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Predicting Freezing Time for Keropok Lekor

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ABSTRAK

Proses penyejukbekuan *keropok lekor* dikaji secara eksperimen dan simulasi berangka pemindahan haba tidak mantap. Perubahan suhu di tengah sampel *keropok lekor* semasa proses penyejukbekuan di dalam peti sejuk tiupan angin telah diperoleh. Model kaedah berangka yang dibina melibatkan penyelesaian persamaan Fourier untuk silinder fana dan sfera berasaskan nilai entalpi berubah. Pekali pemindahan haba ditentukan melalui kaedah perubahan sifat terma aluminium yang mempunyai dimensi sama seperti sampel *keropok lekor* yang dikaji. Kandungan air, protein kasar, lemak, karbohidrat dan abu ditentukan untuk menilai perubahan sifat terma *keropok lekor* mengikut suhu. Sifat terma iaitu konduktiviti terma, entalpi dan takat beku ditentukan dengan menggunakan pertalian kandungan. Masa penyejukbekuan diperoleh daripada kiraan dan eksperimen menunjukkan perbandingan yang baik di antara mereka, untuk setiap sampel *keropok lekor* berbentuk silinder dan sfera. Bagi sampel *keropok lekor* bergaris pusat 20 mm berbentuk silinder dan sfera, masa penyejukbekuan kepada suhu sejuk beku - 20°C ialah masing-masing 20 min dan 15 min.

ABSTRACT

The freezing process of *keropok lekor* (fish sausage) has been studied experimentally and by numerical simulation of unsteady heat transfer. Core temperature history of *keropok lekor* samples placed in the air-blast freezer were registered. The developed numerical model utilizes the solution of the Fourier equation of heat transfer for an infinite cylinder and for a sphere with variable product enthalpy. Heat transfer coefficient was determined from the thermal history of aluminum cylinder with dimensions similar to experimental *keropok lekor*. The contents of water, crude protein, fat, carbohydrate and ash were determined to evaluate variations of *keropok lekor* thermal properties with temperature. These thermal properties, i.e. thermal conductivity, enthalpy freezing point, were obtained by using composition correlations. Calculated and experimental freezing times are in good agreement with each other, for each of the cylindrical and spherical *keropok lekor* samples. For 20 mm diameter cylindrical and spherical *keropok lekor* samples, the freezing time to achieve a frozen temperature of - 20°C were 20 min and 15 min, respectively.

Keywords: *Keropok lekor*, freezing time, thermal properties

INTRODUCTION

Most commercial freezing operations of foodstuff are done by using air blast freezer because of its relatively low capital cost and high throughput. Also, it is simple to use and highly flexible since food of different shapes and sizes can be frozen. Embong (1988) found that the shelf life of *keropok lekor* could be extended to more than 7 weeks when packed and frozen in air blast freezer. Chan and Pan (1995) used air blast freezer for

freezing tilapia to determine its freezing point and freezing rate. Chevalier *et al.* (2000) investigated on the freezing rate and ice crystal formation in a cylindrical model food (gelatin) by using air blast freezing and brine freezing techniques. Agnelli and Macheroni (2001) developed a simulation model for implementing cryo-mechanical freezing on foodstuff.

The main objective of this paper is to present the application of modeling technique for investigating the freezing process of common local food product, *keropok lekor* (fish sausage) which in its processed state consists of a mixture of fish meat, starches, salts, monosodium glutamate and sugar. The emphasis is to investigate the freezing process of *keropok lekor* by mathematical modeling to enable numerical simulation of the freezing process be carried out. Freezing of *keropok lekor* was conducted using air blast freezer; this experimental data and some published data were used for validating the modeling and simulation approach. The ultimate output would be the temperature history during freezing which enable us to predict the freezing time of the product.

