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Mathematical Modeling of Frying Oil Temperature During the Deep-Fat Frying Process

Watid Cheevasathianchaiporn* and Chairath Tangduangdee

ABSTRACT

Modeling of oil temperature is useful for designing a fryer with enough power supply to avoid the problem of the oil temperature dropping. The objective of this work was to formulate a mathematical model of the change in oil temperature during the deep-fat frying process. In this work, the power supply and heat loss to the surroundings were taken into account as well as the heat spent in water evaporation and heating the product. The heat transfer coefficient of heat loss was firstly determined during heating of the frying oil without any frying product. A value of around 8.49 W/m$^2\cdot$°C was obtained. The simulated oil temperature was then validated with experimental data from frying chicken breasts. Compared with the observed data, the predicted result was reasonable when the heat resistance between the heating coil and the oil was included in the model.

Key words: deep-fat frying, frying oil temperature, heat resistance between coil and oil, mathematical model, overall heat transfer coefficient of heat loss

INTRODUCTION

Deep-fat (or immersion) frying (DFF) is a cooking and drying process using a hot oil medium and is widely used in food preparation. It may be defined as the process of immersing food material in edible oil or fat at a temperature above the boiling point of water (Farkas *et al*., 1996). Deep-fat fried products are widely consumed in many countries of Europe, Asia and North and South America. Some examples of deep-fat fried products are French-fries, donuts and fried chicken. Many changes in the physical, chemical and nutritional qualities of fried products occur during the process and depend on frying conditions, such as the frying oil temperature, frying time, types of oil and food (Moreira *et al*., 1999). These conditions are controlled by heat and mass transfer between the product being fried, the frying oil and the surroundings. Therefore, many research studies have been conducted in order to understand the process, and to determine how to control the product qualities.

Farkas *et al*. (1996) proposed an elaborate mathematical model to describe heat and mass transfer in an infinite slab undergoing the DFF process. The sample was divided into two regions, the core and the crust. Vijayan and Singh (1997) formulated a heat transfer model for immersion frying of frozen foods. Tangduangdee *et al*. (2004) studied heat and mass transfer in a composite food system during the DFF process. Moisture migration was included in the heat transfer model and the influence of crust thermal

Department of Food Engineering, Faculty of Engineering, King Moungkut's University of Technology Thonburi, Bangkok 10140, Thailand.

*	Corresponding author, e-mail: watid.chee@yahoo.com

properties was studied. Most researchers made an assumption of an isothermal boundary condition to simplify the model. This meant that the frying oil temperature was kept constant throughout the process. However, in reality the frying oil temperature changes suddenly, especially in the initial stage of frying when the food is immersed in the oil, except in the case where there is a high ratio of the oil-to- product volume, which is usually found in a laboratory. For batch frying, the frying oil temperature drops substantially and then increases gradually to the fryer setting temperature (Chen and Moreira, 1997). Few attempts have been made to include heat loss to the surroundings and to the heat supply in the model. Chen and Moreira (1997) proposed a model of oil temperature change, but the heat loss and power supply terms were not included. Rywotycki (2002) developed a mathematical model of heat energy consumption in a continuous frying process at steady state by using a constant overall heat transfer coefficient of 1.4 W/m$^{2}\cdot$°C to determine the thermal power transmitted through a continuous fryer casing. Rungjumrus (2005) designed a vacuum fryer and calculated the power supply by assuming that the heat loss to the surroundings was about 10% of the heat supply. Modeling of the oil temperature change is not only useful for designing the fryer to supply enough power, but also for simulating an appropriate oil volume-to- product ratio to avoid the problem of the oil temperature dropping. The objective of this study was to formulate and validate a predictive model of oil temperature during the frying process.

