BULK REFRIGERATION OF FRUITS AND VEGETABLES

PART I: THEORETICAL CONSIDERATIONS OF HEAT AND MASS TRANSFER

by

Bryan R. Becker, Ph.D., P.E., Member ASHRAE
Associate Professor
Mechanical and Aerospace Engineering Department

Anil Misra, Ph.D., P.E.
Assistant Professor
Civil Engineering Department

Brian A. Fricke, Student Member ASHRAE
Research Assistant
Mechanical and Aerospace Engineering Department

University of Missouri-Kansas City
5605 Troost Avenue
Kansas City, MO 64110-2823

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Bryan R. Becker, Ph.D., P.E. (Member ASHRAE), Anil Misra, Ph.D., P.E.
and
Brian A. Fricke (Student Member ASHRAE)
University of Missouri-Kansas City
5605 Troost Avenue, Kansas City, MO 64110-2823

ABSTRACT

A computer algorithm was developed which estimates the latent and sensible heat loads due to the bulk refrigeration of fruits and vegetables. The algorithm also predicts the commodity moisture loss and temperature distribution which occurs during refrigeration. This algorithm includes the combined phenomena of transpiration, respiration, air flow, and convective heat and mass transfer. The development and performance of the computer algorithm are presented in two parts. This paper, Part I, discusses commodity thermophysical properties and flowfield parameters which govern the heat and mass transfer from fruits and vegetables. Commodity thermophysical properties include transpiration and respiration, while flowfield parameters include psychrometric properties and convective heat and mass transfer coefficients. Part I describes the modeling treatment of these properties and parameters. The second paper, Part II, discusses the heat and mass transfer models, compares algorithm results to experimental data, and describes a parametric study utilizing the algorithm. Existing bulk load heat transfer models are also reviewed in Part II.
(Keywords: fruits; vegetables; refrigeration; heat transfer; mass transfer; transpiration; respiration; thermophysical properties; flowfield parameters; models)

1 INTRODUCTION

The storage life of a commodity is drastically affected by the temperature and humidity of its surroundings. Precooling, the process of rapidly removing heat from freshly harvested fruits and vegetables prior to transportation, has long been known to effectively retard ripening and control microbial processes (Baird and Gaffney, 1976). The refrigeration of fruits and vegetables retards respiratory heat generation, wilting due to moisture loss, and spoilage caused by the invasion of bacteria, fungi and yeasts. Refrigeration also retards undesirable growth or sprouting by the commodity itself (USDA, 1986).

The effect of temperature on the storage life of commodities can be significant. For example, the USDA (1986) reports that some cultivars of apples ripen as much during one day at 21°C (70°F) as they do during 10 days at -1°C (30°F). Thus, to maximize their marketability, fruits and vegetables must be promptly precooled after harvest and kept in refrigerated storage.

To ensure optimum commodity quality during refrigeration, the temperature and humidity of the conditioned air within the refrigerated facility must be precisely controlled. In order to properly design such a facility and its associated refrigeration equipment, the designer must estimate both the sensible and latent heat loads due to the stored commodity. This requires knowledge of the complex interaction of the various thermophysical processes which occur within and around the commodities. These processes include convective heat and mass transfer as well as transpiration and respiration which are exhibited by living organisms such as fresh fruits and vegetables.

The present papers (Part I and II) describe a computer algorithm which was developed to aid in the design of bulk refrigeration facilities for fruits and vegetables. This computer model utilizes a porous media approach to estimate the latent and sensible heat loads due to the bulk refrigeration of fruits and vegetables. The combined phenomena of transpiration, respiration, air flow, and convective heat and mass transfer are included in the model. In addition to latent and sensible heat loads, the computer algorithm also predicts the commodity moisture loss which occurs during refrigeration and the temperature distribution within the commodity. Therefore, not only is the computer model an aid to the designer of refrigeration facilities, it is also of value to facility operators as a tool for the evaluation of alternative refrigeration strategies.

This paper (Part I) focuses upon the pertinent factors which govern the heat and mass transfer from fresh fruits and vegetables. These factors include both thermophysical properties of commodities as well as flowfield parameters. Thermophysical properties of commodities include transpiration and heat generation due to respiration, as well as commodity specific heat and thermal conductivity. Flowfield parameters include water vapor pressure in the refrigerated air and at the commodity surface, humidity ratio, and, air density, specific heat, thermal conductivity and dynamic viscosity, as well as convective heat and mass transfer coefficients. Accurate treatment of these various thermophysical properties and flowfield parameters is necessary to assure that the computer algorithm yields reasonable results. The present work describes this treatment, which is based upon a thorough review of a wide variety of sources.

