Transpiration and Respiration of Fruits and Vegetables

Bryan R. Becker, Ph.D., P.E. and Brian A. Fricke[1]

ABSTRACT

Transpiration is the process by which fresh fruits and vegetables lose moisture. This process includes the transport of moisture through the skin of the commodity, the evaporation of this moisture from the commodity surface and the convective mass transport of the moisture to the surroundings. This paper discusses the pertinent factors which affect transpiration and identifies mathematical models for predicting the rate of transpiration. Predicted transpiration coefficients and transpiration rates are compared to experimental data found in the literature. Respiration is the chemical process by which fruits and vegetables convert sugars and oxygen into carbon dioxide, water, and heat. The effect of respiration upon the transpiration rate of commodities is discussed and correlations are developed to estimate the respiratory heat generation of various commodities.
Keywords. Fresh fruits and vegetables, Mathematical model, Vapor pressure, Rates

INTRODUCTION

During postharvest handling and storage, fresh fruits and vegetables lose moisture through their skins via the transpiration process. Commodity deterioration, such as shriveling or impaired flavor, may result if moisture loss is high. In order to minimize losses due to transpiration, and thereby increase both market quality and shelf life, commodities must be stored in a low temperature, high humidity environment. In addition to proper storage conditions, various skin coatings and moisture-proof films can be used during commodity packaging to significantly reduce transpiration and extend storage life (Ben-Yehoshua, 1969).

Metabolic activity in fresh fruits and vegetables continues for a short period after harvest. The energy required to sustain this activity comes from the respiration process (Mannapperuma, 1991). Respiration involves the oxidation of sugars to produce carbon dioxide, water and heat. The storage life of a commodity is influenced by its respiratory activity. By storing a commodity at low temperature, respiration is reduced and senescence is delayed, thus extending storage life (Halachmy and Mannheim, 1991). Proper control of the oxygen and carbon dioxide concentrations surrounding a commodity is also effective in reducing the rate of respiration.

Properly designed and operated refrigerated storage facilities will extend the storage life of commodities by providing a low temperature, high humidity environment which reduces moisture loss and decreases respiratory activity. A thorough knowledge of the transpiration and respiration processes will allow both the designer and operator of cold storage facilities to achieve optimum storage conditions. This paper identifies the pertinent factors which influence the transpiration and respiration processes. In addition, mathematical models for estimating transpiration rates are identified. Furthermore, correlations are developed to determine the rate of carbon dioxide production and the heat generation due to respiration.

FACTORS AFFECTING TRANSPIRATION

[1]Bryan R. Becker, Ph.D., P.E. is an Associate Professor and Brian A. Fricke is a Research Assistant in the Mechanical and Aerospace Engineering Department, University of Missouri-Kansas City, Kansas City, MO 64110-2823.

Moisture loss from a fruit or vegetable is driven by a difference in water vapor pressure between the product surface and the environment. The product surface may be assumed to be saturated, and thus, the water vapor pressure at the commodity surface is equal to the water vapor saturation pressure evaluated at the product's surface temperature. However, dissolved substances in the moisture of the commodity tend to lower the vapor pressure at the evaporating surface slightly (Sastry et al., 1978).

Evaporation which occurs at the product surface is an endothermic process which will cool the surface, thus lowering the vapor pressure at the surface and reducing transpiration. Respiration within the fruit or vegetable, on the other hand, tends to increase the product's temperature, thus raising the vapor pressure at the surface and increasing transpiration. Furthermore, the respiration rate is itself a function of the commodity's temperature (Gaffney et al., 1985). In addition, factors such as surface structure, skin permeability, and air flow also effect the transpiration rate (Sastry et al., 1978). Thus, it can be seen that within fruits and vegetables, complex heat and mass transfer phenomena occur, which must be considered when evaluating the transpiration rates of commodities.

TRANSPIRATION MODELS

The basic form of the transpiration model is given as follows:

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

In its simplest form, the transpiration coefficient, k_t, is considered to be a constant for a particular commodity. Additionally, it is assumed that the commodity surface temperature and the ambient air temperature are equal. Thus, assuming that the surface is in a saturated condition, the surface water vapor pressure, P_s, becomes the water vapor saturation pressure evaluated at the ambient temperature.

Sastry et al. (1978) performed an extensive literature review, compiled a list of constant transpiration coefficients for various fruits and vegetables, and discussed a simplified transpiration model. The compiled transpiration coefficients omitted any dependence upon water vapor pressure deficit, skin permeability, or air velocity.

Various researchers (Pieniazek, 1942; and Lentz and Rooke, 1964) have noted that the transpiration rate decreases at high vapor pressure deficits. Drying of the skin tissue, or the decrease in skin permeability which results from the drying, was believed to be the cause of reduced transpiration at high vapor pressure deficits. Fockens and Meffert (1972) modified the simple transpiration coefficient to model variable skin permeability and to account for air flow rate. Their modified transpiration coefficient takes the following form:

$$k_t = \frac{1}{\frac{1}{k_a} + \frac{1}{k_s}} \tag{2}$$

The air film mass transfer coefficient, k_a, describes the convective mass transfer which occurs at the surface of the commodity and is a function of air flow rate. The skin mass transfer coefficient, k_s, describes the skin's diffusional resistance to moisture migration and is a function of the water vapor pressure deficit. Hence, variable air flow rate and skin permeability were both accounted for in the Fockens and Meffert transpiration coefficient model. However, evaporative cooling, respiration, and vapor pressure lowering effect were neglected in Fockens and Meffert's work.

Various researchers, Lentz and Rooke (1964), Gac (1971), Gentry (1970), Dypolt (1972) and Talbot (1973), have noted that evaporative cooling and respiration have a significant influence upon the surface temperature of the commodity and thus, the commodity surface temperature and the ambient air temperature may not be equal. Therefore, the water vapor pressure at the commodity surface may not be equal to the water vapor saturation pressure evaluated at the ambient air temperature. The surface water vapor pressure must be evaluated at the surface temperature of the commodity. Also, when performing experiments on tomatoes, Sastry and Buffington (1982) noted that the skin mass transfer coefficient, k_s, did not depend upon the vapor pressure deficit, as was assumed by Fockens and Meffert (1972). Rather, the behavior of the transpiration rate was attributed to the increasing slope of the water vapor pressure versus temperature curve. Therefore, Sastry and Buffington developed a transpiration model similar to that of Fockens and Meffert, but which included the effects of evaporative cooling and respiration. Their model incorporates a theoretical equation for determining the commodity surface temperature, thus providing for a more accurate determination of the surface water vapor pressure. Their model yields improved accuracy of the estimated transpiration rate at high and low water vapor pressure deficits. However, it neglects the effects of vapor pressure deficit upon the skin mass transfer coefficient, k_s.

