-\varepsilon)^2} \tag{12}$$

Equation 12 includes a tortuosity factor to account for the meandering path of the flow in a porous media, a constant to account for geometry and a hydraulic radius.

For this study it was assumed that the velocity induced by natural convection between layers can be expressed as

$$v_{i,l}^n = \frac{K_p}{\mu}(\rho_a \beta g(T_{s,i}^n - T_{s,i+1}^n)) \tag{13}$$

The direction of the velocity is dependent upon the temperature difference between the product surfaces. The effect of the velocity is to transport mass (water vapor) and energy to an adjacent layer by bulk flow. It was assumed that product heat generation would create temperature differences between product surfaces in adjacent layers so that the direction of the total velocity was predominantly in the positive i direction.

By performing an energy balance for each node in the moist air void volumes, the finite difference equations were developed. At each node, the accumulation of energy within the void volume is equal to the heat transfer by conduction, energy gain or loss due to dry air and water vapor bulk flow caused by natural convection currents in the vertical direction and the energy flow from the product surface to the void volume

$$\begin{aligned} \rho_a \varepsilon V_i c_{v,a} \frac{T_i^{n+1} - T_i^n}{\Delta t} + \rho_v \varepsilon V_i c_{v,v} \frac{T_i^{n+1} - T_i^n}{\Delta t} = \\ kA \frac{T_{i+1}^n - T_i^n}{\Delta z} + kA \frac{T_{i-1}^n - T_i^n}{\Delta z} \\ + \rho_a v_{i-1}^n A c_{p,a} (T_{i-1}^n - T_i^n) + \rho_a v_i^n A c_{p,a} (T_{i+1}^n - T_i^n) \\ + \rho_v v_{i-1}^n A c_{p,v} (T_{i-1}^n - T_i^n) + \rho_v v_i^n A c_{p,v} (T_{i+1}^n - T_i^n) \\ + hA_s(T_{s,i}^n - T_i^n) \end{aligned} \tag{14}$$

The energy terms for water vapor in equation 14 were considered negligible because these terms are two orders of magnitude less than the energy terms for dry air. The energy equation then becomes

$$\rho_a \varepsilon V_i c_{v,a} \frac{T_i^{n+1} - T_i^n}{\Delta t} = kA \frac{T_{i+1}^n - T_i^n}{\Delta z} + kA \frac{T_{i-1}^n - T_i^n}{\Delta z}$$
$$+ \rho_a v_{i-1}^n A c_{p,a} (T_{i-1}^n - T_i^n) + \rho_a v_i^n A c_{p,a} (T_{i+1}^n - T_i^n)$$
$$+ hA_s (T_{s,i}^n - T_i^n) \tag{15}$$

Rearranging,

$$T_i^{n+1} = \left(1 - \frac{2kA \, \Delta t}{\rho_a \varepsilon V_i c_{v,a} \, \Delta z} - \frac{v_{i-1}^n A \, \gamma \Delta t}{\varepsilon V_i} - \frac{v_i^n A \, \gamma \Delta t}{\varepsilon V_i} - \frac{hA_s \, \Delta t}{\rho_a \varepsilon V_i c_{v,a}} \right) T_i^n$$
$$+ \frac{kA \, \Delta t}{\rho_a \varepsilon V_i c_{v,a} \, \Delta z} (T_{i+1}^n + T_{i-1}^n) + \frac{v_{i-1}^n A \gamma \Delta t}{\varepsilon V_i} + \frac{v_i^n A \gamma \Delta t}{\varepsilon V_i} T_{i+1}^n + \frac{hA_s \, \Delta t}{\rho_a \varepsilon V_i c_{v,a}} T_{s,i}^n \tag{16}$$

Similarly for the bottom layer

$$T_1^{n+1} = \left(1 - \frac{kA \, \Delta t}{\rho_a \varepsilon V_1 c_{v,a} \Delta z} - \frac{v_1^n A \, \gamma \Delta t}{\varepsilon V_1} - \frac{hA_s \, \Delta t}{\rho_a \varepsilon V_1 c_{v,a} \Delta z} \right) T_1^n$$
$$+ \frac{kA \, \Delta t}{\rho_a \varepsilon V_1 c_{v,a} \Delta z} T_2^n + \frac{v_1^n A \, \gamma \Delta t}{\varepsilon V_1} T_2^n + \frac{hA_s \, \Delta t}{\rho_a \varepsilon V_1 c_{v,a} \Delta z} T_{s,i}^n \tag{17}$$

The difference between equations (16) and (17) is that at the bottom layer no heat transfer will occur to a lower layer (i-1) since the boundary is assumed to be insulated. Equation (16) accounts for the heat transfer to layers i+1 and i-1 from layer i. Equation (16) is also used used to simulate the top layer, for which the i+1 term is room air temperature.

The cross-sectional surface area A for heat transfer between the layers was assumed to be

$$A = \frac{\varepsilon V_i}{\Delta z} \tag{18}$$

By performing a mass balance for each node in the air void volumes, the finite difference equations for humidity were developed. At each node the accumulation of humidity in the void volume is equal to the flow of water vapor by diffusion, natural convection currents in the vertical direction and the transpiration rate from the product surface to the void volume. For any node located in the bulk except at the bottom layer

$$\begin{aligned}\rho_a \varepsilon V_i \frac{H_i^{n+1} - H_i^n}{\Delta t} &= \rho_a DA \frac{H_{i+1}^n - H_i^n}{\Delta z} + \rho_a DA \frac{H_{i-1}^n - H_i^n}{\Delta z} \\ &+ \rho_a v_{i-1}^n A(H_{i-1}^n - H_i^n) + \rho_a v_i^n A(H_{i+1}^n - H_i^n) \\ &+ KA_s(P_{s,i}^n - P_i^n)\end{aligned} \tag{19}$$

Rearranging terms

$$\begin{aligned}H_i^{n+1} &= \left(1 - \frac{2DA\,\Delta t}{\varepsilon V_i} - \frac{(v_{i-1}^n + v_i^n)A\,\Delta t}{\varepsilon V_i}\right)H_i^n \\ &+ \frac{DA\,\Delta t}{\varepsilon V_i}(H_{i+1}^n + H_{i-1}^n) + \frac{v_{i-1}^n A\,\Delta t}{\varepsilon V_i}H_{i-1}^n + \frac{v_i^n A\,\Delta t}{\varepsilon V_i}H_{i+1}^n + \frac{KA_s\,(P_{s,i}^n - P_i^n)\Delta t}{\rho_a \varepsilon V_i}\end{aligned} \tag{20}$$

Similarly for the bottom layer

$$H_1^{n+1} = \left(1 - \frac{DA\,\Delta t}{\varepsilon V_1} - \frac{v_1^n A\,\Delta t}{\varepsilon V_1}\right)H_1^n + \frac{DA\,\Delta t}{\varepsilon V_1}\,H_2^n + \frac{v_1^n A\,\Delta t}{\varepsilon V_1}\,H_2^n + \frac{KA_s\,(P_{s,1}^n - P_1^n)\Delta t}{\rho_a \varepsilon V_i} \tag{21}$$

The difference between equations (20) and (21) is that at the bottom layer no mass transfer will occur to a lower layer (i-1) since the boundary is assumed to be insulated. Equation (20) accounts for water vapor transport from layers i+1 and i-1 to layer i. Equation (20) is also used to simulate the top layer of the bulk, for which the i+1 term is room humidity.

To model the heat flow from the product to the air in the void spaces, the spherical products were divided into elemental volumes to determine temperature gradients within the product. Using the elemental product volumes of Figure 8 and performing an energy balance on each node, the finite difference equations were developed. At each node, the rate of change of the heat capacity of the elemental volume is equal to net conductive heat transfer in the radial direction and the amount of respiratory heat generated. For any interior node except at the center

$$\rho_p V_r c_{p,p} \frac{Tp_r^{n+1} - Tp_r^n}{\Delta t} = k_p A_{r-1} \frac{Tp_{r-1}^n - Tp_r^n}{\Delta r} + k_p A_r \frac{Tp_{r+1}^n - Tp_r^n}{\Delta r} + \dot{q} V_r \tag{22}$$

Rearranging terms

$$Tp_r^{n+1} = \left(1 - \frac{k_p A_{r-1}\,\Delta t}{\rho_p V_r c_{p,p}\,\Delta r} - \frac{k_p A_r\,\Delta t}{\rho_p V_r c_{p,p}\,\Delta r}\right) Tp_r^n + \frac{k_p A_{r-1}\,\Delta t}{\rho_p V_r c_{p,p}\,\Delta r} Tp_{r-1}^n + \frac{k_p A_r\,\Delta t}{\rho_p V_r c_{p,p}\,\Delta r} Tp_{r+1}^n + \frac{\dot{q}\,\Delta t}{\rho_p c_{p,p}} \tag{23}$$

Similarly for the center node

$$Tp_1^{n+1} = \left(1 - \frac{k_p A_1\,\Delta t}{\rho_p V_1 c_{p,p}\,\Delta r}\right) Tp_1^n + \frac{k_p A_1\,\Delta t}{\rho_p V_1 c_{p,p}\,\Delta r} Tp_2^n + \frac{\dot{q}\,\Delta t}{\rho_p c_{p,p}} \tag{24}$$

On the surface of the product, the nodes are treated as non-capacitance nodes; there are no elemental volumes associated with these nodes. This type of node requires a less stringent time step and a detailed discussion of this type of node was presented by Chau et al. (1984). At the surface:

$$Tp_s^{n+1} = \frac{h A_s T_i^{n+1} + \dfrac{k_p A_{s-1} Tp_{s-1}^{n+1}}{\Delta r/2} - k_T A_s (P_{s,i}^{n+1} - P_i^{n+1}) L}{h A_s + \dfrac{k_p A_{s-1}}{\Delta r/2}} \tag{25}$$

Initial air, humidity and velocity conditions for the model are

$$T_i^o = T_{\text{room air}}$$

$$H_i^o = H_{\text{room air}}$$

$$v_i^o = 0$$

Equations (13), (16), (17), (20) and (21) are the set of equations from which the air temperature and humidity can be calculated at some given time. Equations (23), (24) and

(25) are the set of equations from which the temperatures of the various nodes within the elemental product volumes can be calculated at some given time.

