A NUMERICAL MODEL OF MOISTURE LOSS AND HEAT LOADS IN REFRIGERATED STORAGE OF FRUITS AND VEGETABLES

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
U.S.A.

30 January 1996

A Numerical Model of Moisture Loss and Heat Loads in Refrigerated Storage of Fruits and Vegetables

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, U.S.A.

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 paper discusses the modeling methodology utilized in the current computer algorithm and describes the development of the heat and mass transfer models. The results of the computer algorithm are compared to experimental data taken from the literature. In addition, this paper also reviews existing numerical models for determining the heat and mass transfer in bulk loads of fruits and vegetables.

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. 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. 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 cold storage, the temperature and humidity of the conditioned air within the refrigerated, bulk storage facility must be precisely controlled. To properly design such a bulk storage facility and its associated refrigeration equipment, the designer must estimate both the sensible and latent heat loads due to the stored commodity. Estimates of the commodity moisture loss and the temperature distribution during storage are important to the facility operator. All of these estimates require knowledge of the complex interaction of the various thermophysical processes which occur within and around the commodities.

Therefore, a computer algorithm was developed to aid in the design and operation of refrigerated, bulk storage facilities. This computer model utilizes a porous media approach to estimate the latent and sensible heat loads in refrigerated storage 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, the computer algorithm also predicts the commodity moisture loss which occurs during refrigerated storage and the temperature distribution within the commodity. The modeling methodology utilized in this computer algorithm is described and the results of the computer model are compared to experimental data taken from the literature.

A review of the literature has revealed several existing models of the heat transfer in the bulk refrigeration of fruits and vegetables. Bakker-Arkema and Bickert (1966), Baird and Gaffney (1976), Adre and Hellickson (1989), Gan and Woods (1989), Talbot et al. (1990) and MacKinnon and Bilanski (1992) have all presented bulk load heat transfer models. However, none of these models provide a thorough treatment of moisture loss modeling, heat of respiration and temperature gradient within the commodity. In addition, the models are not applicable to a wide variety of commodities. Hence, these existing bulk load heat and mass transfer models are not adequate to fulfill the needs of the designers and operators of bulk refrigeration facilities. Therefore, the current computer algorithm was developed to estimate the latent and sensible heat loads as well as the moisture loss and temperature distribution in the bulk refrigeration of fruits and vegetables. This current computer algorithm is capable of modeling a wide variety of commodities.

2 MODELING METHODOLOGY

The computational model is based upon a one dimensional air flow pattern within the bulk load of commodities, as depicted in Figure 1. In the computational model, the bulk load is represented as a porous medium composed of "commodity computational cells." The refrigerated air is modeled as "air parcels" which move through the "commodity computational cells."

Calculation commences with a specified initial temperature and humidity for the commodity bulk load and the air contained within it. As shown in Figure 1a, the time-stepping begins with the first refrigerated "air parcel" moving into the first "commodity computational cell." At the same time, each of the initial "air parcels" moves from its original cell into the adjacent cell, while the "air parcel" within the last "commodity computational cell" moves from the bulk load into the plenum of the refrigeration unit. Within each "commodity computational cell," the commodity transpiration, $\dot{m}_1$, is calculated for the time-step, ?*t*. The mass fraction of water vapor in each "air parcel" is then updated to reflect the effects of transpiration. Subsequently, within each cell, the heat generation due to commodity respiration, *W*, the heat transfer from the commodity, *Q*, and the evaporative cooling due to transpiration are calculated for the time-step. Then, within each cell, the commodity temperature and the "air parcel" temperature are both updated to reflect the effects of the calculated respiration, heat transfer and evaporative cooling, thus completing the calculations for this time-step.

As shown in Figure 1b, the first "air parcel" moves to the second "commodity computational cell" and a newly refrigerated second "air parcel" moves into the first "commodity computational cell." This second "air parcel" encounters the previously updated commodity temperature in the first "commodity computational cell."