Chau et al. (1987) improved upon the Fockens and Meffert model even further by including radiative heat transfer and the vapor pressure lowering effect in their transpiration model. They also noted that the skin mass transfer coefficient, k_s, did not vary with water vapor pressure deficit, thus, contradicting Fockens and Meffert while agreeing with Sastry and Buffington.

Air Film Mass Transfer Coefficient

The air film mass transfer coefficient, k_a, describes the convective mass transfer which occurs at the evaporating surface of a commodity. Hence, the air film mass transfer coefficient, k_a, can be estimated by using a Sherwood-Reynolds-Schmidt correlation (Sastry and Buffington, 1982). The Sherwood number, *Sh*, is defined as follows:

$$\mathrm{Sh} = \frac{k_{a'} d}{d} \tag{3}$$

In general, convective mass transfer from a spherical fruit or vegetable is modeled by the following:

$$\mathrm{Sh} = \frac{k_{a'} d}{d} = p(\mathrm{Re})^q (\mathrm{Sc})^r \tag{4}$$

where *Re* is the Reynolds number ($u_\infty d/\nu$) and *Sc* is the Schmidt number (ν/d). The exponents q and r and the constant p in Eq. 4 are fit to experimental data. Chau et al. (1987) recommended a correlation which was taken from Geankoplis (1978):

$$\mathrm{Sh} = 2.0 + 0.552\ \mathrm{Re}^{0.53}\ \mathrm{Sc}^{0.33} \tag{5}$$

Dimensional analysis of the above Sherwood-Reynolds-Schmidt correlation indicates that the driving force for $k_{a'}$6 is concentration. However, the driving force in the transpiration models is vapor pressure. Thus, a conversion from concentration to vapor pressure is required. The conversion is given as follows:

$$k_a = \frac{1}{R_{H2O} T} k_{a'} \tag{6}$$

Skin Mass Transfer Coefficient

The skin mass transfer coefficient, k_s, describes the resistance to moisture diffusion through the skin of a commodity. Fockens and Meffert (1972) suggested the following relationship for the skin mass transfer coefficient:

$$k_{s'} = \frac{d}{m\,s} \tag{7}$$

The diffusional resistance, μ, is the ratio of the diffusion of water vapor in air to that of the diffusion of water vapor through the porous skin of the commodity. When performing experiments on apples, Fockens and Meffert noted that the quantity μs varied with humidity. At high humidity, the diffusional resistance was found to be low. Fockens and Meffert attributed this to the swelling of skin cells due to the absorption of moisture. Large intercellular spaces are then created and the resistance to diffusion is decreased. At low humidity, the skin cells lose moisture and become flattened. The intercellular spaces become smaller and the diffusional resistance is increased.

Sastry and Buffington (1982) also proposed a similar relation for the skin mass transfer coefficient:

$$k_{s'} = \frac{d f}{s} \tag{8}$$

However, in contrast to the observations of Fockens and Meffert, Sastry and Buffington noted that in their experiments on tomatoes the skin mass transfer coefficient did not vary appreciably with vapor pressure deficit.

As with the air film mass transfer coefficient, dimensional analysis of the skin mass transfer coefficient indicates that the driving force is concentration. Thus, the skin mass transfer coefficient must be converted from concentration to vapor pressure before it is used in the transpiration models:

$$k_s = \frac{1}{R_{H2O}\,T} k_{s'} \tag{9}$$

Experimental Determination of the Skin Mass Transfer Coefficient

The skin mass transfer coefficient, k_s, can be determined experimentally by placing the fruit or vegetable into an environmental chamber, in which the dry bulb and dew point temperatures can be controlled. The weight loss from the commodity is measured frequently during the course of the experiment. The weight loss of the commodity includes both the moisture loss due to transpiration and the carbon loss due to respiration.

Physical dimensions of the commodity, such as surface area, volume, and diameter, are measured and an air flow rate reading past the commodity is also taken. With this information, the air film mass transfer coefficient, k_a, can be calculated using a Sherwood-Reynolds-Schmidt correlation.

Air temperature readings are taken and the surface temperature of the commodity is measured or estimated with theoretical equations. The vapor pressure lowering effect at the product surface is determined by analysis of the commodity's skin. Thus, the water vapor pressure at the commodity surface and the water vapor pressure of the surrounding air can be determined.

The transpiration rate, $\dot{m}$ 10, water vapor pressure difference, $(P_s - P_a)$, and the air film mass transfer coefficient, k_a, are now known. The skin mass transfer coefficient, k_s, can then be determined by using the following transpiration model:

$$\dot{m} = \frac{P_s - P_a}{\frac{1}{k_s} + \frac{1}{k_a}} \tag{10}$$

Experimental determination of the skin mass transfer coefficient, k_s, has been performed by Chau et al. (1987) and Gan and Woods (1989). These experimental values of k_s, along with estimated values of skin mass transfer coefficient for grapes, onions, plums and potatoes, are given in Table 1.

Determination of the Vapor Pressure Difference

In order to use the transpiration models, the difference between the water vapor pressure at the evaporating surface of the commodity and the water vapor pressure in the ambient air must be determined. The surface water vapor pressure is a function of the temperature at the surface of the commodity and the vapor pressure lowering effect (VPL) caused by dissolved substances. Thus, the water vapor pressure at the evaporating surface, P_s, becomes:

$$P_s = VPL * P_{sat,T_S} \tag{11}$$

Chau et al. (1987) have performed experiments to determine the vapor pressure lowering effect for various fruits and vegetables (see Table 1). The ambient water vapor pressure is a function of both the ambient dry and wet bulb temperatures and may be determined by psychrometric formulae.