A digital computer program was written to calculate the numerical solution for Equations (13), (16), (17), (20), (21), (24) and (25). Each step of the numerical solution is presented in Figure 9 and inputs to the computer program are listed in Table 5.

Ames (1977) discussed the stability criterion for simple explicit numerical routines which solve parabolic equations of the form

$$U_t = a\ u_{xx} + b\ u_x + c\ u + d \tag{26}$$

where a, b, c and d can be functions of x and t. The simple explicit finite difference expression for equation (26) can be written in the form

$$U_{i,j+1} = c_i U_{i+1,j} + c_o U_{i,j} + c_{-i} U_{i-1,j} + k\ d_{i,j} \tag{27}$$

and its stability criterion is c_o must be greater than zero. Ames (1977) stated that satisfying the stability criterion also assured convergence of the method to a solution when the equations where properly derived.

Equations (16), (17), (20), (21), (23) and (24) are parabolic equations which have the form presented in equation (27). Using the analysis presented by Ames (1977), the stability criterion for these equations is such that the bracketed terms of the equations must be greater than zero. Stability is maintained and convergence assured if

$$\left(1 - \frac{2kA\ \Delta t}{\rho_a \varepsilon V_i c_{v,a}\ \Delta z} - \frac{v_{i-1}^n A\ \gamma \Delta t}{\varepsilon V_i} - \frac{v_i^n A\ \gamma \Delta t}{\varepsilon V_i} - \frac{h A_s\ \Delta t}{\rho_a \varepsilon V_i c_{v,a}}\right) > 0 \tag{28}$$

$$\left(1 - \frac{kA\ \Delta t}{\rho_a \varepsilon V_1 c_{v,a} \Delta z} - \frac{v_1^n A\ \gamma \Delta t}{\varepsilon V_1} - \frac{h A_s\ \Delta t}{\rho_a \varepsilon V_1 c_{v,a} \Delta z}\right) > 0 \tag{29}$$

$$\left(1 - \frac{2DA\ \Delta t}{\varepsilon V_i} - \frac{(v_{i-1}^n + v_i^n) A\ \Delta t}{\varepsilon V_i}\right) > 0 \tag{30}$$

$$\left(1 - \frac{DA\ \Delta t}{\varepsilon V_1} - \frac{v_1^n A\ \Delta t}{\varepsilon V_1}\right) > 0 \tag{31}$$

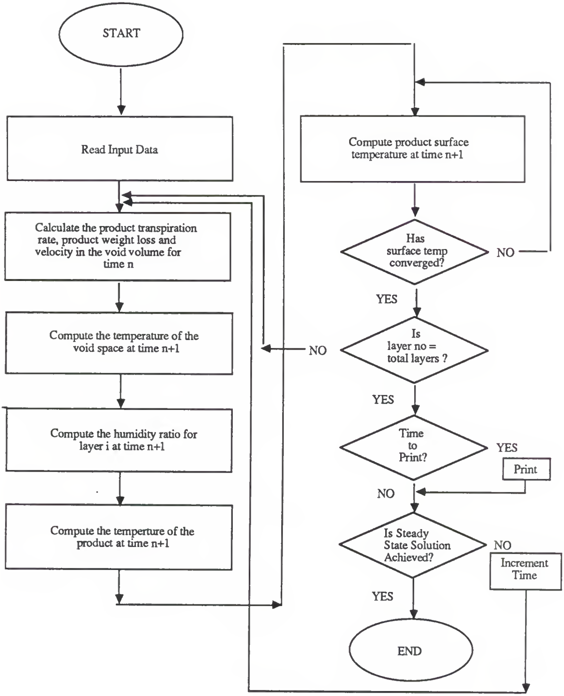

Figure 9. Flow Diagram for the Numerical Calculations of the Bulk Transpiration Model

TABLE 5

Inputs to the Numerical Model

initial air temperature
product diameter
number of layers
product density
product respiration rate
void volume
time increment
bulk depth
initial humidity
initial product temperature
number of products per layer
product respiration rate
product thermal conductivity
product overall mass transfer coefficient
product specific heat

$$\left(1-\frac{k_pA_{r-1}\,\Delta t}{\rho_pV_rc_{p,p}\,\Delta r}-\frac{k_pA_r\,\Delta t}{\rho_pV_rc_{p,p}\,\Delta r}\right)>0 \tag{32}$$

$$\left(1-\frac{k_pA_1\,\Delta t}{\rho_pV_1c_{p,p}\,\Delta r}\right)>0 \tag{33}$$

Choosing the number of nodes for both within the product and within the bulk affects the spatial increments and subsequently the stability and accuracy of the model. Six nodes were chosen to simulate the interior of the product, although it was expected that low rates of heat transfer would result in a negligible temperature gradient within the product. The bulk was divided into eight layers of 20 oranges so that direct comparison of the numerically predicted product weight loss and the experimentally determined product weight loss could be achieved. The bulk was also divided into twelve layers to determine the consistency of the numerical equations. The temperature and humidity values calculated for the twelve-layer simulation were 2.5% different than the temperature and humidity values calculated by the eight-layer simulation. The twelve-layer simulation, however, required more than twice the computational time than the eight-layer simulation.

Equations 28 - 33 were used to calculate a stable time increment and time increments larger than 4 seconds created instabilities. Time increments lower than 3 seconds resulted in unacceptable truncation errors, requiring double-precision variables and longer computational time.

To check the validity of the model against experimental data, thermal and physical properties of the oranges and air must be known. The physical and thermal properties of Florida Valencia oranges related to heat transfer were reported by Gaffney and Baird (1980). The reported properties for thermal conductivity and specific heat for the orange flesh and rind (Table 6) were used in this model. The density of the experimental samples was measured using the water displacement method. The transpiration coefficient for Valencia oranges was measured using the technique described earlier within this document.

TABLE 6

Thermal Properties of Valencia Oranges

	Thermal Conductivity W/m-K	Specific Heat J/kg-K
Flesh	0.469	3900
Rind	----*	3550

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* Rind thermal conductivity was assumed to be the same as flesh thermal conductivity.

The thermal properties of air and the diffusion coefficient of water vapor through air were taken form engineering handbooks.

The Nusselt number (Nu) is a dimensionless heat transfer coefficient. Johns and Lawn (1985) stated that the Nusselt number for heat transfer between individual spheres located within an array of spheres in stationary air is equal to five. Holman (1981) presented the an equation for natural convection heat transfer from spheres

$$\mathrm{Nu} = 2.0 + 0.5(\mathrm{GR} \times \mathrm{PR})^{0.25} \qquad (34)$$

where

$$\mathrm{GR} = \frac{g\rho^2\beta(T^n_{s,i} - T^n_i)d^3}{\mu^2}$$

$$\mathrm{PR} = \frac{\mu c_{p,a}}{k}$$

In equation (34) the Grashof number (GR) accounts for the buoyancy effects on the heat transfer coefficient at the product surface. The Prandtl number (PR) accounts for the effect of the relative magnitudes of fluid momentum and thermal diffusion on the heat transfer coefficient.

The results presented by Johns and Lawn (1985) and Holman (1981) indicate that the natural convection heat transfer between the surface of a sphere and its immediate environment can be described by a Nusselt number of 2 to 5. These results and equation 28 were used to determine if the numerically calculated natural convection heat transfer from the product surface to the void volume was consistent with results previously published.

Experimental Procedures

An environmental chamber was used to establish and control the drybulb and dewpoint temperatures of air (Figure 7). A detailed description of this experimental apparatus was presented earlier in this document.

The oranges were kept in an experimental apparatus placed in this controlled room. The apparatus was a wooden box insulated against mass and heat transfer by epoxy and one inch of fiberglass insulation. Eight layers of Valencia oranges were placed in this box along with twenty-four 36-gage thermocouples at various locations within the void volumes and oranges.

The product surface area A_s for transpiration was determined by measuring the contact area between oranges having the packing pattern shown in Figure 7. This contact area was subtracted from the product surface area to obtain A_s.

Ten experiments were conducted to determine the transpiration rates of Valencia oranges within the bulk configuration. The tests were conducted at constant storage conditions (either at 4.4 °C or at 8.6 °C) with relative humidity at 85% to create a vapor pressure deficit to induce transpiration. For each test 160 oranges were placed into the environmental chamber and allowed to reach room temperature. The oranges were then individually weighed at the storage temperature and then immediately placed into the experimental apparatus. The experiments lasted 1 to 14 days after which all individual oranges were immediately weighed. Average weight loss rates within the bulk store were recorded and temperatures within the store were recorded using a Campbell Scientific CR21X datalogger.

RESULTS AND DISCUSSION

Determination of the Coefficients K and K_s

To determine the transpiration coefficient K_s product weight loss rate, surface area, linear dimensions and freezing points must be determined. Table 7 lists the product properties measured for the seventeen fruits and vegetables studied.

This study has defined K and K_s on a per unit area basis (Equation 1) because transpiration rate is a function of the product surface area. However, transpiration coefficients reported on a mass basis are more convenient to use because product weight determination is easier to perform than product surface area determination. Correlations between surface area and product weight were determined and the results are shown in Table 8.

Table 9 presents the average K and K_s on an area basis for the products tested and Table 10 presents the same data on a mass basis. The large standard deviations presented in Table 9 indicate that the K and K_s coefficients are highly variable for individuals within a given variety. These highly variable coefficients may have occurred due to the possibility of different product physiological conditions, including injuries which were not detectable at the time of experimentation.

