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TRANSPORT PROPERTIES OF CELLULAR FOOD MATERIALS UNDERGOING FREEZE-DRYING

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ABSTRACT

Both sliced and mashed apples have been freeze-dried at various surface temperatures under the usual pressure range of commercial operations. The surface of sliced samples could not be maintained at above 10℃ in order to prevent the frozen layer from melting, while that of mashed samples was allowed to heat up to 70℃.

Thermal conductivities and permeabilities were determined by applying the uniformly-retreating-ice front model to the dried layer of the samples undergoing freeze-drying. The effects of freezing rate on transport properties were found to be critical for the mashed samples. The results indicated that the drying rate of sliced samples was limited by the transfer rate of water vapor flowing through the dried layer.

A cellular structural model was proposed for predicting the permeability of the dried layer, based on the resistance of a cell membrane to the molecular transfer of water vapor.

INTRODUCTION

Thermal conductivity and permeability for the dried layer of the material are indispensable for the prediction of the drying rate during freeze-drying of food. However, available literatures are limited on the drying characteristics and transport properties of cellular food materials such as fresh fruit and vegetables. Particularly, the effects of operating parameters on the drying rate as well as transport properties have not been investigated in connection with the freezing and freeze-drying operations.

The objectives of this work are 1) to measure the drying characteristics, thermal conductivity and permeability for sliced and mashed apples, 2) to reveal the influences of freezing rate as well as temperature and pressure of the dried layer

upon these transport properties, and 3) to develop a structural model for predicting the permeability of a cellular food material.

THEORETICAL MODEL

Figure 1 shows a uniformly-retreating-ice front model to determine the transport properties for the dried layer of the material undergoing freeze-drying (Sagara et al., 1982). In the model, the material is assumed to have the geometry of a semi-infinite slab and the dried layer is separated from the frozen layer by the sublimation front. The insulated bottom can be regarded as the center line of the material heated by radiation from both surfaces of the material. Furthermore, the model has several assumptions; that is, 1) Drying proceeds under a quasi-steady state condition. 2) The change in temperature and pressure in the material, and the movement of the sublimation front are negligible during calculation. 3) The linear distribution in temperature and pressure exists across the dried layer, and the temperature of the frozen layer is uniform and equal to that of sublimation front. 4)

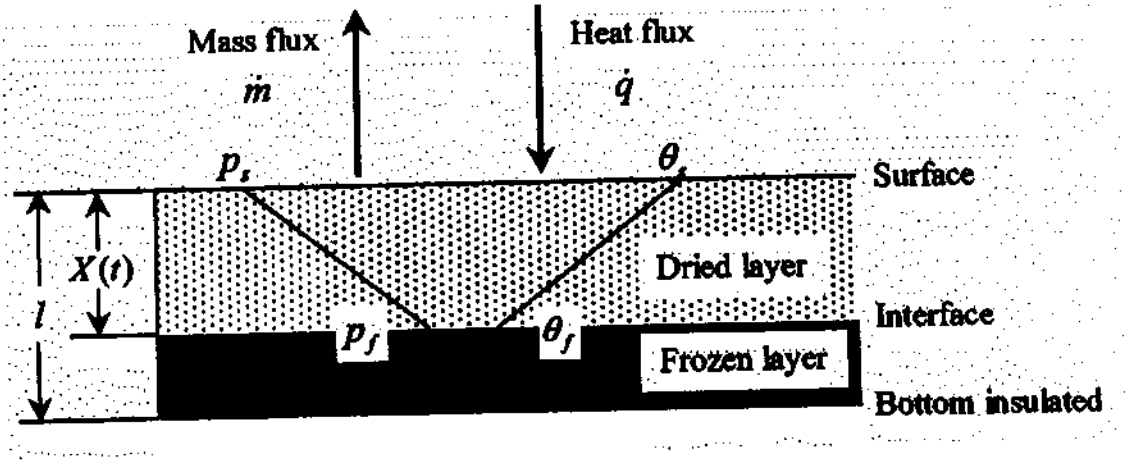

FIGURE 1 Freeze-drying model for transport properties analysis

The heat supplied through the dried layer is consumed completely as the latent heat at the sublimation front.

