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Research Article

Heat transfer coefficients of a deep fat fryer

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Abstract

Heat transfer coefficient of a fryer is useful for design in order to control the temperature of frying oil at a desired level. A mathematical model of the frying oil temperature was developed to determine the heat transfer coefficient of an electrical fryer by creating an energy balance in the controlled volume of the frying oil. In this work, power supply and heat loss to the surrounding were taken into account, apart from heat spent for water evaporation and heating a product. The heat transfer coefficients were segregated into two parts: 1) heat transfer coefficient due to heat transmitted from casing of the fryer to the environment (*K*-value), 2) heat transfer coefficient between the heating coil and the frying oil (*U*-value), which was divided into U_{up}-value when the power supply was turned on and U_{down}-value when turned off. Initially, these values were determined without frying food at a setting temperature of 180°C and it was found that the *K*, U_{up} and U_{down}-values were 10.4, 3, 150 and 2,700 W/m^2·°C, respectively. However, when two pieces of chicken breast of 225 g each were fried in 3 litres of palm oil at 180°C, the coefficients rose up to 38, 20, 300 and 17,200 W/m^2·°C for *K*, U_{up} and U_{down}-values, respectively.

Keywords: food, energy, chicken breast, frying oil temperature, mathematical modeling

Introduction

Deep-fat or immersion frying (DFF) is a cooking and drying process by hot oil medium and is a common unit operation widely used in food preparation. It is probably best defined as the process of immersing food material in an edible oil or fat at a temperature above the boiling point of water [1]. Deep-fat fried products are widely consumed in many countries of Europe, Asia, North and South America. Some examples of deep-fat fried products are french-fries, doughnuts, fried chicken, etc. While the food is fried, many changes in the product in terms of physical, chemical and nutritional qualities occur and depend on the frying conditions, i.e., frying oil temperature, frying time, types of oil and food [2]. These conditions are controlled by heat and mass transfers between the product being fried, frying oil and surrounding. Therefore, much research has been conducted in order to understand the process and to control the product qualities, especially the effects of change in frying oil temperature during the frying process.

In the real frying process, the frying oil temperature suddenly changes, especially in the initial stage of frying when the food is immersed into the oil. This is in the exception of a high ratio of oil to product volume, which is usually found only in a laboratory. For batch frying, the frying oil temperature drops substantially and after that increases gradually to the fryer setting temperature [3]. Little attempt has been made to include heat loss to the surrounding and heat supply to the model. Chen and Moreira [3] proposed the model of oil temperature change but the heat loss and the power supply terms were not included. Rywotycki [4] developed a mathematical model of thermal energy consumption in a continuous frying process at steady state by using a constant heat transfer coefficient of 1.4 $W/m^2 \cdot °C$ to calculate heat loss from the fryer casing to the environment. Rungjumrus [5] designed a vacuum fryer and calculated power supply by assuming that the heat loss to the surrounding was about 10% of the heat supply. Modelling of the oil temperature change is not only useful for designing the fryer to supply sufficient power but also for simulating an appropriate oil volume to product ratio to avoid the problem of oil temperature dropping. The objective of this study was, therefore, to formulate and validate a predictive model of oil temperature during frying process and to determine the overall heat transfer coefficients of the fryer.

Materials and Methods

Mathematical model

The change of frying oil temperature during deep-fat frying process can be calculated by making an energy balance within a controlled volume of the frying oil. Heat accumulation within the controlled volume resulting in the frying oil temperature change depends on power supply, energy spent on water evaporation, energy spent on heating food and heat transmitted to the surroundings, and is given by [5]:

$$Q_{oil} = Q_{input} - Q_{evaporation} - Q_{heat} - Q_{loss} \quad (1)$$

where Q_{oil} is the heat accumulation in the frying oil and can be calculated by the following equation.

$$Q_{oil} = \rho_{oil} V_{oil} C_{p,oil} \frac{dT_{oil}}{dt} \quad (2)$$

where T_{oil} is the oil temperature (°C), which is time-dependent.