Table 1. Commodity skin mass transfer coefficient, vapor pressure lowering effect (VPL) and respiration coefficients.†

Product	Skin Mass Transfer Coefficient, k_s, g/(m^2·s·MPa)			VPL	Respiration Coefficients	
	Low	Mean	High		f	g
Apples	0.111	0.167	0.227	0.98	5.687×10^{-4}	2.598
Blueberries	0.955	2.19	3.39	0.98	7.252×10^{-5}	3.258
Brussels	9.64	13.3	18.6	0.99	0.002724	2.573
Cabbage	2.50	6.72	13.0	0.99	6.080×10^{-4}	2.618
Carrots	31.8	156.	361.	0.99	0.05002	1.793
Grapefruit	1.09	1.68	2.22	0.99	0.003583	1.998
Grapes	--	0.4024	--	0.98	7.056×10^{-5}	3.033
Green Peppers	0.545	2.159	4.36	0.99	3.510×10^{-4}	2.741
Lemons	1.09	2.08	3.50	0.98	0.01119	1.774
Lima Beans	3.27	4.33	5.72	0.99	9.105×10^{-4}	2.848
Limes	1.04	2.22	3.48	0.98	2.983×10^{-8}	4.733
Onions	--	0.8877	--	0.98	3.668×10^{-4}	2.538
Oranges	1.38	1.72	2.14	0.98	2.805×10^{-4}	2.684
Peaches	1.36	14.2	45.9	0.99	1.300×10^{-5}	3.642
Pears	0.523	0.686	1.20	0.98	6.361×10^{-5}	3.204
Plums	--	1.378	--	0.98	8.608×10^{-5}	2.972
Potatoes	--	0.6349	--	0.98	0.01709	1.769
Snap Beans	3.46	5.64	10.0	0.99	0.003283	2.508
Sugar Beets	9.09	33.6	87.3	0.96	8.591×10^{-3}	1.888
Strawberries	3.95	13.6	26.5	0.99	3.668×10^{-4}	3.033
Swedes	--	116.6	--	0.99	1.652×10^{-4}	2.904
Tomatoes	0.217	1.10	2.43	0.99	2.007×10^{-4}	2.835

† A portion of this data is reproduced from Chau et al. (1987) and Gan and Woods (1989).

EXPERIMENTAL VERIFICATION OF THE TRANSPIRATION MODEL

To verify its accuracy, transpiration coefficients predicted by the model were compared with empirical data from various researchers compiled by Sastry et al. (1978). The skin mass transfer coefficient, k_s, was based upon the experimental data reported by Chau et al. (1987) and Gan and Woods (1989), while the air film mass transfer coefficient, k_a, was derived from the Sherwood-Reynolds-Schmidt correlation taken from Geankoplis (1978).

In this comparison, the model was used to determine transpiration coefficients for commodities at a temperature of 2°C which were subjected to air with a dry bulb temperature of 1.67°C and a wet bulb temperature of 1.0°C. The air velocity was 0.01 m/s. Three calculated transpiration coefficients, k_t, are presented for each commodity corresponding to the low, mean and high values of skin mass transfer coefficient, k_s, as found in the literature and tabulated in Table 1.

As shown in Table 2, the calculated mean transpiration coefficients, k_t, for all the commodities fall within the range of data summarized by Sastry et al. (1978) except for brussels sprouts. Better agreement is obtained for brussels sprouts if the value of k_s reported by Chau et al. (1987) is increased by 150%. Due to differences in the experimental techniques used by the various researchers, the empirical data shown in Table 2 has a wide variation. Nevertheless, it is encouraging that the current model predicts transpiration coefficients which agree well with this experimental data.

Lentz (1966) experimentally studied the effects of air velocity on the transpiration coefficient of carrots. Air at a temperature of 1.0°C with a water vapor pressure deficit of 46.7 Pa flowed past the carrots. Commodity weight loss was recorded at various air velocities ranging from 0 to 1.4 m/s. Figure 1 shows the experimentally determined transpiration coefficients versus air velocity along with the transpiration coefficients calculated by the mathematical model. The transpiration model is in very good agreement with Lentz's experimental data.

Table 2. Comparison of transpiration coefficient.

Commodity	Calculated Value k_t (mg/kg·s·MPa)			Empirical Data (Sastry et al., 1978)	
	Low	Mean	High	k_{ave} (mg/kg·s·MPa)	k_{range} (mg/kg·s·MPa)
Apples	11.0	16.5	22.4	42	16 - 100
Blueberries	324	727	1100	--	--
Brussels	1370	1710	2120	6150	3250 - 9770
Cabbage	134	267	376	223	40 - 667
Carrots	502	625	648	1207	106 - 3250
Grapefruit	69.5	103	131	81	29 - 167
Grapes	122	122	122	123	21 - 254
Green Peppers	81.6	292	519	--	--
Lemons	101	183	288	186	139 - 229
Lima Beans	1800	2310	2930	--	--
Limes	78.9	159	234	--	--
Onions	57.4	57.4	57.4	60	13 - 123
Oranges	98.6	121	146	117	25 - 227
Peaches	101	611	966	572	142 - 2089
Pears	41.9	54.4	92.2	69	10 - 144
Plums	127	127	127	136	110 - 221
Potatoes	42.7	42.7	42.7	44	2 - 171
Snap Beans	1390	2110	3280	--	--
Sugar Beets	165	284	371	--	--
Strawberries	907	2420	3630	--	--
Swedes	550	550	550	469	--
Tomatoes	17.8	85.7	176	140	71 - 365

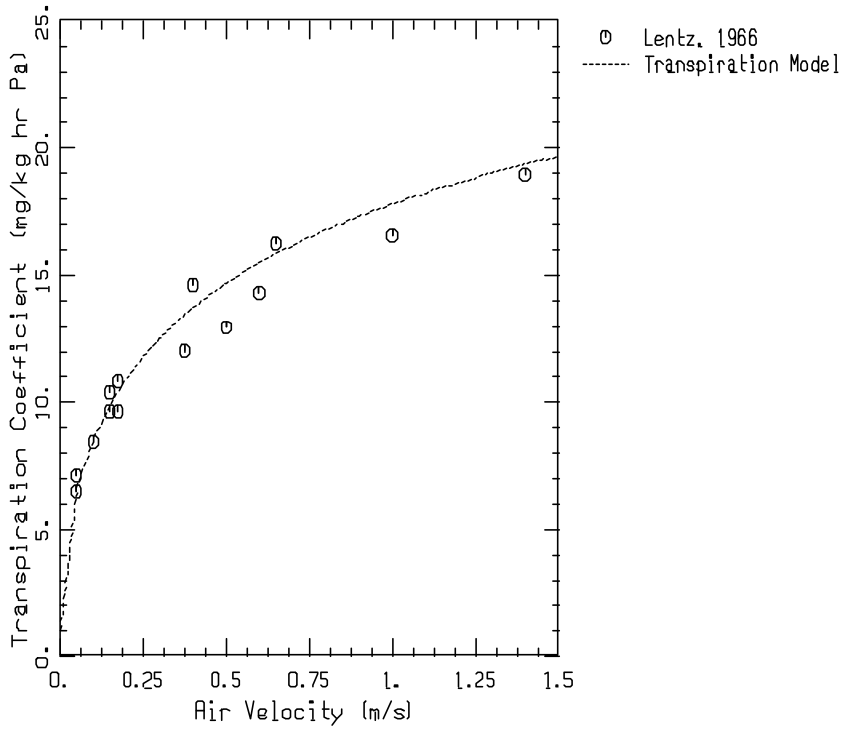

Figure 1. Transpiration coefficient vs. air velocity for carrots (Lentz, 1966).