Table 11 lists the average transpiration coefficient K_s for the seventeen fruits and vegetables in descending order with the characteristics of the product surface to show, in a qualitative sense, the effect of the surface characteristics on K_s. Carrots and sugarbeets are root and tuber crops which have a surface of suberized cells with typically little or no waxy layer. These crops had exceptionally high transpiration coefficients. The transpiration coefficient for peaches was high, perhaps due to the postharvest practice of removing the surface "hair" from the commodity. This practice removes the greatest

TABLE 7

Measured Product Properties for the Seventeen Fruits and Vegetables

Product	Weight[1] Lost g/hr	Average Surface Area m^2	Average Major Axis m	Freezing Point C	VPL
Red Delicious Apples	0.0153	0.0183	0.0745	-1.1	0.99
Tifblue Blueberies	0.00346	0.000527	0.0127	-1.8	0.98
Ranpac Brussels Sprouts	0.130	0.00326	0.0254	-1.1	0.99
Cabbage	1.18	0.0775	0.157	-1.1	0.99
Pacmore Carrots	1.23	0.0105	0.0290	-0.7	0.99
Marsh Grapefruit	0.0234	0.0326	0.104	-1.4	0.99
Jupiter Green Peppers	0.0820	0.0242	0.0785	-1.6	0.98
Eureka Lemons	0.0276	0.0116	0.05709	-4.6	0.96
Speckled Lima Beans	0.0680	0.00373	0.01778	-1.0	0.99
Persian Limes	0.0541	0.0118	0.0326	-4.0	0.96
Valencia Oranges	0.0756	0.0182	0.0747	-3.2	0.97
Red Globe Peaches	0.633	0.0166	0.0605	-1.1	0.99
D'Anjou Pears	0.051	0.0186	0.0708	-1.8	0.98
Contender Snap Beans	0.0714	0.00337	0.0102	-0.7	0.99
Sugarbeets	2.63	0.0492	0.0778	-3.8	0.96
Pajaro Strawberries	0.138	0.00292	0.0305	-1.0	0.99
Sunny Tomatoes	0.0858	0.0169	0.0360	-0.6	0.99

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1 - at storage conditions of 15.5 °C - 24 °C, 50 %RH

TABLE 8

Linear Correlation of Surface Area to Product Weight

Equation: Surface Area (m^2) = a + b * Weight (g)

Product	a	b	r^2	range (g)	n[1]
Red Delicious Apples	0.00723	0.0000602	0.926	135-230	30
Tifblue Blueberries	0.000163	0.0002370	0.953	0.8-2.8	24
Ranpac Brussel Sprouts	0.001110	0.0001330	0.701	7.5-22.	30
Cabbage	0.0442	0.0000288	0.906	880-1840	30
Pacmore Carrots	0.00427	0.0000599	0.678	80-130	24
Marsh Grapefruit	0.0130	0.0000416	0.912	350-515	30
Jupiter Green Peppers	0.00798	0.000104	0.844	180-235	50
Eureka Lemons	0.00408	0.0000636	0.687	100-160	25
Speckled Lima Beans	0.000258	0.000563	0.400	4.0-6.0	12
Persian Limes	0.00238	0.000064	0.697	135-240	25
Valencia Oranges	-0.000473	0.0000798	0.917	200-280	30
Red Globe Peaches	0.00612	0.0000510	0.920	130-240	30
D'Anjou Pears	0.00252	0.0000716	0.854	205-250	30
Contender Snap Beans	0.00186	0.000273	0.348	4.0-9.0	35
Sugarbeets	-0.0900	0.0000436	0.944	1000-1400	6
Pajaro Strawberries	0.00106	0.000164	0.820	13.0-20.0	30
Sunny Tomatoes	0.00429	0.0000621	0.766	165-220	20

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n is the number of samples

TABLE 9

Average and Standard Deviation for K and K_s - Area Basis

Product	K g/m^2-s-MPa avg	 std dev	K_s g/m^2-s-MPa avg	 std dev
Red Delicious Apples	0.167	0.00948	0.167	0.0269
Tifblue Blueberries	1.94	0.574	2.19	0.640
Ranpac Brussels Sprouts	11.1	3.20	13.3	2.44
Cabbage	4.28	1.26	6.72	2.84
Pacmore Carrots	92.0	36.8	156	75.9
Marsh Grapefruit	1.67	0.37	1.68	0.33
Jupiter Green Peppers	1.31	0.49	2.15	0.71
Eureka Lemons	2.08	0.64	2.08	0.64
Speckled Lima Beans	4.04	0.61	4.33	0.592
Persian Limes	2.13	0.32	2.22	0.56
Valencia Oranges	1.67	0.25	1.72	0.208
Red Globe Peaches	14.1	5.20	14.2	5.20
D'Anjou Pears	0.684	0.125	6.69	0.149
Contender Snap Beans	4.35	1.09	5.64	1.77
Sugarbeets	24.9	8.96	33.6	20.1
Pajaro Strawberries	11.2	1.02	13.6	4.80
Sunny Tomatoes	0.90	0.012	1.10	0.674

TABLE 10

Average K and K_s - Mass Basis

Product	K g/kg-s-MPa avg	Ks g/kg-s-MPa avg
Red Delicious Apples	0.0166	0.0166
Tifblue Blueberries	0.666	0.751
Ranpac Brussels Sprouts	2.24	2.68
Cabbage	0.285	0.447
Pacmore Carrots	9.29	15.7
Marsh Grapefruit	0.116	0.116
Jupiter Green Peppers	0.203	0.333
Eureka Lemons	0.204	0.204
Speckled Lima Beans	2.44	2.62
Persian Limes	0.170	0.177
Valencia Oranges	0.129	0.133
Red Globe Peaches	1.14	1.15
D'Anjou Pears	0.00928	0.00930
Contender Snap Beans	2.65	3.44
Sugarbeets	0.918	1.24
Pajaro Strawberries	2.88	3.50
Sunny Tomatoes	0.0749	0.0915

TABLE 11

Average K_s and Product Surface Descriptions

Product	K_s g/m^2-s-MPa	Product Surface Description
Pacmore Carrots	156	No cuticle, corky periderm
Sugarbeets	33.6	No cuticle, corky periderm
Red Globe Peaches	14.2	Surface hairs removed Smooth waxless surface
Pajaro Strawberries	13.6	Unknown
Ranpac Brussels Sprouts	13.3	Leafy surface, stomata may be opened or closed
Cabbage	6.72	Leafy surface, little or no waxy surface
Contender Snap Beans	5.64	Little or no waxy surface
Speckled Lima Beans	4.33	Little or no waxy surface
Persian Limes	2.22	Waxy surface
Tifblue Blueberries	2.19	Waxy surface
Jupiter Green Peppers	2.15	Waxy surface
Eureka Lemons	2.08	Waxy surface
Valencia Oranges	1.72	Waxy surface
Marsh Grapefruit	1.68	Waxy surface
Sunny Tomatoes	1.10	Waxy surface Highly impermeable
D'Anjou Pears	0.686	Waxy surface Highly impermeable
Red Delicious Apples	0.167	Waxy surface Highly impermeable

resistance to transpiration and yields a smooth skinned surface with little waxy surface. Those products with leafy surfaces and possible open stomata such as brussels sprouts were high in K_s, followed by strawberries (surface type unknown). Moderate transpiration coefficients were calculated for cabbage, lima beans and snap beans which have cuticle surfaces with little or no waxy surface. Low transpiration coefficients were calculated for citrus which may or may not have surfaces with stomata at the stem end (oranges, limes, grapefruit, lemons) and products with waxy surfaces (green peppers, blueberries). Very low transpiration coefficients were calculated for fruits with a highly impermeable waxy layer (tomatoes, pears and apples). The postharvest practice of waxing fruits did contribute to the lowering of the K_s coefficient. A 25% smaller K_s transpiration coefficient was measured for waxed limes compared to unwaxed limes.

The K_s tranpiration coefficient was defined to be dependent only on the product surface condition and not on the air flow past the product or environmental conditions.

To determine the effect of air flowrate on the transpiration coefficient K_s, transpiration was monitored from commodities in two different velocity air streams. Statistical analysis (Analysis of Variance - one way) and Figures 10 - 26 show that the K_s transpiration coefficient is not affected by air velocity past the products. No commodity tested displayed a K_s transpiration coefficient dependent on rate of airflow. Airflow rate past the product affects the K_a air film mass transfer coefficient alone and from equations 3 and 10 it can be concluded that higher velocity air streams will effectively decrease the influence of K_a on K, and K_s can be more accurately calculated from experimental weight loss data (Chau et al, 1985).