The first term on the RHS represents the heat transfer rate from the power supply to keep the oil temperature constant at a setting temperature controlled by an on-off controller and can be estimated by;

$$Q_{input} = U(t) A_{coil} LMTD(t) \quad (3)$$

where A_{coil} is the surface area of the heating coil (m^2), *LMTD* is the log mean temperature difference (°C) between the oil and coil temperatures, which is also time-dependent during the course of frying and is experimentally determined in order to estimate the time-dependent *U*-values.

$$LMTD^{j+1/2} = \frac{\left(T_{coil}^{j} - T_{oil}^{j}\right) - \left(T_{coil}^{j+1} - T_{oil}^{j+1}\right)}{\ln\left[\left(T_{coil}^{j} - T_{oil}^{j}\right) / \left(T_{coil}^{j+1} - T_{oil}^{j+1}\right)\right]} \quad (4)$$

where T_{coil} is the surface temperature of heating coil (°C). The superscripts *j* and *j*+1 are time-interval of data acquisition. Once the time-dependent *U*-values were estimated, an average *U*-value was determined.

The second and the third terms in Eq. (1) associate with the fried food in terms of heat for water evaporation and sensible heat transfer rate and are given by;

$$Q_{evaporation} = m_{food,dry} \lambda \frac{dM_{d,av}}{dt} \quad (5)$$

$$Q_{heat} = m_{food} C_{p,food} \frac{dT_{food,av}}{dt} \quad (6)$$

where m_{food} is the mass of food, (kg), $m_{food,dry}$ is the dry mass of food (kg), $M_{d,av}$ is the volume average moisture constant (kg/kg) and $T_{food,av}$ is the volume average temperature of food being fried (°C).

The last term is heat loss to the surrounding and given by;

$$Q_{loss} = KA_{fryer}(T_{oil} - T_{sur}) \quad (7)$$

where A_{fryer} is the external surface area of the fryer (m^2) including the cover of the fryer, *K* is the average heat transfer coefficient for the casing of the fryer ($W/m^2 \cdot °C$) and T_{sur} is the surrounding temperature (°C).

To solve the equations, three initial conditions (t=0) are needed:

$$T_{oil} = T_{oil,0} \quad (8)$$

$$T_{food,av} = T_{food,av0} \quad (9)$$

$$M_{d,av} = M_{d,av0} \quad (10)$$

In the case of no food being fried, the terms associated with the food are neglected and *K*- and *U*-values are then estimated by comparing the predicted results with the experimental data.

Determination of heat transfer coefficient

In this study, the heat transfer coefficient is divided into 2 parts, namely, internal heat transfer coefficient between heating coil and frying oil (*U*-value) and transmitted heat transfer coefficient between the frying oil and the environment (*K*-value) corresponding to Q_{input} and

Q_{loss}, respectively. Initially, 3-litres of palm oil was heated to a setting temperature of 180°C without frying food by an electrical heater of 1,800 W controlled by an on-off controller. A batch fryer, with a capacity of 4 litres (Model F-2000, Fagor) and 1,560 cm^2-external surface area (A_{fryer}), was used. The oil temperature near the heating coil surface (T_{coil}), the oil temperature (T_{oil}) and the surrounding temperature (T_{sur}) were recorded using thermocouples (T-type) and 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. Initially, K-value was estimated from the following equation:

$$K = \frac{\sum_{n=1} (W \times t_n)}{t_{total} A_{fryer} (T_{coil} - T_{sur})} \tag{11}$$

where W is electrical power supplied to the heating coil (W), t_n is interval time of power on (s) and t_{total} is the total experimental time (s).

Once an estimated K-value is known, the time-dependent U-value is then calculated by Eq. (12).

$$U^{j+1/2} = \frac{1}{A_{coil} LMTD^{j+1/2}} \left[\rho_{oil} V_{oil} C_{p,oil} \frac{T_{oil}^{j+1} - T_{oil}^{j}}{\Delta t} + K A_{fryer} (T_{oil}^{j} - T_{sur}) \right] \tag{12}$$

where A_{coil} is the surface area of the heating coil (0.0255 m^2), $LMTD^{j+1/2}$ and $U^{j+1/2}$ are average values in the time interval Δt. Finally, the average values throughout the process were determined for each experiment. In this study, the experiments were conducted in triplicate and then the average U-value was determined. The true value of U-value was checked again by comparing the oil temperatures obtained from prediction and observation.

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 no frying food and frying food. For the latter case, chicken breast of 225 g per each was used as the sample. MATLAB® (V.7.5.0:R2007b) program was employed to numerically solve the model of both cases with constant thermophysical properties. The heat capacities are 3,530 and 2,200 J/kg·°C for chicken breast and oil, respectively, and the density of the frying oil is 920 kg/m^3 [5].