BASIC EQUATIONS AND ASSUMPTIONS FOR MATHEMATICAL MODELLING

As a physical phenomenon with phase change, the food freezing process is characterized by the generation and development of the freezing front which involves a considerable amount of latent heat being absorbed within this front. Two physical models for freezing are commonly in use namely, the continuously varying k(T) and H(T) model, and the unique phase change front model (Cleland, 1990). The former approach is being applied here for investigating the *keropok lekor* freezing process. This involves solving numerically the heat conduction equations given below:
for a cylinder

$$\rho(T)\frac{\partial H(T)}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left[k(T)r\frac{\partial T}{\partial r}\right] \tag{1}$$

and for a sphere

$$\rho(T)\frac{\partial H(T)}{\partial t}=\frac{1}{r^2}\frac{\partial}{\partial r}\left[k(T)r^2\frac{\partial T}{\partial r}\right] \tag{2}$$

with the following initial and boundary conditions:

$$T = T_0 \text{ for } t = 0; \qquad h(T_s)(T_\infty - T_s) = k(T)\left(\frac{\partial T}{\partial r}\right)_{r=R} \tag{3}$$

where convective heat transfer coefficient (h) is a function of the surface temperature (T_s) and $H(T)$, $k(T)$ are temperature dependent product enthalpy and thermal conductivity respectively.

Equations (1, 2) were solved numerically using finite difference approach, with the enthalpy as unknown variable on a fixed grid. Consequently, calculated value of enthalpy allowed the determination of the temperature in each point of the grid. As time

increment added, this temperature value is used for enthalpy calculation corresponding to the new time step. The number of $N = 40$ evenly distributed radial grid points was established as adequate for obtaining a good precision. The discretisation gave the following expressions for the enthalpy values:

For a Cylinder
surface (n=N):

$$H_N^{t+1} = H_N^t + \frac{2\Delta t}{\rho(T'_N)(\Delta r)^2\left(2N-\frac{1}{2}\right)}\left(hN\Delta r\left(T_b - T'_N\right)\right)$$

$$-k\left(\frac{T'_N - T_{N-1}^t}{2}\right)(N-1)\left(T_N^t - T_{N-1}^t\right) \tag{4}$$

interior (n=N-1...1):

$$H_n^{t+1} = H_n^t + \frac{\Delta t}{\rho\left(T_n^t\right)n(\Delta r)^2}\left(k\left(\frac{T_{n+1}^t + T_n^t}{2}\right)\left(T_{n+1}^t - T_n^t\right)\left(n+\frac{1}{2}\right)\right) \tag{5}$$

$$-k\left(\frac{T_n^t + T_{n-1}^t}{2}\right)\left(T_n^t - T_{n-1}^t\right)\left(n-\frac{1}{2}\right)$$

center (n=0):

$$H_0^{t+1} = H_0^t + \frac{4\Delta t\left(k\left(\frac{T_1^t + T_0^t}{2}\right)\left(T_1^t - T_0^t\right)\right)}{\rho\left(T_0^t\right)(\Delta r)^2} \tag{6}$$

For a Sphere
surface ($n=N$):

$$H_N^{t=1} = H_N^t + \frac{\Delta t}{\rho\left(T_N^t\right)(\Delta r)^2\left(\frac{N^2}{2}-\frac{N}{4}-\frac{1}{24}\right)}\left(hN^2\Delta r\left(T_b - T_N^t\right)\right)$$

$$-k\left(\frac{T_N^t - T_{N-1}^t}{2}\right)\left(N-\frac{1}{2}\right)^2\left(T_N^t - T_{N-1}^t\right) \tag{7}$$

interior ($n=N$-1...1):

$$H_n^{t+1} = H_n^t + \frac{\Delta t}{\rho\left(T_n^t\right)\left(N^2+\frac{1}{2}\right)(\Delta r)^2}\left(k\left(\frac{T_{n+1}^t+T_n^t}{2}\right)\left(T_{n+1}^t-T_n^t\right)\left(n+\frac{1}{2}\right)^2\right) \tag{8}$$

$$-k\left(\frac{T_n^t+T_{n-1}^t}{2}\right)\left(T_n^t-T_{n-1}^t\right)\left(n-\frac{1}{2}\right)^2$$

center (n=0):

$$H_0^{t+1} = H_0^t + \frac{6\Delta t\left(k\left(\frac{T_1^t+T_0^t}{2}\right)\left(T_1^t-T_0^t\right)\right)}{\rho\left(T_0^t\right)(\Delta r)^2} \tag{9}$$

