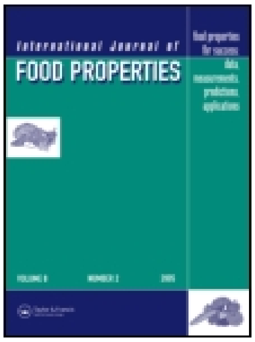

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EFFECTIVE THERMAL CONDUCTIVITY OF POTATO DURING FRYING: MEASUREMENT AND MODELING

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ABSTRACT

The effective thermal conductivities of potato were measured at various stages of the frying process. Samples were taken at 30 s intervals during frying, and two different methods (line heat source and modified Fitch method) were used to measure the effective thermal conductivity. An iterative Kopelman model was used for the prediction of thermal properties. The effective thermal conductivity decreased as frying time increased. The variation of experimental measurements by both methods and modeling were within 10% over most of the range studied. The probe method yielded values that were not significantly different than the modified Fitch method. Lower standard deviations were obtained with the modified Fitch method.

INTRODUCTION

An important consideration in the modeling of frying is the determination of engineering properties; in particular the thermal conductivity. For materials like fried potato, the measured thermal conductivity is an apparent one, called the effective thermal conductivity. Methods for measurement can be divided into two broad categories, steady-state and transient methods. Transient methods are preferred over steady-state methods due to short experimental duration and minimization of moisture migration problems. Recently, Rahman (1995) reviewed most of the measurement methods of thermal conductivity for food.

The line heat source method (Sweat, 1995) is popular for most food applications. The theory was reviewed by many authors (Hooper and Lepper, 1950; Nix et al., 1967; Murakami et al., 1996). Another transient method, useful for relatively poor conductors is the Fitch method (Fitch, 1935). More recently, the Fitch apparatus has been modified and the original copper plates have been reduced in size for measuring thermal conductivity of small food particles (Zuritz et al., 1989; Rahman, 1991; Chen et al., 1998).

The modeling of thermal conductivity based on composition has been a subject of considerable interest (Murakami and Okos, 1989) to avoid complex and time consuming measurements of thermal conductivity for food products with wide formulations. It is important that such models incorporate information on thermal conductivity of individual components while minimizing reliance on empirical factors.

The objective of this study was to determine the effective thermal conductivity of fried potatoes using the line heat source and modified Fitch methods, and to compare experimental results using a composition-based model for thermal conductivity.

MATERIALS AND METHODS

The potato sample was cut into rectangular pieces of 5cm x 5cm x 0.5cm in size by using a manually operated cutting device and its size was checked by using a caliper (Mitutuyo, Japan). Frying was carried out in a controlled temperature tank having a capacity of 2.0 liters oil. Sunflower oil at 150°C was used as the frying medium. Samples were taken at 30s time intervals during a 5-min. frying period. Moreira et al. (1997) showed that most of the oil was absorbed during cooling after frying and leaving some at the surface. Therefore, French fries were drained on a paper towel to eliminate the oily surface layer, which may affect the thermal conductivity results. Thermal conductivity measurements were done using two different methods. Statistical analysis (t-test) was done to determine if there is any significant difference between the two methods.

Line Heat Source Method

The experimental apparatus used for the research is shown in Figure1. The sample container was a tin can of dimensions 63.5 mm inside diameter and 73 mm height, covered with a lid, at the center of which was attached the probe (needle). The stainless steel syringe needle was 1.25 mm outside diameter and 40 mm long. An insulated constantan wire of 0.076 mm diameter was used as the line heat source and the temperature was measured with a chromel-constantan thermocouple of 0.076 mm diameter. The ratio of the probe length/diameter was higher than 25 as recommended in the literature (Sweat, 1995).

In the case of raw potato, the entire sample was shaped and placed into the sample container. In the case of fried potatoes, the method used by Moreira et al. (1995) for tortilla chips was used for the measurement of thermal conductivity. In this method, potato slices were sandwiched around the probe and pressed to minimize the void spaces.