Numerous papers have been published which report the effect of water vapor pressure deficit upon commodity weight loss. The USDA (1962) present weight loss versus vapor pressure deficit data for lemons, oranges and peaches. Both lemons and oranges were stored at 16°C while peaches were stored at 0.56°C. Figures 2, 3 and 4 show the USDA data along with the results of the transpiration model for lemons, oranges and peaches, respectively. The transpiration model is in good agreement with the experimental data.

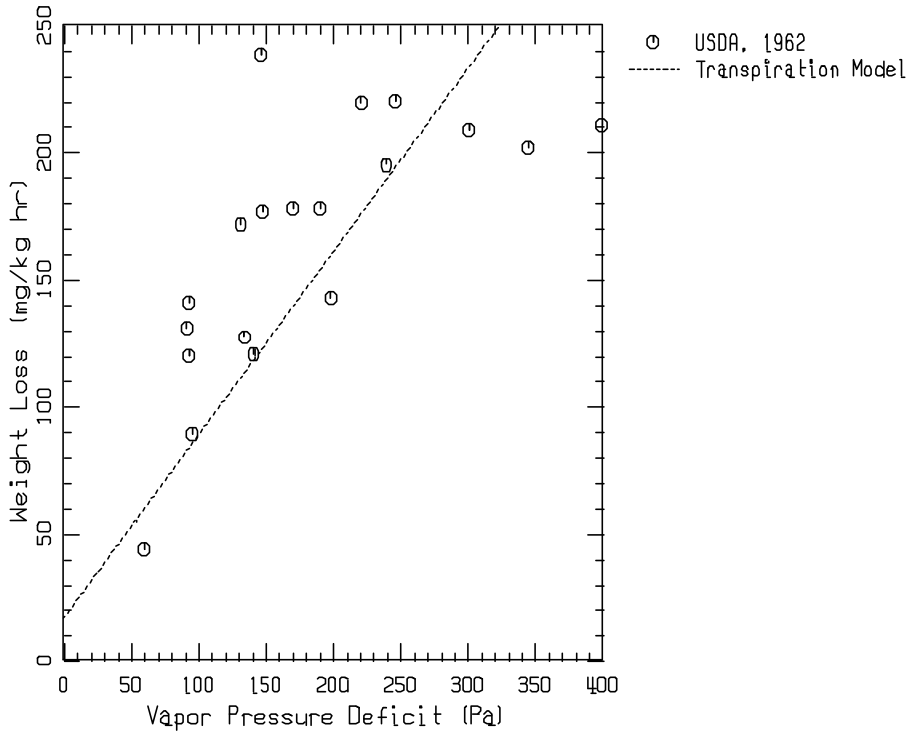

Figure 2. Weight loss vs. water vapor pressure deficit for lemons (USDA, 1962).

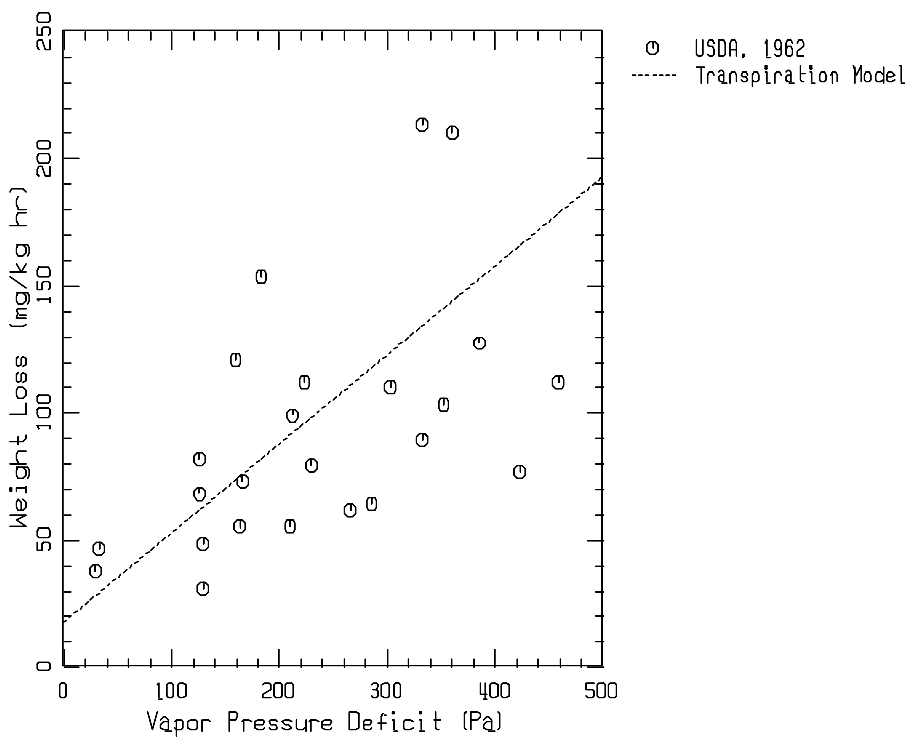

Figure 3. Weight loss vs. water vapor pressure deficit for oranges (USDA, 1962).

