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Estimation method for determining surface film conductance during cooling of fish packages

Ibrahim Omer Mohamed* and Kassim Ali Abass,†**

*Faculty of Engineering, University Putra Malaysia,
**Faculty of Food Science and Technology, University Putra Malaysia, 43400, Serdang, Malaysia
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Abstract−This paper presents an alternative method for determining the surface film conductance of an infinite fish slab subjected to the cooling process. Many methods have been published, but their solutions have inherent appreciable inaccuracy and limitations. The present authors used the temperature histories of five locations within a slab sample of fish, obtained by the experimental investigation part of this work, along with the *inverse heat conduction problem* (IHCP) technique to develop a correlation for variable surface film conductance. When the above correlation was used for temperature predictions, the predicted and experimentally measured temperature distribution profiles were compared numerically. Better agreement than that implemented by other investigators was achieved. This revealed the accuracy and superiority of the present method, and the limitations of other methods are overcome in this method.

Key words: Cooling, Fish, Surface Film Conductance, IHCP

INTRODUCTION

Knowledge of surface film conductance during heating and cooling processes is essential for heating and cooling equipment design [1,2]. For most of the industrial heat transfer analysis, surface film conductance values are predicted by the appropriate Nu-Re correlation [3]. This often results in poor prediction of temperature in foods because most foods have high water content. The temperature gradient within food samples such as fresh vegetables and fruits or meat and fish during pre-cooling process stimulates internal rearrangement of water molecules that makes the actual values of surface film conductance higher than that predicted from the Nu-Re correlation [4]. Ansari and co-workers [2,5] investigated the surface film conductance of infinite slabs of Patin packages during the pre-cooling process. They showed the superiority of their methods compared with others through the better agreement between the predicted and the measured temperature profiles at the sensors locations.

A critical look at those temperature profiles coincidence indicates that still there is a need to develop a new method that yields better agreement between the experimental and calculated temperature profiles. Therefore, the aim of this work is to present a new and more accurate method for estimating surface film conductance during cooling of food packages and to compare it with some earlier published work.

MATERIAL AND METHODS

Experimental and theoretical investigations were carried out on slab shaped samples of freshwater Malaysian Patin fish. The work started initially with measurement of mass density, thermal conductivity and specific heat of the fish samples, which were elaborated earlier by the author in a previous work [6].

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 meter long galvanized iron sheet air duct of 0.33 m×0.31 m section, which was insulated with 15 mm thick glass wool. The air was cooled by passing it over the cooling coils of an 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 preheater, 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 6 ms^{-1}.

The test container was designed in a form of rectangular block (made from polystyrene foam) with dimensions of 2.54×22.5×22.5 cm depth, length and width, respectively. The two major surfaces (22.5×22.5 cm) were covered by copper sheets of 0.1 mm thickness. The four remaining minor surfaces (2.54×22.5 cm) were surrounded by wooden sash to support that block. A central cavity of dimensions 2.54×2.54×5.08 cm was implemented in the middle of that block to accommodate the fish sample. Fig. 2 reveals that the fish sample within the test container is surrounded by four insulated peripheral walls, whereas the remaining opposite surfaces were in touch with the two copper covers to allow symmetrical one-dimensional heat transfer to take place. To fix the container inside the test duct, a pair of insulated hooks was attached to the inside of the upper surface of the test section. The test container was fastened to the upper hooks with the help of thin cotton threads to avoid heat conduction. The characteristic length, z_0, of the fish sample was half the thickness of test container (1.27 cm). Five copper-constantan thermocouples beads were installed inside the fish flesh, at