The sample container filled with the sample and inserted probe in the center of the can was placed in a constant temperature bath at 25°C for equilibration. After the initial temperature was recorded, the probe heater was activated; time and probe temperature were recorded at 0.2 sec time intervals for 30 sec by using a data logger

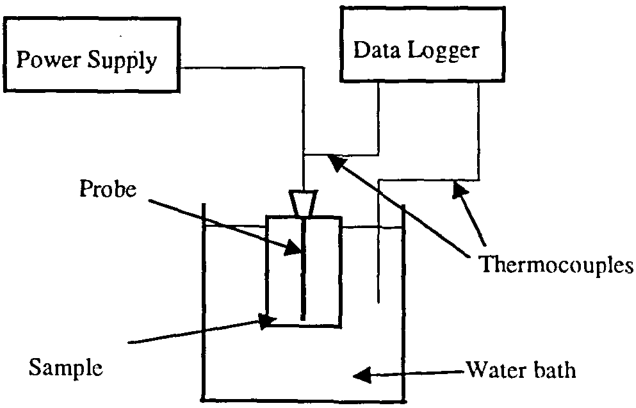

Figure 1. Experimental setup for thermal conductivity probe

(21X Micro logger, Campbell Scientific Inc., Logan, Utah, USA). Based on visual inspection, the initial data points were discarded in order to eliminate any transient initial effects. Linear regression line was fitted to the ln(time)-temperature data. The run was normally rejected if the coefficient of determination (r^2) was lower than 0.99. The effective thermal conductivity was calculated as described by Sweat and Haugh (1974) from the following equation:

$$k = \frac{I^2 R \ln(t_2 / t_1)}{4\pi(T_2 - T_1)} \tag{1}$$

Modified Fitch Method

The experimental apparatus used for the experiments is shown in Figure 2. A sample, 0.65 cm in diameter and 0.5 cm in thickness was cut from the center portion of the potato pieces of 5cm x 5cm x 0.5cm in size and its size was checked by using caliper (Mitutuyo, Japan). The sample was placed on the copper plug and equilibrated to room temperature (25°C). The initial sample temperature was recorded prior to the test. Then the copper rod, the temperature of which was kept constant at 35°C by circulating a fluid, was lowered and contacted with the sample. Time and temperature data were recorded at 5 s time intervals for 10 min. using a data logger (21X Micrologger, Campbell Scientific Inc., Logan, Utah, USA) at the same time. Based on visual inspection, the initial data points (first 20s) were discarded to eliminate transient initial effects. Regression line was fitted to the $\ln[(T_0-T_\infty)/(T-T_\infty)]$ vs. time. A satisfactory fit was defined as a straight line with coefficient of determination (r^2)≥0.995. When r^2 fell below this value, the topmost points were discarded, one point at a time until the r^2 was at least 0.995.

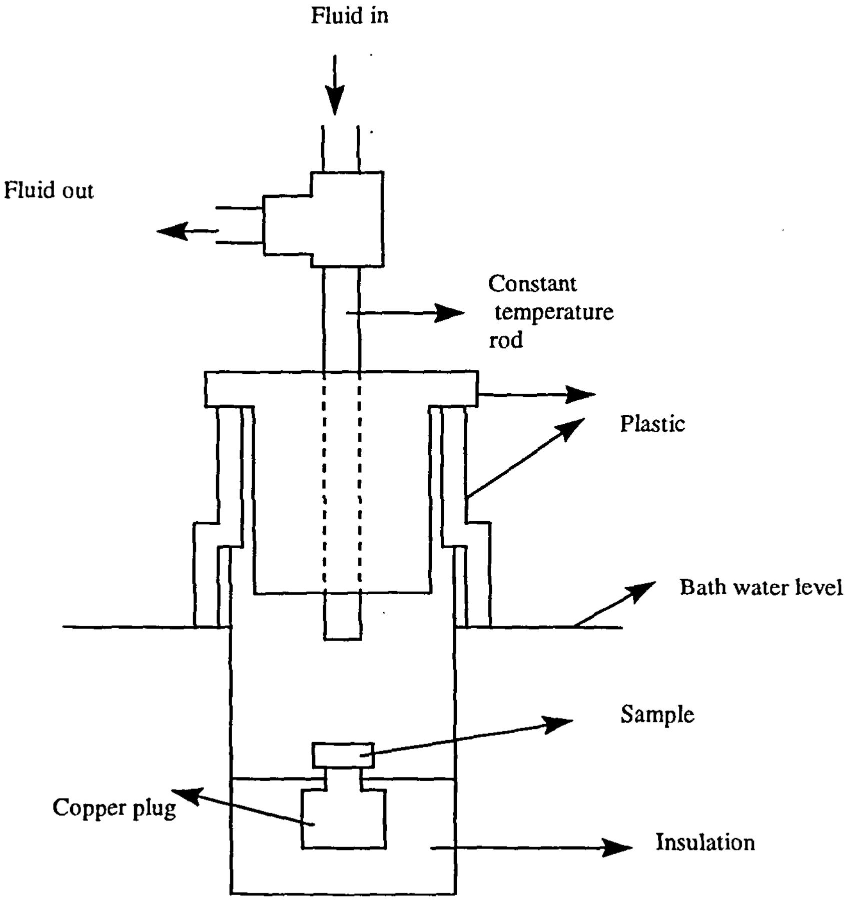

Figure 2. Experimental setup for modified Fitch method

The effective thermal conductivity was calculated as described by Zuritz et al. (1989) from the following equation:

