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Research Paper

NUMERICAL MODEL OF THERMAL DIFFUSIVITY FOR PEMPEK LENJER BOILING

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Thermal diffusivity data during boiling process was used to determine specification of boiling condition, especially to determine the correct time and temperature of boiling process. Determination of thermal diffusivity coefficient (α) on material usually is conducted by means of analytical method and chemical composition, i.e., thermal diffusivity is the ratio of thermal conductivity to specific heat and spesicific density of material. Thermal diffusivity coefficient can also be determined by using numerical model based on temperature distribution during boiling process. The research objectives were to determine thermal diffusivity coefficient of pempek lenjer by using numerical model, to compare thermal diffusivity coefficients obtained from numerical model and the one based on chemical composition and analytical method as well as to determine the optimum time and temperature of pempek lenjer boiling for each formulation. Data analysis for thermal diffusivity was conducted by using computer software of Engineering Equation Solver (EES) Ver 8.914. The results showed that thermal diffusivity coefficient obtained by using numerical model was similar to the one based on chemical composition and analytical method. Therefore, numerical model can be used due to its capability to detect the changes of temperature and thermal diffusivity for each observation unit (minute) during boiling process. Thermal diffusivity coefficients based on numerical model, chemical composition and analytical method were in the range of 1.36×10^{-7} to 1.62×10^{-7} m^2/s, 1.302×10^{-7} to $1.478.10^{-7}$ m^2/s and 1.313×10^{-7} to $1.483.10^{-7}$ m^2/s, respectively. The required boiling times and center point temperatures for formula of fish dominant pempek lenjer and tapioca flour dominant pempek lenjer were 22 minutes and 87^{o}C as well as 13 minutes and 80^{o}C, respectively.

Keywords: numerical model, thermal diffusivity, boiling, pempek lenjer.

INTRODUCTION

Pempek lenjer (cylindrical form) is one of Indonesia traditional food made from milled fish flesh, tapioca flour or sagu flour, water, salt and cooking ingredients as enchancing flavor. The pempek processing stages are fish flesh milling,

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materials mixing, pempek forming and boiling process (Karneta, 2010). The cooking stage (or boiling) is one of important stage because thermal and mass diffusivities was occurred in this stage as well physicochemical reaction such as protein denaturation and starch gelatinization. Thermal diffusivity is one of physical property related to heat transfer within material with dimension unit of m^2/s or it can defined as rate of heat which is diffused to outside or inside the material and heat was naturally distributed into all of material parts (Fontana *et al.*, 2001; Huang and Liu*,* 2009).

Thermal diffusivity is important to determine the rate of temperature change on material which in turn can be used to determine the energy requirement or optimum temperature in processing operation, especially for materials that are sensitive to heat (Singhal *et al.,* 2008 ; Tastra *et al*., 2006; Suroso, 2006). High value of thermal diffusivity coefficient results in faster thermal diffusion within material (Jain and Pathare, 2007; Singhal *et al.*, 2008) which produce shorter cooking time. Thermal diffusivity on pempek boiling is very important to determine the optimum time and temperature for pempek cooking. According to Olivera and Salvadori (2008), thermal diffusivity data during cooking process was used to determine specification of cooking condition, especially to determine proper time and temperature of cooking, to guarantee the safety in term of microbiology as well as to maintain food nutrition and food organoleptic characteristics.

Heat transfer occurs due to temperature gradient on materials in form of conduction, convection and radiation modes or combination of them. Heat transfer in solids is occurred in conduction mode, whereas heat transfer in liquids is occurred in convection mode. Heat transfer in solids is occurred due to movement of atoms at high temperature in which those atoms capable to transfer heat (Huang and Liu, 2009). Conduction heat transfer in an object had produced the slowest point of heat receiver (cold point) which located in center of object (Jaczynski and Park, 2002; and Opaku *et al*., 2006). Heat transfer on cylindrical object is assumed only occurred in radial direction so that temperature distribution in a point will highly depend on environment temperature which is the closest to that point and can be determined by using numerical method (Crank,1998; Heldman and Lund, 2007).