Based on these assumptions, the equations of the heat and mass flux are introduced, and thus the thermal conductivity and permeability are given as the following equations, respectively:

$$\lambda = \alpha \rho_w l^2 (\Delta H + \int_{\theta_f}^{\theta_s} c_p d\theta) / N \tag{1}$$

$$K = \beta \rho_w l^2 R T_f / N M_w \tag{2}$$

where,

$$\alpha = \frac{1-m}{(\theta_s - \theta_f)/(-dm/dt)} \tag{4}$$

$$\beta = \frac{1-m}{(p_f - p_s)/(-dm/dt)} \tag{3}$$

EXPERIMENTAL

Sample holder

Two types of the sample holder were prepared for the sliced as well as mashed samples, respectively. Figure 2 show a radiant heating apparatus used for the sliced samples. The sample was located at the central position of the apparatus, and its circumference was insulated with the fiber-glass. Thus both sample surfaces were heated by radiant heaters assembled with silicon heaters and copper plates. Temperatures of both surfaces and center of the sample were monitored by using thermocouple probes made of 0.2mm copper-constantan wires.

Figure 3 shows another type prepared for the mashed samples. The sample holder was a Plexiglas dish with 70mm inside diameter and 15mm in height. To promote one-dimensional freezing and freeze-drying, a fiber glass insulation was placed around the side of the sample holder, and the bottom of it was insulated with a Polyurethane foam plate. The change in temperature distribution within the sample was measured with four thermocouple probes. The thermocouple junctions for measuring and controlling the surface temperature were placed just under the exposed surface of the sample.