The second paper (Part II) discusses the modeling methodology utilized in the current computer algorithm and describes the development of the heat and mass transfer models. Part II also compares the results of the computer algorithm to experimental data taken from the literature, and, describes a parametric study which was performed with the algorithm. In addition, the second paper also reviews existing numerical models for determining the heat transfer in bulk loads of fruits and vegetables.

2 THERMOPHYSICAL PROPERTIES OF COMMODITIES

The estimation of the mass and heat transfer which occurs in the bulk refrigeration of fruits and vegetables requires knowledge of various thermophysical properties of commodities. Mass transfer calculations require the determination of the transpiration rate which depends upon the air film mass transfer coefficient, the skin mass transfer coefficient and the vapor pressure lowering effect of the commodity. Heat transfer calculations require the determination of the heat generation due to respiration as well as the specific heat and thermal conductivity of the commodity.

2.1 Transpiration

Transpiration is the moisture loss process exhibited by fresh fruits and vegetables. It 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. The driving force for transpiration is a difference in water vapor pressure between the surface of a commodity and the surrounding air. Thus, the basic form of the transpiration model is given as follows:

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

where $\dot{m}$ is the transpiration rate per unit area of commodity surface, k_t is the transpiration coefficient, P_s is the water vapor pressure at the surface of the commodity, and P_a is the ambient water vapor pressure. In its simplest form, the transpiration coefficient, k_t , is considered to be a constant for a particular commodity. However, 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:

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

where k_a is the air film mass transfer coefficient and k_s is the skin mass transfer coefficient. 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.

2.1.1 Air Film Mass Transfer Coefficient

The air film mass transfer coefficient, k_a , can be estimated by using the Sherwood-Reynolds-Schmidt correlations (Sastry and Buffington, 1982). The Sherwood number, *Sh*, is defined as follows:

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

where $k_{a'}$ is the air film mass transfer coefficient, *d* is the diameter of the commodity and δ is the coefficient of diffusion of water vapor in air. For convective mass transfer from a spherical fruit or vegetable, Sastry and Buffington (1982) recommended a Sherwood-Reynolds-Schmidt correlation of the form:

$$\mathrm{Sh} = 2.0 + 0.37\,\mathrm{Re}^{0.6}\mathrm{Sc}^{0.33} \tag{4}$$

which was taken from Edwards et al. (1972) and Geankoplis (1972). In the above equation, *Re* is the Reynolds number, $Re = u_\infty d/\nu$, and *Sc* is the Schmidt number, $Sc = \nu/\delta$, where u_∞ is the free stream air velocity and ν is the kinematic viscosity of air. Chau et al. (1987), however, suggested a different Sherwood-Reynolds-Schmidt correlation which was taken from Geankoplis (1978):

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

For purposes of consistency, the Sherwood-Reynolds-Schmidt correlation given in Equation (5) is employed in the current model. As discussed below, in Section 2.1.2, Chau et al. (1987) used Equation (5) to extract, from experimental data, the values of the skin mass transfer coefficient, k_s, which are incorporated in the current algorithm.

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

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

where R_{H2O} is the gas constant for water vapor and *T* is the mean temperature of the boundary layer.

2.1.2 Skin Mass Transfer Coefficient

The skin mass transfer coefficient, k_s, which describes the resistance to moisture migration through the skin of a commodity, is based upon the fraction of the product surface covered by pores. Although it is difficult to theoretically determine the skin mass transfer coefficient, experimental determination has been performed by Chau et al. (1987) and Gan and Woods (1989). To accomplish this, they measured the rate of weight loss, $\dot{m}$, and the water vapor pressure deficit, $(P_s - P_a)$, as well as the air flow rate and the diameter of the commodity. The air film mass transfer coefficient was calculated using Equation (5) and the skin mass transfer coefficient was then determined from the following equation:

$$\dot{m} = \frac{P_s - P_a}{\frac{1}{k_a} + \frac{1}{k_s}} \tag{7}$$

These experimental values of k_s are given in Table 1, along with estimated values of the skin mass transfer coefficient for grapes, onions, plums and potatoes. Note that three values of skin mass transfer coefficient are tabulated for most of the commodities. These values correspond to the spread of the experimental data.

2.1.3 Vapor Pressure Lowering Effect

In the absence of dissolved substances, the surface water vapor pressure, P_s, in Equation (1), is the water vapor saturation pressure evaluated at the surface temperature of the commodity. However, dissolved substances, such as sugars, tend to lower the water vapor pressure at the surface of the commodity. From Raoult's law (Moore, 1972), the vapor pressure lowering effect can be found as follows:

$$VPL = \frac{1}{1 + \frac{0.018 \Delta T_f}{1.86}} \tag{8}$$

where VPL is the vapor pressure lowering effect of the commodity and ΔT_f is the freezing point depression (in °C) at the product surface (Gaffney et al., 1985). Chau et al. (1987) have performed experiments to determine the freezing point depression and have tabulated the vapor pressure lowering effect for various fruits and vegetables (see Table 1).