The determination of thermal diffusivity coefficient (α) on materials usually is determined in indirect way, i.e., thermal diffusivity coefficient is the ratio of thermal conductivity and specific heat and material density which can be presented as follows :

$$\alpha = \frac{k}{\rho C p} \qquad \text{...(1)}$$

According to Choi and Okos (1986) in Heldman and Lund (2007), determination of thermal diffusivity value obtained from ratio of material thermal conductivity (k) and specific heat (C_p) and material density (ρ) based on chemical composition of material was as follows :

$$k = k_m m_m + k_p m_p + k_f m_f + k_c m_c + k_a m_a \qquad \text{...(2)}$$

$$C_p = C_{pm} m_m + C_{pp} m_p + C_{pf} m_f + C_{pc} m_c + C_{pa} m_a \qquad \text{...(3)}$$

$$\frac{1}{\rho} = m_m \frac{1}{\rho m} + m_p \frac{1}{\rho p} + m_f \frac{1}{\rho f} + m_c \frac{1}{\rho c} + m_a \frac{1}{\rho a} \qquad \text{...(2)}$$

Thermal diffusivity coefficient can also be determined by using numerical model based on temperature distribution during boiling process (Figure 2). The numerical model is assumed to be better because it is capable to detect the changes of temperature and thermal diffusivity at each observation unit during pempek's boiling process which can reduce the probability of material damage due to heat treatment. The direct determination of α value by using numerical model is conducted if data of temperature distribution (T) in relation to time (t) and distance from material's center point (r) had been determined. The measurement is conducted by using thermocouple for materials having sphere and cylindrical forms in one dimension.

RESEARCH OBJECTIVES

1. To determine the estimated thermal diffusivity coefficient of pempek lenjer by using numerical model and to compare it with thermal diffusivity coefficients based on chemical composition and analytical method.
2. To determine the optimum time and temperature of pempek lenjer boiling process for each formulation by using numerical model.

RESEARCH METHOD

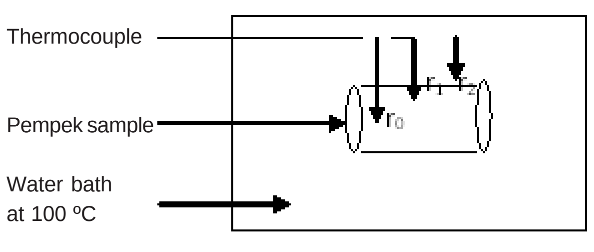
This study was conducted at Agricultural Technology Laboratory, Faculty of Agriculture, Sriwijaya University from January to April 2015. Materials used in this study were tapioca flour, snakehead fish (*Ophicepallus striatus* Blkr), table salt and ice water. Formulation of fish and tapioca flour (F) in this study were as follows : $F_1 = 1 : 0.5$; $F_2 = 1 : 1.0$; $F_3 = 1 : 1.5$ and $F_4 = 1 : 2.0$, whereas temperature (T) treatments were T_1 = 75ºC ; T_2 = 80ºC ; T_3 = 85ºC ; T_4 = 90ºC and T_5 = 95ºC. Determination of thermal diffusivity coefficients based on analytical method and chemical composition were used as control treatment.

RESEARCH PROCEDURE

a. Production of pempek lenjer dough according to the formula with addition of water and 2.5% of table salt. The addition of water follows the equation below : 75% dough weight – (water content of fish x fish weight) – (water content of flour x flour weight).

b. Weighing of 350 g pempek dough followed by moulding it into cylindrical form (*lenjer*) and subsequently boiling it in waterbath at temperature of 100º C. Mesurement of pempek's temperature was done by providing K-type thermocouple network (Figure 1) which was installed at three measurement points during the boiling process. This thermocouple was installed to guarantee the position of sample temperature measurements at center point (r_0) = 0 cm, middle point (r_1) = 1 cm and surface point (r_2) = 2 cm. Samples that had already achieved temperatures of 75ºC, 80ºC, 85ºC, 90ºC and 95ºC on center point of pempek were uplift and air dried.

Figure 1: Experimental Design For Temperature Distribution Measurement On Pempek Lenjer Boiling Process



c. Determination of thermal diffusivity coefficient based on chemical composition.

