American Journal of Food Technology 2 (4): 281-287, 2007
ISSN 1557-4571

An Inverse Estimation Method for Surface Film Conductance During Cooling of Fish Packages

[1]K.A. Abbas and [2]Ibrahim O. Mohamed
[1]Department of Food Technology, Faculty of Food Science and Technology,
University Putra Malaysia, Malaysia
[2]Department of Food Sciences, College of Food System,
United Arab Emirates University, UAE

Abstract: A temperature history detected by measuring sensor, along with other relevant system's parameters have been used to predict the surface film conductance through transient temperature measurements in fish flesh samples during their cooling in a chilled air duct at a constant temperature of 1°C. The Inverse Heat Conduction Problem (IHCP) solution was performed by using the sequential function specification method to estimate heat flux, which was then utilized to solve the direct problem for the temperature distribution at any position including at the sensor position on the fish sample using Crank-Nicolson implicit finite difference scheme. The predicted and measured temperature distribution profiles were compared numerically, yielding good agreement indicating the accuracy of the present approach in calculating surface film conductance.

Key words: Cooling, fish, surface film conductance, IHCP

INTRODUCTION

In many food processing applications, including cooling and freezing, transient heat transfer occurs between the cooling medium and the solid item. In such circumstances, surface film conductance values are predicted usually by the appropriate Nusselt-Reynold's-Prandtle correlation (Becker and Fricke, 2004; Abbas *et al*., 2006).

Based on experimental and theoretical studies, researchers (Hafiz and Ansari, 2000; Ansari *et al*., 2003, 2004) reported that, these values of surface film conductance are found to give poor results and the actual values are higher than those predicted from the Nusselt -Reynold's-Prandtle correlation.

A critical look to those literatures indicates that still there is a need to develop a new approach (Fricke and Becker, 2002), which yields an accurate surface film conductance during precooling process, which may be of great importance for designers of cold storage; refrigerators and heat transfer equipments in food industry.

MATERIALS AND METHODS

The present research 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. As 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:

Corresponding Author: K.A. Abbas, Department of Food Technology, Faculty of Food Science and Technology, University Putra Malaysia, Malaysia Tel: (+603-8946-8534)

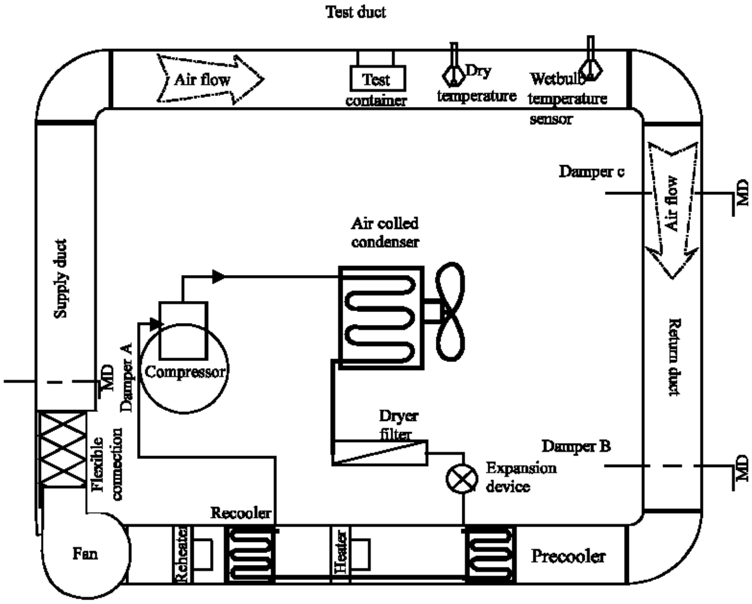

Fig. 1: Schematic diagram of air blast cooling duct

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

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

The 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. This plant as well as the experimental procedure had been reported and detailed earlier in literature in a similar work (Abbas *et al.*, 2006). The temperature of the circulating air inside the test duct was maintained constant at 1°C and the velocity of the air was kept constant throughout the experiments at 6 m $\sec^{-1}$.

The test container of rectangular shape which is shown in Fig. 2, was designed to allow symmetrical one-dimensional heat transfer to take place within the samples and to avoid any moisture evaporation to the air stream. The characteristic length, z_0, of the fish sample is half the thickness of test container (1.2 in. or 1.27 cm). A copper-constantan thermocouple bead (sensor) was installed inside the fish flesh, at the depth of $z_0/5$ from the sample surface. The thermocouple was 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 (Seven-eights 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 conducting surfaces 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.

