Application of heat transfer equations during unsteady-state condition to Indonesian cooked fermented soybean (Tempeh) in boiling and during cooling period

E Yusraini* and T Karo-Karo

Department of Food Science and Technology, Faculty of Agriculture, Universitas Sumatera Utara, Medan, Indonesia.

E-mail: *era.yusraini@usu.ac.id or era_yusraini@yahoo.com

Abstract. Tempeh originated from Indonesia. This nutritious food usually served after boiled, fried, steamed, or baked. The time duration to cook tempeh needs to analyses, especially to maintain its nutritional benefits. This study aimed to test the unsteady-state heat transfer equation's suitability based on the Schneider chart during tempeh's boiling and cooling. The stick-shaped tempeh using banana leaf packaging was cut to a size of 2 cm. The temperature at the centre of the tempeh during the heat and air penetration was measured every two minutes using a digital thermometer. The \( c_p \) and \( k \) equations for predicting tempeh's thermal diffusivity during the boiling and cooling time were not suitable. It resulted in inaccuracy in predicting the temperature inside the geometric centre in the experimental data using unsteady-state equations. The line equation based on experimental data at the boiling time was \( y_b = -1.91 x^2 + 23.69 x + 27.68; R^2 = 0.99 \) and during the cooling time was \( y_c = 0.57 x^2 - 10.37 x + 96.75; R^2 = 0.99 \).

1. Introduction

Tempeh is a typical Indonesian food originating from Central Java and known already throughout the world. This product results from the fermentation of dry cooked soybean using yeast Rhizopus sp and Mucor sp [1]. The main nutritional content of tempeh is protein around 41-51% [2], and without aflatoxins [3]. In its serving, tempeh can directly be consumed because it has been boiled before the fermentation process is carried out. However, tempeh usually is processed into various types of food by heating, such as boiling, steaming, frying, and baking. Boiling and steaming are the alternative ways to preserved tempeh before it is stored in a refrigerator [4]. The heat application of high temperature in the long term can reduce the food product's nutritional content, including tempeh. Thus, the temperature of the product during heating needs to be predicted.

During the heat transfer process, the temperature of the product always changes until it reaches the temperature of the heating medium. This transfer of heat is called transition heat transfer or unsteady-state heat transfer. Some of the unsteady-state heat transfer equations in food products are lumped-system analysis when the products are liquid which mixed well, using the Heisler charts, Schneider charts, or the Ball method [5]. However, when the Fourier number is less than 1 due to the thermal diffusivity of products is low, Schneider charts are more helpful [5].

Several publications have described the use of unsteady-state heat transfer in food products such as [6-8]. So far, there has been no testing on the application of unsteady-state heat transfer at tempeh.
This study aimed to test the unsteady-state heat transfer equation’s suitability based on the Schneider chart at tempeh during boiling and cooling time.

2. Materials and methods
The raw material for fermented tempeh using banana leaf packaging was obtained from small and medium industries in Medan, North Sumatra, Indonesia. The stick-shaped tempeh was then cut to a size of 2 cm. The temperature measuring instrument used was a portable digital thermometer (TM-902C with accuracy ± 2°C) attached to the centre of the product. The testing process was carried out by boiling one litre of distilled water in a container. Thus, the initial temperature of boiling water was measured before the tempeh pieces were added. Heated tempeh was tested for its specific gravity first. The temperature at the centre of the tempeh during heat penetration were measured every two minutes until the temperature of the heating medium was reached. Then, tempeh was transferred from boiling water to air at room temperature. The temperature at the centre of the tempeh during air penetration were measured too in every two minutes. Each treatment was carried out three times. Furthermore, the temperature at the centre of tempeh at a certain condition was calculated using equation models which read based on Schneider chart. The thermal conductivity (k) and the specific heat (c_p) of tempeh were calculated based on the Sweat (1974) and Siebel (1892) equations respectively [5]. The particle density of tempeh was measured according to [5] which accounts as ratio of the actual value of mass to its volume. The temperature results obtained from the measuring instrument were then compared with predictions using equations and the percent error was calculated.