Thus, the water vapor pressure at the evaporating surface, P_s, becomes:

$$P_s = VPL \bullet P_{ws}(T_s) \tag{9}$$

where $P_{ws}(T_s)$ is the water vapor saturation pressure evaluated at the surface temperature of the commodity, T_s. The water vapor saturation pressure is determined from the psychrometric formulae discussed in Section 3.1.

2.2 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 the commodity, leading to increased transpiration (Sastry et al., 1978). Thus, it can be seen that respiration can cause transpiration to occur in saturated environments.

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

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + 2667\ \text{kJ} \qquad (10)$$

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:

$$\dot{m}_{CO2} = f \bullet \left(\frac{9T_m}{5} + 32 \right)^g \qquad (11)$$

where $\dot{m}_{CO2}$ 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 2. 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, Figure 1 gives the carbon dioxide production correlation for apples along with the corresponding USDA data. Note that for every 10°C (18°F) increase in temperature, the rate of carbon dioxide production more than doubles. This behavior is evident in all commodities.

The chemical reaction, Equation (10), indicates that for every 6 moles of carbon dioxide produced, there are 2667 kJ (2530 Btu) of heat generated. Thus, for every one milligram (3.527×10^{-5} oz.) of carbon dioxide produced, 10.7 joules (0.0101 Btu) of heat are generated (USDA, 1986). The rate of respiratory heat generation per unit mass of commodity, W (J/kg h), then becomes:

$$W = (10.7)(\dot{m}_{CO2}) \tag{12}$$

2.3 Specific Heat

The USDA (1986) gives the following correlation which relates the specific heat of a commodity to its moisture content:

$$c = (33.5)(w_{H2O}) + 837 \tag{13}$$

where c is the specific heat of the commodity (J/kg K) and w_{H2O} is the percent water content of the commodity. In addition, the USDA (1986) also reports typical values for the water content of various fruits and vegetables which are given in Table 2.

2.4 Thermal Conductivity

The literature review revealed three expressions which relate the thermal conductivity of a commodity to its moisture content. Sweat (1986) gives the following expression:

$$k = 0.148 + 0.493\left(\frac{w_{H2O}}{100}\right) \tag{14}$$

where k is the thermal conductivity (W/m K) and w_{H2O} is the moisture content in percent. Gaffney et al. (1985), used an equation of the form:

$$k = A\left(\frac{w_{H2O}}{100}\right) + B\left(1 - \frac{w_{H2O}}{100}\right) \tag{15}$$

where A and B are constants (A = 0.55 W/m K, B = 0.26 W/m K).

Thermal conductivity can also be determined from the thermal diffusivity, α, as follows:

$$k = \alpha \rho c \tag{16}$$

where c is the specific heat and ρ is the density of the commodity. ASHRAE (1993), in turn, reports the following correlation for the thermal diffusivity, α, of a commodity:

$$\alpha = 0.088 \times 10^{-6} + (\alpha_w - 0.088 \times 10^{-6})(w_{H2O}) \tag{17}$$

where α_w is the thermal diffusivity of water at the commodity temperature (m^2/s).

The method presented by Sweat (1986) was found to agree most closely with the measured thermal conductivity data reported by the USDA (1986) and thus, Sweat's method is utilized in the current computer algorithm.

3 FLOWFIELD PARAMETERS

In addition to the thermophysical properties of commodities, the current modeling methodology requires various flowfield parameters. Mass transfer calculations require the evaluation of the water vapor pressure at the commodity surface and in the surrounding refrigerated air, as well as the diffusion coefficient of water vapor in air. Heat transfer calculations require determination of the air density and specific heat, as well as the effective heat transfer coefficient. The effective heat transfer coefficient, in turn, depends upon the thermal conductivity and dynamic viscosity of the air.

3.1 Water Vapor Saturation Pressure

In the current algorithm, the water vapor saturation pressure is used to determine the vapor pressure at the surface of the commodity which is required for the transpiration calculation. The water vapor saturation pressure is also used to calculate various properties of moist air, principally the saturation humidity ratio.

ASHRAE (1993) indicates that the water vapor saturation pressure can be determined using the following equation:

$$\begin{aligned}\log_{10}(P_{ws}) = 10.79586(1-\theta) + 5.02808\log_{10}(\theta) \\ + 1.50474 \times 10^{-4}(1-10^{-8.29692[1/\theta-1]}) \\ + 0.42873 \times 10^{-3}(10^{4.76955(1-\theta)}-1) \\ - 2.2195983\end{aligned} \tag{18}$$

where P_{ws} is the water vapor saturation pressure (atm), $\theta = 273.16/T_{a,absolute}$, and $T_{a,absolute}$ is the absolute air temperature (K).