MATERIALS AND METHODS

Mathematical model

The frying oil temperature during the deep-fat frying process can be modeled using an energy balance within the controlled volume of the frying oil. Heat accumulation within the control volume resulting in an oil temperature change depends on the heat input (or power supply), energy spent on water evaporation, energy spent on heating food and heat transmitted to the surroundings. Equation 1 calculates the change in the oil temperature:

$$\rho_{oil}V_{oil}C_{poil}\frac{\partial T_{oil}}{\partial t} = Q_{input} - m_{food,dry}h_{fg}\frac{\partial M_{d,av}}{\partial t} - m_{food}C_{pfood}\frac{\partial T_{food,av}}{\partial t} - KA(T_{oil} - T_{sur}) \quad (1)$$

The second and the third terms on the right hand side of Equation 1 represent the heat for the moisture evaporation rate and the sensible heat transfer rate of the food being fried, respectively, and can be calculated from the average moisture and temperature changes at a given time (Equations 2 and 3).

$$Q_{evaporation} = m_{food,dry}h_{fg}\frac{\partial M_{d,av}}{\partial t} \quad (2)$$

$$Q_{heat} = m_{food}C_{pfood}\frac{\partial T_{food,av}}{\partial t} \quad (3)$$

The fourth term defines the heat transmitted to the surrounding. The *K*-value can be determined experimentally by recording the power supply in any time interval (t_n) without frying food. The oil temperature is kept constant using a temperature controller. Heat loss to the surroundings is therefore equal to the average power supplied (Q_{input}). An average *K*-value can be calculated from Equation 4.

$$K = \frac{\sum_{n=1} (W \times t_n)}{t_{total}A(T_{coil} - T_{sur})} \quad (4)$$

In this paper, the *K*-value was determined and the simulation of the oil temperature change without frying food and undergoing the frying process was validated with observed data.

Determination of overall heat transfer coefficient for the casing of the fryer (*K*-value)

To determine the heat loss from the frying oil to the surroundings, a four-liter batch fryer (Model F-2000, Fagor) was used, with a surface area of 1,560 cm^2. A total of 3 L of palm oil was heated to a setting temperature of 180°C by an electrical heater of 1800 W and controlled by a temperature controller. The oil temperature near the heating coil surface (T_{coil}) and the surrounding temperature (T_{sur}) were recorded using thermocouples (T-type) and a data logger (Model DX 1012-4-2, Yokogawa, China) as shown in Figure 1. During heating of the frying oil, the elapsed time for power supply on-off (t_n) was collected and then the overall heat transfer coefficient (K-value) was calculated using Equation 4. Three replications were used for determination of the K-value and then the oil temperature change was computed and compared with the observed data.

Solution and validation of mathematical model

In this study, the frying oil temperature was numerically solved using the finite difference method for both cases of sample and no sample presence. The program was coded with the MATLAB® (V.7.5.0:R2007b) program. The frying sample used in this study was chicken breast, which had a weight and initial temperature of around 225 g and 23°C, respectively. The thermophysical properties of the sample and frying oil were assumed constant. The heat capacity of the sample was 3530 J/kg·°C. The heat capacity and density of the frying oil were 2200 J/kg·°C and 920 kg/m^3, respectively (Rungjumrus, 2005).

For this experiment, two pieces of chicken breast were fried in the batch fryer containing hot palm oil at a setting temperature of 180°C with an oil-to-sample ratio of 8:1 (V/V). The temperature of the sample at three different locations was measured using the thermocouples and then an average temperature of the sample was calculated, whereas the average moisture content was measured by sampling at 0, 30, 60, 120,180, 240 and 300 s (AOAC, 1995). Each experiment had two replications.

RESULTS AND DISCUSSION

The results of the study were divided into two parts. Firstly, the heat transfer coefficient for the heat loss from the fryer casing to the surrounding was determined and then the oil temperature change was validated with an experiment without frying food. Secondly, the oil temperature change during the frying of the chicken breasts was simulated and experimentally validated.