At the beginning of freezing, the heat capacity of the nearest to the surface layer of the $\Delta r/2$ thickness is assumed negligible giving the 'initial' surface temperature

$$T_N^0 = \frac{\Delta rNhT_b + k\left(\frac{T_N^0-T_{N-1}^0}{2}\right)\left(N-\frac{1}{2}\right)T_{N-1}^0}{k\left(\frac{T_N^0-T_{N-1}^0}{2}\right)\left(N-\frac{1}{2}\right)+\Delta rNh} \tag{10}$$

Solution of the Equations (1,2) as given by Equations (6,9) requires the approximation of thermal properties of the product as temperature changes. This is achieved by firstly, determining *keropok lekor* compositions experimentally by proximate analysis; and next approximating the properties by utilizing appropriate correlations based upon product compositions. The selected correlations for the product physical properties as a function of temperature are listed below (Kenneth *et al.*, 1997):

Freezing (melting) point as a function of water content X_w:

$$T_f = \frac{1-X_w}{0.06908-0.439.X_w} \tag{11}$$

ice fraction: for $T \geq T_f$, $X_I = 0$; for $T < T_f$, $X_I = (X_W - X_B)\left[1-\frac{T_f}{T}\right]$ (12)

density: $$\rho(T) = \left[\frac{X_W(T)}{\rho_W}+\frac{X_I(T)}{\rho_I}+\frac{X_F}{\rho_F}+\frac{X_P}{\rho_P}+\frac{X_C k_C}{\rho_C}+\frac{X_S k_S}{\rho_S}\right] \tag{13}$$

thermal conductivity:

$$k(T)=\rho(T)\left[\frac{X_I(T)k_I}{\rho_I}+\frac{X_W(T)k_W}{\rho_W}+\frac{X_F k_F}{\rho_F}+\frac{X_P k_P}{\rho_P}+\frac{X_C k_C}{\rho_C}+\frac{X_S k_S}{\rho_S}\right] \quad (14)$$

heat capacity:

for $T \geq T_f$, $c_u = X_W c_W + X_F c_F + X_P c_P + X_s c_S$;

$$\text{for } T < T_f,\ c(T) = cu - (XW - XB).\left[\frac{\lambda_I T_f}{T^2}+(c_W - c_I)\right] \quad (15)$$

enthalpy:

for $T > T_f$ $\quad H(T) = cu(T - Tf)$;

for $T \leq T_f$

$$H(T) = (X_F c_F + X_P c_P + X_C)(T - T_f) + (X_W(T)c_W + X_I(T)c_I(T - T_f) - \lambda_I X_I(T) \quad (16)$$

Numerical simulation of the freezing process was carried out based on the modeling approach described above so that the calculated result could be compared with experimental result. The approximations of physical properties of *keropok lekor* using the above correlations (11) - (16) and the numerical simulation of the freezing process were implemented by the application of Mathcad 2000 software package, following the algorithm as shown in *Fig. 1.*

EXPERIMENTAL PROCEDURE

Proximate analysis was carried out in order to establish the composition of commercially produced *keropok lekor* used in this study. The homogeneous *keropok lekor* dough were analysed in triplicate samples for water, crude protein, fat, carbohydrates and ash (solids) contents according to Pearson (1976). The moisture content was determined by oven method, fat by Soxhlet apparatus, and the dried sample from fat was used to determine the ash content. Nitrogen content was analysed by Kjeldahl method, using 0.15 g of sample; protein content was then obtained by multiplying the nitrogen content by 6.25.

Based on the standard lumped thermal capacity method, the heat transfer coefficient (h) was determined experimentally from the thermal history of an aluminium body, with the shape and dimension similar to the treated *keropok lekor* sample. The value of h has been obtained from the slope of a plot of ln T versus t of the following equation:

$$\ln T^* = \ln\frac{T - T_b}{T_0 - T_b} = -\frac{hA}{mc_{Al}}t \quad (17)$$

In the freezing process, *keropok lekor* sausages were frozen in the air-blast freezer (ARMFIELD FT36-C) with freezing air temperature of - 30°C. The product core (centre-line) temperature evolution with time was measured by using a data acquisition system (KRESSTLER DATATAKER DT50) with T-type thermocouple. Thermocouple wires were assembled along centre-line to prevent inaccuracy due to radial heat flux.