†To whom correspondence should be addressed.
E-mail: Ali_kassim@hotmail.com

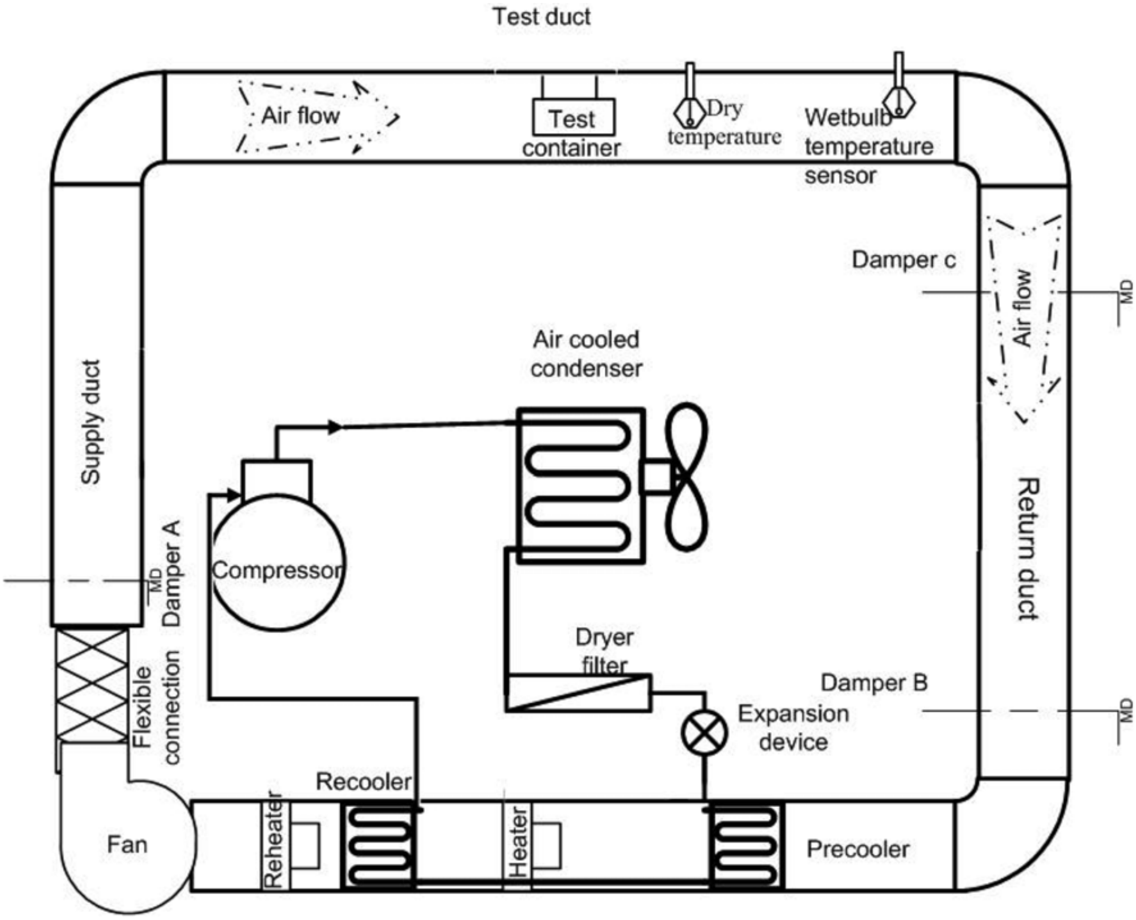

Fig. 1. Schematic diagram of air blast cooling duct.