Overall heat transfer coefficient for heat loss (K) and oil temperature change without frying food

To determine the heat transfer coefficient of heat loss (K-value), an attempt to keep the oil temperature constant at 180°C was made using a controller. The K-value was then calculated by

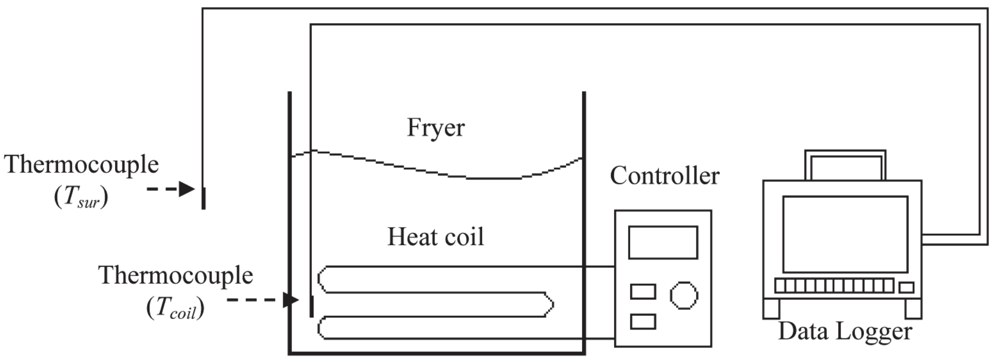

Figure 1 Schematic of equipment for experiment.

Equation 2, with an assumption of no heat accumulation in the frying oil. The calculated K-value was around 12.83 W/m$^{2}\cdot$°C. However, fluctuation of the oil temperature was observed. Equation 1 was then solved for the oil temperature change using the K-value of 12.83 W/m$^{2}\cdot$°C and compared with observed data as shown in Figure 2. It was found that the pattern of the simulated (- - -) and the observed (.......) oil temperature changes were the same, but different in frequency. It was probably caused by the heat accumulation in the heating coil when the power was turned off, thereby slowing the response. After tuning the K-value to 8.49 W/m$^{2}\cdot$°C, the predicted oil temperature represented by the solid line (—) was preferable when compared to the experiment. The adjusted value was further employed to simulate the oil temperature change during the frying of the chicken breasts.

Validation of oil temperature model during frying process

Figure 3 shows the average temperature and moisture content of the chicken breast undergoing frying. The temperature and the moisture changes at a given time ($dT_{food,av}/dt$ and $dM_{d,av}/dt$) were calculated from empirical Equations 5 and 6 obtained by curve fitting:

$$T_{food,av} = 23.0249 + 0.9804t^{0.6838} \qquad R^2=0.9979 \qquad (5)$$

$$M_{d,av} = 1.4844 + 1.4403\exp(-0.0041t) \qquad R^2=0.9911 \qquad (6)$$

Figure 4 presents the oil temperature versus frying time. The highest oil temperature during frying was around 180°C because the amount of heat that accumulated in the heating coil when the power was turned off during the frying process was much less than when no food was being fried. Thus, the upper and lower limits of the oil temperature in the model were set at 180° C and 173°C, respectively, instead of 185°C and 173°C in the without-frying case. As expected, when the sample was immersed in the frying oil, the oil temperature suddenly dropped and was lower than the predicted temperature. That meant the 1800 W of power could not be directly supplied