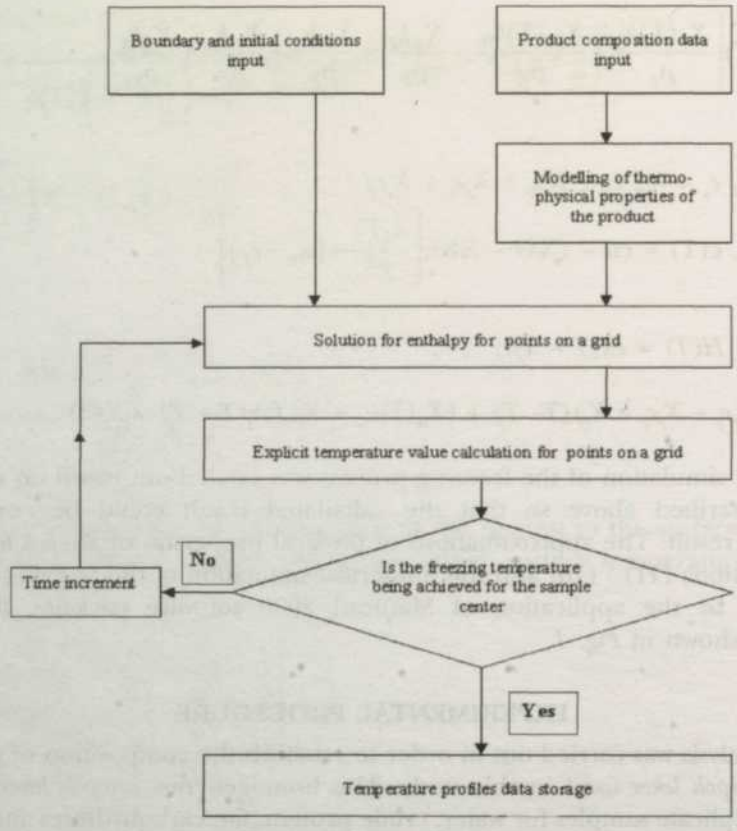


Fig. 1: Modelling algorithm

RESULTS AND DISCUSSIONS

Proximate Analysis

Proximate analysis showed that the *keropok lekor* (fish sausage) used in this study contained about 55.0% water, 8.5% crude protein (conversion factor for *keropok lekor*, N x 6.25), 0.5% fat, 31.5% carbohydrate and 4.5% ash as shown in Table 1. However, the composition depends on the ratio of fish meat to flour, type of fish and other additional flavors, which can vary according to individual producer's choice. The rather high percentage of fat in the published data (Table 1) is attributed to the addition of groundnut oil during processing.

Heat Transfer Coefficient

From the slope of a plot of Equation (17) as shown in *Fig. 2*, the value of heat transfer coefficient (h) was approximately 80 W/m^2 °C.

Thermal Properties

Utilizing the composition data obtained in Table 1, the thermo-physical properties variations with temperature were determined by using the correlations as given in Equation (11) through (16). This theoretical simulation of the thermal physical properties was implemented in a Mathcad software package. The typical changes in thermal

TABLE 1
Basic composition of *keropok lekor*

Composition (percentage)	Determined value (present paper)	Published data (Ibrahim, Ishak, 1980)
Water content	55.00	53.00
Fat	0.50	13.00
Crude protein	8.50	8.50
Carbohydrate	31.50	23.50
Ash	4.50	2.00