As the time-stepping continues, each "air parcel" traverses the entire commodity bulk load. The mass fraction of water vapor contained in each "air parcel," when it exits the bulk load, is used to calculate the latent heat load corresponding to that "air parcel," while its temperature is used to calculate its sensible heat load. As this algorithm time-steps towards a steady state, an estimate of the time histories of the latent and sensible heat loads, as well as commodity moisture loss and temperature distribution, are obtained.

3 MASS TRANSFER CALCULATION

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. Hence, the moisture loss from a single commodity item is modeled as follows:

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

where k_t is the transpiration coefficient, P_s is the water vapor pressure at the surface of the commodity and P_a is the water vapor pressure in the refrigerated air. Both P_s and P_a are evaluated at the previous time step by utilizing psychrometric relationships. Fockens and Meffert (1972) suggest that the transpiration coefficient, k_t, can be modeled as follows:

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

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 can be calculated with a Sherwood-Reynolds-Schmidt correlation (Geankoplis, 1972; Geankoplis, 1978). The skin mass transfer coefficient, k_s, describes the skin's diffusional resistance to moisture migration. Chau et al. (1987) and Gan and Woods (1989) have tabulated the skin mass transfer coefficient for various commodities.

During the time step, *?t*, the mass of water vapor in the air of the computational cell increases as follows:

$$m_{H_2O}^1 = m_{H_2O}^0 + \dot{m}_t \Delta t \tag{3}$$

where m_{H2O}^1 is the updated mass of water vapor in the air, m_{H2O}^0 is the mass of water vapor in the air from the previous time step, $\dot{m}_t$ 5 is the transpiration rate in the computational cell and *?t* is the time step size. The updated mass fraction of water vapor in the air of the computational cell, m_f^1, then becomes:

$$m_f^1 = \frac{m_{H2O}^1}{m_a^0 + \dot{m}_t \, \Delta t} \tag{4}$$

where m_a^0 is the mass of air within the computational cell. With the updated mass fraction of water vapor in the air, the relative humidity within the computational cell may be determined via psychrometric relationships. This completes the transpiration calculations for one computational cell for the current time step.

4 HEAT TRANSFER CALCULATION

In order to make the modeling of commodity heat transfer tractable, the commodities were assumed to be spherical in shape with uniform internal heat generation due to respiration. It was further assumed that the temperature within a commodity varied only in the radial direction. With these assumptions, the governing form of the transient heat equation is formally written as follows (Incropera and DeWitt, 1990):

$$\frac{k}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial T}{\partial r}\right)+\rho W=\rho c\frac{\partial T}{\partial t} \tag{5}$$

where r denotes the radial direction within the commodity, k is the commodity thermal conductivity, T is the commodity temperature, W is the respiratory heat generation of the commodity per unit mass, *?* is the commodity density, c is the commodity specific heat, and t is time.

An explicit finite difference technique was applied to Equation (5) by dividing a commodity into N spherical shells. The resulting finite difference equation applicable to the interior nodes is given as follows:

$$\frac{k A_{i-1}(T^0_{i-1}-T^0_i)}{\Delta r}+\frac{k A_i(T^0_{i+1}-T^0_i)}{\Delta r}+\rho v_i W_i=\frac{\rho c v_i(T^1_i-T^0_i)}{\Delta t} \tag{6}$$

where A_{i-1} is the area through which heat is transferred from the neighbor node, *?r* is the distance between nodes, $T_{i-1}{}^0$ is the temperature of the neighbor node at the previous time step, T_i^0 is the temperature of the current node at the previous time step, A_i is the area through which heat is transferred from the current node, $T_{i+1}{}^0$ is the temperature of the neighbor node at the previous time step, W_i is the heat generation per unit mass due to respiration for the current node, v_i is the volume of the current node and T_i^1 is the temperature of the current node at the current time step. For the case of the center node, the left-most term on the left hand side of Equation (6) vanishes.