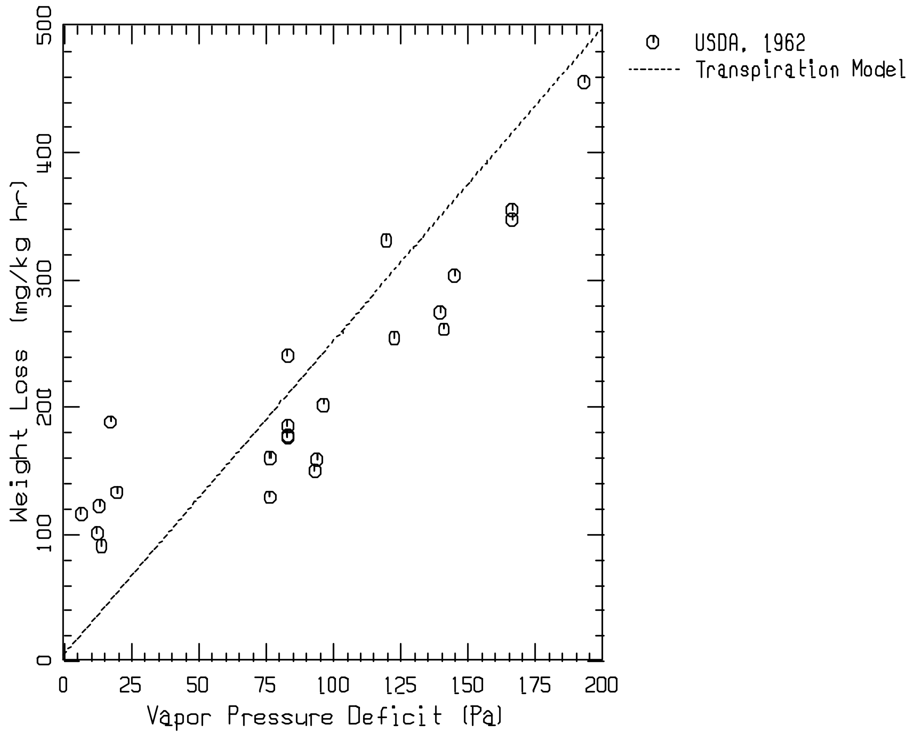

Figure 4. Weight loss vs. water vapor pressure deficit for peaches (USDA, 1962).

Lentz and Rooke (1964) present weight loss versus vapor pressure deficit data for apples. Air with a temperature of 0°C to 3°C and a velocity of 0.5 m/s flowed past the apples. Figure 5 shows the Lentz and Rooke experimental data along with the output from the transpiration model. The weight loss predicted by the model compares favorably with the experimental data.

Sastry and Buffington (1982) experimentally determined the transpiration rate of tomatoes as a function of water vapor pressure deficit at three different air temperatures. Air at either 10°C, 13°C or 16°C with a velocity of 0.0036 m/s was used to cool the tomatoes. Figures 6, 7 and 8 show the Sastry and Buffington data along with the output from the transpiration model for the three air temperatures. In all three cases, the transpiration model predicts slightly higher transpiration rates than those experimentally determined by Sastry and Buffington.

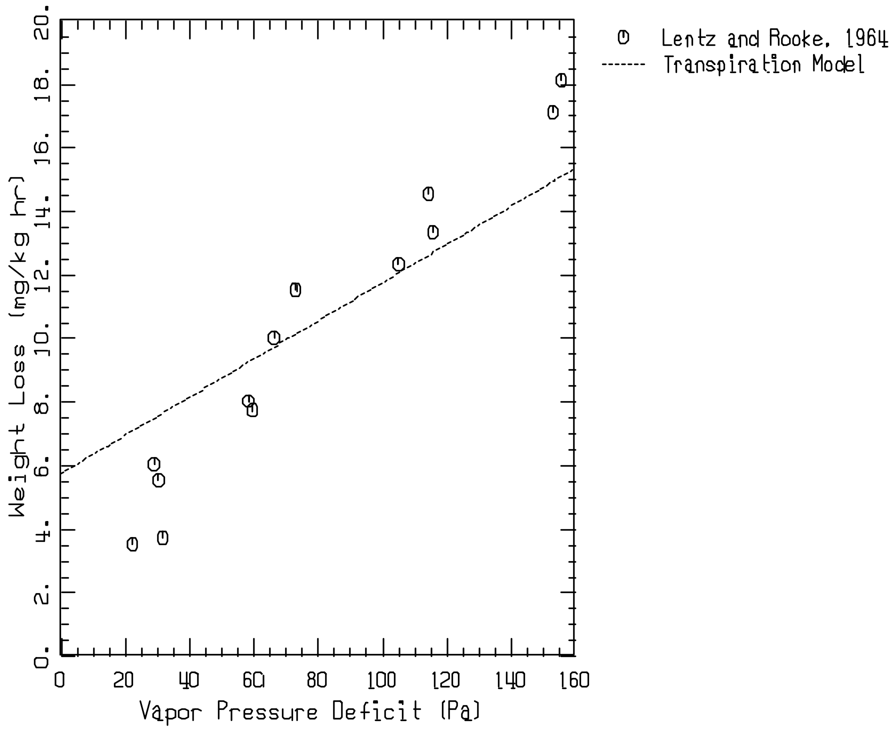

Figure 5. Weight loss vs. water vapor pressure deficit for apples (Lentz and Rooke, 1964).

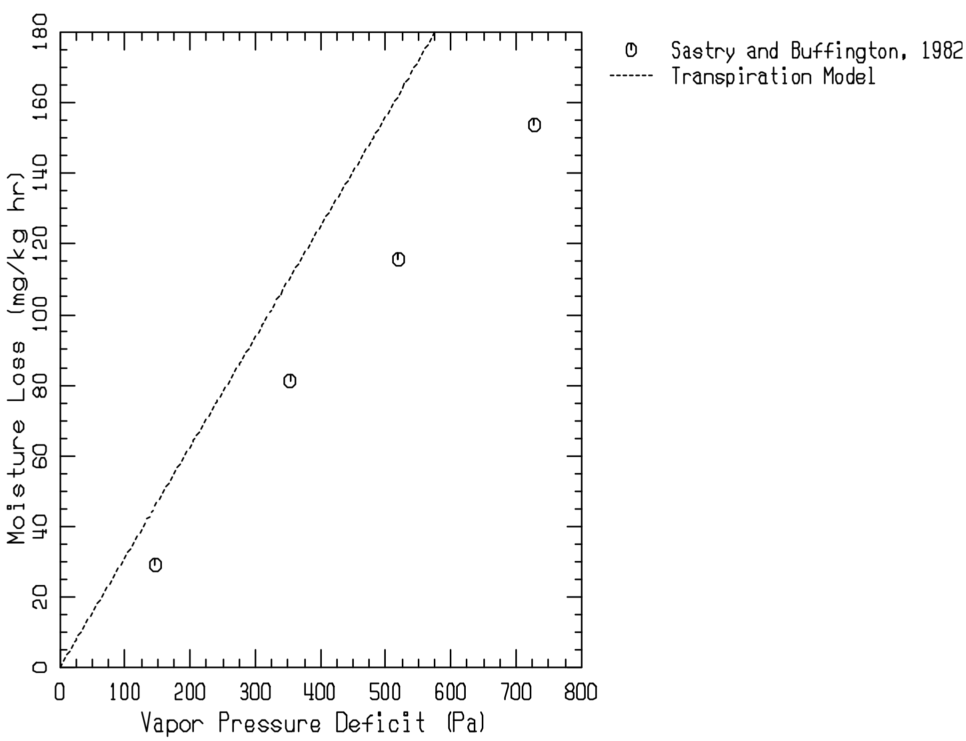

Figure 6. Weight loss vs. water vapor pressure deficit for tomatoes, air temperature of 10°C (Sastry and Buffington, 1982).