3.2 Humidity Ratio

The humidity ratio, which is the ratio of the mass of water vapor in a sample of air to the mass of dry air in that sample, can be determined by the following method if the dry bulb temperature, T_a, and the wet bulb temperature, T_a^*, of the refrigerated air are known (ASHRAE, 1993).

First, the water vapor saturation pressure is evaluated at the wet bulb temperature, $P_{ws}(T_a^*)$, using Equation (18). Next, the saturation humidity ratio is evaluated at the wet bulb temperature using:

$$w_s^* = \frac{0.62198\, P_{ws}(T_a^*)}{P - P_{ws}(T_a^*)} \tag{19}$$

where w_s^* is the saturation wet bulb humidity ratio, $P_{ws}(T_a^*)$ is the saturation vapor pressure evaluated at the wet bulb temperature and P is the atmospheric pressure. Finally, the humidity ratio of the refrigerated air is found by:

$$w = \frac{(1093 - 0.556\,T_a^*)\, w_s^* - 0.240(T_a - T_a^*)}{1093 + 0.444\,T_a - T_a^*} \tag{20}$$

where w is the humidity ratio of the refrigerated air, w_s^* is the saturation wet bulb humidity ratio, T_a is the dry bulb refrigerated air temperature (°C) and T_a^* is the wet bulb refrigerated air temperature (°C).

3.3 Water Vapor Pressure in Refrigerated Air

ASHRAE (1993) states that the water vapor pressure in the refrigerated air can be found by:

$$P_a = \frac{Pw}{0.62198 + w} \tag{21}$$

where P_a is the water vapor pressure in the refrigerated air, P is the air pressure and w is the refrigerated air humidity ratio.

3.4 Density

The density of the moist, refrigerated air can be obtained from the following equation (ASHRAE, 1977):

$$\rho_a = \frac{28.9645\,P}{R_u\,T_{a,absolute}}(x_a + 0.62198\,x_w) \tag{22}$$

where ρ_a is the air density (kg/m^3), P is the air pressure (kPa), R_u is the universal gas constant (8.3144 kJ/kg K), $T_{a,absolute}$ is the absolute air temperature (K), x_a is the mole fraction of dry air and x_w is the mole fraction of water vapor in the air. The mole fractions can be found by using the following equations:

$$x_a = \frac{0.62198}{0.62198 + w} \tag{23a}$$

$$x_w = \frac{w}{0.62198 + w} \tag{23b}$$

where w is the humidity ratio.

3.5 Specific Heat

The specific heat of moist air is given by (Threlkeld, 1970):

$$c_{p,a} = 1.00 + 1.88\,w \tag{24}$$

where $c_{p,a}$ is the specific heat of air (kJ/kg °C) and w is the humidity ratio of the air.

3.6 Thermal Conductivity

In general the thermal conductivity of moist air is a function of both moisture content and temperature. However, ASHRAE (1993) states that the thermal conductivity of moist air is approximately identical to that of dry air within the temperature range of -40°C to 120°C (-40°F to 248°F). Therefore, in the present work, the thermal conductivity of moist air is approximated by that of dry air at the same temperature by using the following relationship which was obtained via a least-squares fit to data given by Karlekar and Desmond (1982):

$$k_{air} = 0.02397 + 7.590 \times 10^{-5}\, T_a \qquad (25)$$

where k_{air} is the thermal conductivity of air (W/m °C) and T_a is the air temperature (°C). A plot of this relationship is given in Figure 2.

3.7 Dynamic Viscosity

For the temperature range of -40°C to 120°C (-40°F to 248°F), the viscosity of moist air varies little from that of dry air (ASHRAE, 1993). Therefore, in the present work, the dynamic viscosity of moist air is approximated by that of dry air at the same temperature by using the following relationship which was obtained via a least-squares fit of dry air data reported by ASHRAE (1993):

$$\mu_{air} = 17.19 + 0.0429\, T_a \qquad (26)$$

where μ_{air} is the dynamic viscosity of air (10^{-6} N s/m^2) and T_a is the air temperature (°C). This correlation is plotted in Figure 3.

3.8 Diffusion Coefficient of Water Vapor in Air

Sastry and Buffington (1982) report an equation for estimating the diffusion coefficient of water vapor in air, δ, which was taken from the National Research Council (1929):

$$\delta = \delta_o \left(\frac{T_{a,\ absolute}}{273.15} \right)^{1.75} \left(\frac{P_o}{P_i} \right) \tag{27}$$

where δ_o is the diffusivity at the reference temperature, 273.15 K, $T_{a,absolute}$ is the dry bulb air temperature (K), P_o is the reference pressure (1 atm) and P_i is the total pressure (atm).