At the surface of the commodity, convection heat transfer, radiation heat transfer, and evaporative cooling due to transpiration must be considered. Thus, the finite difference equation at the commodity surface becomes:

$$\frac{k A_{N-1}}{\Delta r}(T^0_{N-1}-T^0_N)+h_{eff}A_s(T^0_a-T^0_N)-L\dot{m}A_s+\rho v_N W_N=\frac{\rho c v_N(T^1_N-T^0_N)}{\Delta t} \tag{7}$$

where A_{N-1} is the area through which heat is transferred from the neighbor node, *?r* is the distance between nodes, $T_{N-1}{}^0$ is the temperature of the neighbor node at the previous time step, T_N^0 is the temperature of the surface node at the previous time step, A_s is the surface area of a single commodity item, T_a^0 is the air temperature at the previous time step, L is the latent heat of vaporization for water, $\dot{m}$ 10 is the transpiration rate per unit area of commodity surface, v_N is the volume of the surface node and T_N^1 is the temperature of the surface node at the current time step. The effective heat transfer coefficient, h_{eff}, includes both convection and radiation:

$$h_{eff}=h_{convection}+h_{radiation} \tag{8}$$

The convection heat transfer coefficient, $h_{convection}$, is determined via a Nusselt-Reynolds-Prandtl correlation (Geankoplis, 1972; Geankoplis, 1978), while the radiation heat transfer coefficient, $h_{radiation}$, is given by:

$$h_{radiation}=\sigma(T_s+T_a)(T^2_s+T^2_a) \tag{9}$$

where T_s is the commodity surface temperature, T_a is the air temperature and σ is the Stefan-Boltzman constant.

The formulation given by Equations (6) and (7) defines the temperature distribution within a single commodity item. However, Equation (7) requires knowledge of the temperature of the air parcel resident within the "commodity computational cell," T_a^0. This air temperature is determined at each time step by performing a heat balance between the air parcel and that portion of the bulk load which is contained within the "commodity computational cell:"

$$n_c\, h_{eff}\, A_s(\,T_a^0 - T_N^0\,) = m_a^0\; c_{p,a} \frac{(\,T_a^1 - T_a^0\,)}{\Delta\, t} \tag{10}$$

where n_c is the number of commodity items resident within the "commodity computational cell," m_a^0 is the mass of air in the computational cell and $c_{p,a}$ is the specific heat of air. This completes the formulation of the heat transfer model for one computational cell.

Since Equations (6), (7) and (10) are explicit finite difference equations, they can be solved directly for the updated nodal temperatures. The heat transfer calculation begins at the commodity center node and proceeds outward to the air parcel. This completes the heat transfer calculation for one computational cell for the current time step.

5 EXPERIMENTAL VERIFICATION OF THE COMPUTER ALGORITHM

To verify the accuracy of the current computer algorithm, its calculated results were compared with experimental data obtained from the literature. Baird and Gaffney (1976) reported experimental data taken from bulk loads of oranges. They recorded commodity center and surface temperatures at the air exit of a bulk load for a period of two hours. The bulk load of oranges was 0.67 m (2.2 ft) deep and the commodities were initially at 32°C (90°F). The refrigerated air was at a temperature of -1.1°C (30°F) and approached the bulk load with a velocity of 0.91 m/s (3.0 ft/s). Figure 2 shows Baird and Gaffney's experimental data along with the output from the current computer algorithm. Comparison of the model results with Baird and Gaffney's data on oranges shows that the current algorithm correctly predicts the trends of commodity temperatures with a maximum error of 1.4°C (2.5°F).

Brusewitz et al. (1992) conducted experiments to determine moisture loss from peaches during post-harvest cooling. The post-harvest cooling was performed at 4°C (39°F), 92% relative humidity in a chamber with 20 air changes per minute for a period of four days. Peaches were picked in the morning when the ambient temperature was 16°C (61°F). Experimental data from Brusewitz et al. shows that the peaches lost 2.5% of their weight due to moisture loss during the four day cooling period. The current computer algorithm predicted a weight loss of 2.53% at the end of the four day period, in good agreement with the experimental data. Figure 3 shows the results from the current computer algorithm as well as the experimental data.

