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Modelling of the Internal Cooling of Fish during Ice Storage

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Modelling of the Internal Cooling of Fish during Ice Storage*

Dilip Jain and Pankaj Pathare

Abstract

The internal cooling of fish has been studied on the basis of Newton's cooling law. Experiments were conducted by cooling of the Indian major carp (Catla catla) of different weights with ice in an insulated box. Exponential model describing cooling of objects having irregular shape has been investigated. The developed model could predict the fish cooling with ice within a percent error of 0.74. The thermal properties of fish cooling with ice have been evaluated. The cooling data such as cooling coefficients, average surface heat transfer coefficient, thermal resistance, thermal capacitance, half cooling time and seven-eighth cooling time were determined for individual fish. The results show that the half cooling time and seven-eighth cooling time increased and the cooling rate decreased with increase in the weight of fish, respectively. Thermal resistance was independent of fish weight and having an average value of 1. 22 °C W-1. Thermal capacitance increased with fish weight and ranged from 665.8 to 4639.3 J °C-1. The average surface heat transfer coefficient of fish cooling with ice ranged from 11.68 to 34.41 W m-2 °C-1.

KEYWORDS: cooling coefficient, surface heat transfer coefficient, thermal resistance, thermal capacitance, cooling model

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1. INTRODUCTION

The fisheries sector of India contributes nearly Rs. 220 billion, which is 4.6% of the agricultural and 1.4% of the total national GDP. It is one of the main areas to provide the foreign exchange through export (Ayyappan and Pillai, 2005).

Fish is highly perishable and having a short storage life. Temperature is a very important factor, which accelerates the process of spoilage. The spoilage reactions connecting on the death of the fish proceed at a very rapid rate. Only a few hours delay at 15 – 20 ^{o}C will reduce the storage life of fish by several days (Hansen and Jensen, 1982). Preservation is necessary to reduce spoilage of the fish and to prolong the shelf-life. Preservation differs from processing. Preservation aims to alter the factors that aid spoilage without changing taste, texture and the physical appearance of the fish. Cooling is a common and important preservation technique to maintain the quality and prevent the spoilage of the products (Dincer, 1995a). The simplest method of cooling of fish is icing (Govindan, 1985).

Icing is widely accepted for chilling of fish as the economical and readily available method (Chaudhuri, 1966). It is especially valuable for preserving fish in ice, since a very rapid cooling is possible through intimate contact between fish and small pieces of ice. Ice keeps the chilled fish moist and glossy, and also prevents the dehydration (Graham et al, 1992).

There is an ever-increasing need for information on the thermo-physical properties of the products. Limited investigations have been reported in order to analyse the cooling data and to estimate process parameters of fish during icing. Mathematical modelling is important for optimum management of operating parameters and prediction of ice cooling system. Recently, Jain et al, 2005 have developed the exponential and asymptotic models to represent the cooling of *Rohu* fish (*Labeo Rohita*) in ice and studied the cooling coefficient and surface heat transfer coefficient.

In order to design cooling systems and to establish optimum cooling conditions, there is need to determine the thermal cooling data in terms of the cooling coefficient, surface heat transfer coefficient, Biot number, thermal capacitance, thermal resistance, half cooling time and seven-eighth cooling time for the fish. However, the irregular shape of biological material (like fish) makes it difficult to study the cooling parameters. Therefore, the present study is undertaken to determine cooling process parameters for individual fish (of different sizes) with help of mathematical model.

2. THEORETICAL CONSIDERATION

2.1. Modelling of cooling

Considering the internal temperature gradient very small and the transient problem is treated by "lumped thermal capacity" approach, then the first law of thermodynamics defines that the heat out of object during time *dt* is equal to the decrease in internal thermal energy of the object during this time. If the temperature of the object is considered to be uniform than this may be written as (Pitts and Sissom, 1998; Jain et al, 2005);

$$\bar{h}A_f(T_f - T_{ice})dt = -\rho_f C_f V_f dT_f \tag{1}$$

$$\frac{dT_f}{T_f - T_{ice}} = \frac{-\bar{h}A_s}{\rho_f C_f V_f}dt \tag{2}$$

by integrating equation (2) and applying initial condition $T_f(0) = T_{f,0}$:

$$\frac{T_f - T_{ice}}{T_{f,0} - T_{ice}} = \exp\left[-\frac{\bar{h}A_f}{\rho_f C_f V_f}t\right] \tag{3}$$