Pempek that had already well cooked based on center point temperature of pempek was analyzed by using proximate analysis consisting of water content, protein content, lipid content, carbohydrate content, fiber content and ash content according to AOAC procedure.

Calculation of thermal diffusivity coefficient based on chemical composition of material was done by using the following equations :

$$k = k_m m_m + k_p m_p + k_f m_f + k_c m_c + k_a m_a$$

$$C_p = C_{pm} m_m + C_{pp} m_p + C_{pf} m_f + C_{pc} m_c + C_{pa} m_a$$

$$= m_m + m_p + m_f + m_c + m_a$$

d. Determination of thermal diffusivity coefficient using analytical method.

Thermal diffusivity coefficient using analytical method was determined by calculating the magnitudes of thermal conductivity coefficient k (W/m.^{o}C), specific heat Cp (kJ/kg.^{o}C) and density (kg/m^3) using the following equation:

$$\alpha = \frac{k}{\rho Cp}$$

e. Data analysis of thermal diffusivity based on numerical model was done by using computer program software of *Engineering Equation Solver* (EES) Ver 8.914.

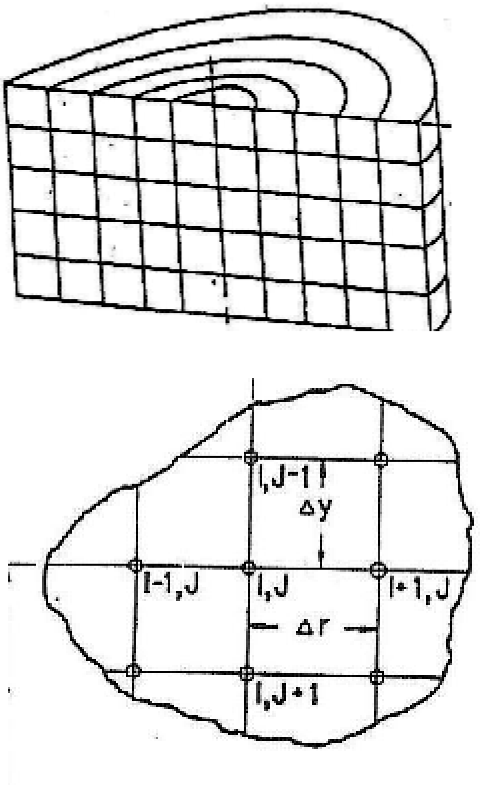
RESULTS AND DISCUSSION

Determination of Thermal Diffusivity Based on Numerical Model

Temperature distribution by using numerical method was determined from temperature distribution at a point which was close to that temperature such as shown in Figure 2.

Three dimension object such as a cube has sides length of Δx Δy Δz (Gerald, 2005). If a material quantity can be represented by its concentration (C), then at a period of Δt the change of material's concentration should be equal to net flux input of material during that time period (F). This expression mathematically can be presented as follows:

Figure 2: Temperature Distribution of Pempek Lenjer Using Numerical Method



$$F_x(x) - F_x(x + \Delta x)\Delta y\Delta z +$$

$$(C^{i+\Delta r} - C^{i})\Delta xy\Delta z = \Delta t\ F_y(y) - F_y(y+\Delta y)\Delta x\Delta z +$$

$$F_z(z) - F_z(z+\Delta z)\Delta x\Delta y \qquad ...(5)$$

where $F_x(x + \Delta x) = F_x(x) + . \Delta x$

Factor of Δx Δy Δz can be omitted so that equation (5) has the following form:

$$\frac{\rho c}{\partial t} + \frac{\partial Fx}{\partial x} + \frac{\partial Fy}{\partial y} + \frac{\partial Fz}{\partial z} = 0 \qquad ...(6)$$