6 CONCLUSIONS

This paper has described the development and performance of a computer algorithm which estimates the latent and sensible heat loads as well as the moisture loss and temperature distribution in the bulk refrigeration of fruits and vegetables. This algorithm, which was developed as an aid to both the designer and the operator of refrigeration facilities, is capable of modeling a wide variety of commodities.

In the computational model, the bulk load is represented as a porous medium composed of "commodity computational cells" and the refrigerated air is modeled as "air parcels" which move through these "commodity computational cells." A mass transfer model was developed to update the mass fraction of water vapor within each "commodity computational cell" at each time step. An explicit finite difference formulation of the transient heat equation in spherical coordinates was derived which accounts for both radiation and convection heat transfer at the commodity surface. This formulation yields the temperature distribution within the commodities resident in each "commodity computational cell" at each time step. It also yields the temperature of the "air parcel" resident within each "commodity computational cell" at each time step.

To verify the accuracy of the current algorithm, its calculated results were compared with experimental data obtained from the literature. The results of these comparisons show good agreement between the numerical results and the experimental data for both temperature and moisture loss.

NOMENCLATURE

A_i	surface area of i^{th} node
A_s	single commodity surface area
c	specific heat of commodity
$c_{p,a}$	specific heat of air
$h_{convection}$	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_s	skin mass transfer coefficient (driving force: vapor pressure)
k_t	transpiration coefficient
L	latent heat of vaporization of water
m_a^0	mass of air at time t
m_f^1	mass fraction of water vapor in air at time t + ?t
m_{H2O}^0	mass of water vapor in air at time t
m_{H2O}^1	mass of water vapor in air at time t + ?t
$\dot{m}$	transpiration rate per unit area of commodity surface
$\dot{m}_t$	transpiration rate in computational cell
n_c	number of commodities in computational cell
P_a	ambient water vapor pressure
P_s	water vapor pressure at evaporating surface of commodity
Q	heat transfer
r	commodity radius
t	time
T	commodity temperature
T_a	dry bulb air temperature
T_a^0	air temperature at time t
T_a^1	air temperature at time t + ?t
T_i^0	temperature of i^{th} node at time t
T_i^1	temperature of i^{th} node at time t + ?t
T_N^0	temperature of surface node at time t
T_N^1	temperature of surface node at time t + ?t
T_s	product surface temperature
v_i	volume of i^{th} node
v_N	volume of surface node
W	rate of respiratory heat generation of commodity per unit mass of commodity
W_i	rate of respiratory heat generation of commodity per unit mass of commodity for node i

?r	length of node in radial direction
?t	time step size
?	density of commodity
s	Stefan-Boltzman constant

REFERENCES

Adre, N., and M.L. Hellickson. 1989. Simulation of the Transient Refrigeration Load in a Cold Storage for Apples and Pears. *Transactions of the ASAE* 32(3): 1038-1048.

Baird, C.D., and J.J. Gaffney. 1976. A Numerical Procedure for Calculating Heat Transfer in Bulk Loads of Fruits or Vegetables. *ASHRAE Transactions* 82(2): 525-540.

Bakker-Arkema, F.W., and W.G. Bickert. 1966. A Deep-Bed Computational Cooling Procedure for Biological Products. *Transactions of the ASAE* 9(6): 834-836, 845.

Brusewitz, G.H., X. Zhang, and M.W. Smith. 1992. Picking Time and Postharvest Cooling Effects on Peach Weight Loss, Impact Parameters, and Bruising. *Applied Engineering in Agriculture* 8(1): 84-90.

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.

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.

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.

Geankoplis, C.J. 1972. *Mass Transfer Phenomena*. New York: Holt, Rinehart, and Winston.

Geankoplis, C.J. 1978. *Transport Processes and Unit Operations*. Boston: Allyn and Bacon.

Incropera, F.P., and D.P. DeWitt. 1990. *Fundamentals of Heat an d Mass Transfer*. New York: John Wiley and Sons.