Temperature in the centre were estimated according to [5]. Firstly, Biot number (Bi number) and Fourier number (Fo number) were computed. From Schneider chart [9] for infinite slab, the temperature ratio can be read and finally the geometric centre’s temperature was calculated. The tempeh characteristics (analysed) and thermal properties (collected from literature) are presented in Table 1.

| Table 1. Physical characteristic and thermal properties of the studied tempeh |
|-----------------------------------------------|-----------------|------------------------------|
| Width (m) | Equations [4] | Value (means ± standard deviation)* |
| Particle density; ρ (kg m⁻³) | - | 740 ± 20* |
| Moisture (%) ; X_w | - | 65.1 ± 0.8* |
| c_p (kJ kg⁻¹ °C⁻¹) | 0.837 + 3.349 (X_w) | 3.013 |
| k (W m⁻¹ °C⁻¹) | 0.148 + 0.493 (X_w) | 0.468 |
| α (m² dt⁻¹) | k /ρ c_p | 2.1 x 10⁻⁷ ± 1.4 x 10⁻⁸* |
| h boiling water (W m⁻² °C⁻¹) [4] | - | 3000 |
| h air (W m⁻² °C⁻¹) [4] | - | 31 |

Note: List of symbols
- c_p = specific heat (kJ kg⁻¹ °C⁻¹)
- k = thermal conductivity (W m⁻¹ °C⁻¹)
- h = convective heat transfer coefficient (W m⁻² °C⁻¹)
- α = thermal diffusivity (m² s⁻¹)

3. Results and discussion
The geometric shape of analysed tempeh was slab which could be cut easily for width 0.02 m. However, these products had irregular arrangement which combined between cooked soybean and the hyphae resulted different density (Table1). Density of tempeh from [10] was around 0.72 g cm⁻³ or 720 kg m⁻³. The difference of density with studied result (740 kg m⁻³) was due to different variety of bean and the starter. The moisture content of studied tempeh (Table 1) is 65.1 ± 0.8%. This value was
quite similar to that observed by [11] from Java island, Indonesia, which around 67.1 ± 6.73%. Furthermore, these results were higher than tempeh from the USA [12] (59.56%), UK [13] (61.0%), and from Pakistan [14] (62.38%). Tempeh moisture variation occurred probably due to different processes during tempeh fermentation related to production steps (boiling-stripping-soaking-acidification-washing-inoculation with yeast-packaging and fermentation), environmental conditions such as temperature and relative humidity, and time of fermentation.

The polynomial lines and equations of regression at both conditions while boiling and cooling time from experimental data can be seen in Figure 1 and Figure 2. These regression lines have a high coefficient of determination around 0.99, which determined that it can predict tempeh temperature with a size around 2 cm during boiling and cooling time.

![Figure 1](image1.png)

**Figure 1.** The temperature increases during boiling time of tempeh with equation

\[ y_b = -1.91x^2 + 23.69x + 27.68; \quad R^2 = 0.99 \]  

(1)

![Figure 2](image2.png)

**Figure 2.** The temperature decreases during cooling time of tempeh with equation

\[ y_c = 0.57x^2 - 10.37x + 96.75; \quad R^2 = 0.99 \]  

(2)
The temperature in geometric centre were shown in Table 2. The calculated results have disagreed well with the experimental data obtained from boiling and cooling tests. It is probably caused by high diffusivity of tempeh more than the prediction value from \( c_p \) and \( k \) equations due to contained hyphae. The unsteady-state equations are useful for tempeh during heat transfer operations if other \( c_p \) and \( k \) equations are inputted since the thermal diffusivity is related to the temperature. The higher the temperature applied, the higher the rate of temperature spread through a material.

