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Simultaneous Heat and Mass Transfer Analysis During Air Blast Precooling of Fish Packages

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Abstract: Heat and mass transfer analyses are made on exposed food during air blast cooling by using the concept of temperature dependent surface film conductance. An IHCP technique was developed and used to estimate the total surface film conductance of rectangular freshwater fish samples through transient temperature time measurements in one single interior point beneath the surface. Its effective value was found to decrease with diminishing temperature. The variation was regressed to obtain a nonlinear correlation. When this was used to solve the one-dimensional heat conduction equation with heat and mass transfer surface boundary condition equation, a good overall agreement was observed between the computed and the measured temperature variations in comparison with the existing method (Nu-Re-Pr correlation), used earlier. The proposed method simplifies the solution of simultaneous heat and mass transfer problems.

Key words: Effective film conductance, fish, heat transfer, mass transfer

INTRODUCTION

Air blast precooling is a common process in the food industry. The food to be preserved in cold storage is first cooled to the preservation temperature in a separate precooling chamber. This practice reduces the size and capacity of the refrigeration equipment to be used in the warehouse, resulting in economy of its initial and running costs. Some of the foods are precooled after properly packing or canning. Precooling of these packaged foods involves only heat transfer from its surface and mathematical modeling and analysis of such problems is easy. Both classical and numerical solutions of such problems have been reported by many investigators (Pflug *et al*., 1965; Hayakawa, 1972; Baird and Gaffney, 1976; Ansari, 1984; Dincer, 1993). The surface film conductance required to make these solutions are those calculated from the Nu-Re-Pr correlations available in the literature (Ansari, 1984; Chapman, 1984, Dincer, 1998). However, there are practical situations in which unpackaged foods are air-cooled. In such cases, cooling takes place due to convection as well as due to moisture evaporation from the produce surface. Moisture evaporation results in latent cooling, which is quite significant and cannot be neglected. Numerous mathematical models of surface boundary condition equations have been developed and reported by many investigators to account for the cooling effect of moisture evaporation from exposed foods (Ansari, 1984; Dincer and Yildis, 1995). Dincer (1995 and 1998) considered that the latent heat removed from the evaporating surface causes a lowered surface temperature and consequently an incremental factor stands for moisture loss effect must be added to the convective surface film conductance. The surface film conductance values for such cases will be identified as the total surface film conductance, which take care of both heat and moisture transfer effects.

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In the present study, the objective is to develop a new (IHCP) method by which, the total effective surface film conductance values could be calculated rather than using the Nu-Re-Pr cumbersome and non accurate method, for fish packages undergoes simultaneous heat and mass transfer during air blast cooling process.

MATERIALS AND METHODS

The present study was performed by the means of air blast cooling duct at the Food Engineering Lab of Faculty of Food Science and Technology in University Putra Malaysia in 2006.

Experimental and theoretical investigations were carried out on a slab shaped samples of freshwater Malaysian Patin fish. The work was started initially with mass density and water mass fraction (W) measurements of the fish samples whereas the thermal conductivity and specific heat were determined (Abbas *et al.*, 2006) as follows:

$$k = 0.080 + 0.52W \tag{1}$$

$$cp = 1.672 + 2.508W \tag{2}$$

An air-blast cooling duct, shown in Fig. 1, was designed and fabricated for the measurement of surface film conductance of fish sample, which requires temperature–time records inside fish flesh during its transient cooling. The test rig consisted of a 4 m long galvanized iron sheet air duct of 0.33×0.31 m section, which was insulated with 15 mm thick glass wool. The air was cooled through passing it over the cooling coils of a R-22 refrigeration system. The temperature of the circulating air inside the test duct was maintained constant at 1°C. It was controlled through the adjustable pre-