To determine the effect of water vapor pressure deficit between the evaporating surface and surrounding environment on the transpiration coefficient K_s, two experimental chambers were controlled at two different relative humidities. The dewpoint was controlled at the same value within both chambers and the air drybulb was varied to establish the environmental relative humidity. As forced air was blown past the products,

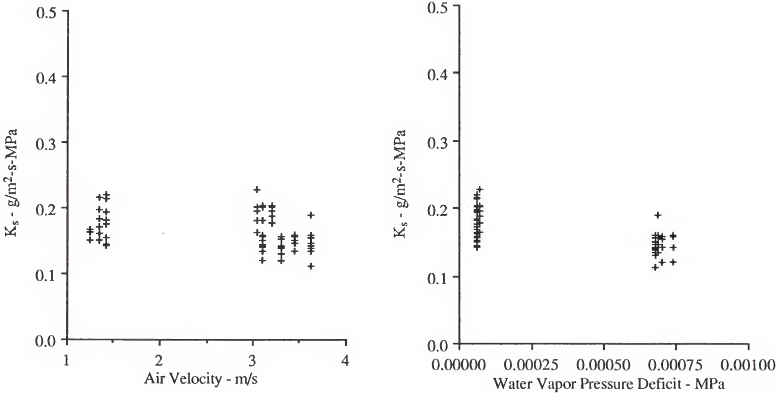

Figure 10. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Red Delicious Apples

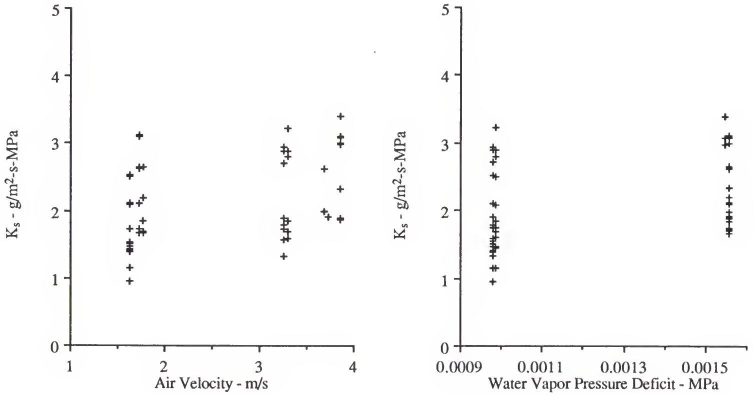

Figure 11. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Tifblue Blueberries

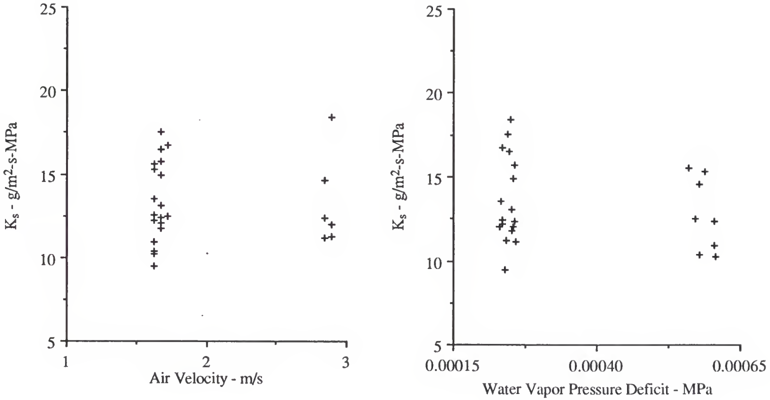

Figure 12. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Ranpac Brussels Sprouts

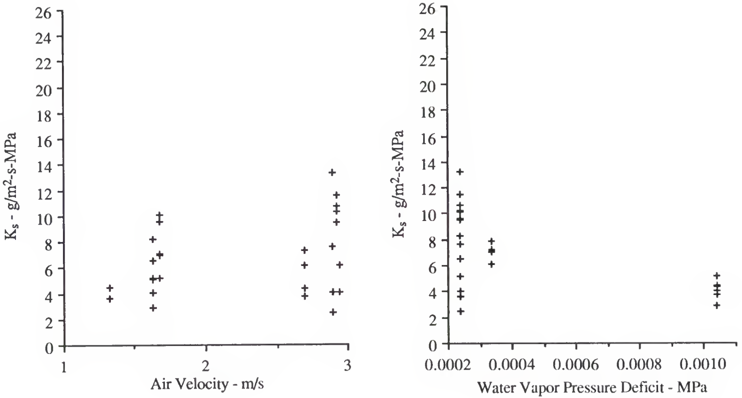

Figure 13. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Cabbage

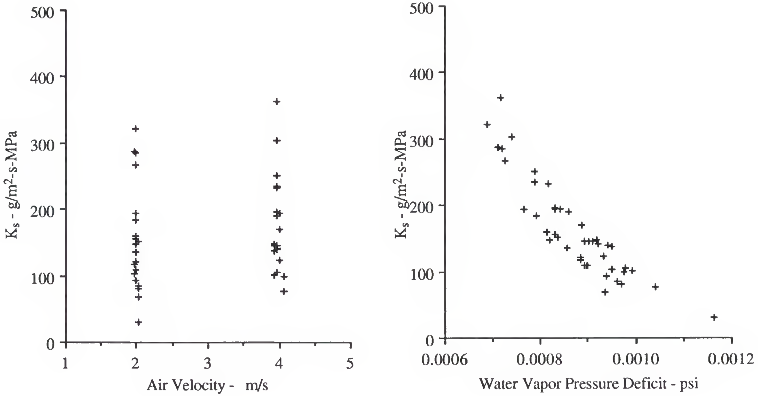

Figure 14. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Pacmore Carrots

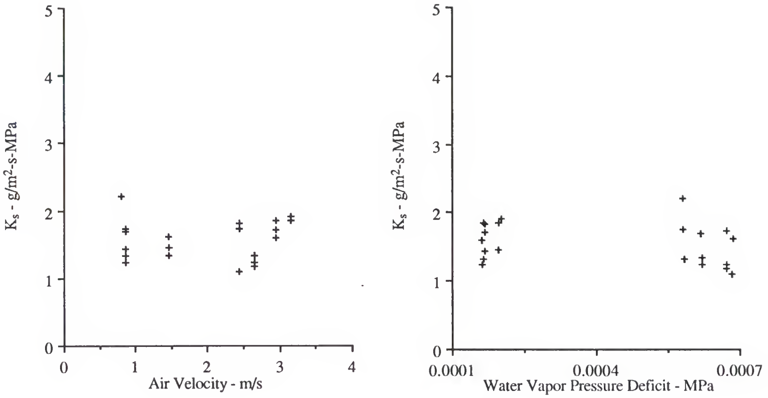

Figure 15. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Marsh Grapefruit

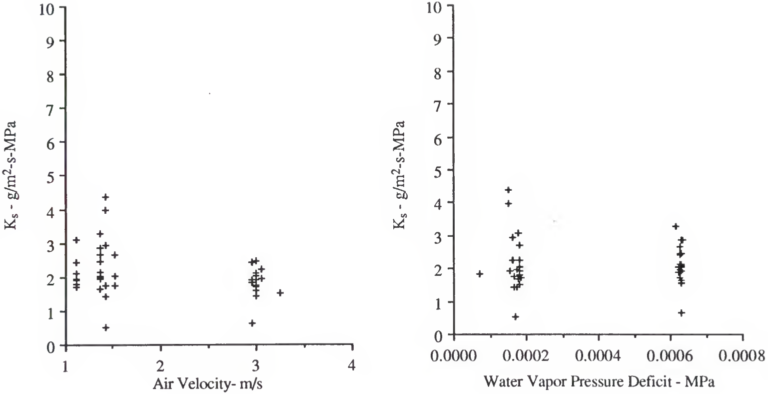

Figure 16. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Jupiter Green Peppers

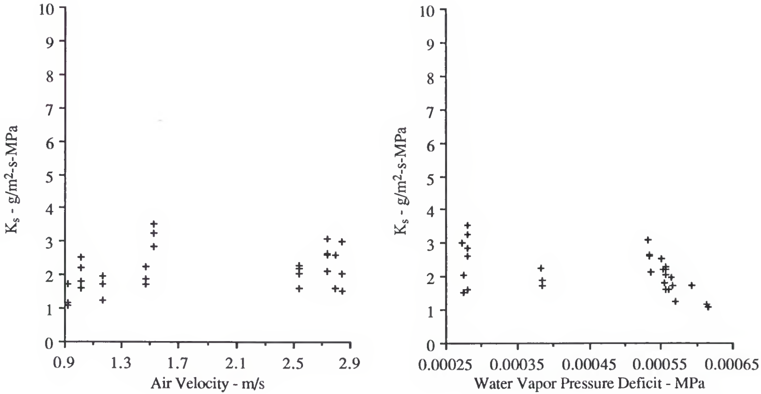

Figure 17. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Eureka Lemons

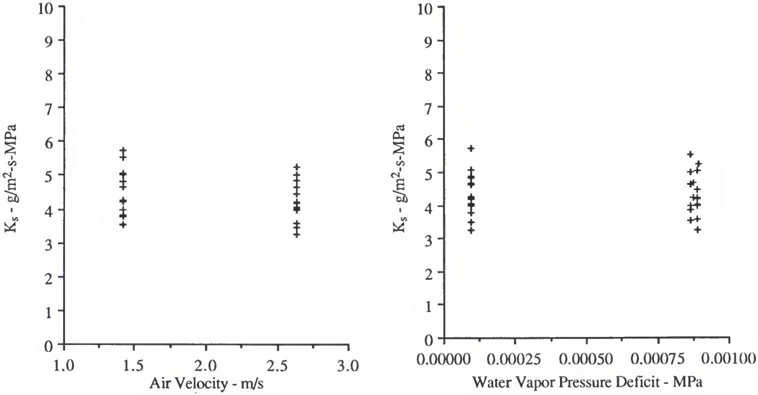

Figure 18. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Speckled Lima Beans