MacKinnon, I.R., and W.K. Bilanski. 1992. Heat and Mass Transfer Characteristics of Fruits and Vegetables Prior to Shipment. *SAE Technical Paper 921620*. Warrendale, PA: SAE.

Talbot, M.T., C.C. Oliver, and J.J. Gaffney. 1990. Pressure and Velocity Distribution for Air Flow Through Fruits Packed in Shipping Containers Using Porous Media Flow Analysis. *ASHRAE Transactions* 96(1): 406-417.

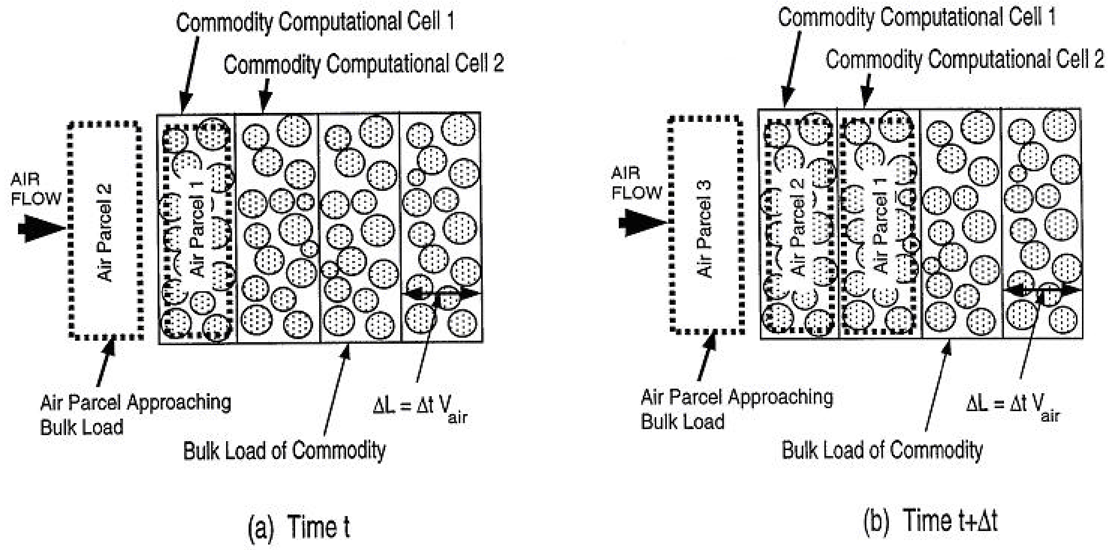

Figure 1. Computational model of refrigerated air flow through bulk load of commodity.