3.9 Effective Heat Transfer Coefficient

The heat transfer, Q, between the surface of a commodity and the surrounding refrigerated air consists of convection heat transfer, Q_c, and radiation heat transfer, Q_r:

$$Q = Q_c + Q_r \tag{28}$$

Convection heat transfer is determined from Newton's Law of Cooling (Incropera and DeWitt, 1990):

$$Q_c = h_{convection} A_s (T_s - T_a) \tag{29}$$

where A_s is the commodity surface area, T_s is the commodity surface temperature, T_a is the surrounding refrigerated air temperature and $h_{convection}$ is the convection heat transfer coefficient described below, in Section 3.9.1. Radiation heat transfer can be expressed in a similar form:

$$Q_r = h_{radiation} A_s (T_s - T_a) \tag{30}$$

with a radiation heat transfer coefficient, $h_{radiation}$, as defined in Section 3.9.2. In the present work, an effective heat transfer coefficient, h_{eff}, is used to account for both the convection and radiation heat transfer:

$$h_{eff} = h_{convection} + h_{radiation} \tag{31}$$

The heat transfer, Q, between the commodity surface and the refrigerated air can then be written as follows:

$$Q = h_{eff} A_s (T_s - T_a) \tag{32}$$

where A_s is the commodity surface area, T_s is the commodity surface temperature and T_a is the refrigerated air temperature.

3.9.1 Convection Heat Transfer Coefficient

The convection heat transfer coefficient, $h_{convection}$, can be estimated by using the Nusselt-Reynolds-Prandtl correlations (Incropera and DeWitt, 1990). The Nusselt number, *Nu*, is defined as follows:

$$Nu = \frac{h_{convection}\, d}{k_{air}} \tag{33}$$

where $h_{convection}$ is the convection heat transfer coefficient, *d* is the diameter of the commodity and k_{air} is the thermal conductivity of air.

Since the convective heat transfer and convective mass transfer processes are governed by similar mechanisms, Nusselt-Reynolds-Prandtl correlations can be formed which correspond to the previously described Sherwood-Reynolds-Schmidt correlations given in Equations (4) and (5). This can be accomplished by replacing the Sherwood number, *Sh*, and the Schmidt number, *Sc*, with the Nusselt number, *Nu*, and the Prandtl number, $Pr = \nu/\alpha$, respectively. The resulting Nusselt-Reynolds-Prandtl correlation which corresponds to Equation (4) is given as follows:

$$Nu = 2.0 + 0.37\, Re^{0.6}\, Pr^{0.33} \tag{34}$$

while that which corresponds to Equation (5) is given by the following:

$$Nu = 2.0 + 0.552\, Re^{0.53}\, Pr^{0.33} \tag{35}$$

In the current computer algorithm, Equation (5) is used to determine the air film mass transfer coefficient, and therefore, Equation (35) is used to determine the convection heat transfer coefficient.

3.9.2 Radiation Heat Transfer Coefficient

In the present work, the radiation heat transfer coefficient, $h_{radiation}$, is determined by linearizing the radiation heat transfer equation. In general, the equation governing the radiation heat transfer between the surface of a commodity and the surrounding refrigerated air is given as follows (Incropera and DeWitt, 1990):

$$Q_r = A_s F \sigma [\varepsilon_s \alpha_a T_s^4 - \varepsilon_a \alpha_s T_a^4] \quad (36)$$

where A_s is the commodity surface area, F is the radiation view factor, σ is the Stefan-Boltzmann constant, ε_s is the emissivity of the commodity surface, α_a is the absorptivity of the refrigerated air, T_s is the commodity surface temperature, ε_a is the emissivity of the refrigerated air, α_s is the absorptivity of the commodity surface and T_a is the refrigerated air temperature. To simplify this equation, the commodity is assumed to be surrounded by refrigerated air and to exhibit blackbody radiation. With these assumptions, the following simplified form of the radiation heat transfer equation is obtained:

$$Q_r = \sigma A_s (T_s^4 - T_a^4) \quad (37)$$

This equation can then be factored to yield the following form:

$$Q_r = \sigma (T_s + T_a) (T_s^2 + T_a^2) A_s (T_s - T_a) \quad (38)$$

With the radiation heat transfer coefficient, $h_{radiation}$, defined as follows:

$$h_{radiation} = \sigma (T_s + T_a) (T_s^2 + T_a^2) \quad (39)$$

Equation (38) takes the form of Equation (30) and $h_{radiation}$ can then be combined with $h_{convection}$ to yield the effective heat transfer coefficient, h_{eff}, as shown in Equation (31).

