Comparison and modeling of microwave tempering and infrared assisted microwave tempering of frozen potato puree

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Microwave tempering and infrared assisted microwave tempering of frozen foods were simulated by using finite difference method. The effects of microwave power and infrared power on tempering were discussed. Three different microwave power levels (30%, 40%, and 50%) and three different infrared power levels (10%, 20%, and 30%) were used. The increase in microwave power level and infrared power level decreased tempering times. The change of heat capacity and the dielectric properties of frozen potato puree with respect to time were measured. The temperature distribution inside the sample was modeled, and the predicted results were compared with experimental results. The predicted temperatures showed good agreement with the experimental results.

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1. Introduction

In many countries, potato puree is a common way of serving potato. Instant potato purees are produced by an industrial process of cooking, mashing, and drying to yield a packaged product that can be reconstituted in the home in seconds by adding hot water or milk with very little expenditure of time and effort. Potato puree is used mostly in catering industry, and frozen vegetable purees have a good potential market in Europe (Alvarez et al., 2004).

Frozen food is defined as ‘tempered’ when its temperature is raised from that of a solidly frozen condition to some higher temperature, still below the initial freezing point, at which it is still firm but can readily be further processed (James, 1999). Thawing is usually regarded as complete when the center of the food sample has reached 0 °C. Lower temperatures (e.g., -5 to -2 °C) are acceptable for food that is destined for further processing, but such food is tempered rather than thawed (James and James, 2002). Conventional thawing is a long process and can often compromise the product quality. Microwave thawing is a novel method having the advantages of fast heating rate, improved bacterial control and low costs. Minimizing thawing times will reduce microbial growth, chemical deterioration and excessive water loss caused by dripping or dehydration (Taher and Farid, 2001). Dielectric properties of food materials, which are dielectric constant and dielectric loss factor, are the electrical properties which measure the interaction of the food with electromagnetic fields. Dielectric constant reflects the ability of a material to store electromagnetic energy, and loss factor measures the ability of a material to dissipate electric energy into heat (Calay et al., 1995). It is important to know the dielectric properties of food materials to develop effective microwave heating processes. In literature, there are a few studies on the dielectric properties of mashed potatoes (Guan et al., 2004; Fasina et al., 2003), but these studies did not include the freezing temperatures. Although there was one study measuring the dielectric properties of mashed potatoes as a function of temperature at lower temperature range (Regier et al., 2001), it is necessary to obtain more data of dielectric properties of potato puree at a wider freezing temperature range.

Infrared (IR) radiation is the part of the electromagnetic spectrum that is predominantly responsible for the heating effect of the sun. Infrared radiation is found between the visible light and radio waves, and can be divided into three different categories, namely, near-infrared radiation (NIR), mid-infrared radiation (MIR), and far-infrared radiation (FIR) (Ranjan et al., 2002). Halogen lamp heating provides near-infrared radiation and its region in the electromagnetic spectrum is near the visible light with higher frequency and lower penetration depth than the other infrared radiation categories. A number of approaches have been developed to model the microwave thawing process of frozen foods (Chamchong and Datta, 1999a,b; Taher and Farid, 2001; Basak, 2003; Liu et al., 2005).

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The microwave power absorbed can be modeled by using Lambert’s law or Maxwell’s equations. In Lambert’s law, the microwave power attenuates exponentially as a function of penetration distance into the dielectric material (Liu et al., 2005). In several modeling studies heat generation during microwave thawing has been described by using Lambert’s law (Zeng and Faghri, 1994; Chamchong and Datta, 1999a,b; Taher and Farid, 2001). On the other hand, Maxwell’s equations can predict the absorption of energy and incorporate the reflections at front and back surfaces as well as all internal interfaces (Liu et al., 2005). Simply, the exact solution of Maxwell’s equations for microwave propagation is based on both the transmitted and reflected waves, whereas Lambert’s law is based purely on transmission (Basak, 2004). There are also significant number of studies based on Maxwell’s equations (Basak and Ayappa, 2002; Basak and Meenakshi, 2006; Samanta and Basak, 2008). Liu et al. (2005) and Basak (2004) compared Lambert’s law and Maxwell’s equations for microwave heating analysis. Liu et al. (2005) found that in regard to temperature distribution, the simulations based on Lambert’s law predicted results similar to those predicted by using Maxwell’s equations and both were compatible with the experimental results. Basak (2004) concluded that Lambert’s exponential law predicts results qualitatively similar to those with the exact solution within the low dielectric material, but the absorbed power with Lambert’s law may be overestimated within the high dielectric material, as a result, the temperature distribution may not be evaluated accurately if there is a strong coupling between the energy balance and electric field equations. In our study, Lambert’s law was used to represent the heat generation during microwave tempering because of the low dielectric properties of frozen potato puree.