The dimensionless temperature, which is a function of the temperatures of product and medium, is expressed as (Dincer et al, 1992):

$$\theta = \frac{T_f - T_{ice}}{T_{f,0} - T_{ice}} \tag{4}$$

In present study, the medium is ice, therefore $T_{ice} = 0$, thus equation (3) becomes:

$$\frac{T_f}{T_{f,0}} = \exp\left[-\frac{\bar{h}A_f}{\rho_f C_f V_f}t\right] \tag{5}$$

It is assumed that there is a perfect contact between the product (fish) and medium (ice). The equation (5) takes the form:

$$\theta = \exp(-Ct) \tag{6}$$

and $$C = \frac{\bar{h}A_f}{\rho_f C_f V_f} \tag{7}$$

Where *C* is the cooling coefficient, denotes the change in product temperature per unit change in cooling time for each temperature difference between the products and the surrounding. It is incorporated with all the variables that effect cooling.

The specific heat of fish can be estimated (Siebel, 1982) as:

$$C_f = 837 + 334.9w_f \tag{8}$$

The exponential temperature decay given in equation (5) is analogous of the voltage decay during discharge of an electrical capacitor, which is given by (Pitts and Sissom, 1998):

$$\frac{E}{E_0} = \exp\left[-\frac{t}{(RC)_e}\right] \tag{9}$$

to make the analogy complete, now we define the thermal time constant for fish by:

$$(RC)_{th} \equiv \left(\frac{1}{\bar{h}A_f}\right)(\rho_f C_f V_f) \equiv (R_{th})(C_{th}) \tag{10}$$

so that

$$\theta = \exp\left[-t/(RC)_{th}\right] = \exp\left[-(\mathrm{Bi})(\mathrm{Fo})\right] \tag{11}$$

Where;

$$\mathrm{Bi} = \frac{\bar{h}L_f}{k_f} \tag{12}$$

The characteristic linear dimension as conductive path, L may be obtained for irregular shape of fish by dividing the volume of fish by its surface area

and $$\mathrm{Fo} = \frac{\alpha_f t}{L_f^{\,2}} \tag{13}$$

Now, equation (6) is a perfect exponential expression and in the Newtonian cooling, there is no lag exists in the start of heat transfer from the centre to the surface. The presence of a time lag between a change in temperature at the surface and at the centre of a product requires a modification in the basic equation. Equation (6), which has been modified into is a single term exponential model and represented by the experimental data of cooling of irregular product (fish) (Dincer, 1995a; Dincer, 1995b) as

$$\theta = J\exp(-Ct) \tag{14}$$

Where, J is the possible lag factor at the start of cooling and is equated as $(T_{f,a} - T_{ice})/(T_{f,0} - T_{ice})$.

By substituting $\theta = 0.5$ into equation (14), the half cooling time, which is one of the most meaningful in practical application, is found to be:

$$H = \frac{\ln(2J)}{C} \tag{15}$$

Also, by substituting $\theta = 0.125$ into equation (14), the seven-eighth cooling time is found as:

$$S = \frac{\ln(8J)}{C} \tag{16}$$

The linear regression technique was used to solve the exponential models by simplifying the exponential equations into the linear form of logarithmic values of dimensionless temperature.

The adequacy of the model has been determined by the coefficient of correlation r, which should be close to one, the reduced values of the standard errors e_s and the mean square of the deviation χ^2 (Jain and Pathare, 2004).

3. EXPERIMENTATION

Freshwater Indian major carp *Catla* fish (*Catla catla*) was used for the present study. The proximate composition of *Catla* fish is 76.3 % moisture, 19.6 % protein, 1.3% fat and 0.9 % ash (Nair and Mathew, 2000). The live fish procured from the local fishpond were held in the water tank until used within 1-2 days. The moisture content of *Catla* fish was determined by drying the fish sample at temperature of 130 °C (Gerasimov and Antonova, 1979) and observed as 76.3 % on a wet basis (3.219 kg water kg^{-1} dry matter).