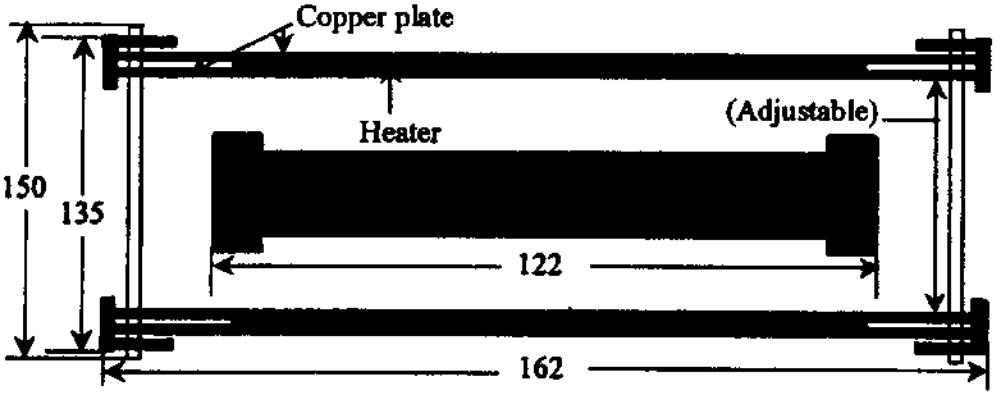

FIGURE 2 Schematic diagram of sample holder for the sliced samples

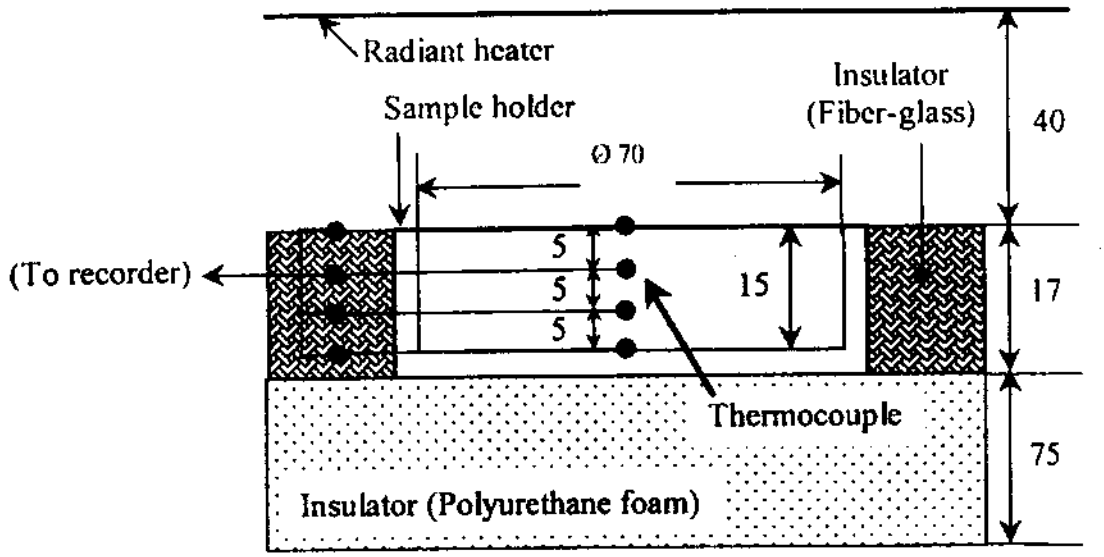

FIGURE 3 Schematic diagram of sample holder for the mashed samples

MATERIALS AND PROCEDURE

Both sliced and mashed apples of 15mm thick were employed as the material to be dried. Sliced samples were cut out horizontally at the equator part, which has the largest diameter in the range from 80 to 90mm. The cores of them were removed with the cork borer whose inside diameter was 20mm.

The sample was frozen one-dimensionally by using a cooling copper plate at the surface temperature ranging from –27 to -44°C, and then freeze-dried at a constant surface temperature ranging from –10 to 70°C under the usual pressure range of commercial operations. The moisture contents of dried samples were determined by Karl Fisher titration method, and the initial moisture contents were calculated based on these data.

RESULTS AND DISCUSSION

Figure 4 shows the drying characteristics obtained for a sliced sample. As shown in the figure, the surface temperature of the sliced sample could not be maintained at a constant temperature of above 10°C in order to prevent the frozen layer from melting. On the other hand, that of the mashed sample was allowed to heat up to 70°C, showing the greater drying rate comparing with the sliced sample.

Drying rates of these two samples had a tendency to reach the maximum value as the surface temperature reached at a control temperature and after that, to decrease exponentially. However, the maximum drying rate of the mashed sample was about 2.5 times greater than that of the sliced one. This marked difference was interpreted in terms of the larger resistance against the molecular transfer of water

Transport Properties

Figure 5 and 6 show the plots of the thermal conductivities and permeabilities obtained for sliced samples. As shown in the figure, the temperature and pressure dependence of thermal conductivity were not observed apparently, while the permeability showed the tendency to decrease with an increase in the average pressure of the dried layer.