Microwave-infrared combination is a new technology combining near-infrared heating with microwaves. There are a few studies on infrared assisted microwave heating (Datta and Ni, 2002; Keskin et al., 2004; Sakiyan et al., 2007), but there is no study on modeling of infrared assisted microwave thawing or tempering.

The purpose of this study is to model the temperature distribution inside the frozen potato puree during microwave tempering and infrared assisted microwave tempering by finite difference model. It was also aimed to compare temperature profiles of frozen potato puree during microwave tempering and infrared assisted microwave tempering. In addition, the dielectric properties and heat capacity of the frozen potato puree were measured at different temperatures.

2. Theory

A mathematical model was proposed to predict the temperature profile inside the frozen potato puree sample. Average moisture loss measurements were done for microwave tempering and infrared assisted microwave tempering, and it was found that moisture loss was not significant. Therefore, moisture loss was assumed to have negligible effect on the heat transfer during tempering and also on the physical properties of the frozen potato puree. Chamchong and Datta (1999a) also found that average moisture loss during microwave thawing was less than or equal to 1% and could be assumed to be negligible during thawing. Thus, the physical properties of potato puree were taken as only temperature dependent.

To simplify the governing equations and boundary conditions, several assumptions have been done. First of all, the initial temperature was considered as uniform within the sample. The sides and the bottom of the sample were insulated by aluminum foil, so the heat transfer was assumed to be one-dimensional (Fig. 1).

The density of the potato puree sample was measured as 1395 kg/m³. The thermal conductivity of frozen potato puree was estimated by Eq. (1) (Choi and Okos, 1986):

\[ k(T) = 2.01 + 1.39 \times 10^{-3} \times T - 4.33 \times 10^{-6} \times T^2 \]  

where \( T \) is temperature in °C, and \( k \) is thermal conductivity (W/m·°C). The heat capacity values of frozen potato puree were measured by DSC and the results are given in Section 4.1.

Penetration depth is defined as the distance from the surface of the material at which the microwave power decreases to 1/e (~37%) of its original value, and it is also controlled by the dielectric properties. Penetration depth (\( D_p \)) was calculated by using the following formula (2):

\[ D_p = \frac{\lambda_0}{2\pi(2\varepsilon')^{0.5}} \left( 1 + \left( \frac{\varepsilon'}{\varepsilon_0} \right)^{0.5} \right)^{-0.5} \]

where \( \lambda_0 \) is the wavelength of the microwave energy in free space (12.24 cm at 2450 MHz), \( \varepsilon' \) is dielectric constant and \( \varepsilon_0 \) is loss factor (Von Hippel, 1954). The penetration depth is calculated by using Eq. (2), and the results are given in Section 4.2.

2.1. Modeling of microwave tempering

The one-dimensional unsteady state heat conduction equation with heat generation is used to describe microwave heating of material undergoing tempering:

\[ \frac{\partial}{\partial z} (\rho C_p T) = \frac{\partial}{\partial z} \left( k(T) \frac{\partial T}{\partial z} \right) + Q_{gen,mw} \]  

where \( \rho \) (kg/m³), \( C_p \) (J/kg·°C), and \( k \) (W/m·°C) are the density, heat capacity, and thermal conductivity of the potato puree sample, respectively. \( Q_{gen,mw} \) is the internal heat generation (W/m³) caused by microwave energy, and assumed as an exponential decay represented by Lambert’s law with varying penetration depth (Datta and Ni, 2002), which is commonly related to the microwave surface absorption \( Q_0 \) as follows (Taher and Farid, 2001):

\[ Q_{gen,mw} = Q_0 \text{mw} e^{-\left(\frac{z}{D_p(mw)}\right)} \]  

where \( D_p \) is the penetration depth in m. \( Q_0 \text{mw} \) (W/m²) was estimated by trial and error to fit the experimental data as Zeng and Faghri (1994) did since a reliable way to measure it directly was not available.