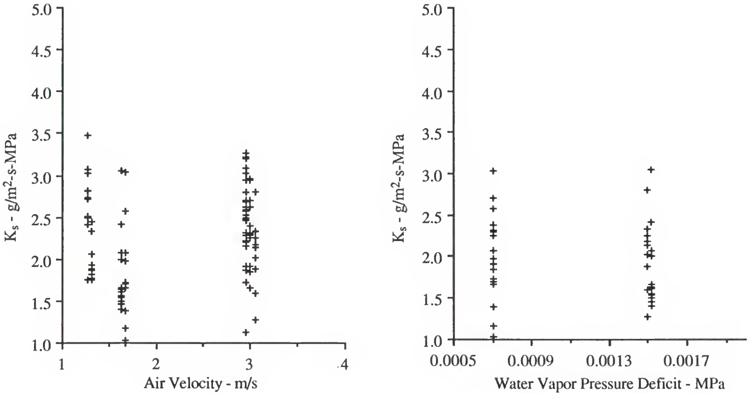

Figure 19. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Persian Limes

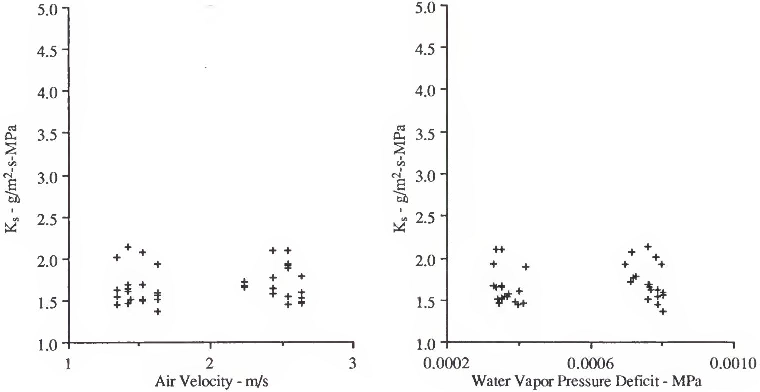

Figure 20. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Valencia Oranges

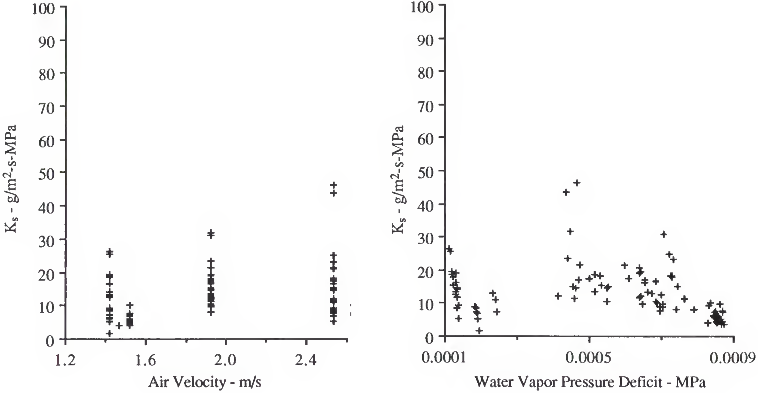

Figure 21. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Red Globe Peaches

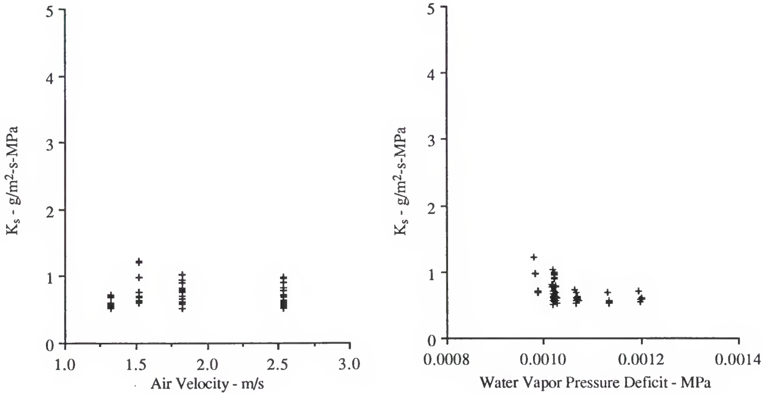

Figure 22. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for D' Anjou Pears

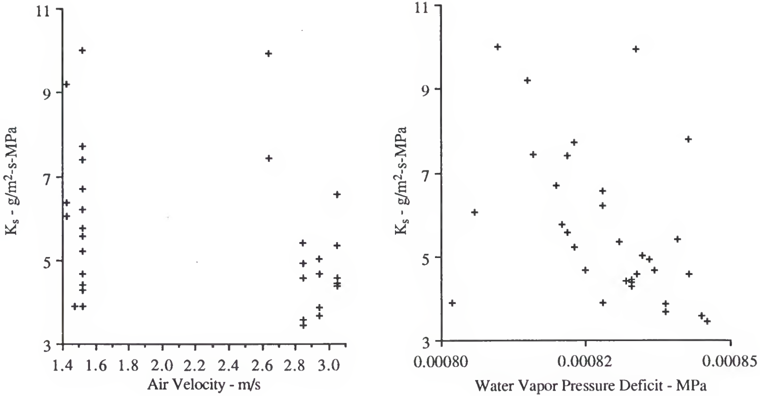

Figure 23. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Contender Snap Beans

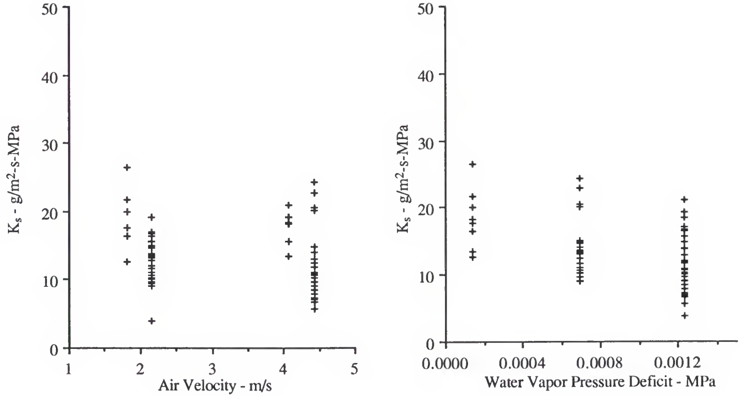

Figure 24. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Pajaro Strawberries

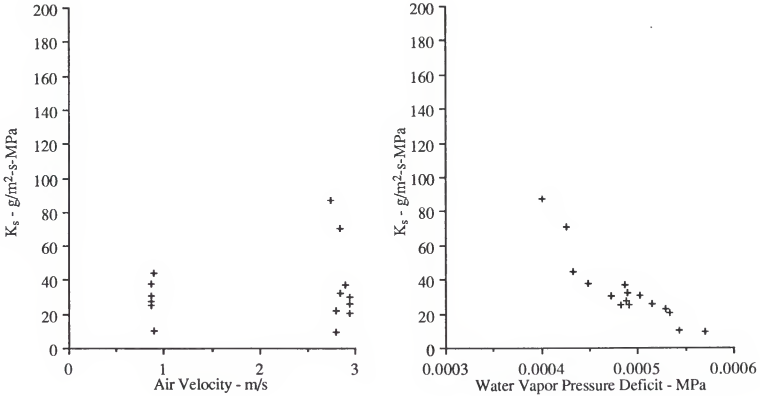

Figure 25. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Sugarbeets

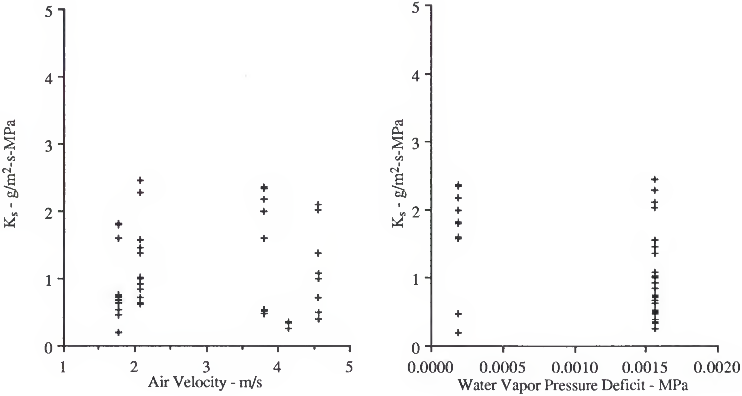

Figure 26. Variation of K_s with Air Velocity and Water Vapor Pressure Deficit for Sunny Tomatoes

establish the environmental relative humidity. As forced air was blown past the products, a water vapor deficit was established and controlled. Figures 10 - 26 show that K_s is not typically a function of the water vapor deficit between the evaporating surface and the surrounding environment. The exceptions to this were Pacmore carrots and sugarbeets because the magnitude of their K_s coefficients were found to decrease with increasing water vapor deficit (Figures 14 and 25). These exceptions were statistically significant (Analysis of Variance - one way) at the 0.10 level. Figure 27 shows that during experimentation the K_s coefficient did not significantly vary with increasing percent moisture loss. The effect of water vapor pressure deficit on K_s for Pacmore carrots and sugarbeets appears not to be due to dessication of the surface but some other product characteristic which was outside the scope of this study to determine.

The K_s transpiration coefficient was not typically found to be a function of time or percent weight loss (Figures 28 - 42). However, the K_s coefficient for Sunny tomatoes and Tifblue blueberries was found to decrease with time (Figures 43 and 44). This trend is statistically significant at the 0.01 level and regressions were performed (Table 12) to determine the relationship. The K_s coefficient for tomatoes and blueberries may have decreased with time due to dessication of the evaporating surface or stem scar during transpiration.

The overall mass transfer coefficient K was determined for products placed in still air. These coefficients and other values reported in the literature are listed in Table 13. The K coefficients reported in this research are not necessarily in agreement with the literature because the conditions chosen for experimentation were not the same and different product varieties were selected. The experimental conditions chosen in previous research may not have accounted for all effects on the transpiration rate of horticultural products. This research has presented a procedure which accounts for the various effects which may influence transpiration and an experimental procedure was chosen to mimimize these effects on the transpiration rate.