4 CONCLUSIONS

This paper focused upon the commodity thermophysical properties and the flowfield parameters which govern the heat and mass transfer from fresh fruits and vegetables.

A mathematical model for transpiration was identified which utilizes a variable transpiration coefficient consisting of an air film mass transfer coefficient and a skin mass transfer coefficient. A Sherwood-Reynolds-Schmidt correlation was given for the air film mass transfer coefficient while values of the skin mass transfer coefficient for various commodities were tabulated. In addition, the vapor pressure lowering effects of various commodities were tabulated from published data.

A model was developed which relates respiratory heat generation to commodity temperature via carbon dioxide production. Empirical correlations were developed and presented which relate the carbon dioxide production of various commodities to their temperature.

The literature review revealed methods for estimating the specific heat and thermal conductivity of commodities as a function of their moisture content. Typical values of the moisture content of various commodities were tabulated.

Psychrometric functions were given for the calculation of the water vapor pressure in the refrigerated air and at the commodity surface as well as the density and specific heat of refrigerated air. Correlations were developed and presented which relate both the thermal conductivity and dynamic viscosity of dry air to temperature. An equation for estimating the diffusion coefficient of water vapor in air was identified.

A Nusselt-Reynolds-Prandtl correlation was given for the convection heat transfer coefficient. An expression for the radiation heat transfer coefficient as a function of temperature was derived. An effective heat transfer coefficient was defined as the sum of the convection and radiation heat transfer coefficients.

The theoretical considerations presented in this paper, involving thermophysical properties of commodities and flowfield parameters, form the foundation for the computer algorithm which is presented in the second paper.

NOMENCLATURE

A	constant for commodity thermal conductivity correlation
A_s	single commodity surface area
B	constant for commodity thermal conductivity correlation
c	specific heat of commodity
$c_{p,a}$	specific heat of air
d	diameter of fruit or vegetable

f	carbon dioxide production vs. temperature correlation coefficient
F	radiation view factor
g	carbon dioxide production vs. temperature correlation coefficient
$h_{convection}$	convection heat transfer coefficient
h_{eff}	effective heat transfer coefficient
$h_{radiation}$	radiation heat transfer coefficient
k	thermal conductivity of commodity
k_a	air film mass transfer coefficient (driving force: vapor pressure)
$k_{a'}$	air film mass transfer coefficient (driving force: concentration)
k_{air}	thermal conductivity of air
k_s	skin mass transfer coefficient (driving force: vapor pressure)
k_t	transpiration coefficient
$\dot{m}$	transpiration rate per unit area of commodity surface
$\dot{m}_{CO2}$	carbon dioxide production rate
Nu	Nusselt number
P	atmospheric pressure
Pr	Prandtl number
P_a	ambient water vapor pressure
P_i	atmospheric pressure
P_o	reference pressure
P_s	water vapor pressure at evaporating surface of commodity
$P_{ws}(T)$	water vapor saturation pressure evaluated at temperature T
Q	heat transfer
Q_c	convection heat transfer
Q_r	radiation heat transfer
Re	Reynolds number
R_{H2O}	gas constant for water vapor
R_u	universal gas constant
Sc	Schmidt number
Sh	Sherwood number
T	mean temperature of the boundary layer

T_a	dry bulb air temperature
T_a^*	wet bulb air temperature
$T_{a,absolute}$	dry bulb air temperature in absolute degrees (K)
T_m	mass average temperature of commodity
T_s	commodity surface temperature
u_∞	free stream air velocity
VPL	vapor pressure lowering effect
w	humidity ratio
w_{H2O}	percent moisture content of commodity
w_s^*	saturation humidity ratio
W	rate of respiratory heat generation of commodity per unit mass of commodity
x_a	mole fraction of dry air
x_w	mole fraction of water vapor in air
α	thermal diffusivity of commodity
α_a	absorptivity of air
α_s	absorptivity of commodity surface
α_w	thermal diffusivity of water
δ	coefficient of diffusion of water vapor in air
ΔT_f	freezing point depression at product surface
ε_a	emissivity of air
ε_s	emissivity of commodity surface
θ	dimensionless temperature ratio
μ_{air}	dynamic viscosity of air
ν	kinematic viscosity of air
ρ	density of commodity
ρ_a	density of air
σ	Stefan-Boltzman constant

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Table 1. Commodity skin mass transfer coefficient and vapor pressure lowering effect (VPL).[†]