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

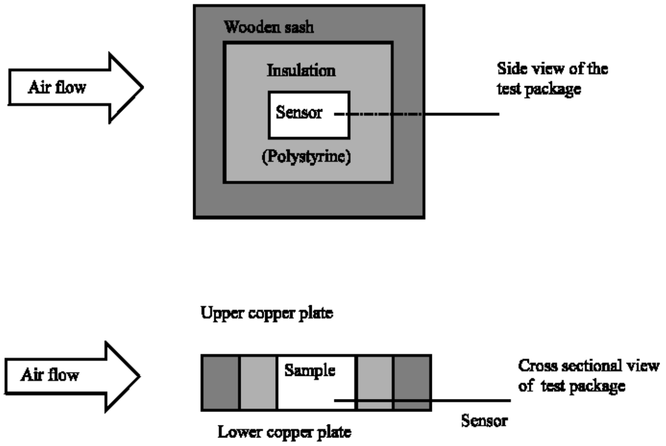

Fig. 2: Test container details

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, center boundary condition and surface boundary condition are given by the following system of Eq. 3-6.

$$\rho c\frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial z^2} \tag{3}$$

with initial and boundary conditions:

at $t = 0$ $T(z, 0) = To$ (4)

at $z = 0$ and $t > 0$ then $\frac{\partial T}{\partial z} = 0$ (center of the slab sample) (5)

at $z = zo$ and $t > 0$ then $-k\frac{\partial T}{\partial z} = q(t)$ (heat transfer surface) (6)

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

$$S_m = \sum_{i=1}^{r} (Y_{m+i-1} - T_{m+i-1})^2 \tag{7}$$

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. 7 with respect to q_m and used Taylor series expansion and developed the following algorithm for calculating heat flux.

$$q_m = q_{m-1} + \frac{\sum\limits_{i=1}^{r} (Y_{m+i-1} - T_{m+i-1}) X_{m+i-1,m}}{\sum\limits_{i=1}^{r} X^2_{m+i-1,m}} \tag{8}$$

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

$$X_{m+i-1} = \frac{\partial T_{m+i-1,m}}{\partial q_m} \tag{9}$$

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

$$\rho c \frac{\partial X}{\partial t} = k \frac{\partial^2 X}{\partial z^2} \tag{10}$$

With initial and boundary conditions:

$$\text{at } t = 0 \qquad X(z,0) = 0 \tag{11}$$

$$\text{at } z = 0 \quad \text{and } t > 0 \qquad \frac{\partial X}{\partial z} = 0 \tag{12}$$

$$\text{at } z = L \quad \text{and } t > 0 \qquad \frac{\partial X}{\partial z} = 1 \tag{13}$$

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

$$h_m = \frac{q_m}{T_{cm} - ((Y_m + Y_{m-1})/2)} \tag{14}$$

Computer Program

A FORTRAN computer program was written to solve numerically Eq. 3-6 and Eq. 10-13 based on Crank-Nicholson implicit finite difference discretization. Equation 8 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

Table 1 shows the measured and calculated thermo physical properties of the fish sample.

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

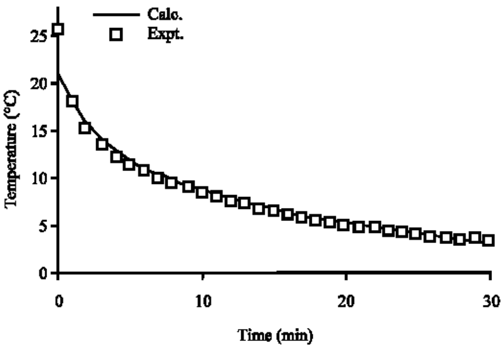

Fig. 3: Experimental and calculated temperature history at the sensor position

The above information along with initial and known boundary condition were 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 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:

$$\mathrm{RMS} = \left[\sum_{i=1}^{N} \left(\frac{Y_i - T_i}{N} \right)^2 \right]^{0.5} \tag{15}$$

The above equation resulted in a value of RMS of 0.2°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 3 shows comparison between the calculated temperature from the estimated heat flux and the measured temperature at the sensor position.

Ansari *et al*. (2003, 2004) developed plots similar to that shown in Fig. 3 and they reported that, the better coincidence between the calculated and the measured temperature histories, the more accurate approach is. Based on above it is clear that the excellent agreement between these two temperature histories in the present study, indicating the reliability, accuracy and superiority of the author approach among the existing ones. Beck *et al*. (1996) 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.