The work was started by weighing the fish on an electronic balance an accuracy of ± 0.1 g. Volume of the fish was measured by the water displacement method (Rahman, 1995). The density of fish was calculated in weight per volume (kg m^{-3}). Surface area of fish was determined by Simpson's method (Sastry, 1985). The fish was divided longitudinally into equal segment of 20 mm width. The perimeter of each side of segment of fish was measured to the nearest mm using a flexible measuring tape. The mean perimeter was calculated of each segment. The surface area was calculated by multiplying the width of segment to the summation of average perimeters.

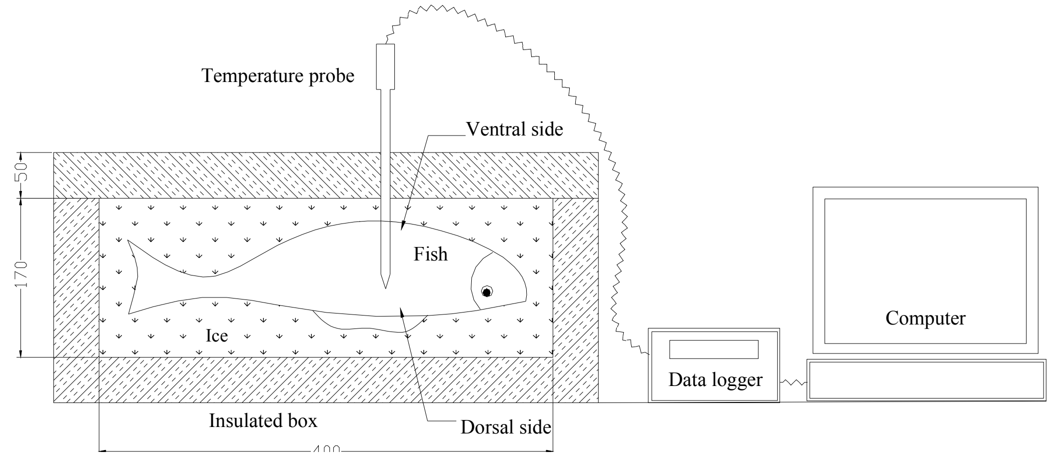

Figure 1. Schematic diagram of experimental arrangement of *Catla* fish cooling with ice; all dimensions in mm (drawing not to scale).

An experimental set-up used for fish cooling is shown in Figure 1. An aluminium box of 400 mm length, 150 mm breadth and 170 mm height with insulation all around by 50 mm thick thermo-coal sheet is used for cooling the fish with ice. The insulated aluminium box was initially filled with small ice flakes up to 50 mm thickness. In order to insert the temperature probe at the desired depth (centre) of the fish thickness, a needle was pierced into the fish from its vertebral side. The temperature probe thus inserted through this hole into the fish and penetrates slightly into the dorsal muscles. It is considered as thermal centre for longest time of cooling. The fish was immediately kept in ice after taking the physical observation. The fish was placed in the box with pierced temperature probe as down the dorsal side and the box was stuffed with ice flakes to ensure the perfect contact between ice and fish (Figure 1). Experiments were conducted with different weight ranging from 0.200 to 1.400 kg of fish, since this is the most common range of weight of *Catla* fish for harvesting from pond and marketing. Replications with the same weight were not possible as difficult to obtain the fish with the same weight. Therefore, 25 experiments were conducted with different weight of fish and the ten experiments were used for present analysis. The inside temperature of the fish flesh was recorded with the help of data logger (ADAM 4520) at an interval of 5 min and stored in the computer. The initial temperature of the fish was observed as 29.5 ^{o}C and the fish was cooled to 0.0 ^{o}C.