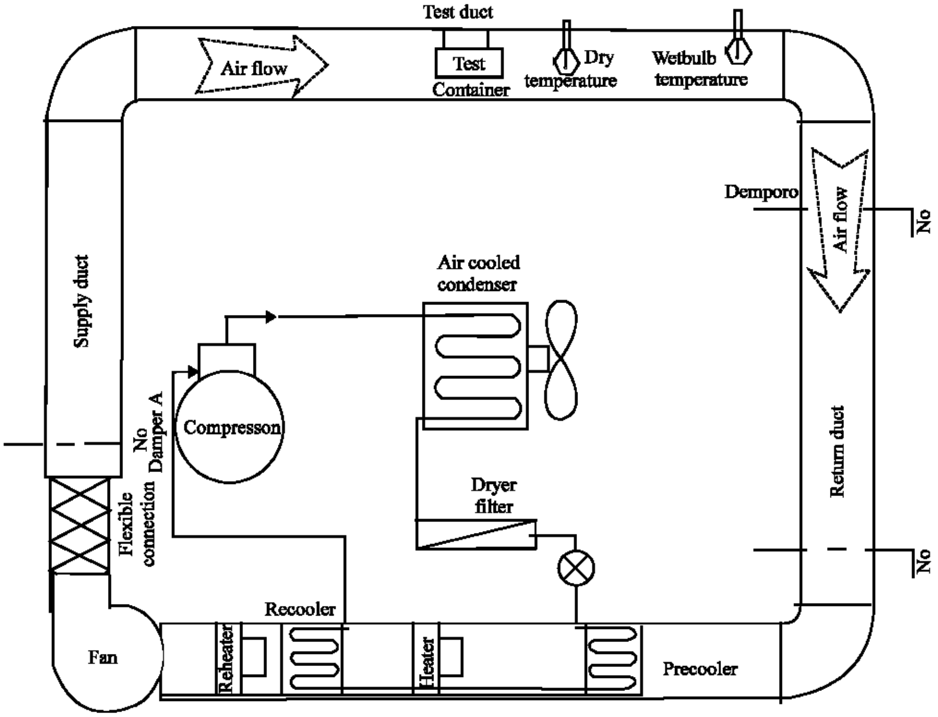

Fig. 1: Schematic diagram of air blast cooling duct

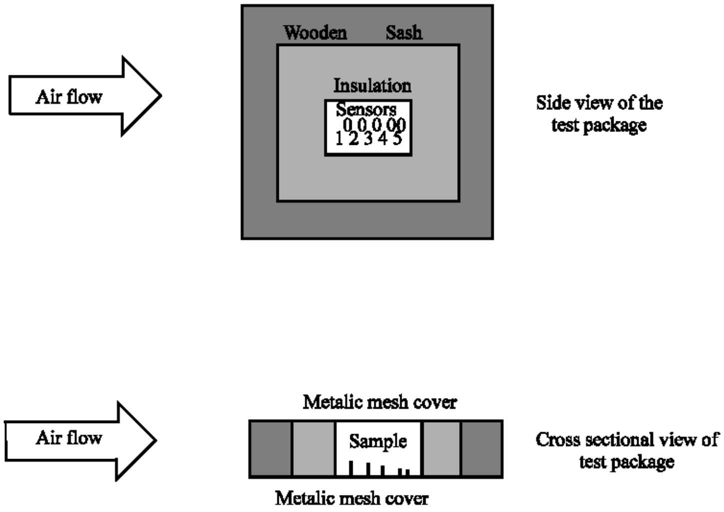

Fig. 2: The test container

heater, heater, defrost-heaters as well as by adjusting the evaporator pressure of the refrigeration system. The dampers A, B and C were provided to control the velocity of air passing over the test container. The velocity of the air was kept constant throughout the experiments at 4.67 m s^{-1}.

The test container of rectangular shape is shown in Fig. 2. It consists of two metallic mesh sheets covers of thickness (0.1 mm) parallel to the direction of the air stream, whereas the remaining faces of the rectangular were thermally insulated to allow symmetrical one-dimensional heat transfer to take place. The main function of the mesh sheets is to support the sample within the test container and to allow moisture evaporation to the air stream. In order to fix the container inside the test duct to perform cooling process, two pairs of insulated hooks were attached to the inside of the upper and lower surfaces of the test section. The test container was fastened to the upper and lower hooks with the help of thin cotton threads to avoid heat conduction. The characteristic length, z_0, of the fish sample is half the thickness of test container (1.27 cm). A copper-constant thermocouples beads were installed inside the fish flesh, at the depths of 0, $z_0/5$, $2z_0/5$, $3z_0/5$, $4z_0/5$ from the sample midpoint. Figure 3 clarifies the used system coordinates and typical cooling front, whereas Fig. 4 indicates the behaviour of the temperature history of the above mentioned depths. In order to make it possible to insert the temperature sensor at the desired depth. A fine hole was drilled at the middle of one of the metallic mesh faces of the test container. The temperature inside the fish flesh and the dry bulb and wet bulb temperatures of the circulating air were measured with the help of copper-constant thermocouples. The lead wires of all the thermocouples were connected to a data logger to obtain the temperature measurements at a specified equal time interval, which was maintained at 1 min while time of the experiment was 30 min (7-8 cooling time).