Product	Skin Mass Transfer Coefficient, k_s,g/(m^2·s·MPa)				VPL
	Low	Mean	High	Standard Deviation	
Apples	0.111	0.167	0.227	0.03	0.98
Blueberries	0.955	2.19	3.39	0.64	0.98
Brussels Sprouts	9.64	13.3	18.6	2.44	0.99
Cabbage	2.50	6.72	13.0	2.84	0.99
Carrots	31.8	156.	361.	75.9	0.99
Grapefruit	1.09	1.68	2.22	0.33	0.99
Grapes	--	0.4024	--	--	0.98
Green Peppers	0.545	2.159	4.36	0.71	0.99
Lemons	1.09	2.08	3.50	0.64	0.98
Lima Beans	3.27	4.33	5.72	0.59	0.99
Limes	1.04	2.22	3.48	0.56	0.98
Onions	--	0.8877	--	--	0.98
Oranges	1.38	1.72	2.14	0.21	0.98
Peaches	1.36	14.2	45.9	5.2	0.99
Pears	0.523	0.686	1.20	0.149	0.98
Plums	--	1.378	--	--	0.98
Potatoes	--	0.6349	--	--	0.98
Snap Beans	3.46	5.64	10.0	1.77	0.99
Sugar Beets	9.09	33.6	87.3	20.1	0.96
Strawberries	3.95	13.6	26.5	4.8	0.99
Swedes	--	116.6	--	--	0.99
Tomatoes	0.217	1.10	2.43	0.67	0.99

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

Table 2. Commodity Respiration Coefficients and Water Content.

Commodity	Respiration Coefficients		Percent Water Content*
	f	g	
Apples	5.6871×10^{-4}	2.5977	84.1
Blueberries	7.2520×10^{-5}	3.2584	83.2
Brussels Sprouts	0.0027238	2.5728	84.9
Cabbage	6.0803×10^{-4}	2.6183	92.4
Carrots	0.050018	1.7926	88.2
Grapefruit	0.0035828	1.9982	89.1
Grapes	7.056×10^{-5}	3.033	81.9
Green Peppers	3.5104×10^{-4}	2.7414	92.4
Lemons	0.011192	1.7740	87.4
Lima Beans	9.1051×10^{-4}	2.8480	66.5
Limes	2.9834×10^{-8}	4.7329	89.3
Onions	3.668×10^{-4}	2.538	87.5
Oranges	2.8050×10^{-4}	2.6840	86.4
Peaches	1.2996×10^{-5}	3.6417	89.1
Pears	6.3614×10^{-5}	3.2037	83.2
Plums	8.608×10^{-5}	2.972	86.6
Potatoes	0.01709	1.769	79.5
Snap Beans	0.0032828	2.5077	88.9
Sugar Beets	8.5913×10^{-3}	1.8880	87.6
Strawberries	3.6683×10^{-4}	3.0330	89.9
Swedes	1.6524×10^{-4}	2.9039	89.1
Tomatoes	2.0074×10^{-4}	2.8350	93.0

* USDA (1986).