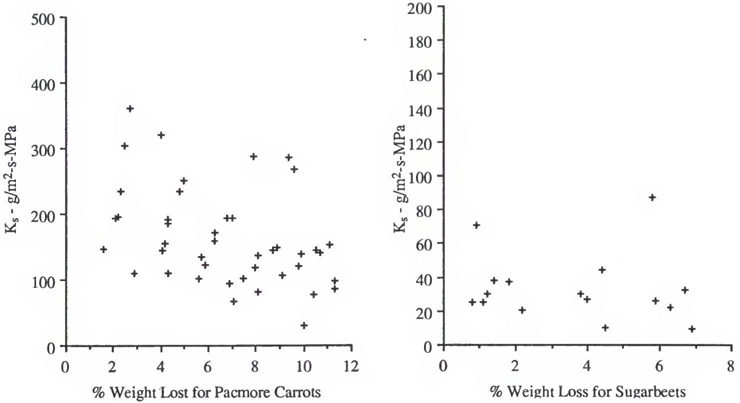

Figure 27. Variation of K_s with % Weight Loss for Pacmore Carrots and Sugarbeets

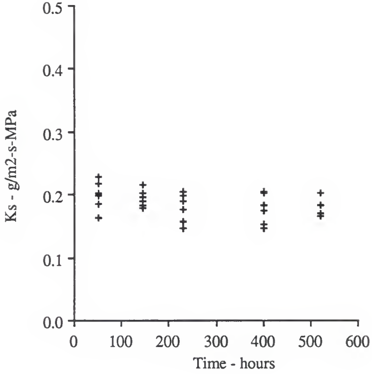

Figure 28. Variation of K_s with Time for Red Delicious Apples

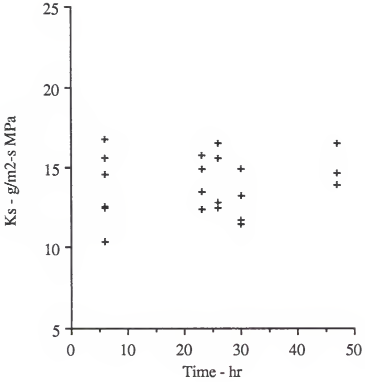

Figure 29. Variation of K_s with Time for Ranpac Brussels Sprouts

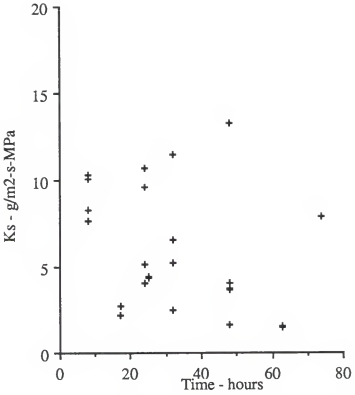

Figure 30. Variation of K_s with Time for Cabbage

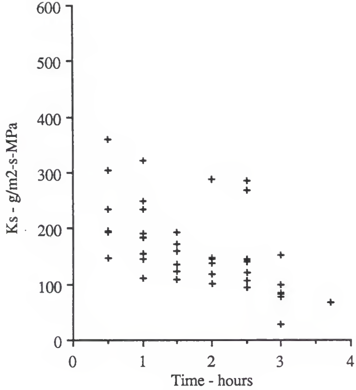

Figure 31. Variation of K_s with Time for Pacmore Carrots

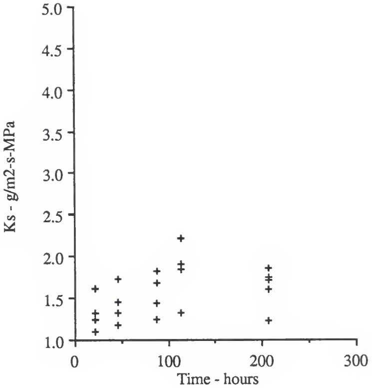

Figure 32. Variation of K_s with Time for Marsh Grapefruit

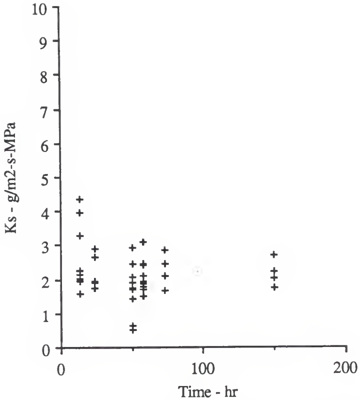

Figure 33. Variation of K_s with Time for Jupiter Green Peppers

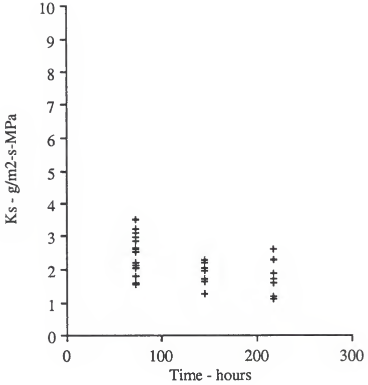

Figure 34. Variation of K_s with Time for Eureka Lemons

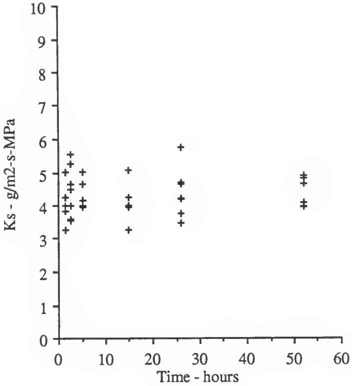

Figure 35. Variation of K_s with Time for Speckled Lima Beans

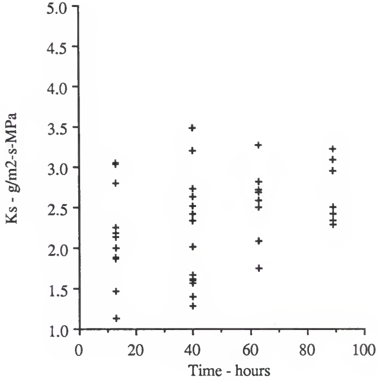

Figure 36. Variation of K_s with Time for Persian Limes

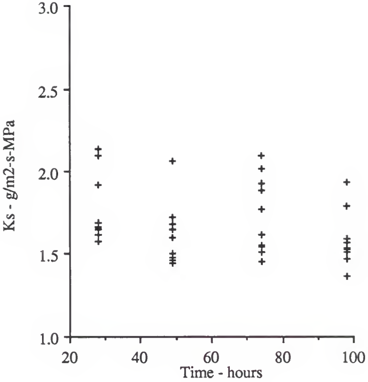

Figure 37. Variation of K_s with Time for Valencia Oranges

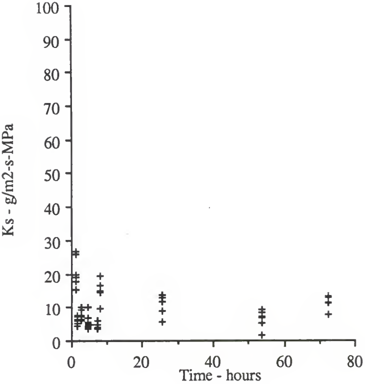

Figure 38. Variation of K_s with Time for Red Globe Peaches

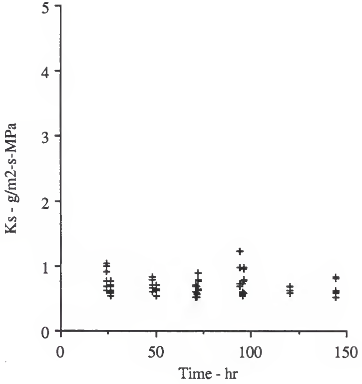

Figure 39. Variation of K_s with Time for D'Anjou Pears

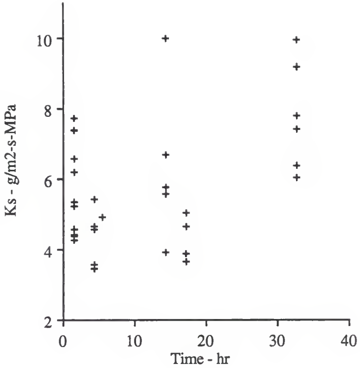

Figure 40. Variation of K_s with Time for Contender Snap Beans

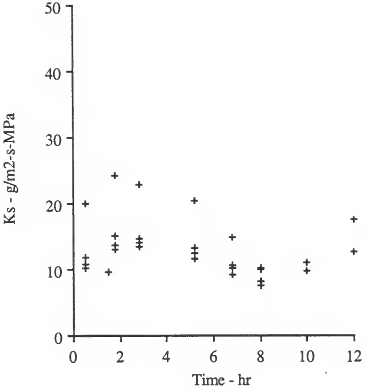

Figure 41. Variation of K_s with Time for Pajaro Strawberries

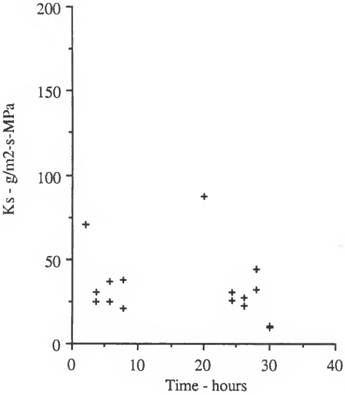

Figure 42. Variation of K_s with Time for Sugarbeets

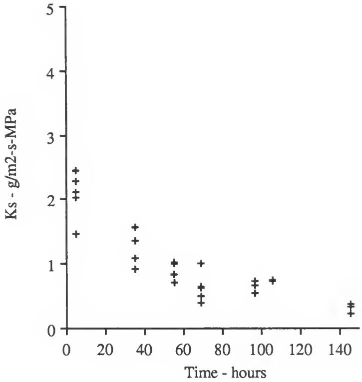

Figure 43. Variation of K_s with Time for Sunny Tomatoes

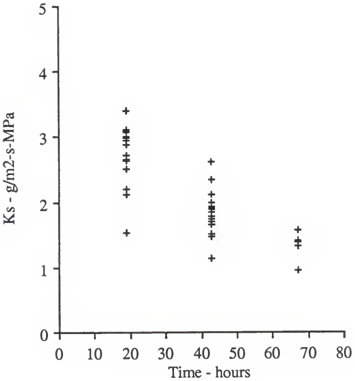

Figure 44. Variation of K_s with Time for Tifblue Blueberries

TABLE 12

Regressions for the Relationship between K_s and Time

Equation: $K_s = a - b * \ln(\text{Time})$

Product	a	b	r^2	n*
Tifblue Blueberries	5.64	1.01	0.6544	24
Sunny Tomatoes	2.91	0.50	0.86255	30