Based on Fick first law, diffusion flux is concentration gradient multiply by diffusion coefficient and can be presented by the following equation:

$$F_i = -D\frac{\partial x}{\partial xi} \qquad ...(7)$$

Substitution of Equation (7) into Equation (6) yield:

$$\frac{\partial c}{\partial t} + \frac{\partial}{\partial xi}\left\{D\frac{\partial c}{\partial x}\right\} = 0 \qquad ...(8)$$

where i = 1, 2, 3 and D = diffusion coefficient. The Equation (8) above is known as governing equation for three dimensions diffusion process. If concentration C can be changed by T and Equation (8) is written in two dimensions, the following equation will be obtained:

$$\frac{\partial T}{\partial t} - D_x\frac{\partial^2 t}{\partial x^2} - D_y\frac{\partial^2 t}{\partial y^2} = 0 \qquad ...(9)$$

Equation (9) in one dimension will have the following form:

$$\frac{\partial T}{\partial t} - D\frac{\partial^2 t}{\partial x^2} \qquad ...(10)$$

Numerical scheme application from Equation (10) is as follows:

$$\frac{T_r^{t+1} - T_r^t}{\Delta t} = D\frac{T_r^{t-1} - 2T_r^t + T_{r+1}^t}{\Delta X^2} \qquad ...(11)$$

Application of thermal diffusivity by using numerical model for pempek lenjer boiling process is as follows:

$$D = \alpha = \frac{\Delta r^2}{\Delta t}$$

$$= \left\{\frac{r\left(T_r^t - T_r^{t-1}\right)}{\left(\Delta r + r\right)T_{r+1}^{t-1} - \left(\Delta r + 2r\right)T_r^{t-1} + r\left(T_{r-1}^{t-1}\right)}\right\} \qquad ...(12)$$

Estimation of temperature distribution at center part of pempek by using fundamental equation of conduction heat transfer (Holman, 1996) is as follows:

$$\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2} + \frac{\partial^2 T}{\partial Z^2} = \frac{\rho Cp}{k}\frac{\partial T}{\partial t} \qquad ...(13)$$

Equation (13) in cylindrical coordinate will have the following form:

$$\frac{1\partial T}{\alpha\partial r} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r}. + + \qquad ...(14)$$

Heat traansfer within cylinder is assumed only at radial direction of cylinder. Heat that exit and enter from axial direction can be neglected. Because temperature change at azimuth direction is too samll, then Equation (14) will have the following form:

$$\frac{1}{\alpha}\frac{\partial T}{\partial r} = \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \qquad ...(15)$$

$\frac{\partial T}{\partial r}$ is the rate of temperature change within a material. If the rate of temperature change is constant, then value of can be expressed in form of a constant, e.g. A, so that Equation (15) will have the following form:

$$\frac{1}{\alpha}A = \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial r^2} \qquad ...(16)$$

$\frac{\partial T}{\partial r}$ is temperature gradient related to timw within a material. If temperature gradient in material is at steady state, then its value is depend on time so that the following equation is obtained:

$$\frac{1}{\alpha}A = \frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} \text{ atau } \frac{Ar}{\alpha} = r\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr} \qquad ...(17)$$

By taking:

$$r\frac{d^2T}{dr^2} + \frac{dT}{dr} = \frac{d}{dr}\left(r\frac{dT}{dr}\right)$$

integration of Equation (17) will yield the following equation:

$$\frac{Ar^2}{2\alpha} + C_1 = r\frac{dT}{dr} \text{ atau } \frac{dT}{dr} = \frac{Ar^2}{2\alpha} + \frac{C1}{r}$$

and reintegration will yield the following equation:

$$T = \frac{Ar^2}{4\alpha} + C_1 \ln r_{+} C2 \qquad ...(18)$$

with the following boundary conditions :

1. Surface temperature (Ts) of material within cylinder (r = R) at time higher than zero (t > 0) is the rate of constant temperature change multiply by time. T = At = Ts at t ˆ 0 , r = R
2. For cylinder axis (r = 0), derivative or temperature gradient = 0 and at time higher than zero = 0 at t > 0, r = 0. By inserting the second boundary condition, then value of C1= 0, whereas by inserting the first boundary condition into Equation (18), the value of C2 = Ts - which in turn yield the following equation:

$$Ts - T = \frac{A(R^2 - r^2)}{4\alpha} \qquad ...(19)$$

By taking r as the center axis, i.e. r = 0 and T is the center temperature of cylinder (Tc), then the above diffusivity equation according to Moura *et al* . (1998) become :