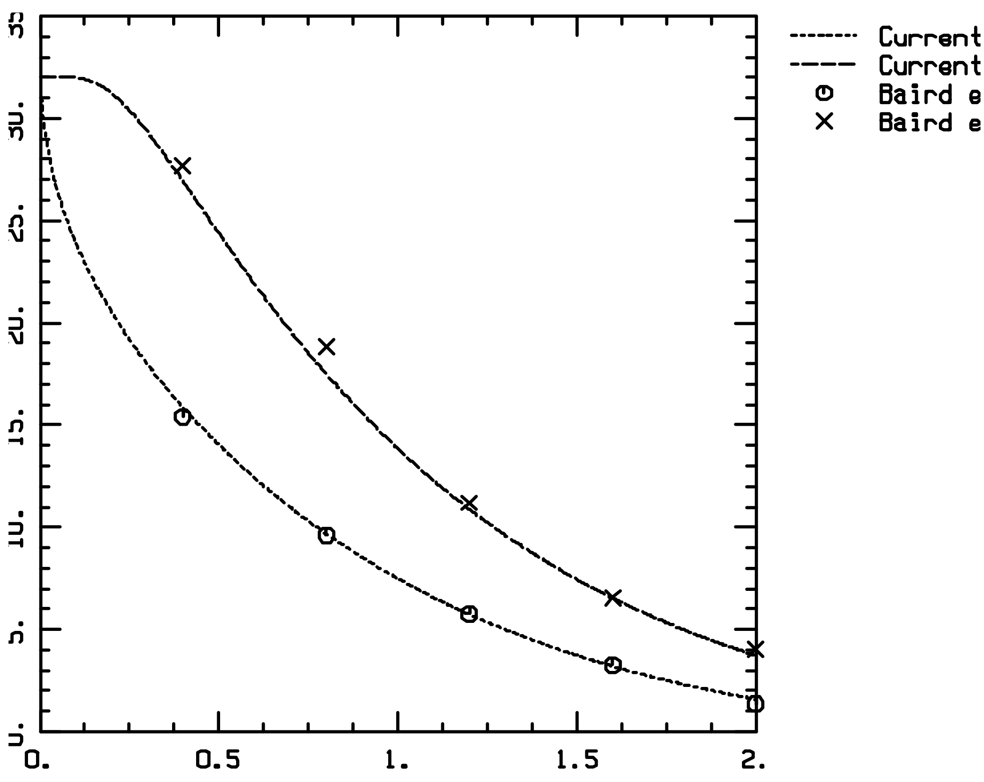

Figure 2. Current numerical results and experimental temperature data for forced air cooling of oranges from Baird and Gaffney (1976).

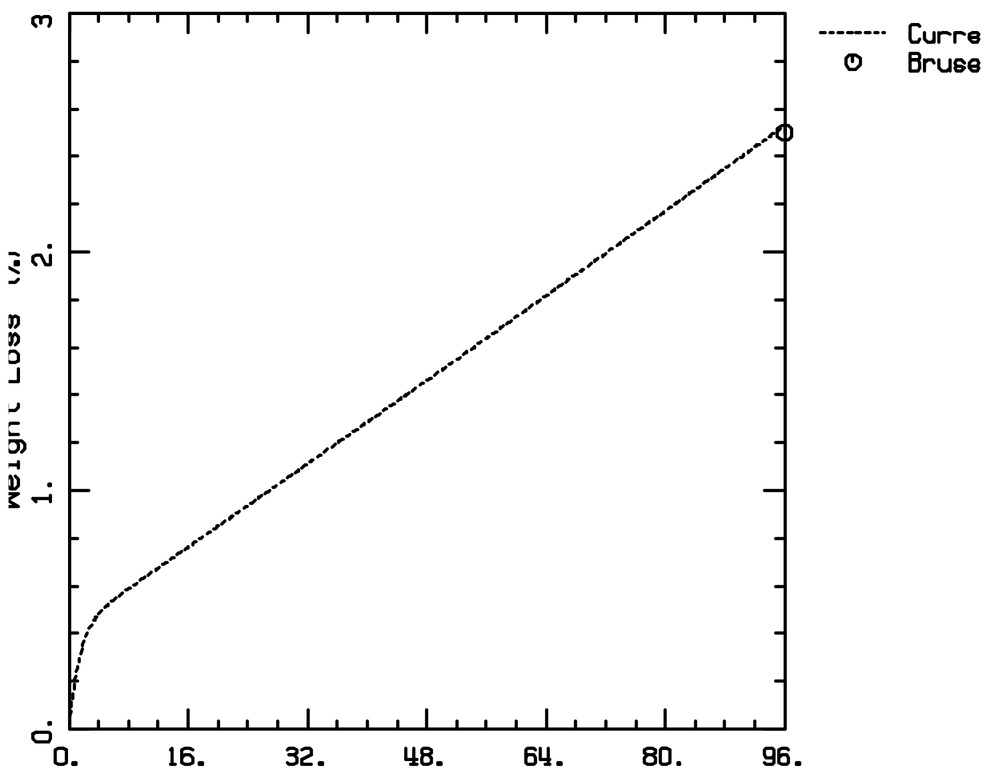

Figure 3. Current numerical results and experimental moisture loss data for post harvest cooling of peaches from Brusewitz et al. (1992).