$$k = \frac{Lm_c c_{pc} \ln((T_0 - T_\infty)/(T - T_\infty))}{tA} \quad (2)$$

The determined thermal conductivity value was multiplied by 0.954 which is the correction factor obtained by comparing the results for a glass sample with measurements made with modified Fitch device and the heat flow meter (ASTM Standard C58-76, ASTM, 1976) (Zuritz et al., 1989). At least three replicates were carried out for each method.

Modeling

A number of models for thermal conductivity exist in the literature (Murakami and Okos, 1989; Rahman, 1995), however many of them contain empirical factors and product-specific information. The model chosen for this study was the one that has been in use for some time (Zuritz and Sastry, 1985), and is under investigation by the North Central Regional Project NC-136, Improvement of Thermal Processes for Foods, USA. The approach is based on that of Kopelman (1966), which describes the thermal conductivity of a composite as the combination of continuous and dispersed phases.

$$k=\frac{k_c[1-Q]}{1-Q[1-(X_d^v)^{1/3}]} \tag{3}$$

where:

$$Q=[X_d^v]^{2/3}\left(1-\frac{k_d}{k_c}\right) \tag{4}$$

This equation is useful for two-component models, but needs modification for multi-component systems. In particular, the definition of continuous and dispersed phases needs specification. Since foods are multi-component systems, and the phases are associated with each other in complex ways, the approach chosen here is to successively determine the thermal conductivity of two-component systems, starting with water continuous, carbohydrate dispersed; then using water-carbohydrate continuous, protein dispersed, and continuing through all phases. This approach has been attempted in a simpler form by Bakshi et al. (1984) using a different sequence of calculation. In the present study, using the order: water (1), carbohydrate (2), protein (3), fat (4), ice (5), ash (6), air (7); the following iterative algorithm was obtained for the thermal conductivity of a system of $i+1$ components

$$k_{comp,i+1}=\frac{k_i[1-Q_{i+1}]}{1-Q_{i+1}\left[1-\left(X_{d,i+1}^v\right)^{1/3}\right]} \tag{5}$$

where the following definitions apply:

$$Q_{i+1}=\left(X_{d,i+1}^v\right)^{2/3}\left[1-\frac{k_{i+1}}{k_i}\right] \tag{6}$$

$$X_{d,i+1}^v=\frac{V_{i+1}}{\sum_1^{i+1}V_i} \tag{7}$$

Thus, for a N-component system, the composite conductivity, $k_{comp,N}$ is given by:

$$k_{comp,N} = \frac{k_{N-1}\left[1 - Q_N\right]}{1 - Q_N\left[1 - \left(X_{d,N}^{v}\right)^{1/3}\right]} \tag{8}$$

Data on densities and thermal conductivity of the respective phases were as given by Choi (1985), and Murakami and Okos (1989).

For this study, moisture and oil contents of potato at various stages of frying were determined. These analyses were repeated at least three times. The oil content of the sample was determined by Soxhlet extraction of 5 g of blended sample with hexane for 8h. (AOAC, 1975). For moisture determination, samples were dried and brought to constant weight in a forced convection oven at 105°C (AOAC, 1975). The data obtained from these analyses are listed in Table 1. The proximate composition at each stage was inferred from composition data for potatoes (USDA-ARS, 1998). Data are presented in Table 2. Since the composition of raw potato consists primarily water and starch, the composition of potatoes during the frying process was inferred by assuming that at each stage of frying, the change in the sum of water and oil contents was balanced by a starch content, to bring the total to 100%. It is recognized that changes in protein and ash contents are also possible, but these are small in comparison to the major components.

RESULTS AND DISCUSSION

Experimental values of thermal conductivity and standard deviations using the two different methods are shown in Table 3. Thermal conductivity of a food depends on its porosity, structure and chemical constituents (Szczesniak, 1983). Since the water is evaporated and oil is absorbed during frying (Gamble et al., 1987) and thermal conductivity of oil is lower than that of water, thermal conductivity of French fries decreases with increasing time.