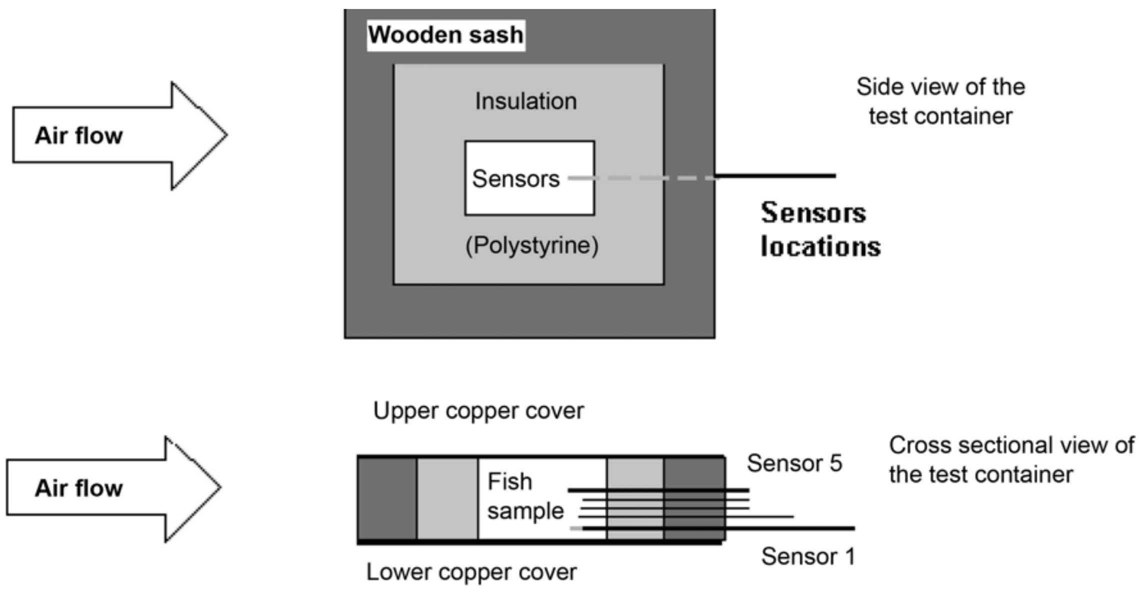

Fig. 2. Test container details.

the depths of $z_0/5$, $2z_0/5$, $3z_0/5$, $4z_0/5$ and z_0 from the sample surface (copper cover).

To insert the temperature sensors at the desired depths, five fine holes were drilled at a distance of $4z_o/5$ mm from each other at the middle of one side of the minor surface of the test container. The temperatures inside the fish flesh and the dry bulb and wet bulb temperatures of the circulating air were measured with the type T copper-constantan thermocouples. The lead wires of the two thermocouples were connected with a data logger. The temperatures were recorded at a specified equal time interval of 1 minute while each experiment lasted for 60 minutes. Initially, the refrigeration system of the chilling duct was run until a constant temperature of 1 °C was achieved. Then the test container was suspended in the test section of the air duct such that the conducting surfaces (copper covers) were parallel to the direction of flow of chilled air stream. The data logger was used to collect the transient temperature-time data.

1. Numerical Temperature Computation

Estimation of temperature at any position and time from transient heat conduction differential equation with prescribed thermal properties, boundary and initial conditions is known as the direct method. On the other hand, determination of the boundary conditions, initial condition or thermal properties from transient temperature measurements is known as an inverse heat conduction problem (IHCP) as many investigators have used this method to estimate boundary conditions in different types of heat transfer problems [7-13].

Slab-shaped fish samples, initially at uniform temperature and exposed suddenly to symmetric cooling on both sides, are as shown schematically in Fig. 3.

The governing heat conduction equation, center boundary condition and surface boundary condition could be described by the following system of Eqs. (1 to 4).

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial z^2} \quad (1)$$

with initial and boundary conditions:

at t=0 $\quad T(z, 0)=To \quad (2)$

at z=0 $\quad$ and t>0 then $\frac{\partial T}{\partial z} = 0$ (center of the slab sample) $\quad (3)$

at $z=z_o$ $\quad$ and t>0 then $-k\frac{\partial T}{\partial z} = q_m$ (surface boundary condition) $\quad (4)$

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

$$S_m = \sum_{i=1}^{r} (Y_{m+i-1} - T_{m+i-1})^2 \quad (5)$$

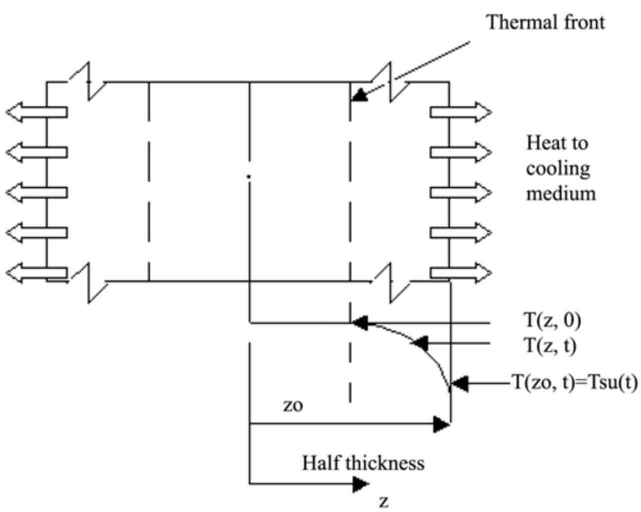

Fig. 3. The coordinate system during pre-cooling.