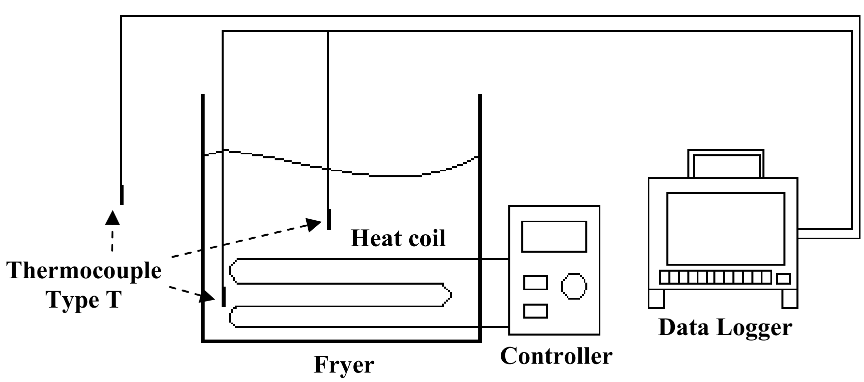

Figure 1. Schematic of equipment for experiment.

To validate the oil temperature model, 2-chicken breasts were fried in palm oil at 180°C with an oil-to-sample ratio of 8:1 by volume. Three different locations were measured for temperature using thermocouples (Type-T) and then an average temperature at a given time was calculated by volume integral method. For moisture content, the sample was taken at 0, 30, 60, 120, 180, 240 and 300 s [6]. The experiment was conducted in duplicate and the average moisture content was determined. The intended simple correlation of time-dependent moisture content and temperature of the food undergoing frying was established in order to verify the oil temperature model.

Results and Discussion

The results of this study were divided into two parts. Firstly, the heat transfer coefficients were estimated and then the oil temperature change was validated with an experiment without frying food. Secondly, the oil temperature change during frying chicken breasts was simulated by the use of simple food models and then validated through the experimental data.

Estimated heat transfer coefficients

Under steady state condition without frying food, the oil temperature was set at 180°C, the *K*-value of approximately 12.8 W/m^2·°C was calculated from Eq. (11) and subsequently used to compute the *U*-value from Eq. (12). It was observed that heat transfer rate between the heating coil and the frying oil during the power turned on and off was remarkably different. Therefore, the *U*-value was divided into 2 terms, i.e. U_{up} and U_{down}-values. The U_{up}-value was determined when the power was turned on and the U_{down}-value when the power was turned off. The estimated U_{up} and U_{down}-values were 4,885.6, 1,426.2 W/m^2·°C, respectively.

Figure 2 shows the change in oil temperature versus time without frying food. The black dot line (●) represents observed data and the broken line (---) is the predicted oil temperature using previous mentioned U_{up} and U_{down}-values. Obviously, the oil temperature from the model responds faster than the real situation. It was probably because of heat resistance and heat accumulation of the heating coil. After tuning *K*, U_{up} and U_{down}-values to 10.4, 3, 150 and 2,700 W/m^2·°C, respectively, the predicted oil temperature represented by the solid line (——) was preferable when compared to the experiment. The adjusted values were further employed to simulate the oil temperature change undergoing frying of a food product.

Validation of oil temperature model undergoing frying chicken breasts

To validate the oil temperature model, time-dependence of volumetric average temperature and moisture content of the fried chicken breasts were fitted with the second order polynomial equation. Thus, the temperature and the moisture changes at a given time ($dT_{food,av}/dt$ and $dM_{d,av}/dt$) were directly calculated from these empirical equations as presented in Eqs.(13) and (14), respectively. Figure 3 shows average temperature and moisture content of the chicken breast undergoing frying.

$$T_{food,av} = 25.6206 + 0.2183t - 0.0003t^2 \qquad R^2=0.9974 \qquad (13)$$

$$M_{d,av} = 2.9217 - 0.0055t + 7.2003\times10^{-6}t^2 \qquad R^2=0.9928 \qquad (14)$$