4. RESULTS AND DISCUSSION

4.1. Fitting of the models

The regression analysis was done relating the cooling time (min) and dimensionless temperature in the exponential model, for the ten experimental data of different weight of individual fish ranging from 0.1952 to 1.3784 kg. Table 1 shows the model coefficients, correlation parameters and cooling parameters for exponential model. The satisfactoriness of the model can be based on a value of the coefficient of correlation r, which should be close to one, and low value of standard error e_s and mean square of the deviation χ^2. It can be observed from Table 1 that the exponential regression provides the correlation parameters; r ranging from 0.9941 to 0.9993; e_s, 0.0102 to 0.0289 and χ^2, 1.1×10^{-4} to 9.0×10^{-4}. The results of exponential regression are also graphically presented in Figure 2 for three different weights of fish, which showed the appropriateness of exponential model for the determination of cooling data. The coefficients of exponential regression were further correlated with the weight of fish (m_f). The parabolic and logarithmic regressions were performed to relate the lag factor and cooling coefficient of cooling model with weight of fish, respectively. The accepted expressions of model coefficients were as follows:

$$J = 1.032 - 0.2327\, m_{\mathrm{f}} + 0.1142\, m_{\mathrm{f}}^2 \qquad (r = 0.8869;\ e_{\mathrm{s}} = 0.0183) \qquad (17)$$

$$C = 0.01443 + 0.199 \exp(-5.998\, m_{\mathrm{f}}) \qquad (r = 0.9989;\ e_{\mathrm{s}} = 0.0012) \qquad (18)$$

Table 1. Coefficients of the exponential model [$\theta = J\exp(-Ct)$] with different weight of *Catla* fish cooling with ice

Physical parameters of fish			Model parameters		Correlation parameters		
Weight m_{f}, kg	Volume V_{f}, 10^{-6} m^3	Surface area A_{f}, 10^{-4} m^2	J	C, min^{-1}	r	e_{s}	χ^2
0.1952	188	247.0	0.9811	0.07660	0.9942	0.0289	9.0×10^{-4}
0.2180	208	264.2	0.9862	0.06686	0.9990	0.0124	1.7×10^{-4}
0.2763	264	326.2	0.9627	0.05428	0.9969	0.0201	4.4×10^{-4}
0.4018	387	390.0	0.9986	0.03062	0.9993	0.0102	1.1×10^{-4}
0.6720	650	475.3	0.9106	0.01814	0.9945	0.0246	6.3×10^{-4}
0.7469	720	501.3	0.9155	0.01776	0.9945	0.0246	6.2×10^{-4}
0.8879	845	585.3	0.9169	0.01609	0.9951	0.0235	5.7×10^{-4}
0.9864	931	646.4	0.9138	0.01501	0.9944	0.0251	6.5×10^{-4}
1.2106	1170	704.7	0.9151	0.01413	0.9941	0.0260	6.9×10^{-4}
1.3784	1310	901.3	0.9316	0.01361	0.9960	0.0220	5.0×10^{-4}

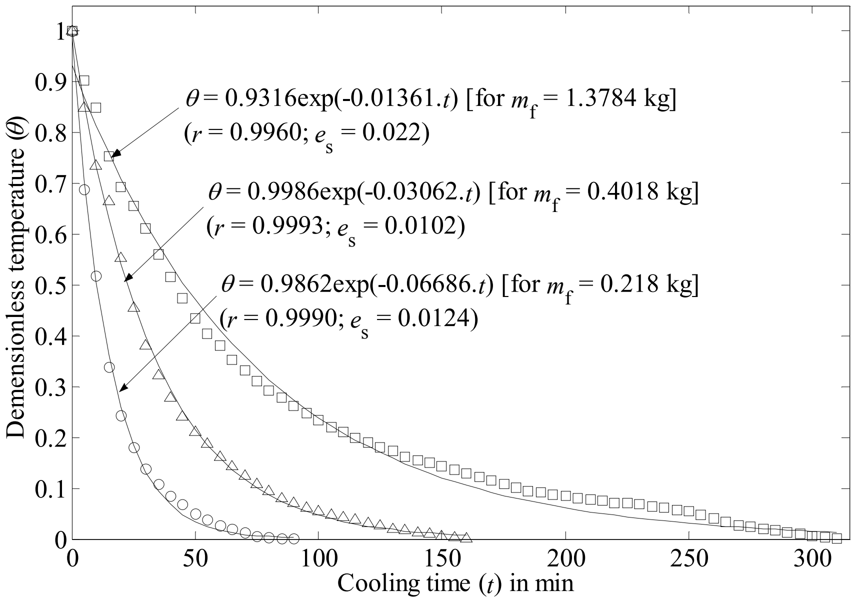

Figure 2. Fitting of exponential model with three different weights of *Catla* fish cooling with ice.