Figure 4 shows that the calculated surface film conductance values which decrease gradually with time in a non-linear fashion, which was fitted to several nonlinear model using least square method, the following model yielded the best fit with the minimum standard error of 2.16 and maximum $R^2 = 0.99$

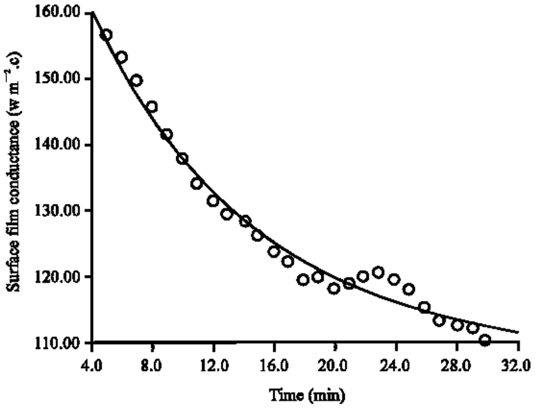

Fig. 4: Surface film conductance versus time curve

$$h = \frac{2.887 + 179.2t^{-1.517}}{0.03224 + t^{-1.517}} \tag{16}$$

It is notable to mention that t in the above equation must be expressed in minutes and it's valid for the period of the present study. The value of surface film conductance determined by the proposed method revealed good agreement between the measured results and the predicted ones.

CONCLUSIONS

With known thermo-physical properties, transient temperature-measurement records at a location of 0.254 cm from the tested sample surface, the boundary heat flux has been estimated through the IHCP technique. The predicted variable values of the heat flux along with the others system parameters were used to find out sequentially the surface film conductance at each time step during the experimental period by applying the finite different technique. A correlation model for surface versus time was developed. This relationship can be used along with the finite difference technique to predict temperature variation at any location in the food flesh.

Nomenclature

c	specific heat of fish (J kg^{-1}. K)
h	surface film conductance (W m^{-2}. K)
k	thermal conductivity (W m^{-1}. K)
N	Number of measurements
q	heat flux at the surface boundary, (w m^{-2})
r	number of future temperature measurements
T	temperature (°C)
t	time (s)
W	water content, % (on wet mass basis)
Y	measured temperature (°C)
z	distance from the centre (m)
z_0	half thickness of the sample (m)

Subscripts and Superscripts

cm	cooling medium
m	discrete time index
o	initial

REFERENCES

Abbas, K.A., M.M.H.M. Megat, S.M. Sapuan, M.A. wan, B. Jamilah and I. Dincer, 2006. Numerical analysis of heat transfer in cooling of fish packages. Int. Commun. Heat Mass Transfer, 33: 889-897.

Ansari, F.A., M.A. Wan and K.A. Abbas, 2003. An improved scheme for temperature calculations in food. J. Energy Conv. Manage., 44: 2373-2382.

Ansari, F.A., K.A. Abbas and S.M. Sapuan, 2004. Estimation of surface film conductance during cooling of fish packages. J. Process Mechanical Eng., 218: 1-6.

Beck, J.V., 1962. Calculation of surface heat flux from an internal temperature history. ASME paper 62-HT-46.

Beck, J.V., 1968. Surface heat flux determination using an integral method. Nucl. Eng. Des., 7: 170-178.

Beck, J.V., 1970. Nonlinear estimation applied to the nonlinear heat conduction problem. Int. J. Heat Mass Transfer, 13: 703-716.

Beck, J.V., B. Blackwell and A. Haji-Sheikh, 1996. Comparison of some inverse heat conduction methods using experimental data. Int. J. Heat Mass Transfer, 39: 3649-3657.

Becker, B.R. and B.A. Fricke, 2004. Heat transfer coefficients for forced air cooling and freezing of selected foods. Int. J. Refrigeration, 27: 540-551.

Fricke, B.A. and B.R. Becker, 2002. Calculation of heat transfer coefficients for foods. Int. Commun. Heat Mass Transfer, 29: 731-740.

Hafiz, A. and F.A. Ansari, 2000. Effect of thermally induced convection currents on the thermal behaviour of cooled liquids. Proceeding of the 4th ISHMT-ASME Conference, pp: 897-902.

Stolz, G., 1960. Numerical solution to an inverse problem on heat conduction for simple shapes. J. Heat Transfer, 82: 20-26.

Tikhonov, A.N. and V.Y. Arsenin, 1977. Solution of Ill-Posed Problems. Winston, V.H. and Sons, Washington, D.C.