RESPIRATION

Respiration is the chemical process by which fruits and vegetables convert sugars and oxygen into carbon dioxide, water, and heat. The heat generated by the respiration process tends to increase the temperature of a commodity. This, in turn, increases the water vapor pressure just below the surface of a commodity, leading to increased transpiration (Sastry et al., 1978). Thus, it can be seen that respiration can cause transpiration to occur in saturated environments.

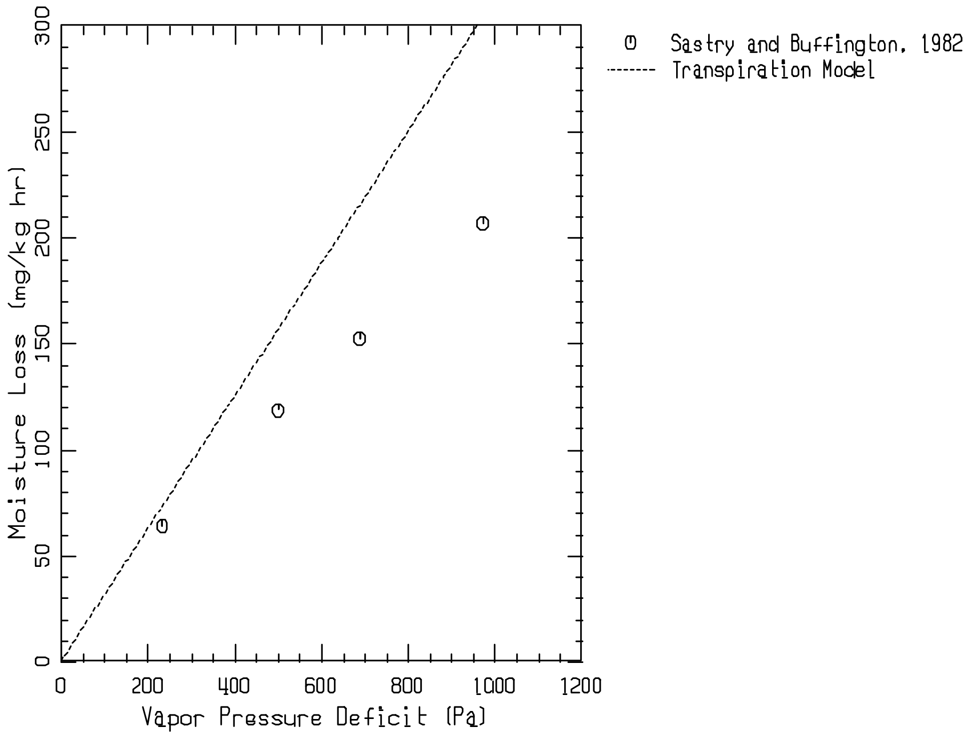

Figure 7. Weight loss vs. water vapor pressure deficit for tomatoes, air temperature of 13°C (Sastry and Buffington, 1982).

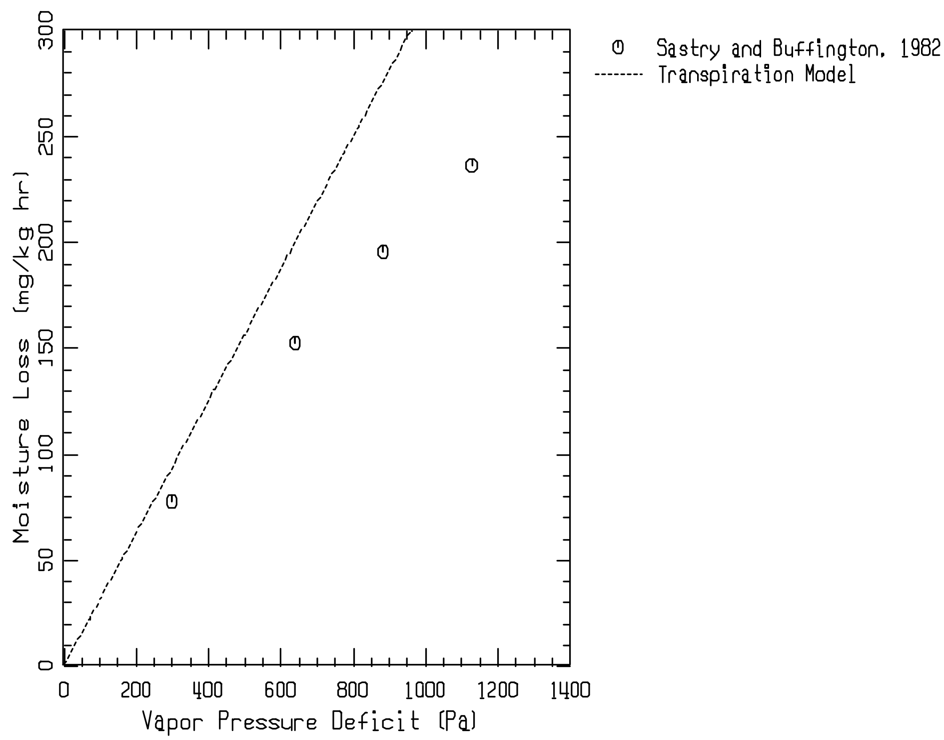

Figure 8. Weight loss vs. water vapor pressure deficit for tomatoes, air temperature of 16°C (Sastry and Buffington, 1982).

During the respiration process, sugar and oxygen are combined to form carbon dioxide, water and heat as follows:

$$C_6H_{12}O_2 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O + 2667\text{ kJ} \tag{12}$$

The rate at which this chemical reaction takes place has been found to vary with the type and temperature of the commodity. More specifically, the rate of carbon dioxide production and heat generation due to respiration can be correlated to the temperature of the commodity.