These expressions can be used to estimate the fish temperature with ice cooling at any time within the range of given weight of fish with the great accuracy. The established model was validated by comparing the computed fish temperature to the observed values of all the tests of experiment. The performance of the model at different weight is shown in Figure 3. The predicted data banded over the straight line of 1:1 ratio and the coefficient of correlation of 1.0. The linear regression of these results gave the following expression:

$$T_{\mathrm{f,pre}} = 1.0079\ T_{\mathrm{f,exp}} - 0.2066 \qquad (r = 1.0,\ e_{\mathrm{p}} = 0.74) \qquad (19)$$

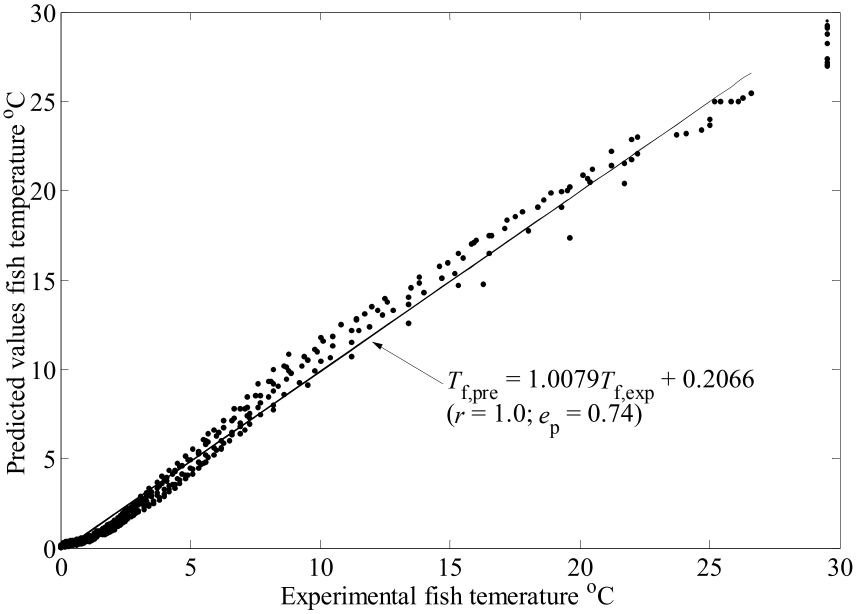

Figure 3 Experimental and predicted values of temperatures of *Catla* fish with ice cooling.

4.2. Prediction of accurate temperature of fish

The dimensionless temperature for the specific weight of fish can be computed at any time with the help of equations (17)-(18) and (14). Now, the temperature during cooling can be calculated with help of expression of dimensionless temperature in equation (3) and with the known value of initial temperature. The value of temperature of fish thus computed would be $T_{\mathrm{f,pre}}$ of the equation (19). The $T_{\mathrm{f,exp}}$ can be calculated from this expression would be the value much close to the measured temperature of fish. This would be the actual prediction of temperature of fish from the above model. The error of prediction of temperature by this method was 0.74 %. Therefore, the above results proved the suitability of the exponential model in describing cooling of fish with ice and determining the thermal properties of fish.

4.3. Thermal properties of fish

Average surface heat transfer coefficient has been calculated with the help of equation (7) on the basis of the cooling coefficient (*C*), which was obtained for exponential model and presented in the Table 2. The average surface heat transfer coefficient is the function of cooling coefficient and physical properties of the fish. It can be observed that the smaller fish are having the higher and the bigger fish having the smaller value of surface heat transfer coefficient. The average surface heat transfer coefficient of fish cooling with ice was ranging from 11.68 to 34.41 W m^{-2} $^{o}C^{-1}$.