### Table 2. Temperature in geometric centre (T~) of the studied tempeh (prediction and experiment)

| Parameters                        | Boiling time (minutes) | 2  | 4  | 6  | 8  |
|-----------------------------------|------------------------|----|----|----|----|
| \( T\sim \) (°C)                 |                        |    |    |    |    |
| \( T_{\text{initial}} / T_i \) (°C) |                        |    |    |    |    |
| Bi number = \( h \ L /k \); at boiling time | 26.6 ± 1.2 | 26.6 ± 1.2 | 26.6 ± 1.2 | 26.6 ± 1.2 |
| Fo number = \( k t / \rho c_p L^2 \) | 0.25 ± 0.02 | 0.50 ± 0.04 | 0.76 ± 0.05 | 1.01 ± 0.06 |
| Temperature ratio = \( (T_c - T\sim) / (T_i - T\sim) \) from Schneider chart | 0.71 ± 0.02 | 0.42 ± 0.04 | 0.25 ± 0.03 | 0.13 ± 0.04 |
| \( T_c \) prediction (°C)       | 47.3 ± 2.3             | 67.9 ± 3.0 | 80.3 ± 2.4 | 88.6 ± 2.7 |
| \( T_c \) experiment (°C)      | 67.7 ± 0.8             | 94.1 ± 1.9 | 97.8 ± 0.1 | 97.8 ± 0.1 |
| Percent error (%)               | 43.4                   | 38.7     | 21.9  | 10.5 |

| Parameters                        | Cooling time (minutes) | 2  | 4  | 6  | 8  |
|-----------------------------------|------------------------|----|----|----|----|
| \( T\sim \) (°C)                 |                        |    |    |    |    |
| \( T_{\text{initial}} / T_i \) (°C) |                        |    |    |    |    |
| Bi number = \( h \ L /k \); at cooling time | 0.66         | 0.66     | 0.66  | 0.66  |
| Fo number = \( k t / \rho c_p L^2 \) | 0.25 ± 0.02 | 0.50 ± 0.04 | 0.76 ± 0.05 | 1.01 ± 0.06 |
| Temperature ratio = \( (T_c - T\sim) / (T_i - T\sim) \) from Schneider chart | 0.94 ± 0.02 | 0.82 ± 0.02 | 0.72 ± 0.03 | 0.63 ± 0.05 |
| \( T_c \) prediction (°C)       | 93.4 ± 1.07            | 85.1 ± 1.25 | 78.2 ± 1.50 | 73.1 ± 3.18 |
| \( T_c \) experiment (°C)      | 77.5 ± 0.72            | 64.6 ± 0.98 | 55.9 ± 0.90 | 49.5 ± 0.75 |
| Percent error (%)               | 17                     | 24.1     | 28.4  | 30.4 |

Note: List of symbols
- \( h \) = convective heat transfer coefficient (W m\(^{-2}\) °C\(^{-1}\))
- \( L \) = dimension or half of width (m)
- \( K \) = thermal conductivity (W m\(^{-1}\) °C\(^{-1}\))
- \( T \) = time of heating (second)
- \( \rho \) = particle density (kg m\(^{-3}\))
- \( c_p \) = specific heat (kJ kg\(^{-1}\) °C\(^{-1}\))
- \( T_c \) = final temperature of geometric centre (tempeh) °C
- \( T\sim \) = temperature of boiling water °C
- \( T_i \) = initial temperature of tempeh °C

There is minimal literature on specific heat and thermal conductivity about fermented soybean. Published literature found only related to specific heat of soybean was [15] that explained specific heat of soybean as \( c_p = 1.444 (1+4.06 \times 10^2 \ M) \), which\( M \) as moisture content around 8.1 to 25%. Another reference was [16], which computed the thermal diffusivity of soybean with similar moisture content ranging approximately \( 4.9 \times 10^{-6} \) to \( 5.11 \times 10^{-6} \) m\(^2\) s\(^{-1}\). These two references had lower values than those used in this study. In addition, the thermal properties of tempeh might to be different from soybeans due to several fermentation steps to produce tempeh.
4. Conclusions
The unsteady-state heat transfer equations (Schneider chart) did not predict very well the temperature of boiling and cooling tempeh. The tempeh structure contained with hyphae could be a possible effect that made the products experience a faster increase in temperature while heat penetration using boiling water and decrease in air temperature than the equation predicted result.

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