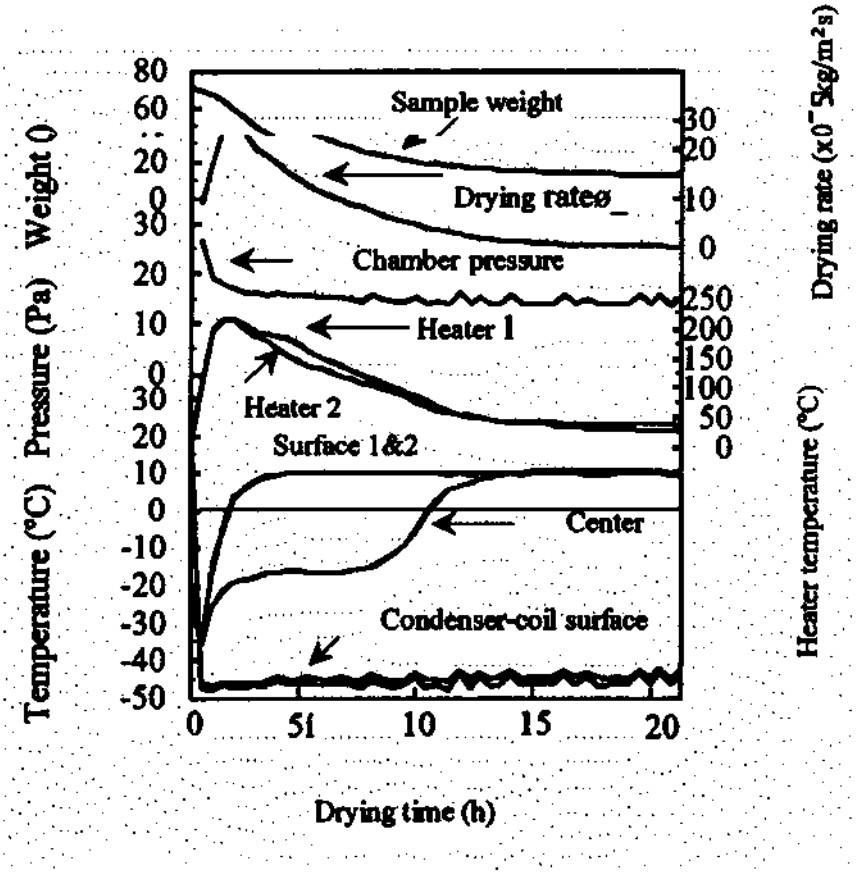

FIGURE 4 Experimental data obtained during freeze-drying of 15mm thick sliced apple having surface temperature of 10°C