In the line heat source method, the standard deviation for raw potato was relatively low, since the whole potato was used for the measurement of thermal conductivity. Standard deviation was higher for fried potatoes, possibly because of the errór due to void spaces between the slices. When the frying time was low, it was more difficult to sandwich the slices around the probe since the sample was not soft enough. Therefore, the standard deviation decreased with increasing frying time as well as the softness.

Standard deviations of thermal conductivity determined using the modified Fitch device were lower than for the line heat source method. It was observed that as frying time increased, standard deviation increased. The main source of error in the modified Fitch method may be due to good contact not being achieved. While the copper rod was being lowered onto the sample, care was taken to provide good contact without disrupting the structure. However, samples fried for long times were so soft that deformation frequently occurred. Therefore, a large number of data points had to be discarded.

Table 1. Moisture and oil contents of potatoes at various stages of frying at 150° C

Time (s)	Moisture Content (% wet basis)	Oil Content (% wet basis)
0	79.90	0.00
30	75.71	2.17
60	70.38	3.60
90	64.67	3.98
120	58.96	5.04
150	55.28	5.12
180	52.64	6.00
210	51.45	6.48
240	50.33	6.50
270	49.43	6.53
300	49.12	6.56

Table 2. Proximate composition data for raw potato (Source: USDA-ARS, 1998)

Constituent	% by weight (wet basis)
Water	78.96
Protein	2.07
Carbohydrate	17.98
Lipid	0.10
Ash	0.89

Table 3. Thermal Conductivity values and standard deviations using the line heat source and modified Fitch methods

Frying Time (s)	k_{eff} (W/m °C) Line heat source	k_{eff} (W/m °C) Modified Fitch
0	0.58±0.013	0.61±0.022
30	0.56±0.092	0.60±0.023
60	0.52±0.091	0.54±0.023
90	0.47±0.084	0.49±0.032
120	0.42±0.072	0.45±0.033
150	0.41±0.071	0.43±0.033
180	0.40±0.064	0.41±0.034
210	0.38±0.052	0.39±0.042
240	0.37±0.051	0.40±0.043
270	0.37±0.043	0.39±0.051
300	0.36±0.042	0.39±0.052

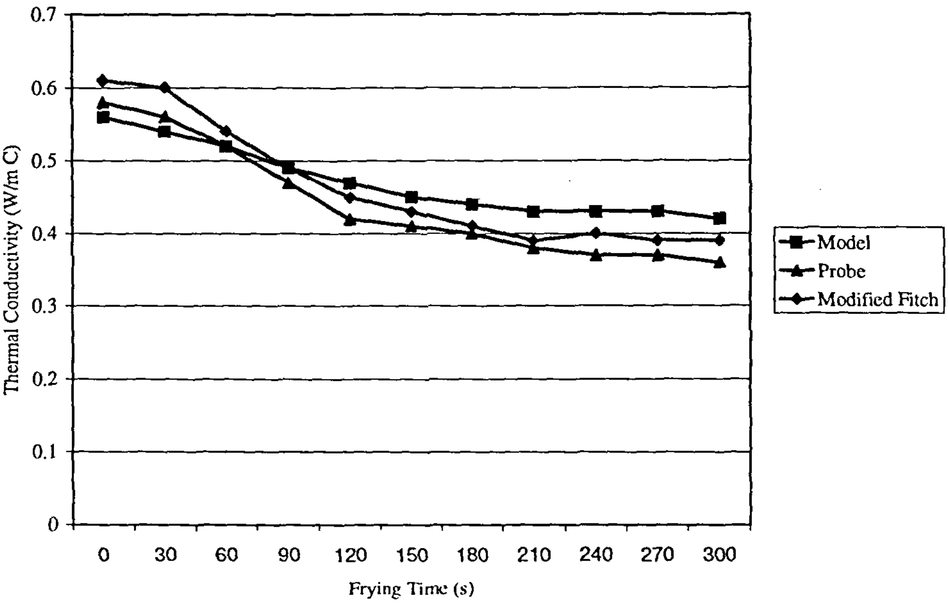

Figure 3. Comparison of model predictions and experimental measurements (■ Model, ▲ Line heat source method, ◆ Modified Fitch method)

It was noted that the line heat source method showed somewhat lower values of thermal conductivity than the modified Fitch method, however there was no statistically significant differences ($\alpha \leq 0.05$). The principal differences between these studies appear to be the location and alignment of the oily surface layer in relation to the measuring elements; and the possible presence of air spaces within the sandwiched samples used in the probe method. It should be noted that a fried sample would exhibit a significant variation in composition near the surface, thus the thermal conductivity in this region is likely to vary markedly with distance. The methods used here do not permit resolution of thermal conductivity on such small scales, thus the values can only be considered as effective conductivity.