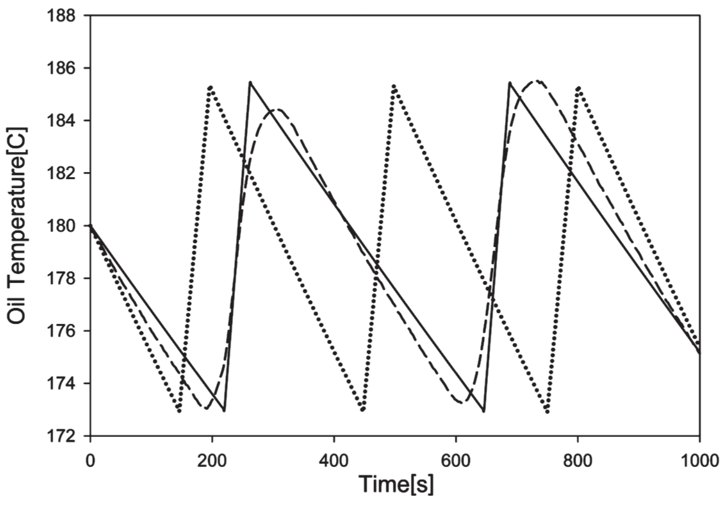

Figure 2 Oil temperature change with time without frying food.
(Settling temperature = 180°C): - - - Experiment,
—— Simulated oil temperature using the K-value of 8.49 W/m$^{2}\cdot$°C,
...... Simulated oil temperature using the K-value of 12.83 W/m$^{2}\cdot$°C.

to the frying oil, but was gradually accumulated within the heating coil and then transferred to the frying oil. The heat transfer rate from the heating coil to the frying oil was therefore lower than that required by the food. As a result, the oil temperature continued to decrease although the power was turned on and appeared only at the first loop of the oil temperature decreasing. Contrary to the model (- - -), a uniform oil temperature within the control volume was assumed and the power was directly supplied to the oil, resulting in an increase in the oil temperature as soon as the

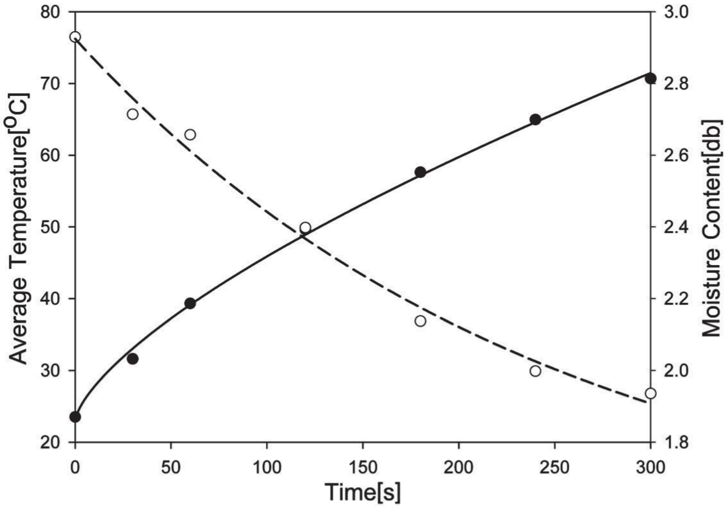

Figure 3 Average temperature and moisture content of sample from experiment:
• Experimental average temperature, ◦ Experimental moisture content,
── Curve average temperature, - - - Curve moisture content.

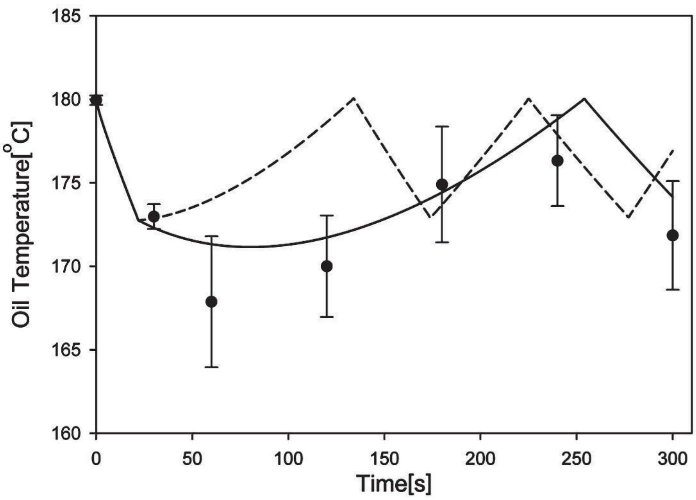

Figure 4 Oil temperature change with time during frying process.
(Settling temperature: 180°C): • Experiment,
── Simulated oil temperature without heat resistance,
- - - Simulated oil temperature with heat resistance.

lower limit was reached. Next, heat resistance between the heating coil and the oil was added to the model and assumed to be linear, with the power supplied with the factor. The factor of 0.24 (or 24% of Q_{input}) was determined by comparing the predicted and observed oil temperature. It was found that the predicted temperature continued to decrease for a short period and then it increased more slowly than the observed data in the first loop.