Table 2. Thermal properties of the *Catla* fish cooling with ice

Weight of fish m_f, kg	Cooling parameters		Heat transfer coefficient $\bar{h}$, W m^{-2} $^{o}C^{-1}$	Thermal resistance ^{o}C W^{-1}	Thermal capacitance J $^{o}C^{-1}$	Biot Number Bi
	H, min	*S*, min				
0.1952	8.80	26.90	34.41	1.1765	665.8	0.9241
0.2180	10.16	30.89	31.07	1.2183	736.6	0.8630
0.2763	12.07	37.61	25.92	1.1823	934.9	0.7402
0.4018	22.59	67.86	17.93	1.4297	1370.5	0.6279
0.6720	33.05	109.47	14.64	1.4369	2301.9	0.7065
0.7469	34.06	112.11	15.05	1.3249	2549.8	0.7630
0.8879	37.69	123.85	13.71	1.2461	2992.5	0.6984
0.9864	40.17	132.53	12.76	1.2124	3297.1	0.6484
1.2106	42.78	140.89	13.85	1.0248	4143.5	0.8111
1.3784	45.72	147.58	11.68	0.9503	4639.3	0.5988

Thermal resistance has been calculated with the help of equation (10). Thermal resistance was independent of fish weight and found with in range from 0.953 to 1.4369 ^{o}C W^{-1} and with an average value of 1.2202 ^{o}C W^{-1}. Thermal capacitance was ranging from 665.8 to 4639.3 J $^{o}C^{-1}$. It can be observed that the thermal capacitance is a function of weight of fish and increase proportionately with weight of fish. The Biot number ranged from 0.5988 to 0.9241, which shows the finite internal and external resistances to the heat transfer from the products. The small values of Bi support the present approach of lump thermal capacity.

5. CONCLUSIONS

Exponential regression model adequately described the individual cooling of Indian major carp *Catla* fish on the basis of statistical parameters such as coefficient of correlation, standard error and mean square of the deviation value. The half cooling time and seven-eighth cooling time increase and the cooling rate decreases with increase in the weight of fish. Thermal resistance of *Catla* fish was computed as 1. 22 ^{o}C W^{-1}. Thermal capacitance increased with weight of fish and was ranging from 665.8 to 4639.3 J ^{o}C^{-1}. The average surface heat transfer coefficient of fish cooling with ice was ranging from 11.68 to 34.41 W m^{-2} ^{o}C^{-1}. The developed model could predict the cooling of fish with time within an error of 0.74 %.

NOMENCLATURE

A	surface area (m^{2})
Bi	Biot number
C	cooling coefficient (s^{-1} or min^{-1})
C_{th}	thermal capacitance (J ^{o}C^{-1})
C_f	specific heat of fish (J kg^{-1} ^{o}C^{-1})
e_p	percent error
e_s	standard error
E	electric voltage (v)
Fo	Fourier number
H	half cooling time (min)
$\bar{h}$	average surface heat transfer coefficient (W m^{-2} ^{o}C^{-1})
J	lag factor
k	thermal conductivity (W m^{-1} ^{o}C^{-1})
L	characteristics length (V_f/A_f) (m)
M	weight of fish (kg)
r	coefficient of correlation
R_{th}	thermal resistance (^{o}C W^{-1})
$(RC)_{th}$	thermal time constant (min)
S	seven-eighth cooling time (min)
t	time (s or min)
T	temperature (^{o}C)
T_f	temperature of the center of fish (^{o}C)
$T_{f,a}$	apparent fish temperature (^{o}C)
V	volume (m^{3})
w	water content, (kg water kg^{-1} of weight)

Greeks

α	thermal diffusivity $[k_f/(\rho_f C_f)]$ ($m^2\ s^{-1}$)
ρ	density ($kg\ m^{-3}$)
θ	dimensionless temperature
χ^2	mean square of deviation

Subscripts

0	initial
e	electric
exp	experimental
f	fish
i	integer 1, 2, 3, ….n
ice	ice
pre	predicted
th	Thermal

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