In the present work, correlations were developed, based upon data given by the USDA (1986), which relate a commodity's carbon dioxide production rate to its temperature. The carbon dioxide production rate can then be related to the heat generation due to respiration.

The resulting carbon dioxide production correlations are of the following form:

$$\dot{m}_{CO2} = f \bullet \left(\frac{9\,T_m}{5} + 32 \right)^g \tag{13}$$

where $\dot{m}_{CO2}$ 14 is the carbon dioxide production per unit mass of commodity (mg/kg h), T_m is the mass average commodity temperature (°C) and *f* and *g* are respiration coefficients which are given in Table 1. The respiration coefficients *f* and *g* were obtained via a least-squares fit to the data published by the USDA (1986). To illustrate these correlations, Figs. 9 and 10 give the carbon dioxide production correlations for apples and tomatoes, respectively, along with the corresponding USDA data. Note that for every 10°C increase in temperature, the rate of carbon dioxide production more than doubles. This behavior is evident in all commodities.

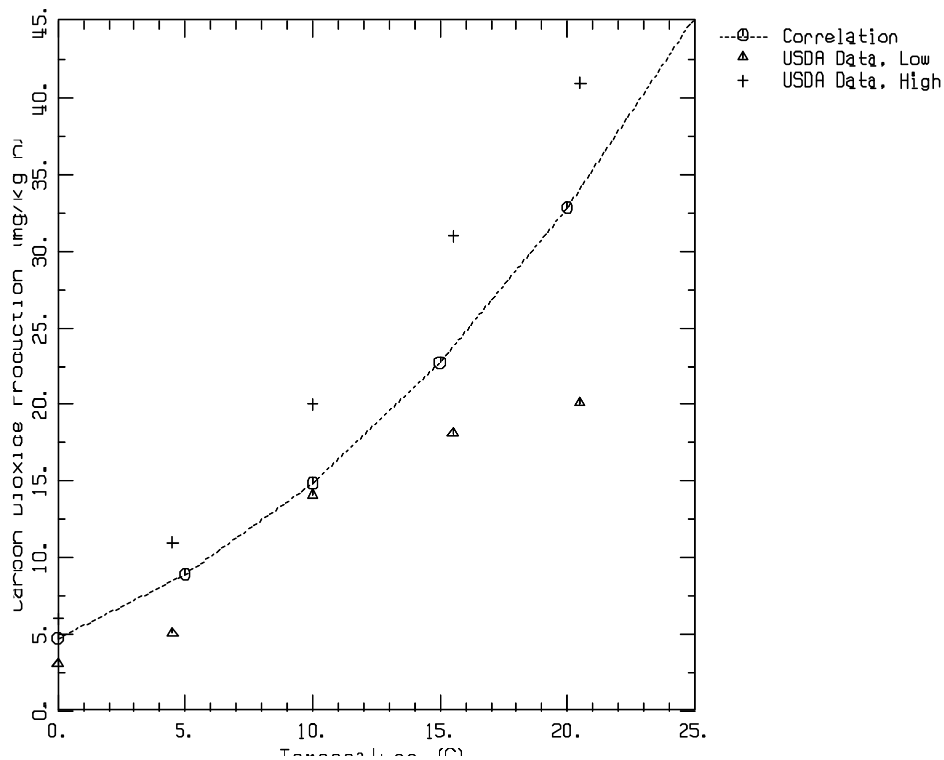

Figure 9. Carbon dioxide production vs. temperature correlation for apples.

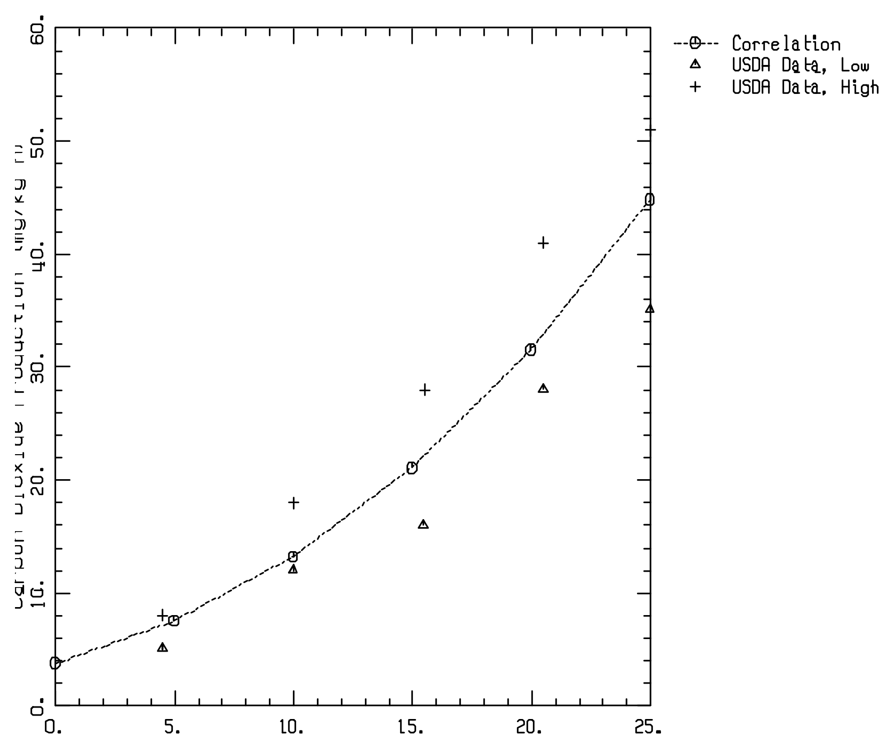

Figure 10.
Carbon dioxide production vs. temperature correlation for tomatoes.