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 a 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. [12] minimized Eq. (5) with respect to q_m and used Taylor series expansion and developed the following algorithm for calculating heat flux.

$$q_m = q_{m-1} + \frac{\sum_{i=1}^{r} (Y_{m+i-1} - T_{m+i-1}) X_{m+i-1,m}}{\sum_{i=1}^{r} X^2_{m+i-1,m}} \quad (6)$$

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

$$X_{m+i-1} = \frac{\partial T_{m+i-1,m}}{\partial q_m} \quad (7)$$

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

$$\rho c \frac{\partial X}{\partial t} = k \frac{\partial^2 X}{\partial z^2} \quad (8)$$

With initial and boundary conditions:

at t=0 $\quad X(z, 0)=0 \quad (9)$

at z=0 and t>0 $\quad \frac{\partial X}{\partial z} = 0 \quad (10)$

at $z=z_o$ and t>0 $\quad -\frac{\partial X}{\partial z} = 1 \quad (11)$

The following equation was used to estimate the convective heat transfer coefficient at discrete time step:

$$h_m = \frac{q_m}{T_{cm} - ((T_{si} + T_{s(i-1)})/2)} \quad (12)$$

2. Computer Program

A FORTRAN computer program developed by the authors, which was used earlier in a similar work [13], has been used. This program was modified to solve numerically Eqs. (1)-(4) and Eqs. (8)-(11) based on Crank-Nicolson implicit finite difference discrimination. Eq. (6) was also incorporated into the program for calculation the heat flux sequentially in time. The program can handle different values of r. However, r=3, was found to be adequate based on a preliminary runs at different r values. The numbers of nodes used were 50 and the time increment was 1 second. After the surface temperature and the heat flux were calculated sequentially, the surface film conductance could be calculated by using Eq. (12).

RESULT AND DISCUSSION

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

The above information, along with initial and known boundary condition, was used as input to the computer program to calculate the heat flux in sequential manner at each time (m). Once the heat flux at the heat transfer surface side was known, the problem became

Table 1. Thermophysical properties of a slab shaped fish sample

Parameter	Notation	Units	Numerical value
Specific heat capacity	C	$KJkg^{-1}K^{-1}$	3.75365
Flesh water content	W	%	0.82
Thermal conductivity	k	$Wm^{-1}\,^{o}C^{-1}$	0.5296
Thermal diffusivity	α	mm^2sec^{-1}	0.1337
Mass density	ρ	kgm^{-3}	1052

a direct problem. The same computer program then calculated the temperature at any position including 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:

$$\mathrm{RMS}=\left[\frac{1}{\mathrm{N}}\sum_{i=1}^{N}(\mathrm{Y}_i-\mathrm{T}_i)^2\right]^{0.5} \tag{13}$$

The above equation resulted in a value of RMS of 0.2 ºC, for the range of pre-cooling Fo>0.2 (i.e., >4 minutes) 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. Fig. 4 shows comparison of the calculated temperature from the estimated heat flux with the measured temperature at $4z/z_o$ for seven-eighths of the cooling time. It is clear that there is an excellent agreement with these two temperature histories, indicating the reliability of the approach and the accuracy of the calculated heat flux.

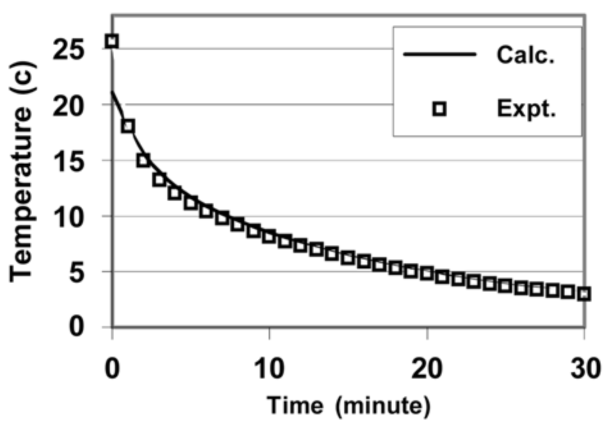

Fig. 4. Experimental and calculated temperature history at the sensor position.