Ks in g/m2-s-MPa, Time in hours

TABLE 13

Overall Mass Transfer Coefficient K
and Values Available in the Literature

Product	Experimentally Determined K g/kg-s-MPa	Literature Values All Varieties K g/kg-s-MPa
Apples	0.0166	0.0156 - 0.0833
Blueberries	0.666	not available
Brussels Sprouts	2.24	3.25 - 9.77
Cabbage	0.285	0.0396 - 0.271
Carrots	9.29	0.323 - 3.25
Grapefruit	0.116	0.052 - 0.167
Green Peppers	0.203	not available
Lemons	0.204	0.139 - 0.229
Lima Beans	2.44	not available
Limes	0.170	not available
Oranges	0.129	0.025 - 0.162
Peaches	1.14	0.142 - 2.08
Pears	0.00928	0.0104 - 0.1438
Snap Beans	2.65	not available
Sugarbeets	0.918	not available
Strawberries	2.88	not available
Tomatoes	0.0749	0.0708 - 0.364

Experimental and Simulation Results for the Bulk Transpiration Model

The experimental data presented in this section are from 1-14-day tests with room air temperature at 8.6 C and air relative humidity at 85%. Ten experiments were conducted to determine the temperature profile and transpiration rates from eight layers of Valencia oranges. Tests were also conducted to determine transpiration from Valencia oranges stored at 4.4 °C and 85% RH. The results from these tests were very similar to the results to be presented for the oranges stored at 8.6 °C and 85% RH. At the higher temperature conditions, environmental control was achieved and accurate data was collected.

The numerical results presented are for 72-hour simulations. Simulation past 72 hours was unnecessary because steady-state heat and mass transfer were achieved.

Figure 45 shows the experimentally measured values and simulation results of moisture lost from the oranges located in the eighth, fifth and first layers of the bulk. The oranges in the eighth layer had relatively high transpiration rates when compared to the lower layers of the bulk. Figure 46 shows the experimentally measured values and simulation results of air and product center temperatures for the eight, fifth and first layers of the bulk. At the conditions of this test, a 0.5 °C air temperature difference was measured in the bulk and the model is predicting a 0.7 °C difference. The numerical model appears to predict well the temperature history and transpiration of the bulk store. Similar results were found for the other layers.

From the results shown in Figures 45 and 46, the assumption of Darcy flow through porous medium appears valid. The Kozeny-Carmen equation includes a tortuosity factor which accounts for the longer pathlength that a fluid must travel in a porous media and it appears the effect of the tortuosity factor is to reduce the airflow by approximately 25%. Without this additional resistance to flow, the model overpredicted transpiration by 70 - 100% for the oranges in the lower layers of the bulk (Figure 47).

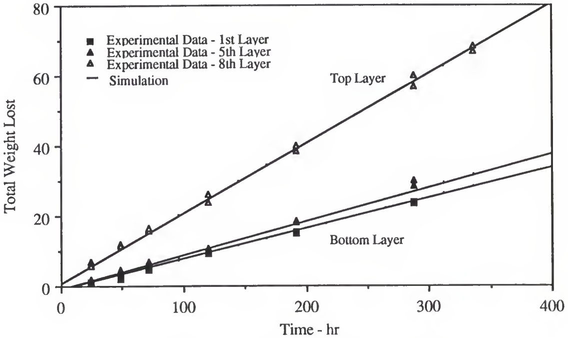

Figure 45. Experimental and Simulation Results for Weight Loss from Valencia Oranges in Bulk Storage

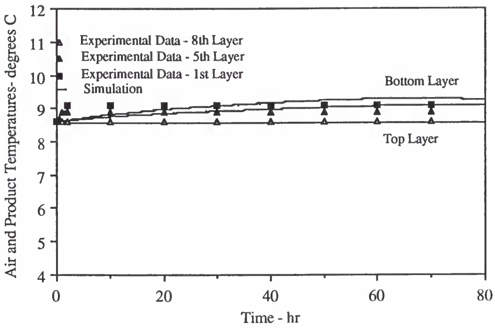

Figure 46. Experimental and Simulation Results for Air and Product Temperatures within the Bulk

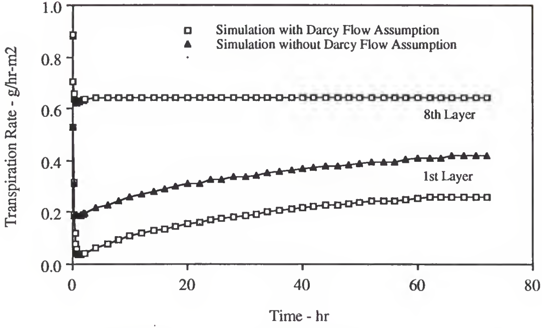

Figure 47. The Effect of Darcy Flow Assumption on the Transpiration Rate at the Lower Layer of the Bulk

Since the model can predict the temperature history and moisture removal history of the bulk successfully, it was then used to study the relative effects of natural convection and diffusion on the transpiration rates from the bulk store.

Figure 48 shows the simulation results for the transpiration rates at the top, middle and bottom layers of the bulk. This figure shows a high initial transpiration rate, followed by a rapid decrease and then a slow rise to a steady state rate. This phenomenon is occurring because

1) The high intial tranpiration rate is driven by an initially high water vapor deficit (Figure 49),
2) The moisture lost during the high initial transpiration rate saturates the void with water vapor and the transpiration rate decreases due to the decrease in water vapor pressure deficit,
3) The slow rise in transpiration rate may be caused by the temperature increase of the bulk due to respiratory heat generation. Heat generation will cause the product surface temperature to increase and density variation may be present in the moist air due to spatial variations in temperature between layers. Product heat generation is creating temperature differences within the bulk and these temperature differences between the layers in the bulk will create natural convection currents and facilitate moisture removal from the bulk store.

Figures 50 and 51 show the effects of natural convection and diffusion on the moisture lost and transpiration rates at the top and bottom layers of the bulk. Curve 1 accounts for the effects of both natural convection and diffusion and curve 2 accounts for the effect of diffusion alone. These figures show that natural convection significantly effects the transpiration rate at the bottom layers of the bulk and diffusion alone will not account for the removal of moisture from the bulk.

During this study the oranges in the top layer had transpiration rates similar to those of single fruits in storage. Relative humidities as high as 99% were calculated for the

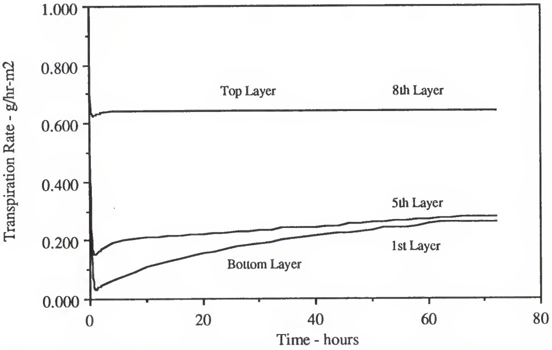

Figure 48. Simulated Transpiration Rates for the Eighth, Fifth and First Layers of the Bulk

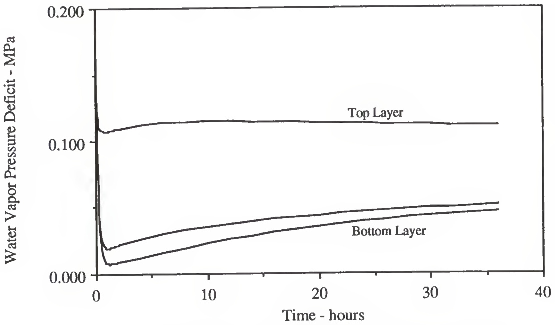

Figure 49. Water Vapor Pressure Deficits within the Bulk

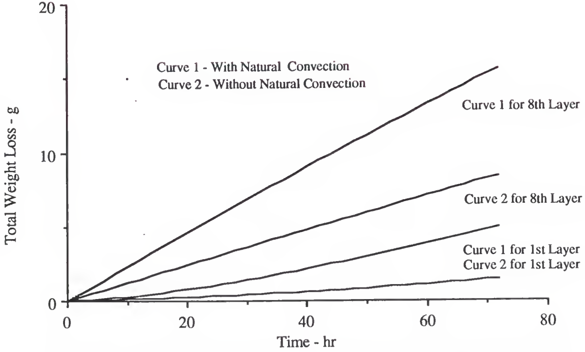

Figure 50. The Effect of the Natural Convection Currents on Bulk Transpiration

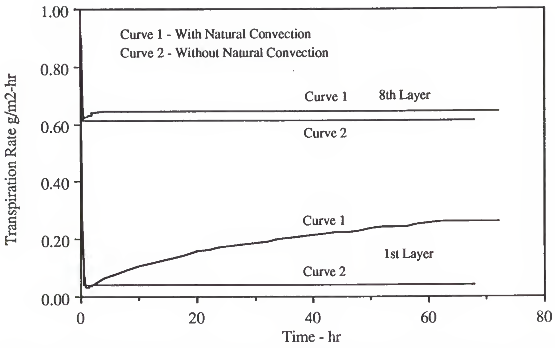

Figure 51. The Effect of Natural Convection Currents on Transpiration Rates in the Bulk

void space surrounding the oranges in the lowest layer. This high relative humidity, compared to the room 85% relative humidity, can help explain the signigicantly lower transpiration rates which were measured. The results presented in this paper indicate that the transpiration rate of Valencia oranges within a bulk store may be significantly different than those for a single fruit in storage and single-product transpiration models cannot be used to predict transpiration rates from Valencia oranges in bulk storage.