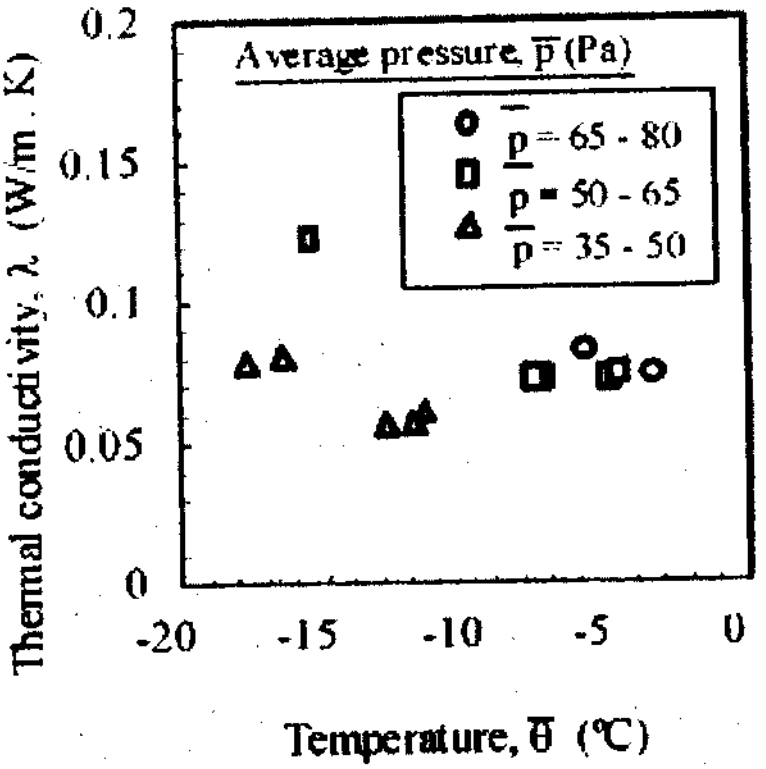

FIGURE 5 Thermal conductivities obtained for the sliced samples

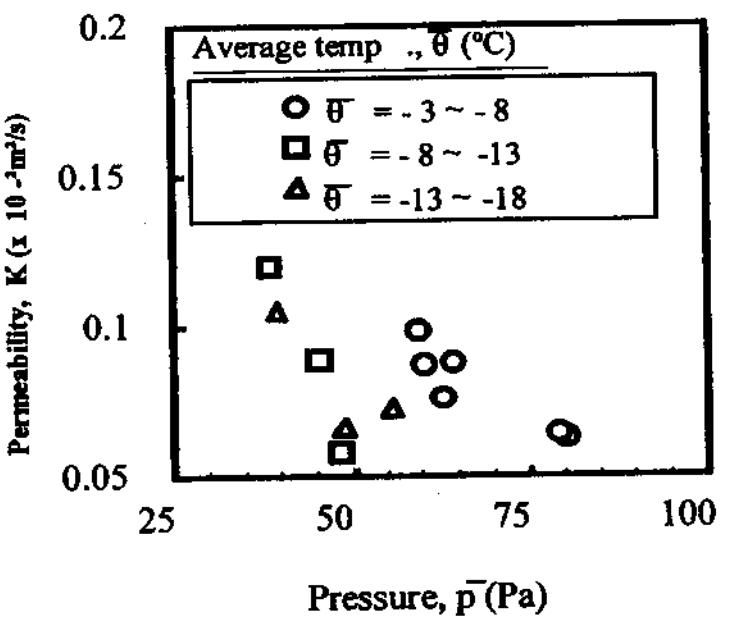

FIGURE 6 Permeabilities obtained for the sliced samples

Figure 7 shows the freezing curves for mashed samples. The changes in temperature at the center during freezing could be regarded as an index of the

freezing rate, and based on these indexes the mashed samples were classified into the group A and B. The freezing rate of the group A was relatively larger than the group B. In order to obtain the quantitative index, the period between two inflection points was defined as the ice-crystallization time, based on the primary differential values of these curves.

Figure 8 shows the permeability against the ice-crystallization time for mashed samples. The permeability data were plotted proportionally to the ice-crystallization time, because the larger ice crystals formed as the freezing rate decreased. Hence, the effects of the freezing rate on transport properties, especially on the permeability, were found to be critical for the mashed cellular food materials.

Cellular structural model

Sagara (1986) developed an approximate method for predicting the structural parameters of the dried layer by considering this dried layer to be a bundle of capillary tubes with the pore space having an equivalent pore radius, porosity and tortuosity factor. The mass flux density of water-vapor flowing through the dried layer may be written

$$\dot{m} = -\frac{KM_w}{RT} grad\ p \tag{5}$$

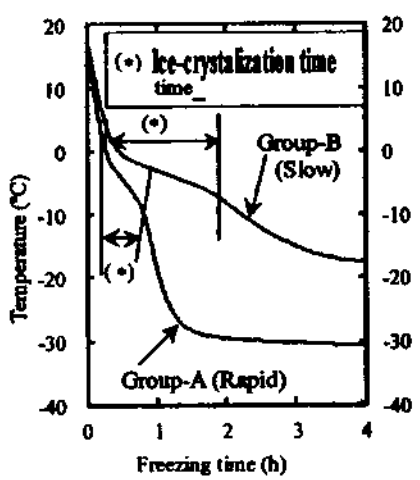

FIGURE 7 Freezing curves for the mashed samples

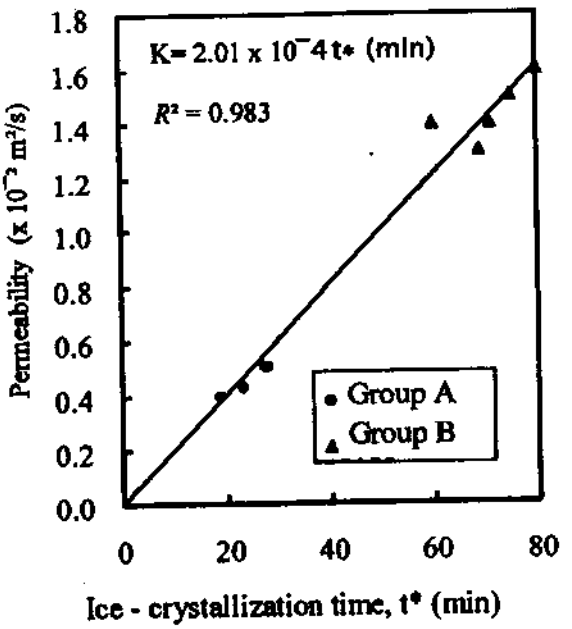

FIGURE 8 Permeability against the ice-crystallization time for the mashed samples

The expressions for the permeability coefficient of a single capillary tube are taken from Mellor and Lovett (1964) ;

$$K = \frac{\varepsilon}{\tau} D_k \Omega \tag{6}$$

where,

$$\Omega = \underbrace{\frac{3\pi}{64}\frac{r}{\lambda}}_{\text{(Poiseulle)}} + \underbrace{\frac{\pi}{4}\frac{2r/\lambda}{(1+2r/\lambda)}}_{\text{(Slip)}} + \underbrace{\frac{1}{1+2r/\lambda}}_{\text{(Knudsen)}} \tag{7}$$