$$\alpha = \frac{AR^2}{4(Ts - Tc)} \qquad ...(20)$$

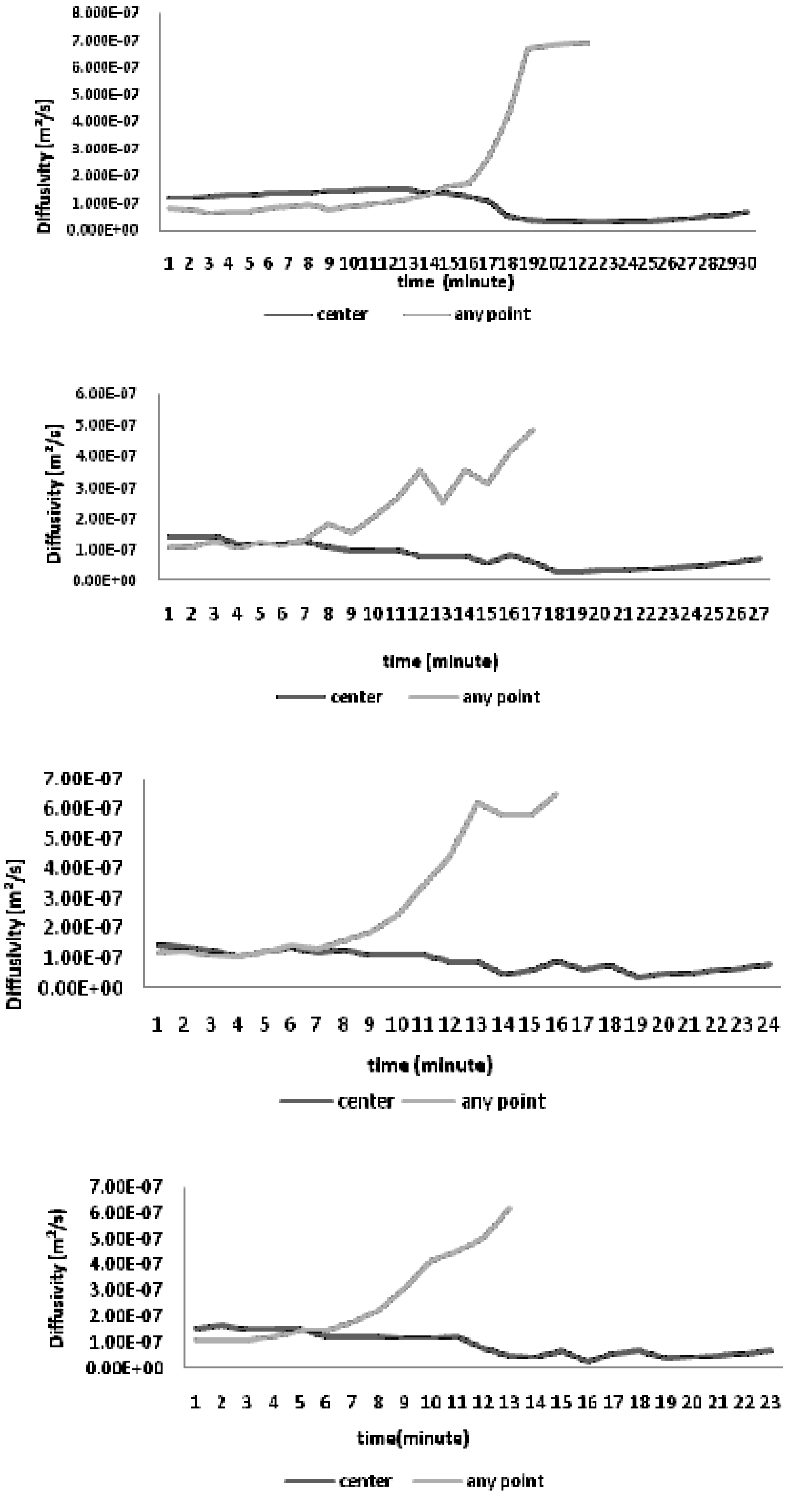
Application of numerical method to determine thermal diffusivity coefficient at center point of pempek lenjer was done by using the following model:

$$\alpha = \frac{\Delta r^2}{4\Delta t}\left\{\frac{\left(T_r^{t+1} - T_r^t\right)}{\left(T_{r+1}^t - T_r^t\right)}\right\} \qquad ...(21)$$