The chemical reaction, Eq. 12, indicates that for every 6 moles of carbon dioxide produced, there are 2667 kJ of heat generated. Thus, for every one milligram of carbon dioxide produced, 10.7 joules of heat are generated (USDA, 1986). The rate of heat generation due to respiration, *W* (kJ/kg h), then becomes:

$$W = (\dot{m}_{CO_2})\left(\frac{10.7\ \text{J}}{\text{mg CO}_2}\right) \tag{14}$$

CONCLUSIONS

This paper discussed pertinent factors which govern the mass transfer from fresh fruits and vegetables. A review of the literature was presented which uncovered two basic forms of the transpiration coefficient for fruits and vegetables. Early researchers attempted to model transpiration with a constant transpiration coefficient. To better explain the transpiration phenomena, the transpiration coefficient was later broken into two components; the air film mass transfer coefficient and the skin mass transfer coefficient. The intent was to account for both the effects of air flow rate and skin permeability upon the transpiration rate. The air film mass transfer coefficient can be estimated by using Sherwood-Reynolds-Schmidt correlations. Controversy exists, however, on the appropriate method by which to model the skin mass transfer coefficient. Fockens and Meffert (1972) believed that the skin mass transfer coefficient was a function of vapor pressure deficit. Experiments performed by Sastry and Buffington (1982) and Chau et al. (1987), on the other hand, suggested that the skin mass transfer coefficient was not dependent upon the vapor pressure deficit. Assuming no dependence upon vapor pressure deficit, Chau et al. (1987) and Gan and Woods (1989) determined constant skin mass transfer coefficients for various fruits and vegetables.

This paper also presented a transpiration model which was based upon a variable air film mass transfer coefficient and a constant skin mass transfer coefficient. To verify its accuracy, transpiration coefficients and transpiration rates predicted by the model were compared to experimental data found in the literature. The transpiration coefficient was found to increase, at a decreasing rate, with air velocity. The transpiration rate was found to increase linearly with water vapor pressure deficit.

Finally, this paper discussed the effects of respiration upon the transpiration rate of fruits and vegetables. The heat generation due to respiration tends to increase the temperature of a commodity, thus leading to an increase in transpiration. The rate of respiration is dependent upon the type of commodity as well as its temperature. Correlations were developed to estimate the respiratory heat generation as a function of temperature for various commodities. These correlations were shown to accurately predict the respiratory behavior of commodities as a function of temperature.

NOMENCLATURE

d	diameter of fruit or vegetable
f	carbon dioxide production vs. temperature correlation coefficient
g	carbon dioxide production vs. temperature correlation coefficient
k_a	air film mass transfer coefficient (driving force: vapor pressure)
k_a'	air film mass transfer coefficient (driving force: concentration)
k_s	skin mass transfer coefficient (driving force: vapor pressure)
k_s'	skin mass transfer coefficient (driving force: concentration)
k_t	transpiration coefficient
$\dot{m}$	transpiration rate per unit area of commodity surface
$\dot{m}_{CO2}$	carbon dioxide production rate
p	constant in Sherwood-Reynolds-Schmidt correlation
P_a	ambient water vapor pressure

P_s	water vapor pressure at evaporating surface of commodity
P_{sat,T_S}	water vapor saturation pressure evaluated at commodity surface temperature
q	exponent in Sherwood-Reynolds-Schmidt correlation
r	exponent in Sherwood-Reynolds-Schmidt correlation
R_{H2O}	gas constant for water vapor
Re	Reynolds number
s	skin thickness of commodity
Sc	Schmidt number
Sh	Sherwood number
T	mean temperature of the boundary layer
T_m	mass average temperature of commodity
$u_{¥}$	free stream air velocity
VPL	vapor pressure lowering effect
W	rate of respiratory heat generation of commodity per unit mass of commodity
d	coefficient of diffusion of water vapor in air
μ	coefficient of diffusional resistance of the skin
v	kinematic viscosity of air
f	fraction of product surface area covered by pores

REFERENCES

1. Ben-Yehoshua, S. 1969. Gas Exchange, Transpiration, and the Commercial Deterioration in Storage of Orange Fruit. *Journal of the American Society for Horticultural Science* 94(5): 524-528.
2. Chau, K.V., R.A. Romero, C.D. Baird, and J.J. Gaffney. 1987. Transpiration Coefficients of Fruits and Vegetables in Refrigerated Storage. *ASHRAE Report 370-RP*. Atlanta: ASHRAE.
3. Dypolt, D.J. 1972. Determination of Transpiration Rates of Green Peppers. M.S. thesis, University of Florida, Agricultural Engineering Department.
4. Fockens, F.H., and H.F.T. Meffert. 1972. Biophysical Properties of Horticultural Products as Related to Loss of Moisture During Cooling Down. *Journal of the Science of Food and Agriculture* 23: 285-298.
5. Gac, A. 1955. Influence of the Relative Humidity of Air on the Loss of Weight of Harvested Fruits During Storage and Ripening. *Proc. 9th Intl. Cong. Refrign.* pp. 4012-4018, 4042-4045.
6. 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.
7. Gan, G., and J.L. Woods. 1989. A Deep Bed Simulation of Vegetable Cooling. In *Agricultural Engineering*, ed. V.A. Dodd and P.M. Grace, pp. 2301-2308. Rotterdam: A.A. Balkema.
8. Geankoplis, C.J. 1978. *Transport Processes and Unit Operations*. Boston: Allyn and Bacon.
9. Gentry, J.P. 1970. A Procedure for Rapidly Determining Transpiration Rates and Epidermal Permeabilities of Fruits. Ph.D. thesis, Michigan State University, East Lansing.
10. Halachmy, I.B., and C.H. Mannheim. 1991. Modified Atmosphere Packaging of Fresh Mushrooms. *Packaging Technology and Science* 4(5): 279-286.
11. Lentz, C.P. 1966. Moisture Loss of Carrots Under Refrigerated Storage. *Food Technology* 20(4): 201-204.
12. Lentz, C.P., and E.A. Rooke. 1964. Rates of Moisture Loss of Apples Under Refrigerated Storage Conditions. *Food Technology* 18(8): 119-121.
13. Mannapperuma, J.D., R.P. Singh, and M.E. Montero. 1991. Simultaneous Gas Diffusion and Chemical Reaction in Foods Stored in Modified Atmospheres. *Journal of Food Engineering* 14(3): 167-183.
14. Pieniazek, S.A. 1942. External Factors Affecting Water Loss From Apples in Cold Storage. *Refrig. Eng.* 44(3): 171.
15. 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.
16. Sastry, S.K., C.D. Baird, and D.E. Buffington. 1978. Transpiration Rates of Certain Fruits and Vegetables. *ASHRAE Transactions* 84(1): 237-254.
17. Talbot, M.T. 1973. Transpiration Rates of Snap Green Beans. M.S. thesis, University of Florida, Agricultural Engineering Department.
18. USDA. 1962. *Effects of Storage Temperature and Humidity on Loss of Weight by Fruit, Marketing Research Report No. 539,* United States Department of Agriculture.
19. USDA. 1986. *The Commercial Storage of Fruits, Vegetables, and Florist and Nursery Stocks, Agricultural Handbook Number 66,* United States Department of Agriculture.