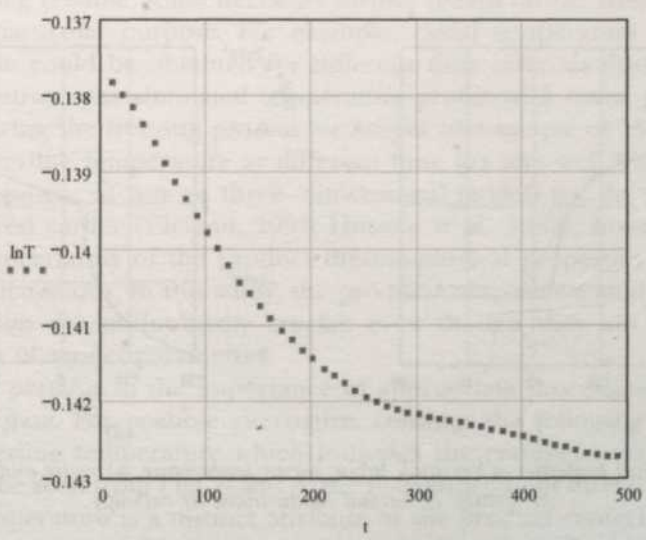


Fig. 2: Plot of ln T *versus* t *for heat transfer coefficient (h) determination*

properties with temperature are plotted in *Fig. 3*, from which the values of the thermaphysical properties of *keropok lekor* can be determined for any desired temperature. Water starts to change phase into ice after the freezing point (-2.6°C). The density is 1110 kgm^{-3} and the thermal conductivity is 0.45 W (m °C)-1 and 1.34 W (m °C)-1 for the fresh and frozen state, respectively. The enthalpy curve for *keropok lekor* presents a melting point of -2.6°C with the latent heat of 180 kJ kg-1.

Comparison of Simulated and Experimental Result

(i) For Gelatin Sample

The results of numerical simulation developed in this study were compared to the experimental data of Macchi (1995) for cylinders of gelatin with 70% water content. Gelatin was chosen as a model foodstuff in order to eliminate the heterogeneous characteristic of most foods. From the thermal point of view, it is representative of different kinds of foods. The functionality of enthalpy (H) with temperature and other properties of gelatin necessary for modeling the entire freezing process were also obtained from Macchi (1995). The enthalpy curve for gelatin shows a melting point of -13.9oC for a cooling rate of 0.1K min-1. The latent heat is 160kJ kg-1 and the thermal

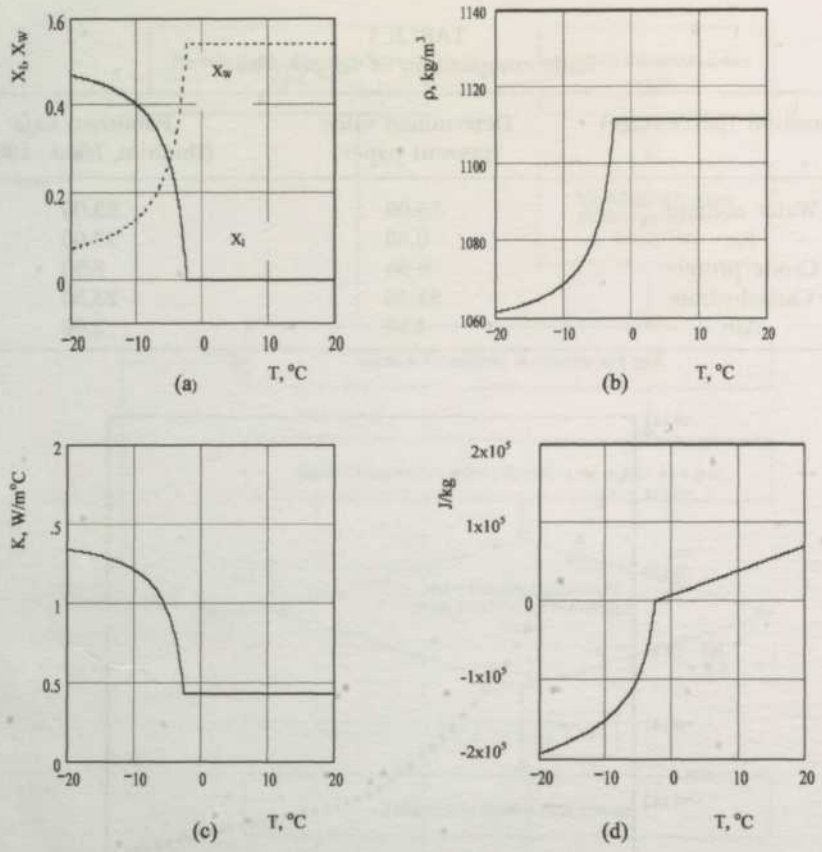


Fig. 3: Physical properties of keropok lekor *versus temperature. a) water and ice fraction; b) density; c) thermal conductivity; d) enthalpy*