However, the model with the heat resistance gave more reasonable results than that without the heat resistance. Moreover, the function of the heat resistance should be related to the coil and coil properties instead of being linear with the power supply.

CONCLUSIONS

A mathematical model was proposed for the heat transfer in frying oil. The power supply and the heat to the surroundings were taken into account. The overall heat transfer coefficient for the casing of a fryer (*K*-value) of 8.49 W/m^2·°C was determined by fitting the model with the observed temperature, while the frying oil was being heated. The model of oil temperature was validated with the experiment. It was found that the predicted temperature changed with the same trend as the observed data, but was different in magnitude. The observed oil temperature suddenly decreased when the chicken breasts were immersed and continued to decrease although power was supplied, whereas the predicted temperature suddenly increased because the predicted power supply was greater than for the live process. Therefore, the heat resistance between the heating coil and the oil was added using a linear function of the power supply with a factor of 0.24. However, it was observed that addition of the heat resistance resulted in a more preferable prediction of the oil temperature. Therefore, the heat resistance was probably non-linear, as the model gave more reasonable results.

NOMENCLATURE

A	Area of heat loss, m^2
C_{pfood}	Heat capacity of fried food, J/kg·°C
C_{poil}	Heat capacity of frying oil, J/kg·°C
h_{fg}	Latent heat of water evaporation, J/kg
K	Overall heat transfer coefficient for the casing of the fryer, W/m^2·°C
m_{food}	Mass of food, kg
$m_{food,dry}$	Mass of food without moisture, kg
$M_{d,av}$	Average moisture content of fried food in dry basis, db
Q_{input}	Heat supply to frying oil, W
t	Time, s
t_n	Time of power supply, s
t_{total}	Total time in experiment, s
T_{coil}	Oil temperature around heat coil, °C
$T_{food,av}$	Average fried food temperature, °C
T_{oil}	Oil temperature, °C
T_{sur}	Surrounding temperature, °C
V_{oil}	Volume of frying oil, m^3
W	Power supply from heat coil, W
ρ_{oil}	Density of frying oil, kg/m^3

LITERATURE CITED

AOAC. 1995. **Official Methods of Analysis of AOAC International.** 16th ed. AOAC International. Verginia.

Chen, Y. and R.G. Moreira. 1997. Modeling of a batch deep-fat frying process for tortilla chips. **Food Bioprod. Process** 75: 181-190.

Farkas, B. E., R. P. Singh and T. R. Rumsey. 1996. Modeling heat and mass transfer in immersion frying. I: model development. **J. Food Eng.** 29: 211-226.

Moreira, R.G., M.E. Castell-Perez and M.A. Barrufet. 1999. **Deep-Fat Frying: Fundamentals and Applications.** Aspen Publishers. Maryland.

Rungjumrus, A. 2005. **Design and Performance Analysis of a Pilot-scale Vacuum Fryer.** M.S. Thesis. King Moungkut's University of Technology Thonburi, Bangkok.

Rywotycki, R. 2002. The effect of fat temperature on heat energy consumption during frying of food. **J. Food Eng.** 54: 257-261.

Tangduangdee, C., S. Bhumiratana and S. Tia. 2004. The role of moisture movement and crust thermal property on heat and mass process during deep-fat frying. **Int. Commun. Heat Mass Transfer** 31: 73-84.

Vijayan, J. and R.P. Singh. 1997. Heat transfer during immersion frying of frozen foods. **J. Food Eng.** 34: 293-314.