In this equation the value of Ω expresses the total of separate contributions due to Poiseulle's flow, slip flow and Knudsen's flow. The mean free path of a water-vapor molecule λ is given by

$$\lambda = \frac{\kappa T}{\sqrt{2}\pi\sigma_w^{\,2} p} \tag{8}$$

and the Knudsen diffusivity defined in terms of the pore radius and the average molecular velocity as follows:

$$D_k = \frac{2}{3}\bar{v}r \tag{9}$$

$$\bar{v} = \left(\frac{8RT}{\pi M_w} \right)^{\frac{1}{2}} \tag{10}$$

Values of permeability calculated by using the equation (6) were plotted in Figure 9, comparing with those of measured for sliced samples. The theoretical values were found to be more than 10 times greater than those of measured ones. In order to eliminate this difference, a cellular structural model was proposed as shown in Figure 10.

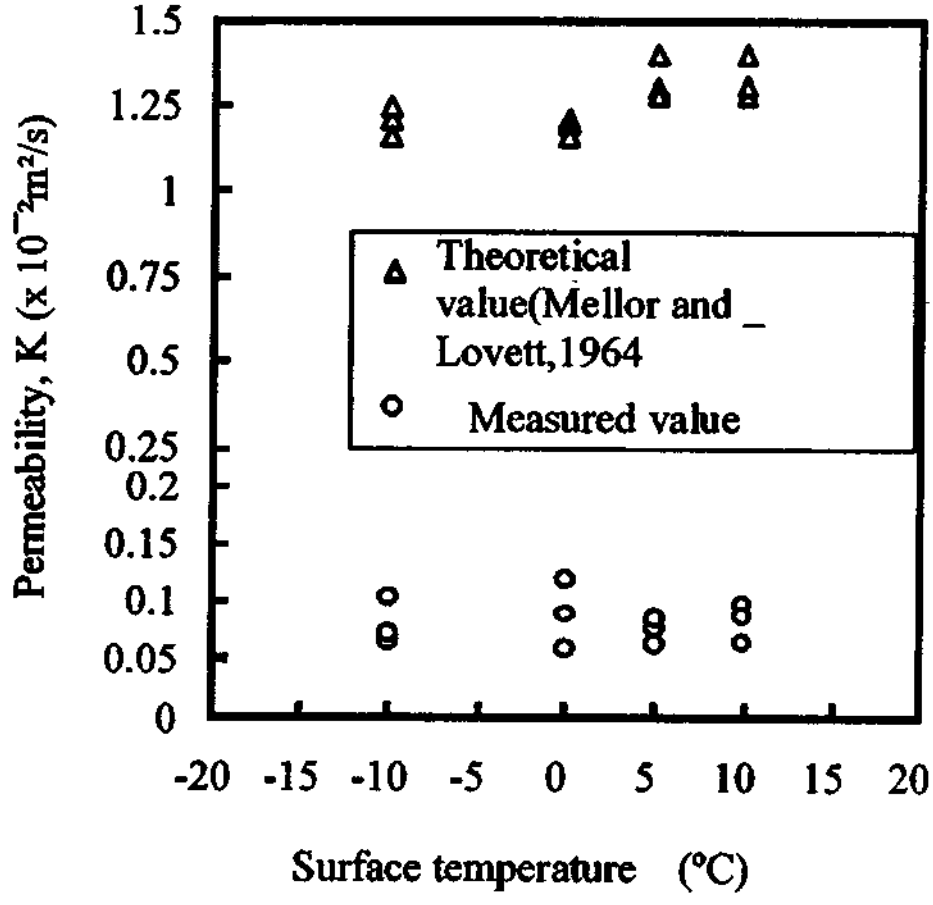

FIGURE 9 Values of permeability calculated by using equation (6) and measured for sliced samples