A comparison between model and experimental results is illustrated in Figure 3. The model was found to satisfactorily describe the experimental trends. A plot of deviations between model and experiment is provided in Figure 4. In general, the values from both methods are within 10% of the model predictions, indicating that the measurements and composition-based predictions are consistent with each other. However, the modified Fitch method yields results that are more consistently in agreement with the model than the line heat source method. It should be noted that the model is based on the average composition of a sample, and thus yields an effective value.

Ideally, it would be necessary to use experimental techniques that would enable resolution of conductivity variations over smaller length scales. Alternatively, if the

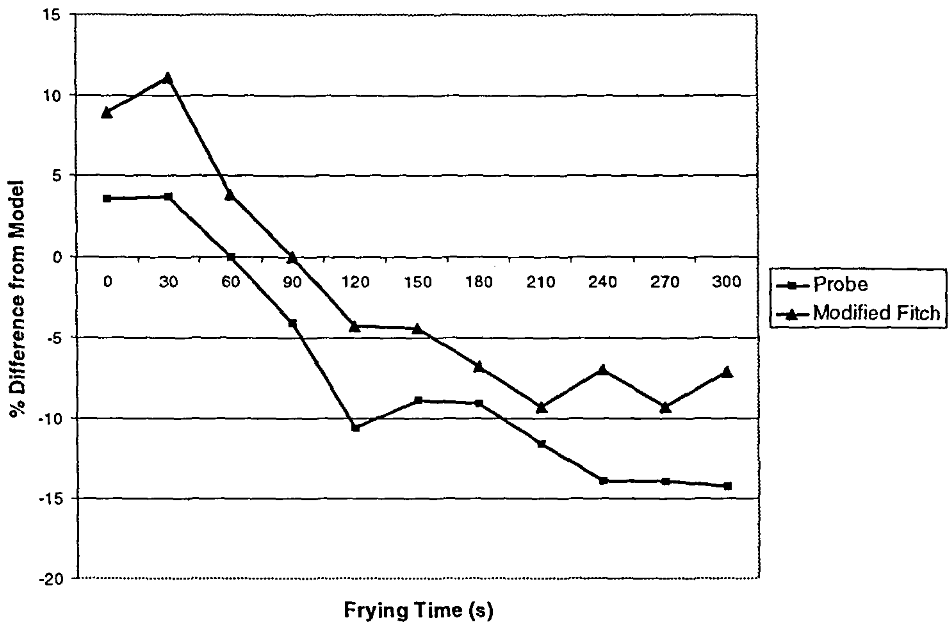

Figure 4. Deviation of experimental measurements from model (▪ Line heat source method, ▲ Modified Fitch method)

composition distribution were known, it would be possible to predict conductivity profiles based on location.

CONCLUSIONS

The effective thermal conductivity of potato tissue during frying decreases with time. The results obtained from the thermal conductivity probe and modified Fitch methods are comparable to each other, and to the values obtained from an iterative Kopelman model. Limitations on probe and sample size apparently causes greater standard deviations in measurements made by the line heat source method.

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LIST OF SYMBOLS

A	Heat transfer area (m^2)
c_{pc}	Specific heat of copper plug (J/kg°C)
I	Electrical current (A)
k	Thermal conductivity (W/m°C)
k_c	Thermal conductivity of continuous phase (W/m°C)
$k_{comp,i+1}$	Composite thermal conductivity of a system of i+1 components (W/m°C)
$k_{comp,N}$	Composite thermal conductivity of N component system (W/m°C)
k_d	Thermal conductivity of dispersed phase (W/m°C)
k_i, k_{i+1}	Thermal conductivity of phase i and $i+1$ respectively (W/m°C)
L	Sample thickness (m)
m_c	Mass of the copper plug (kg)
R	Electrical resistance of heated source per unit length (Ω/m)
t_1, t_2	Time since probe heater was energized (s)
T	Temperature of both sample and copper plug at any time t (°C)
T_∞	Temperature of copper rod (°C)
T_0	Initial temperature of both sample and copper plug (°C)
T_1	Temperature of the probe thermocouple at time t_1 (°C)
T_2	Temperature of the probe thermocouple at time t_2 (°C)
V_i, V_{i+1}	Volume of phase i and i+1 respectively (m^3)
X^v_d	Volume fraction of dispersed phase

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