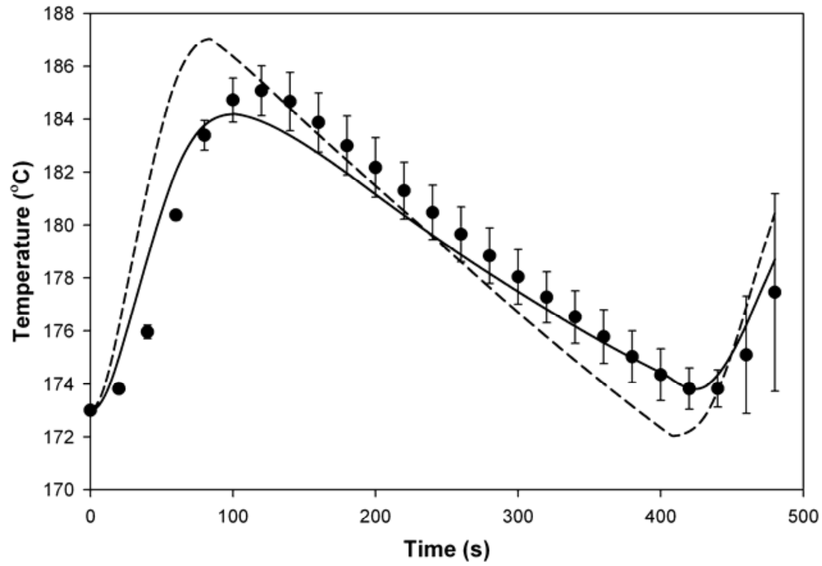

Figure 2. Oil temperature change with time without frying food;

Setting temperature: 180°C: ● Experiment,

- - - Simulated oil temperature using the calculated values (*K*-value: 12.8 W/m^2·°C, U_{up}-value: 4,885.6 W/m^2·°C and U_{down}-value: 1,426.2 W/m^2·°C),

—— Simulated oil temperature using the adjusted values (*K*-value: 10.4 W/m^2·°C, U_{up}-value: 3,150 W/m^2·°C and U_{down}-value: 2,700 W/m^2·°C).

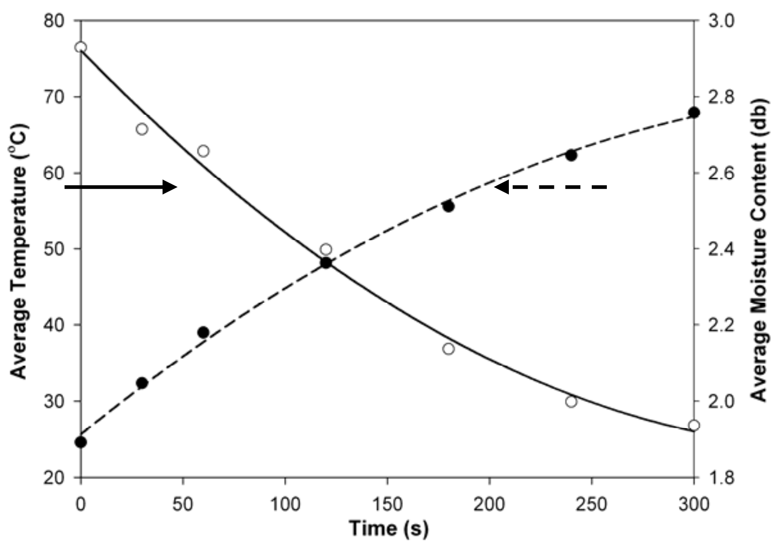

Figure 3. Average temperature and moisture content of fried chicken breasts undergoing frying at 180°C:

● Experimental average temperature,

○ Experimental moisture content,

- - - Fitted average temperature,

—— Fitted moisture content.

Figure 4 presents the change in oil temperature during frying chicken breasts at 180°C. When the sample was immersed into the frying oil, the temperature suddenly dropped because the power supply rate was lower than the energy required by the food. As a result, the oil temperature continued to decrease although the power was still turned on and appeared only at the first loop of the oil temperature decreasing. Using the adjusted *K* and *U*-values from the case of without frying food to predict the oil temperature change indicated by the broken line (---) yielded unreasonable results, when compared with the observed data (●). It was observed that the lowest oil temperature form the experiment was approximately 165°C, whereas the predicted one was 160°C and subsequently increased to a certain level that was lower than the observed data. There were possibly two reasons; firstly, the power supply term in the model determined by the *U*-value was less than the actual value and secondly, higher heat loss to the surroundings due to bubbling turbulence effect of the frying oil, which was determined by the *K*-value. After tuning the *K*, U_{up} and U_{down}-values to be 38, 20, 300 and 17,200 W/m^2·°C, respectively, the reasonable result was obtained as indicated by the solid line (—). It is obvious that heat transfer coefficient of the frying process dramatically changes throughout the course of the process. In this study, temperature dependence of these coefficients was assumed as being small [4]; however, they can be used to further study the transport phenomena within the fried food undergoing non-isothermal boundary condition.