APPLICATION OF THERMAL DIFFUSIVITY COEFFICIENT BY USING NUMERICAL MODEL VERSUS CHEMICAL COMPOSITION AND ANALYTICAL METHOD

Determination of thermal diffusivity coefficient for pempek lenjer with numerical model was done by using model 12 and model 21. After pempek lenjer boiling process, there was dimension increment especially on radial direction of pempek lenjer. Water absorption from initial process is relatively small so that increment assumption can be neglected. Distribution of thermal diffusivity coefficient during boiling process tends to increase at initial stage of process and subsequently is decrease at middle and up to final stages (Figure 3). Because tapioca flour is in form of starch granule, water during heating process will quickly penetrate into granules resulting in expansion. Thermal diffusivity coefficient in this stage was still high so that pempek lenjer capable to absorb heat quickly from water medium. Gelatinization and gel formation on the outer part of pempek lenjer result in decrease of its heat absorption capacity because when the starch granule is broken, its structure become tight resulting in low value of thermal diffusivity coefficient. This is in accord to study result from Fournier *et al.* (2001) which showed that there

Figure 3: Thermal diffusivity coefficient at center point and at any point



was correlation between material hardness and thermal diffusivity coefficient. Thermal diffusivity rate on center point tend to be transiently slower (Ansari *et al*., 2007; Singhal *et al*., 2008) so that temperature on center point tend to be slower in approaching medium temperature compared to temperature near the material surface.

Linear equations for thermal diffusivity by using numerical model were as follows:

Formula 1 : Y = 1.60E-07 - 4.30E-09 X ($r^2 = 0.725$)

Formula 2 : Y = 1.36E-07 - 4.02E-09 X ($r^2 = 0.785$)

Formula 3 : Y = 1.45E-07 - 4.13E-09 X ($r^2 = 0.743$)

Formula 4 : Y = 1.62E-07 - 5.64E-09 X ($r^2 = 0.792$)

Remarks:

Y = thermal diffusivity (m^2/s)

X = time (minutes) for X > 0

Constant condition is assumed to be achieved when the rate of temperature change ºC/minute had relatively stable value for each time. Stable condition time is boiling optimum time because pempek lenjer had already in well cooked condition. Figure 3 showed that any points had achieved maximum value of thermal diffusivity coefficient. The fish dominant formula required longer cooking time because of low thermal diffusivity. This was due to the fact that fish flesh protein experience denaturation at temperature of >70ºC (Suzuki, 1981), whereas tapioca flour experience gelatinization at temperature of 64.5ºC (Haryadi, 1995). High quantity of fish flesh results in high lipid content and protein content which form complex structure with amylose that produce layer or sediment on surface. This in turn disturbed the amylose explusion from granule

Table 1: Thermal Diffusivity Coeffients Based On Chemical Composition Of Pempek After Well Cooked

Formula	Diffusivity α (10^{-7}m^{2}s^{-1}) at well cooked temperatures				
	75 ^{0}C	80 ^{0}C	85 ^{0}C	90 ^{0}C	95 ^{0}C
F1	1,3023±0,010hE	1,3282±0,010gE	1,3484±0,036gD	1,3693±0,077fD	1,3712±0,040 eD
F2	1,3267±0,043hE	1,3476±0,060gD	1,3515±0,012fD	1,4115±0,026dC	1,4244±0,019cB
F3	1,3547±0,042fD	1,3894±0,034eC	1,4191±0,012dB	1,4251±0,022cB	1,4568±0,024bA
F4	1,3912±0,041eC	1,3872±0,045eC	1,4342±0,048cB	1,4403±0,022bcB	1,4784±0,010aA

Remarks : Numbers followed by the sama characters are not significantly different.