Initially, the refrigeration system of the chilling duct was run until a constant temperature of 1°C was achieved. Then the fish package was suspended in the test section of the air duct such that the mesh sides were parallel to the direction of flow of chilled air stream and the data logger was activated to record time temperature data to be used for the estimation of the surface film conductance.

The convective h estimated by the commonly used Nu-Re correlations, do not include the effects of any such phenomena other than that of convection heat transfer. These correlations are taken from the literature and are written in the following generalized form (Chapman, 1984):

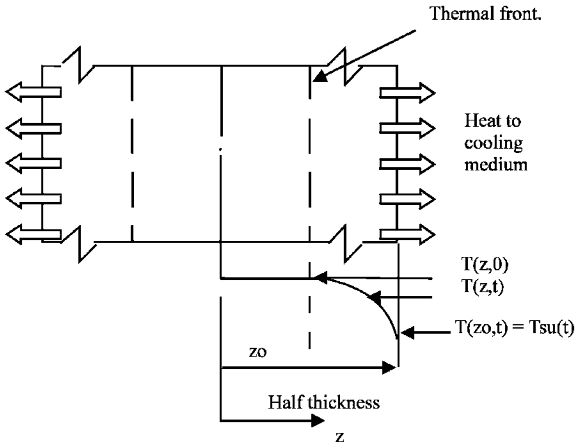

Fig. 3: The coordinate system during precooling

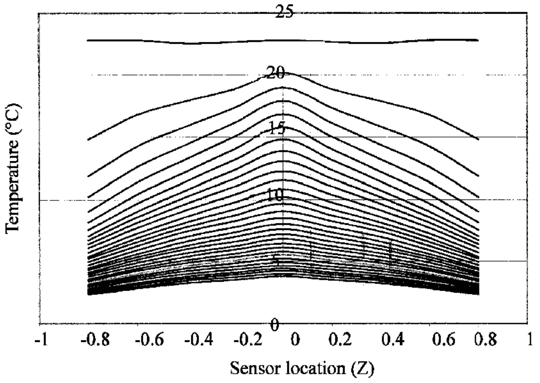

Fig. 4: Temperature- history of the sample

$$\mathrm{Nu} = 0.664\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.333} \tag{3}$$

This equation requires the velocity of the air stream which was measured by an anemometer and the thermophysical properties of air which, were read from the literature (Dincer, 1998) at the mean produce temperature but for accurate calculation those properties should be evaluated at the surface film temperature (the average of the surface and cooling air temperatures). Therefore, the accurate calculation of convective h dictates the instantaneous surface temperature, which in turn will complicate the calculation procedure. The effect of the moisture loss on the convection surface film conductance is defined as follows:

$$h_{me} = h_c\left[\frac{h_{fg}(W_i - W_f)}{cp(T_i - T_f)}\right] \tag{4}$$

Therefore, the total effective surface film conductance should be given in the following form:

$$h_e = h_c + h_{me} \tag{5}$$

Inverse Heat Conduction Problem Formulation

Estimation of temperature at any position and time from transient heat conduction differential equation with prescribed boundary and initial conditions is known as the direct method. While determination of the boundary conditions, initial condition or thermal properties from transient temperature measurements is known as an inverse heat conduction problem (IHCP). There are several pioneer algorithms proposed for the solution of the IHCP including, the exact matching algorithm (Stolz, 1960) the function specification algorithm (Beck, 1962, 1968, 1970) and the regularization algorithm (Tikhonov and Arsenin, 1977). In this research the function specification algorithm will be used to solve for the surface heat flux.

For isotropic slab shaped fish samples, with constant thermal properties, initially at uniform temperature and exposed suddenly to symmetric cooling on both sides, the governing heat conduction equation with heat and mass transfer, center boundary condition and surface boundary condition are given by the following system of Eq. 6-11.

$$\rho cp\frac{\partial T}{\partial t}=k\frac{\partial^2 T}{\partial .z^2}+h_{fg}\frac{\partial W}{\partial t} \tag{6}$$