conductivity is 0.55 W (mK)-1 and 0.95 W (mK)-1 for the fresh and frozen gel, respectively, and density is 1200 kg m-3. The calculated and experimental temperature profiles during freezing in the mechanical freezer are presented in *Fig. 4*. The profiles are at two different positions of the cylinder i.e. at the center and at the surface of the sample. It can be noted that the calculated temperature profiles are very close to the experimental temperature history of the gelatin cylinder. So, the simulation model represents satisfactorily the thermal process of the model foodstuff.

(ii) For *Keropok Lekor* Samples

Fig. 5 presents the experimental and calculated results for freezing of *keropok lekor* samples in the mechanical freezer. The standard geometrical shapes of *keropok lekor* samples (cylindrical and spherical) were utilized for this purpose. In general, calculated and experimental temperature profiles match each other reasonably well for both geometrical shapes. This enables the prediction of freezing time based on the model. It can be seen that the 30 mm diameter cylindrical sample require about 20 minutes to be completely frozen to the freezing point of - 2.6°C, followed by another 10 minutes to achieve a frozen temperature of - 20°C. The 20 mm diameter cylindrical sample required 15 minutes to be completely frozen to - 2.6°C, followed by another 5 minutes to achieve a frozen temperature of - 20°C. The 20 mm diameter spherical sample require a little less than

10 minutes to be completely frozen to - 2.6°C, followed by another 5 minutes to achieve a frozen temperature of - 20°C.

Even though there is some inconsistency below the freezing temperature, this is believed to be attributed to ambiguity of approximations for enthalpy, conductivity and other parameters rather than from other reasons. Although the measurement has been carried out with only one thermocouple located at the thermal center (the slowest cooling point) of the *keropok lekor* sample, the agreement of the calculated temperature profile with the experimental temperature profile for *keropok lekor* is observed to be satisfactory. As such it can be concluded that the temperature time profiles obtained from the simulation model for freezing *keropok lekor* with regular geometrical shapes (cylinder and sphere) are acceptable.

The model being reliable, some necessary further details on the freezing process can be obtained for particular purpose. For example, radial temperature profiles for the *keropok lekor* sample could be obtained for different time intervals during the freezing process. *Fig. 6* illustrates the simulated temperature profile with radial positions at four different times during the freezing process for *keropok lekor* sample of 15mm radius. The experimental centerline temperature at different time fits very well with the simulated result. The development of two- or three- dimensional models for the freezing process has been considered earlier (Cleland, 1991; Hossain *et al.*, 1992); however, it seems in many cases that uncertainty of the product thermo-physical properties mainly controls the accuracy of calculations. In this study, the product composition analysis and relevant correlation selection are undoubtedly crucial; even though they are time- and cost-consuming factors of model parameters.

Another point pertains to the importance of appropriate processing and analysis of the experimental data. For possible alternative, consider the following presentation of the product centerline temperature which indicates the completeness of the freezing process. As it can be seen from *Figs. 4* and *5*, the plateau segment directly associated with freezing point temperature is a distinct attribute of the product centerline temperature history. This dominant peculiarity motivates the presentation of original data for the specific products in terms of dimensionless temperature versus dimensionless time; these modified variables taking the form as;

Dimensionless temperature: $$\bar{T} = \frac{T - T_f}{T_0 - T_b},; \qquad (18)$$

Dimensionless time: $$\bar{t} = \frac{\sqrt{\lambda}}{R} t \qquad (19)$$

In fact the dimensionless time parameter (Equation 19) is built from Biot number by substituting $\sqrt{\lambda}$ for α / R, while the temperature in the form of Equation (18) is attached to the freezing point. For simplicity, T_f = 0 °C can be used for high water content product. With this approach, processed data for *keropok lekor* samples with different diameters are plotted in *Fig. 7*. It is observed that the points tend to converge to a single curve which is supposed to be the generalized centre-line temperature history for the given product. On this basis, the curve could be obtained from low cost experiment with small size sample and the relevant forecast for the product size in use could be done.