Table 2: Thermal diffusivity coeffients of pempek Lenjer Using Analytical Method After Well Cooked

Formula	Diffusivity α (10^{-7}m^{2}s^{-1}) at well cooked temperatures				
	75 ^{0}C	80 ^{0}C	85 ^{0}C	90 ^{0}C	95 ^{0}C
F1	1,3130	1,3280	1,3540	1,3683	1,3759
F2	1,3280	1,3488	1,3513	1,4270	1,4679
F3	1,3880	1,3919	1,4063	1,4263	1,4599
F4	1,3922	1,4014	1,4254	1,4300	1,48302

because of water absorption barrier so that higher energy is required to expel amylose from complex structure of protein and lipid (Richana and Titi, 2004).

The higher the thermal diffusivity coefficient, the faster was the heat energy that was diffused into material so that pempek lenjer was well cooked faster. The rate of heat transfer process from boiling water was affected by water diffusivity property within solid. Pempek surface in direct contact with boiling water had higher water quantity than water quantity within material so that water diffusion process is proceed from surface into material. Water that enters into material will occupy pores and water diffusion process will continue until the end of boiling. Thermal diffusivity coefficient of pempek lenjer by using numerical model was in the range of 1.36 to 1.62 x 10^{-7} m^2/s. Thermal diffusivity coefficient of tapioca flour was 1.346 x 10^{-7} m^2/s, whereas thermal diffusivity coefficient of snakehead fish was 0.671 x 10^{-7} m^2/s (Sun, 2006).

Specific heat of a material is affected by its composition which consisted of protein content, lipid content, carbohydrate content, water content and ash content.

Specific heat will increase if water content of material is increase and vice versa. Specific heat value is directly proportional to thermal conductivity value of a material. Heat transfer rate is affected by thermal properties of material (k dan Cp), initial water content of material, chemical composition of material and temperature of boiling water. Differences in heat conductivity coefficient of pempek was due to differences in temperature and material formulation because heat conductivity coefficient of a material is depend on structure, form, porosity and homogenity of material. This in turn affect the different in heat transfer direction. Heat conductivity (k) is a constant value of material which show material capability to transfer calor or heat conductivity is the rate of calor flow within material. The denser of a material, the lower is its heat conductivity and vice versa.

Thermal diffusivity coefficient of pempek lenjer by using numerical model was in the range of 1.36 to 1.62 x 10^{-7} m^2/s. Thermal diffusivity coefficient of pempek lenjer based on chemical composition was in the range of 1.302 to 1.478 x 10^{-7} m^2/s, whereas thermal diffusivity coefficient based on analytical method was in the range of 1.313 to 1.483 x 10^{-7} m^2/s. Thermal diffusivity coefficients based on numerical model, chemical composition and analytical method were relatively similar so that numerical model can be used because it can detect the changes in temperature and thermal diffusivity at each observation unit (minute) during pempek lenjer boling process.

CONCLUSION

1. Thermal diffusivity coefficients based on numerical model, chemical composition and analytical method were relatively similar so that numerical model can be used because it can detect the changes in temperature and thermal diffusivity at each observation unit (minute) during pempek lenjer boling process.
2. Thermal diffusivity coefficient of pempek lenjer by using numerical model was in the range of 1.36 to 1.62 x 10^{-7} m^2/s. Thermal diffusivity coefficient of pempek lenjer based on chemical composition was in the range of 1.302 to 1.478 x 10^{-7} m^2/s, whereas thermal diffusivity coefficient based on analytical method was in the range of 1.313 to 1.483 x 10^{-7} m^2/s.

3. Formula of fish dominant pempek lenjer required boiling time of 22 minutes with center point temperature of 87 ^{o}C, whereas formula of tapioca flour dominant pempek lenjer required boiling time of 13 minutes with center point temperature of 80 ^{o}C.

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NOMENCLATURE

α = thermal diffusivity (m^2/s)
k = thermal conductivity (J/m.ºC.s)
ρ = density (kg/m^3)
C_p = specific heat (J/kg.ºC)
A = temperature gradient rate (ºC/min)
P = protein
F = lipid
C = carbohydrate

Fi = fiber
A = ash
M = water
c = concentration
T = temperature
t = time
r = material center point

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