It has been found experimentally that;

$$h_{fg}\frac{\partial W}{\partial t}<<k\frac{\partial^2 T}{\partial z^2}$$

accordingly Eq. 6 will be diminished to;

$$\rho cp\frac{\partial T}{\partial t}=k\frac{\partial^2 T}{\partial .z^2} \tag{7}$$

with initial and boundary conditions:

$$\text{at } t=0\ T(z,0)=To \tag{8}$$

$$\text{at } z=0 \qquad \text{and } t>0 \qquad \text{then } \frac{\partial T}{\partial z}=0 \text{ (center of the slab sample)} \tag{9}$$

$$\text{at } z=zo \qquad \text{and } t>0 \qquad \text{then } -k\frac{\partial T}{\partial z}+\frac{h_{fg}}{A}\frac{\partial W}{\partial t}=q(m) \tag{10}$$

Since

$$-k\frac{\partial T}{\partial z}>>\frac{h_{fg}}{A}\frac{\partial W}{\partial t}$$

(experimentally) the above equation diminishes to;

$$-k\frac{\partial T}{\partial z}=q(m) \qquad \text{(heat tranfer suface)} \tag{11}$$

Estimation of the surface heat flux q_m can be obtained from minimization of the following sum of squares function:

$$S_m = \sum_{i=1}^{r} (Y_{m+i-1} - T_{m+i-1})^2 \tag{12}$$

Where, m is index for discrete time. The estimation of q_m involves temperature measurements at time t_m, t_{m+i}.....t_{m+r-i}, the heat flux at $t < t_{m-i}$ is assumed to be known. The heat flux for time t_m to t_{m+r-i} can assume different functional form such as constant, linear, cubic, parabolic or other form. Based on a temporary assumption of constant heat flux for time t_m to t_{m+r-i} Beck *et al.* (1996) minimized Eq. 12 with respect to q_m and used Taylor series expansion and developed the following algorithm for calculating heat flux.

$$q_m = q_{m-1} + \frac{\sum_{i=1}^{r} (Y_{m+i-1} - T_{m+i-1}) X_{m+i-1,m}}{\sum_{i=1}^{r} X_{m+i-1,m}^2} \tag{13}$$

Where X_{m+i-1} is the sensitivity coefficient defined by

$$X_{m+i-1} = \frac{\partial T_{m+i-1,m}}{\partial q_m} \tag{14}$$

From the governing heat conduction equation and the prescribed boundary conditions the following are the equations for the sensitivity coefficients.

$$\rho c \frac{\partial X}{\partial t} = k \frac{\partial^2 X}{\partial z^2} \tag{15}$$

With initial and boundary conditions:

$$\text{at} \quad t = 0 \qquad X(z,0) = 0 \tag{16}$$

$$\text{at} \quad z = 0 \quad \text{and} \quad t > 0 \qquad \frac{\partial X}{\partial z} = 0 \tag{17}$$

$$\text{at} \quad z = L \quad \text{and} \quad t > 0 \qquad \frac{\partial X}{\partial z} = 1 \tag{18}$$

the following equation was used to estimate the surface film conductance at discrete time step:

$$h_m = \frac{q_m}{T_{cm} - ((Y_m + Y_{m-1})/2)} \tag{19}$$

COMPUTER PROGRAM

A FORTRAN computer program was written to solve numerically Eq. 6-11 and 15-18 based on Crank-Nicholson implicit finite difference discretization. Equation 13 is also incorporated into the program for calculating the heat flux sequentially in time. The program can handle different values of r. However, r =3 is found to be adequate based on a preliminary runs at different r-values. The numbers of nodes used were 50 and the time increment is 1 sec.

RESULTS AND DISCUSSION

The calculations of the present research were aiming to estimate the total effective surface film conductance via, the common Re-Nu correlation and the IHCP methods. The properties of fish samples essential to perform heat and mass transfer analyses were Measured and listed already in Table 1. These thermophysical properties were used to make thorough heat and mass transfer analyses on *Patin* freshwater fish samples.

The temperature-time records have been used every time step to estimate the surface temperature. The values of the recorded temperatures (To, T1, T2, T3, T4) along with the corresponding sensors locations Z (0,0.2,0.4,0.6,0.8) have been regressed each time step to choose a suitable model, which yields a reasonable surface temperature. It has been found that the reciprocal quadratic model fitted all the curves of Fig. 5 satisfactorily.

$$T_{\text{surface}} = \frac{1}{a + bZ + cZ^2} \tag{20}$$

The temperature-time records along with the above equation have been used every time step to extrapolate the surface temperature by substituting Z = 1 in the above equation (Fig. 5). Once the surface temperature has been estimated, Eq. 3 was tried along with the relevant air properties to calculate the convective surface film coefficient which was almost stable of 73.78 (w/m^2.c).