In the model a cell is assumed to be a cylindrical geometry having an equivalent diameter d_c and l_c in length, respectively. The n layers of the cell are stacked parallel to the direction of water vapor transfer, within the distance X(t) between the surface and sublimation front of the sample. By utilizing the analogy of electrical circuit, the resistance against the water vapor R_n was determined as the

summation of an equivalent resistance R_s of each membrane. And then these two structural parameters were introduced to modify the existing theoretical equation (6) for the single capillary tube.

$$K = \left(\frac{\varepsilon}{\tau} D_k \Omega\right) / R_n \tag{11}$$

$$R_n = (n+1)R_s \; ; \; R_0 = 1 \tag{12}$$

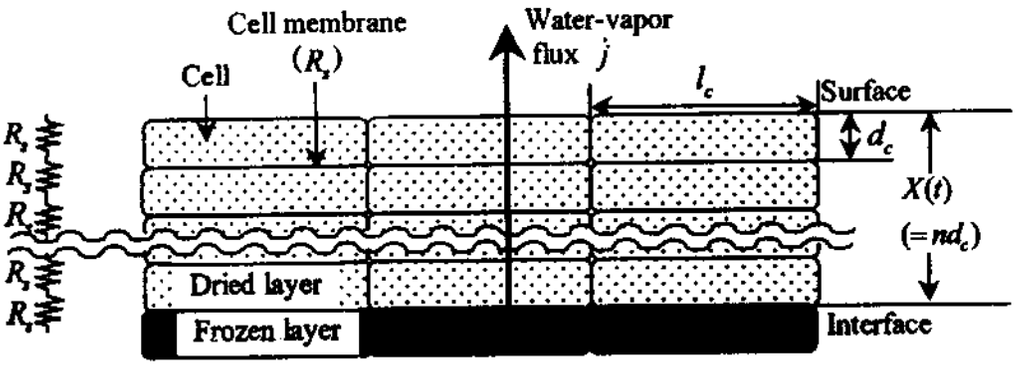

FIGURE 10 Structural model for cellular food materials

In the modified model the tortuosity factor τ was assumed to be unity because of the assumption of cells connected in series, and also the value of Ω can be assumed to be unity under our experimental conditions. The parameters R_n and R_s were calculated for sliced samples. The values of R_n were in the range of 42.5 to 96.2, and those of R_s were 2.9 to 7.3, and the average for them were determined to be 71.4 and 4.41, respectively.

The proposed model can be used to design optimum plant operations, or heating program for the surface of cellular food material whose drying rate is limited by mass transfer rate.

NOTATION

C_p	=	specific heat at constant pressure, J/(kg-K)
D_k	=	Knudsen diffusion coefficient, m^2/s
d	=	diameter, m
H	=	latent heat of sublimation of ice, J/kg
j	=	water-vapor flux, kg/(m^2-s)
K	=	permeability, m^2/s
l	=	thickness of slab, m
$\dot{m}$	=	mass flux density (mass transfer rate), kg/(m^2-s)
m	=	the fraction of water remaining, -

M	=	molecular weight, kg/mol
N	=	1 (in radiant heating upon one surface), -
		4 (in radiant heating upon double surface), -
n	=	number of cells
p	=	pressure, Pa
q	=	heat flux (heat transfer rate), J/(m^2-s)
R	=	gas constant, J/(mol-K)
R_n	=	resistance against the water vapor, -
Rs	=	equivalent resistance of each membrane, -
r	=	equivalent pore radius, m
T	=	absolute temperature, K
t	=	time, s
v	=	average molecular velocity, m/s
$X(t)$	=	position of the sublimation front, -

Greek letters

α	=	constant defined by equation (3)
β	=	constant defined by equation (4)
ε	=	porosity, -
θ	=	temperature, ℃
κ	=	Boltzmann constant
λ	=	thermal conductivity, W/(m-K) (Equation (1))
		mean free path of the gas molecules, m (Equation (5))
ρ	=	density, kg/m^3
σ	=	tortuosity factor, -
Ω	=	total of separate contributions due to Poiseulle's flow, slip flow and Knudsen's flow, -

Subscripts

c	cell	f	sublimation front
s	surface	w	water vapor

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