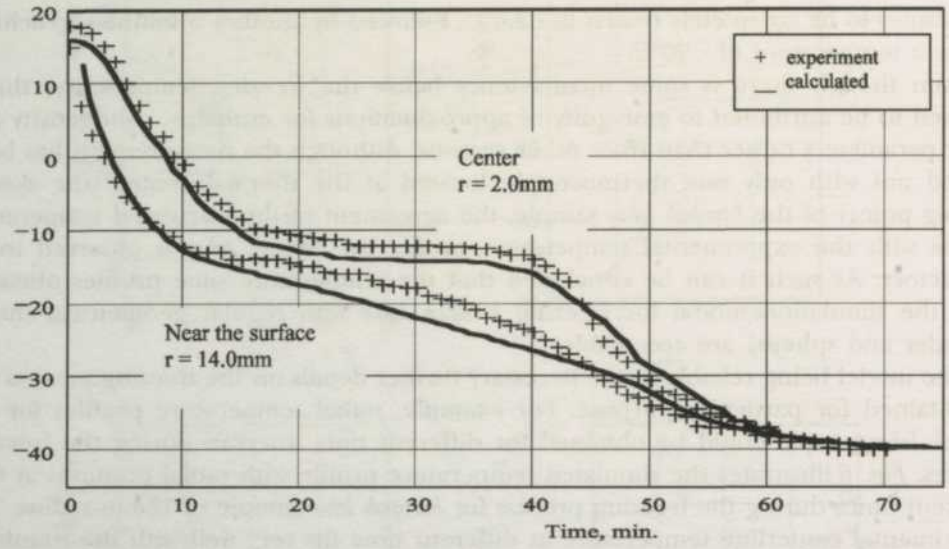


Fig. 4: Experimental (Macchi 1995) and calculated temperature profiles for gelatin cylinders (D=30mm, L=100mm) at different radius frozen in the mechanical freezer (Tair=-40°C)

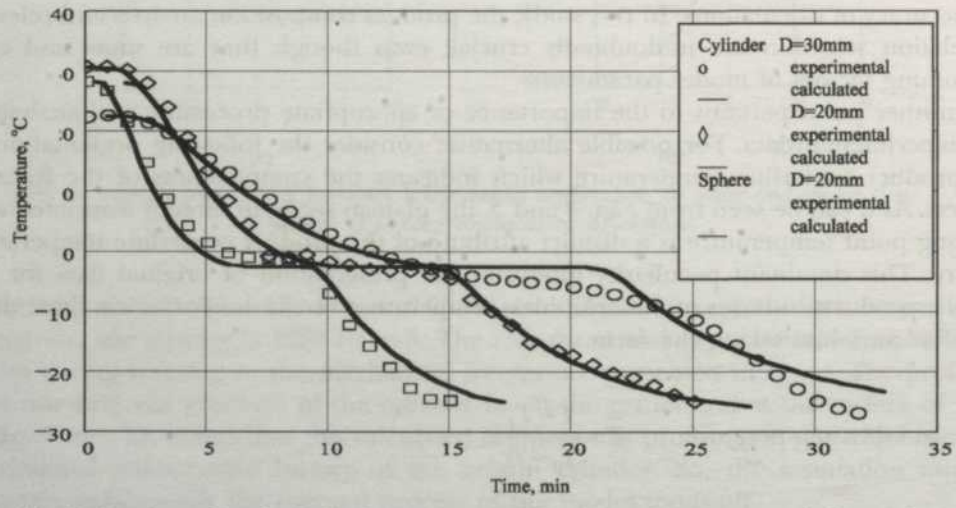


Fig. 5: Experimental and calculated temperature profile evaluated at the center for keropok lekor *frozen in the mechanical freezer (Tair=-30oC), for a cylinder and a sphere samples*