Table 1 information along with initial and known boundary condition was used as an input to the developed computer program so as to calculate the heat flux in sequential manner at each time (m). Once the heat flux at the heat transfer surface side is known the problem became a direct problem, the same computer program then calculates the temperature at any position including at the sensor

Table 1: Thermophysical properties of a slab shaped fish sample

Parameters	Notation	Units	Numerical value
Specific heat capacity	C	KJ.kg^{-1}.k^{-1}	3.75365
Flesh water content	W	%	0.82
Thermal conductivity	k	W.m^{-1}. °C^{-1}	0.5296
Thermal diffusivity	α	mm^2.sec^{-1}	0.1337
Mass density	ρ	Kg.m^{-3}	1052

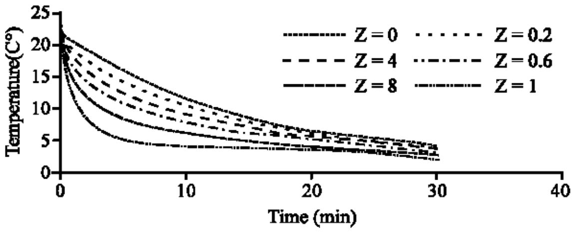

Fig. 5: Temperature history during one experiment

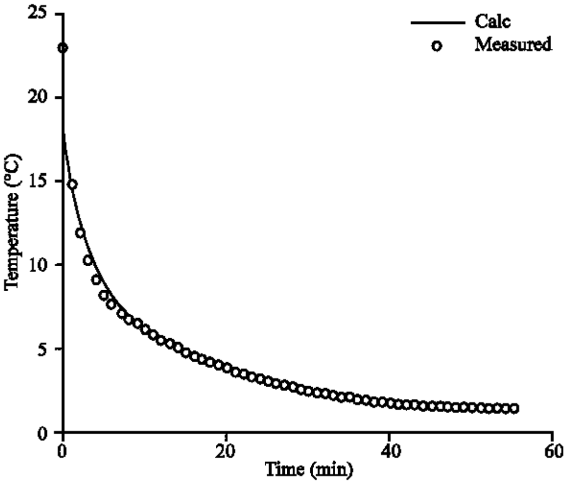

Fig. 6: Validity of IHCP Method

location. The accuracy of the calculated heat flux was checked by comparing the calculated temperature at the sensor position with the measured value, using the root mean squares of the error (RMS) defined by:

$$\mathrm{RMS} = \left[\sum_{i=1}^{N} \left(\frac{Y_i - T_i}{N} \right)^2 \right]^{0.5} \tag{21}$$

The above equation resulted in a value of RMS of 0.23°C, for the range of precooling Fo> 0.2 (i.e., 4 min) until reaching the seven-eights cooling time. The incorporated error is within the allowable error encountered during temperature measurements by thermocouples indicating the accuracy of the calculated heat flux. Figure 6 shows comparison between the calculated temperature from the estimated heat flux and the measured temperature at the sensor position. It is clear that there is an excellent agreement between these two temperature histories indicating the reliability of the approach and the accuracy of the calculated heat flux. Beck *et al.* (1966) investigated different types of function form for heat flux including cubic, parabolic, linear and constant for the function specification method and found that the constant heat flux form resulted in excellent and efficient estimation of the heat flux compared to the experimental heat flux data and the other functional form.

Another visual FORTRAN program was written to solve, Eq. 7-9 and 11 by an optimized explicit finite difference scheme (Abbas *et al.*, 2004). The program was written in such away to predict the temperature histories and compare them with the corresponding experimental histories for the sensors positions 0, zo/5, 2zo/5, 3zo/5, 4zo/5; as well as delivering the standard error between those histories correspondingly.

The requisite values of the total surface film conductance to run the program were calculated by two different methods. The first method was that using Eq. 3-5 which yielded h_{total} = 73.78+28.47. The second method was based on based on IHCP technique using the temperature history of one interior single point possibly nearer to the surface (zo/5 from the surface). This method resulted in nonlinear model during the duration of experimentation presented in Fig. 7. The following Hoerl Model WithStandard Error of 8.9350329 and Correlation Coefficient of 0.9841209 shows reasonable behavior of h.