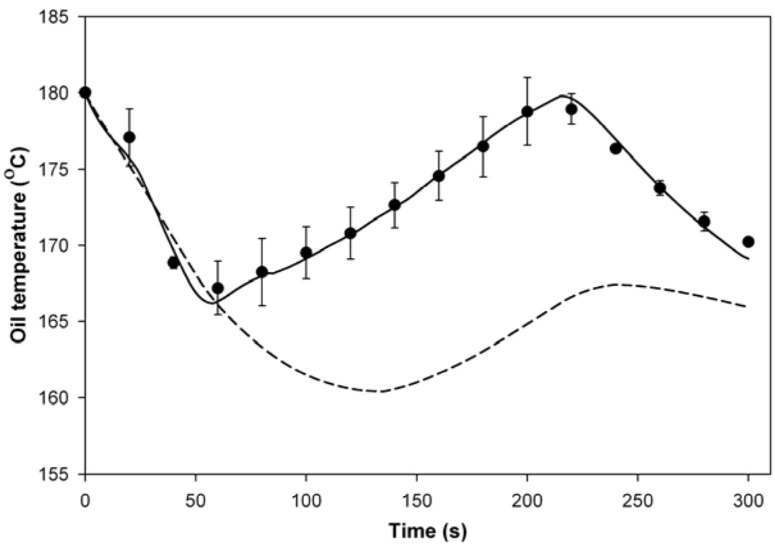

Figure 4. Oil temperature change with time during frying chicken breasts;
Setting temperature: 180°C: ● Experiment,
- - - Simulated oil temperature using the first adjusted values (*K*-value: 10.4 W/m^2·°C, U_{up}-value: 3,150 W/m^2·°C and U_{down}-value: 2,700 W/m^2·°C),
—— Simulated oil temperature using the second adjusted values (*K*-value: 38 W/m^2·°C, U_{up}-value: 20,300 W/m^2·°C and U_{down}-value: 17,200 W/m^2·°C).

Conclusion

The mathematical model of heat transfer in the frying oil and heat transfer coefficient determination were proposed. Power supply and heat loss to the surrounding were taken into consideration and found that they strongly affected the change in oil temperature. Process parameters in terms of heat transfer coefficients for heat loss transmitted from a fryer casting to the environment (*K*-value) and for heat transfer between a heating coil and the frying oil

(U_{up} and U_{down}-values) were experimentally determined. The U_{up} and U_{down}-values are the heat transfer coefficients as the power supply was turned on and off, respectively. The K, U_{up} and U_{down}-values were approximately 10.4, 3, 150 and 2,700 W/m^2·°C, respectively for the case of no frying food and rose up to 38, 20, 300 and 17,200 W/m^2·°C when frying chicken breast. This is likely due to the bubbling turbulence effect of the frying oil, resulting in an enhancement of heat transfer rate to the fried food as well as to the environment. With these adjusted values, the oil temperature prediction gave a reasonable result compared with the experimental data.

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Nomenclature

A_{coil}	Surface area of the heating coil, m^2
A_{fryer}	External surface area of the fryer, m^2
$C_{p,food}$	Heat capacity of fried food, J/kg·°C
$C_{p,oil}$	Heat capacity of frying oil, J/kg·°C
K	Overall heat transfer coefficient for the casing of the fryer, W/m^2·°C
$LMTD$	Log mean temperature difference, °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, kg/kg
$Q_{evaporation}$	Heat for moisture evaporation, W
Q_{heat}	Sensible heat transfer rate of the food being fried, W
Q_{input}	Heat supply to frying oil, W
Q_{oil}	Heat accumulation in the frying oil, W
Q_{sur}	Heat transmitted to the surroundings, 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
λ	Latent heat of water evaporation, J/kg
Superscript j	Time interval