CONCLUSIONS

A versatile model describing cooling and freezing process of *keropok lekor* has been developed. The simulation presented was successfully validated with the experimental results obtained from literature (gelatin cylinder) and from data obtained in this study for *keropok lekor* frozen in mechanical freezer. The fit is satisfactory for the standard geometrical shapes studied (sphere and cylinder). It has been shown that the temperature profile presents a freezing point of -2.6°C for *keropok lekor.* The temperature history during freezing enables the prediction of the freezing time. For a 30 mm diameter cylindrical *keropok lekor* sample, the simulation model predicted a freezing time of 30

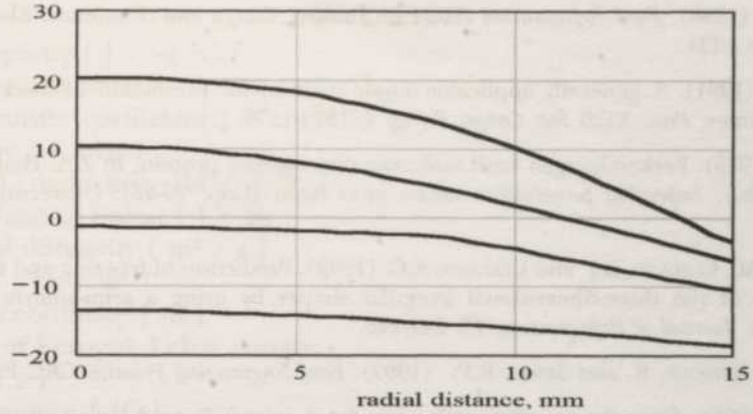


Fig. 6: Calculated temperature profiles for keropok lekor *(R=15mm) for t1=200s, t2=400s, t3=800s and t4=1600s. o - experimental temperature at axis*

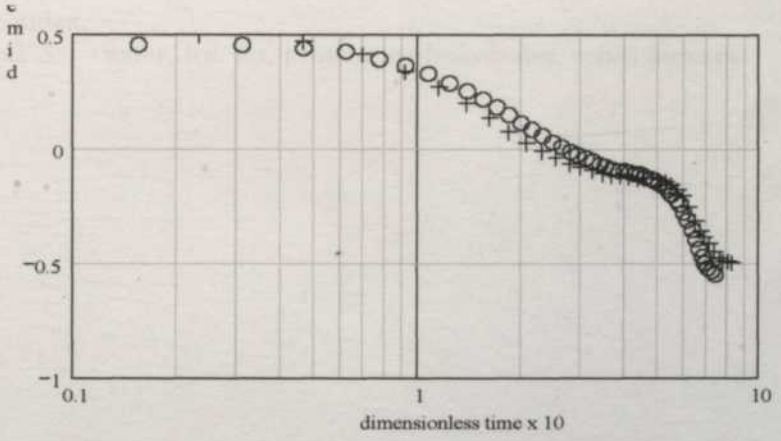


Fig. 7: Centerline temperature generalization for unsteady freezing process of keropok lekor

minutes for the core temperature to achieve the frozen temperature of - 20 °C. Likewise, for 20 mm diameter cylindrical and spherical *keropok lekor* samples, the predicted freezing time to achieve - 20 °C were 20 minutes and 15 minutes, respectively. These predicted freezing times are in good agreement with experimental freezing times. Thus the simulation model could provide a good approximation for predicting of the freezing time for *keropok lekor* with cylindrical and spherical shapes.

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NOTATION

c heat capacity [J / kg °C]
c_u heat capacity at unfrozen state [J / kg °C]
h heat transfer coefficient [W / m^2 °C]
H enthalpy [J / kg]
k thermal conductivity [W / m °C]
λ latent heat of fusion [J / kg]
α thermal diffusivity [m^2 / s]
ρ density [kg / m^3]
r radial coordinate [m]
R radius of Keropok Lekor sausage
t time [s]
T temperature [(C]
T_f freezing temperature [°C]
T_b bulk temperature [°C]
T_s surface temperature [°C]
X component mass fraction
n space index
W, I, F, P, C, S water, ice, fat, protein, carbohydrates, solids indexes.