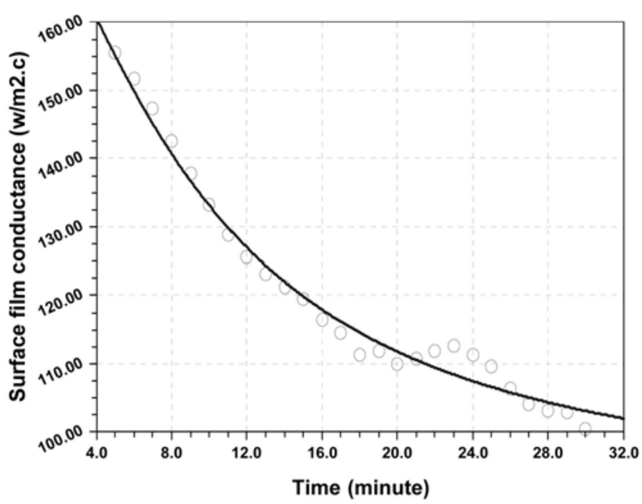

Fig. 5. Surface film conductance versus time curve.

Fig. 5 shows that the calculated surface film conductance values decrease gradually with time in a non-linear fashion. The following model yielded the best fit with the minimum standard error of 2.16 and maximum R^2=0.99.

$$h=\frac{2.887+179.2t^{-1.517}}{0.03224+t^{-1.517}} \tag{14}$$

Note that t in the above equation must be expressed in minutes, and it is valid for the period of the present study. The finite difference program developed by Ansari et al. [2,5] was used to deliver Figs. 6 to 10, which reveals that the proposed method (IHCP) yielded better coincidence with the experimental values. The concept of standard error was used to evaluate those coincidences numerically to provide the behavior of the inherent error along the characteristic length of the sample as plotted in Fig. 11. The calculations revealed that the average standard error along the characteristic length for the references [2] and [5] and the IHCP methods were 0.211, 0.200,

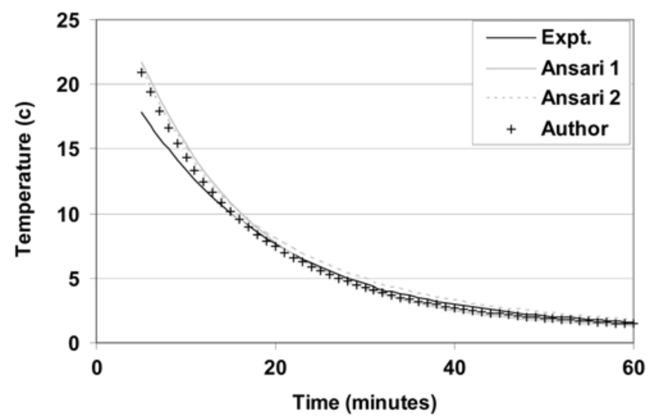

Fig. 6. Coincidence of the predicted and measured temperature profiles at z/z_o=0.

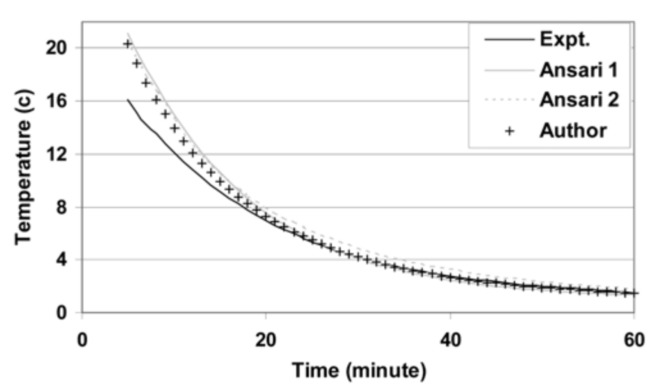

Fig. 7. Coincidence of the predicted and measured temperature profiles at z/z_o=0.2.

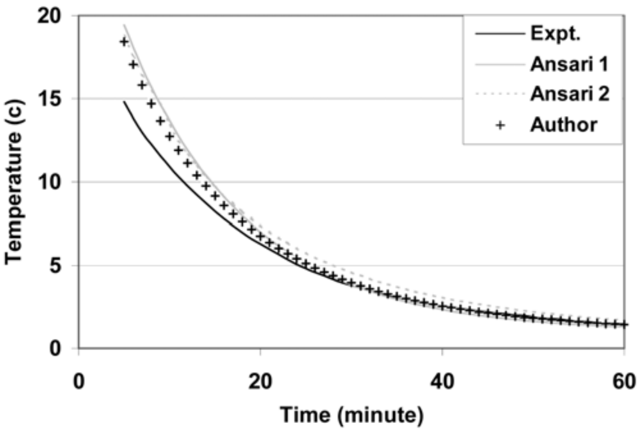

Fig. 8. Coincidence of the predicted and measured temperature profiles at z/z_o=0.4.