CONCLUSIONS AND RECOMMENDATIONS

The overall mass transfer coefficient K and the transpiration coefficient K_s were determined for seventeen fruits and vegetables. The coefficients were found to be highly variable for individuals within a given variety. The K_s coefficient was found not to be affected by the rate of airflow past the product and was not generally found to be affected by water vapor pressure deficit or to change with time. Statistically significant trends exist which indicate that the transpiration coefficient K_s for Pacmore carrots and sugarbeets are affected by water vapor deficit. Statistically significant trends exist that indicate the the transpiration coefficient K_s for Sunny tomatoes and Tifblue blueberries decreases with time.

An experimental procedure to determine the overall mass transfer coefficient K and the K_s transpiration coefficient was presented. The procedure accounts for the effects of air velocity past the commodity, respiration, evaporative cooling, convective heat and mass transfer, radiation heat transfer and the water vapor pressure lowering effect of solutes in solution within the product moisture on the transpiration rate from horticultural commodities. The procedure can also account for the characteristic skin of the perishable commodity but extensive research must be conducted to determine the structural qualities of the product skin and how K_s is related to it.

At the conditions tested, experimental data shows that the transpiration rates for oranges within a bulk store can be as small as 40% of those of single fruits in storage. Single-product transpiration models are not expected to be able to simulate transpiration from products in bulk storage.

A model was developed which provides answers that compare well with experimental data for the transpiration rates and moisture removal from a bulk store of Valencia oranges. At the simulated conditions, natural convection plays a significant role on the removal of moisture from the bulk store.

More research is needed to determine the effects of natural convection in typical industrial storage conditions. This research should include simulation models with boundaries which are not insulated against heat and mass transfer and can account for the variable conditions of the product surface. These variable conditions could include decay or dessication of the product evaporating surface due to transpiration It is anticipated that the model to simulate industrial conditions will require more complicated finite difference equations, such as those for the two and three dimensional energy, mass and momentum equations, and a fine mesh within the bulk store to simulate natural convection currents within the bulk store.

LIST OF REFERENCES

Ames, W. F. 1977. Numerical Methods for Partial Differential Equations. Academic Press, Inc. New York.

Ben-Yehoshua, S. 1969. gas exchange, transpiration and the commercial deterioration on storage of orange fruit. Jour. Amer. Hort. Sci. 94(5): 524-528.

Beukema, K. J., S. Bruin and J. Schenk. 1983. Three-dimensional natural convection in a confined porous medium with internal heat generation. Int. J. Heat Mass Transfer 26(3):452-458.

Burton, W. G., G. Moann and H. G. Wager. 1955. The storage of ware potatoes in permanent buildings. Jour. Agric. Sci. 46:150-169.

Chambers, T. C. and J. V. Possingham. 1963. Wax layer of sultana grapes. Aust. J. Biol. Sci. 16:818-824.

Chau, K. V., J. J. Gaffney and S. Bellagha. 1984. Simulation of heat and mass transfer in products with internal heat generation and transpiration. ASAE technical paper no. 84-6513

Chau, K. V., J. J. Gaffney and R. A. Romero. 1985. A mathematical model for the transpiration of fruits and vegetables. ASAE technical paper no. 85-6005.

Chen, P. M., K. L. Olsen and M. Macheriuk. 1985. Effect of low-oxygen atmosphere on storage scald and quality perservation of "Delicious" apples. J. Amer. Soc. Hort . Sci. 110(1):16-20.

Close, D. J. 1983. Natural convection with coupled mass transfer in porous media. Int. Commun. Heat Mass Transfer 10:465-476.

Dypolt, D. J. 1972. Determination of transpiration rates of green peppers. M. S. thesis, University of Florida.

Edney, K. L. 1983. Top fruit. In Post-Harvest Pathology of Fruits and Vegetables (C. Dennis, ed.). Academic Press, Inc. London.

Fockens, F. H. and H. F. Th. Meffert. 1972. Biophysical properties of horticultural products related to loss of moisture during cooling down. Jour. Sci. Fd. Agric. 23:285-298.

Gaffney, J. J. and C. D. Baird. 1980. Physical and thermal properties of Florida valencia oranges and marsh grapefruit as related to heat transfer. ASAE technical paper no. 880-6011.

Gaffney, J. J., C. D. Baird and K. V. Chau. 1985. Influence of airflow rate, respiration, evaporative cooling, and other factors affecting weight loss calculations for fruits and vegetables. ASHRAE Transactions 91(1b):690-707.

Gentry, J. P. 1971. A procedure for rapidly determining transpiration rates and epidermal permeabilities of fruits. Ph. D. thesis, Michigan State University.

Gentry, J. P., F. G. Mitchell and K. E. Nelson. 1963. Weight loss of grapes and nectarines as related to humidity and air velocity of storage. ASAE Transactions 6(3):254-266.

Hardenburg, R. E., A. E. Watada and C. Y. Wang. 1986. The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks. United States Department of Agriculture. Agriculture Handbook 66.

Hobson, C. E. 1987. Low temperature injury and the storage of ripening tomatoes. J. of Hort. Sci. 62(1):55-62.

Kader, A. 1985. Postharvest biology and technology, an overview. In Postharvest Technology of Horticultural Commodities (A. A. Kader, R. F. Kasmire, F. G. Mitchell, M. S. Reid, N. F. Sommer, J. F. Thompson, eds.). Special publication 3331, Cooperative Extension, University of California.

Lentz, C. P. 1966. Moisture loss of carrots under refrigerated storage. Food Technology 30(4):201-204.

Lentz, C. P. and E. A. Rooke. 1964. Rates of moisture loss of apples under refrigerated storage conditions. Food Technology 18(8):119-121.

Lerew, L. E. 1978. Development of temperature-weight loss model for bulk stored potatoes. Ph. D. thesis, Michigan State University.

Lewis, B. G., W. P. Davies and B. Garrod. (1983). Wound healing in carrot roots in relation to infection by Mycocentrospora acerina. Ann. Appl. Biol. 99:35-42.

Lewis, B. G. and B. Garrod. (1983). Carrots. In Post-Harvest Pathology of Fruits and Vegetables (C. Dennis, ed.). Academic Press, Inc. London.

Lipton, W. J. and B. Mackey. 1987. Physiological and quality responses of brussels sprouts to storage in controlled atmospheres. J. Amer. Soc. Sci. 112:491-496.

Lund, B. M. (1983). Bacterial spoilage. In Post-Harvest Pathology of Fruits and Vegetables (C. Dennis, ed.). Academic Press, Inc. London.

Martin, J. T. and B. E. Juniper. 1970. The Cuticles of Plants. St. Martin's Press, New York.

Mitchell, F. G. 1985. Cooling horticultural commodities. In Postharvest Technology of Horticultural Commodities (A. A. Kader, R. F. Kasmire, F. G. Mitchell, M. S. Reid, N. F. Sommer, J. F. Thompson, eds.). Special publication 3331, Cooperative Extension, University of California.

Moshenin, N. N. 1986. Physical Properties of Plant and Animal Materials: Structure, Physical Characteristics, and Mechanical Properties. Gordan and Breach. New York.

Pieniezek, S. A. 1942. External factors affecting water loss from apples in cold storage. Refrig. Engin. 44(3):171.

Pieniezek, S. A. 1944. Physical characteristics of the skin in relation in appled fruit transpiration. Proc. Amer. Soc. Hort. Sci. 42:231-237.

Prat, M. 1986. Analysis of experiments of moisture migration caused by temperature differences in unsaturated porous medium by means of two-dimensional numerical simulation. Int. J. Heat Mass Transfer 29(7):1033-1039.

Reyes, A. A. and R. B. Smith. 1987. Effect of oxygen, carbon dioxide and carbon monoxide on celery in storage. Hortscience 22(2):270-271.

Robinson, J. E., K. M. Browne and W. G. Burton. 1975. Storage characteristics of some vegetables and soft fruits. Ann. App. Biol. 81:399-408.

Ryall, A. L. and W. T. Pentzer. 1972. Handling, Transportation and Storage of Fruits and Vegetables. Vol 2, fruits and tree nuts. AVI Publishing Co. Westport, CT.

Sastry, S. K., C. D. Baird and D. E. Buffington. 1978. Transpiration rates of certain fruits and vegetables. ASHRAE Transactions 84(2):237-255.

Sastry, S. K. and D. E. Buffington. 1982. Transpiration rates of stored perishable commodities: A mathematical model and experiments on tomatoes. ASHRAE Transactions 88(1):159-184.

Schulze, E. D. 1986. Carbon dioxide and water vapor exchange in response to drought in the atmosphere and in the soil. Ann. Rev. Plant Physi. 37:247-274.

Scott, D. H. and F. J. Lawrence. 1975. Strawberries. In Advances in Fruit Breeding (J. Jarvick and J. N. Moore, eds.). Purdue University Press, West Lafayette, Indiana.

Stewart, W. E., Jr. and C. L. G. Dona. 1986. Low rayleigh number flow in a heat generating porous media. Int. Comm. Heat Mass Transfer 13:281-294.

Talbot, M. T. 1973. Transpiration rates of snap green beans. M. S. thesis, University of Florida.

Thompson, J. F. 1985. Storage systems. In Postharvest Technology of Horticultural Commodities (A. A. Kader, R. F. Kasmire, F. G. Mitchell, M. S. Reid, N. F. Sommer, J. F. Thompson, eds.). Special publication 3331, Cooperative Extension, University of California.

Villa, L. G. 1973. Single particle convective moisture loss from horticultural products in storage. Ph. D. thesis, Michigan State University.

Wardlaw, C. W. and E. R. Leonard. 1940. Studies on tropical fruits. IX. The respiration of bananas during ripening at tropical temperatures. Ann. Bot. 4:269-316.

Wells, A. W. 1962. Effects of storage temperature and humidity on loss of weight by fruit. United States Department of Agriculture. Agricultural marketing research report 539.

Wills, R. B. H., T. H. Lee, D. Graham, W. B. McGlasson and E. G. Hall. 1982. Postharvest, An Introduction to the Physiology and Handling of Fruits and Vegetables. AVI Publishing Co., Westport, CT.

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I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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