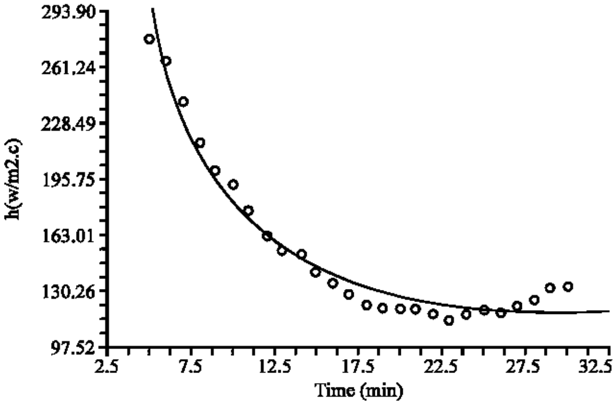

Fig. 7: The variation of IHCP predicted surface film conductance during time of experimentation

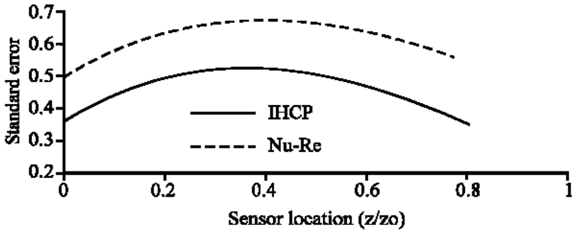

Fig. 8: Inherent error distribution along z

$$h = \frac{1131.99(1.03)^{t}}{t^{0.925}} \qquad (22)$$

The stability, accuracy and simplicity were considered the comparative criteria to investigate the pros and cons of the both used methods. The correlation (Nu-Re-Pr) method always results in quite stable value of h, whereas the IHCP one behaves alike provided that the sensor position as near to the surface as more stability will be resulted in. The standard error concept was utilized to investigate the accuracy. Figure 8 shows the inherent error with the sensor locations. The predicted temperature history that included minimum error is for point of Z = 0 for the Nu-Re-Pr correlation method and point nearest to the surface (of Z = 0.8) for IHCP method, whereas The predicted temperature history that included maximum error is for point at the middle distance between the center and the surface for both methods. In terms of mean inherent error, the IHCP and Correlation methods yielded 0.43 and 0.59, respectively.

From the view point of simplicity; The air properties should be evaluated at the film temperature in performing the correlation method; accordingly at least three sensors locations normal to the surface should be needed to extrapolate the surface temperature, whereas the IHCP method dictates only one sensor location. The concerned calculations will be much more cumbersome and time consuming with the correlation method specially in predicting the surface temperature each time step of record during the experimentations and finding the others air properties. Equation 4 revealed that the correlation method dictates information about the sample during the experimental time weight reduction, whereas that tedious task will not be encountered in the IHCP method.

CONCLUSIONS

The surface film conductance estimation of exposed infinite slabs of Patin fish samples undergoing simultaneous heat and mass transfer during air blast cooling could reliably be done by either using the Nu-Re-Pr correlation or the IHCP method.

The IHCP technique was used successfully to estimate surface film conductance value as an alternative effective method to replace the cumbersome common method Nu-Re correlation that is widely used in food cooling applications. The calculations resulted in a mean value of h_{total} of 102.25 on using the correlation method whereas the IHCP method delivered an effective variable $h_{total,}$ which was strongly function of sample temperature Eq. 22. Both of the values were used to solve numerically the one-dimensional transient heat conduction equation with heat and mass transfer surface boundary condition equation. A superiority of the proposed IHCP method has been observed in comparison with the Nu-Re-Pr in terms of simplicities, stability and accuracy. The study may serve as a good tool for the design and maintenance engineers of heat and mass transfer equipment used in the food processing industry.

Nomenclature

cp = Specific heat of produce (J kg^{-1}. k^{-1})
h = Surface film conductance (W m^{-1}. k^{-1})
k = Produce thermal conductivity (W m^{-1}. k^{-1})
Nu- Nusselt number (hzo/k_{air})
Pr- = Prandtle number (γ/α)
Re = Reynolds number (vzo/γ)
T = Temperature (°C)
t = Time (s)
W = Water content (%)
Z = Relative distance from the midpoint (z/zo)
Greek letters
α = Thermal diffusivity of product (m^2/s)
γ = Kinematic viscosity of air at mean temperature (m^2/s)
Subscripts and superscripts
cm = Cooling medium
i = Initial
f = Final
me = Moisture effect
fg = Latent heat

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