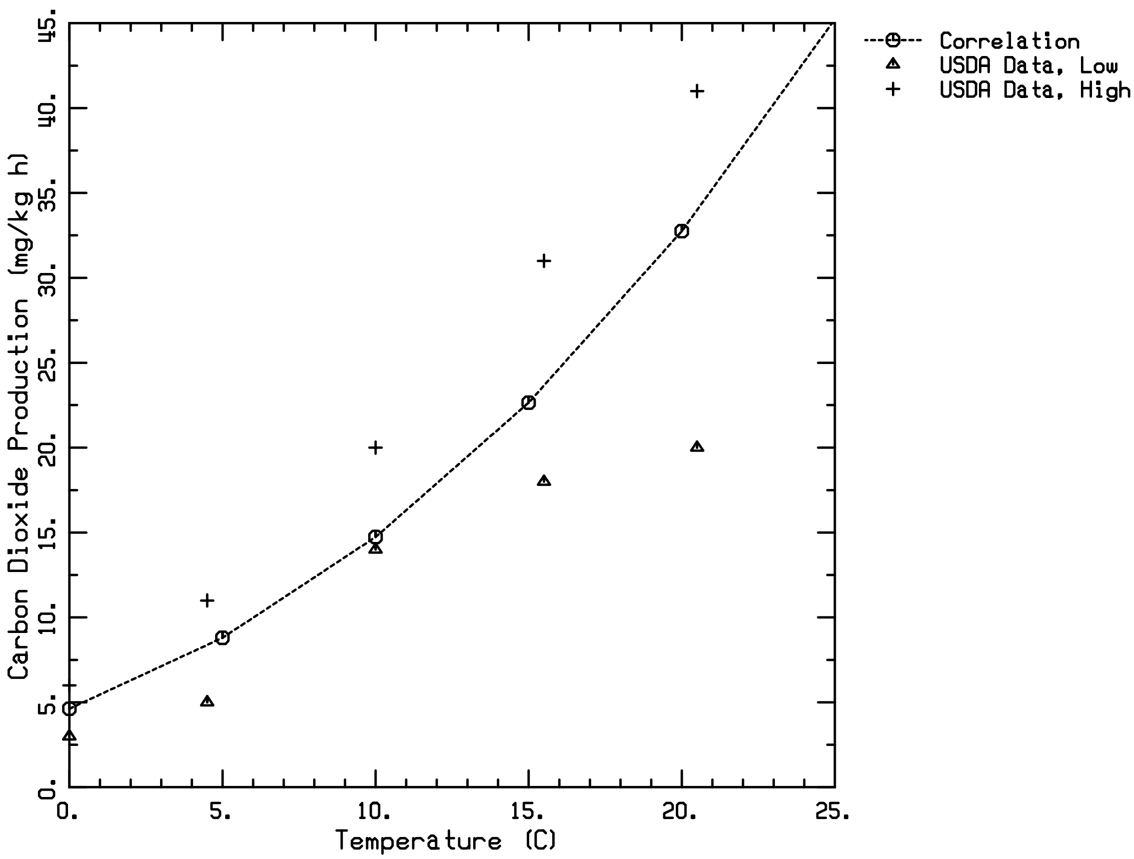

Figure 1. Carbon dioxide production vs. temperature correlation for apples.

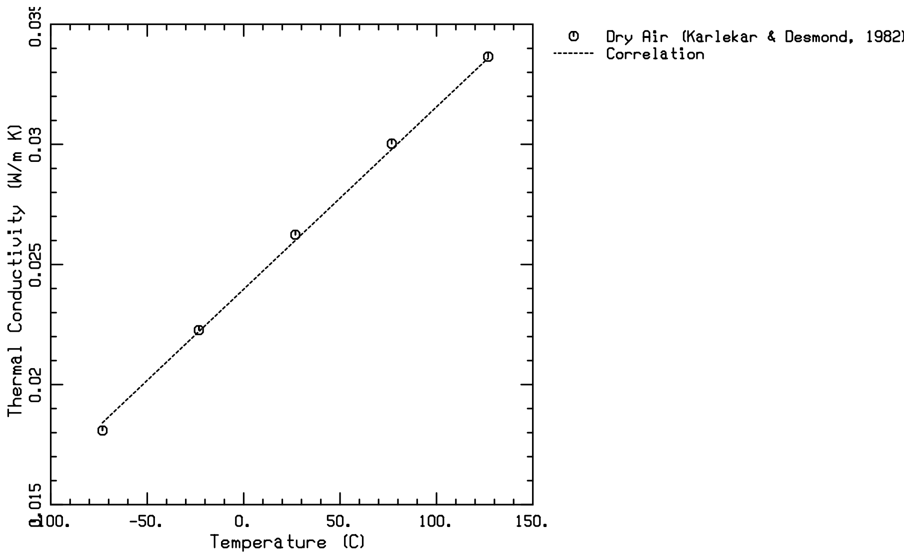

Figure 2. Thermal conductivity vs. temperature correlation for air.

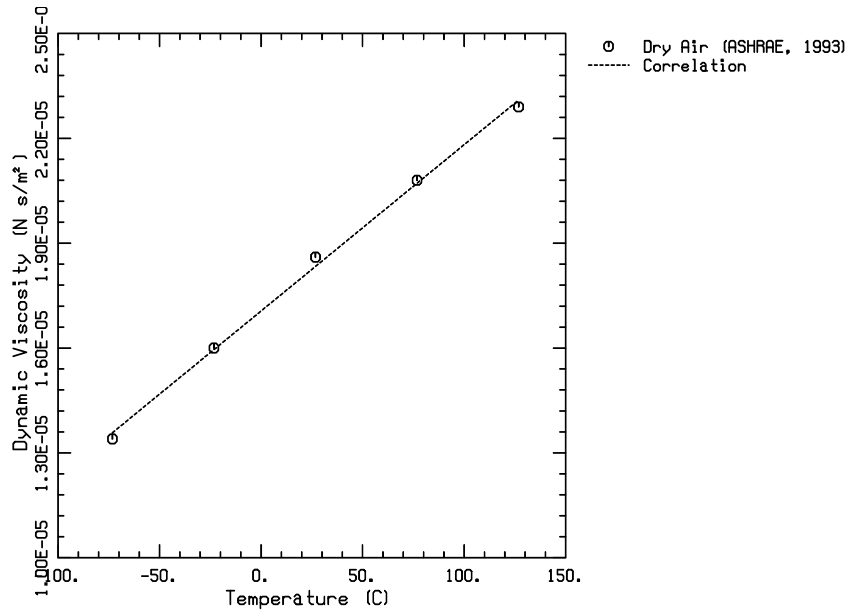

Figure 3. Dynamic viscosity vs. temperature correlation for air.