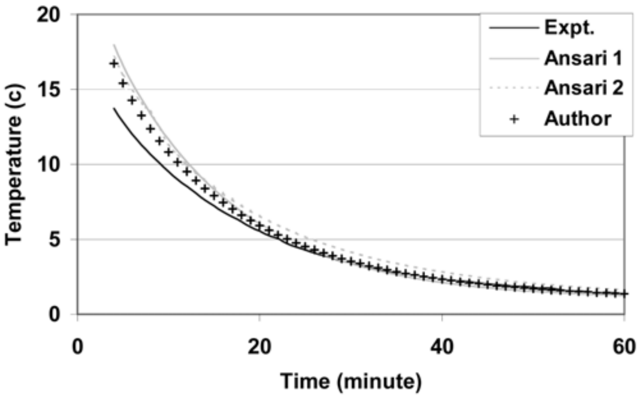

Fig. 9. Coincidence of the predicted and measured temperature profiles at z/z_o=0.6.

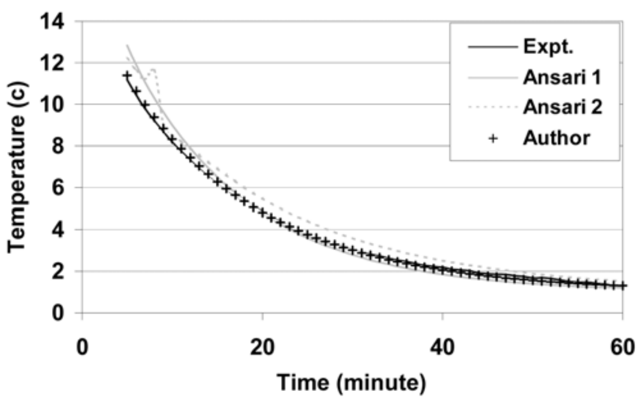

Fig. 10. Coincidence of the predicted and measured temperature profiles at z/z_o=0.8.

and 0.157, respectively.

In terms of sensor position, it is notable to mention here that Ansari methods [2,5] dictated the sensor position within the interval $0 \le z/z_o \le 0.6$, and the yielded results were as accurate as the sensor position near the centerline, i.e. z/z_o=0, whereas in the present work, the sensor location was at z/z_o=0.8 with better accuracy achieved.

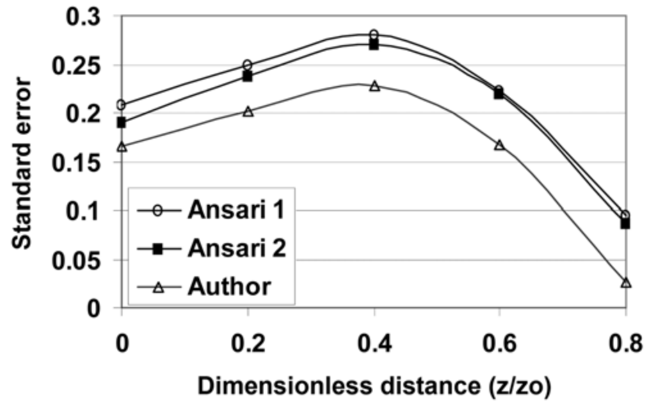

Fig. 11. The inherent error distribution along the characteristic length.

CONCLUSIONS

With known thermophysical properties, transient temperature-measurement records at a location of 0.254 cm from the tested sample surface, the boundary heat flux were estimated through the IHCP technique. The predicted variable values of the heat flux along with the other system parameters were used to find sequentially the convective heat transfer coefficient at each time step during the experimental period by applying the finite different technique. A correlation model for convective heat transfer versus time was developed. When this correlation with those reported earlier was used along with the finite difference technique to predict temperature profiles at many locations in the flesh sample, the IHCP method showed better agreement with the measured temperature profiles to prove its superiority.

NOMENCLATURE

c : specific heat of fish [J/kgK]
Fo : Fourier number [$\alpha t/z_o^2$]
h : convective heat transfer coefficient [W/m^2K]
k : thermal conductivity [W/mK]
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 weight mass basis)
Y : measured temperature
z : distance from the centre [m]
z_o : half thickness of the sample [m]

Subscripts and Superscripts

cm : cooling medium
m : discrete time index
o : initial
s : surface

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