The following initial and boundary conditions are used for microwave tempering:

\[ \text{at } t = 0 \quad 0 < z < L \quad T = T_0 \]  

\[ \text{at } t > 0 \quad z = 0 \quad -k(T) \frac{\partial T}{\partial z} = h(T - T_{\infty}) \]  

\[ \text{at } t > 0 \quad z = L \quad \frac{\partial T}{\partial z} = 0 \]
where \( L \) is the thickness of the sample, \( T_n \) is the surrounding temperature, and \( h \) is the convective heat transfer coefficient of air. In literature, the heat transfer coefficient values used in a microwave oven ranged from 2 to 39.44 (Chamchong and Datta, 1999a). In this study, it was chosen as 20 W/m²·°C for microwave tempering, and 30 W/m²·°C for infrared assisted microwave tempering.

### 2.2. Modeling of near-infrared assisted microwave tempering

The same one-dimensional unsteady state heat conduction equation is used to describe near-infrared assisted microwave tempering with a different generation term:

\[
\frac{\partial}{\partial t} (\rho C_p T) = \frac{\partial}{\partial z} \left(k(T) \frac{\partial T}{\partial z}\right) + Q_{\text{gen}}
\]

where \( Q_{\text{gen}} \) (the total heat generation term) is defined as:

\[
Q_{\text{gen}} = Q_{\text{gen,mw}} + Q_{\text{gen,inf}}
\]

where \( Q_{\text{gen,mw}} \) is the internal heat generation (W/m³) caused by microwave energy, and \( Q_{\text{gen,inf}} \) is the internal heat generation (W/m³) caused by infrared energy.

The infrared power flux was also modeled as an exponential decay similar to microwave power (Datta and Ni, 2002) which is expressed by:

\[
Q_{\text{gen,inf}} = Q_{0,\text{inf}} e^{-\left(\frac{z}{D_{\text{p,inf}}}\right)}
\]

where \( Q_{0,\text{inf}} \) is infrared surface flux, and \( D_{\text{p,inf}} \) is infrared penetration depth which is defined exactly as microwave penetration depth. For this study, \( D_{\text{p,inf}} \) is taken as 3.5 mm for potato tissues from Almeida et al. (2006). \( Q_{0,\text{inf}} \) was estimated by trial and error to fit the experimental data.

In near-infrared assisted microwave heating, on–off cycling of infrared heating depending on the halogen lamp power is important. Such cycling is generally done by turning infrared source on for some of the time during the cycle and turning it off during the rest of the cycle. The fraction of time the power is on is called as Duty cycle and defined as (Chamchong and Datta, 1999):

\[
\text{Duty cycle} = \frac{t_{\text{on}}}{t_{\text{on}} + t_{\text{off}}}
\]

The time values \( t_{\text{on}} \) and \( t_{\text{off}} \) changes with changing halogen lamp power. When the halogen lamp power is increased, \( t_{\text{on}} \) also increases and \( t_{\text{off}} \) decreases.

To solve near-infrared assisted microwave tempering equations, the same boundary conditions are used with microwave tempering.

### 2.3. Solution of the mathematical model

To predict the temperature profile inside the sample, the mathematical model was solved numerically by using the initial and boundary conditions. Explicit finite difference method was used to solve the governing equations. Heat capacity, thermal conductivity, and the penetration depth were taken as dependent on temperature.

The following equations were used:

\[
\frac{\partial T}{\partial t} = \frac{\partial}{\partial z} \left[ \frac{k(T)}{\Delta z} \frac{\partial T}{\partial z} \right] + \frac{\partial q}{\partial z} + \frac{\partial}{\partial z} \left( k(T) \frac{\partial T}{\partial z} \right)
\]

where \( i \) denotes the node position, \( n \) is the time interval, and \( \Delta z \) and \( \Delta t \) are the axial and time increments, respectively.

A MATLAB program was written to solve the resulting set of equations. Time increment was chosen as 0.0005 and spatial increment was 0.001.

### 3. Materials and methods

#### 3.1. Preparation of the sample

A commercial potato puree powder (Knorr, Turkey) having a moisture content of 6% was used as the sample. The chemical composition of the commercial potato puree powder was 72% carbohydrate, 8% protein, and 1% fat. It contained potato, emulsifier (mono- and diglyceride), stabilizer (disodium diphosphate), food preservative (sodium Meta bisulphite), spice extract, and antioxidant (ascorbyl palmitate). Hot water was used to prepare potato puree containing 15% potato puree powder. The potato puree was shaped as a cylindrical slab with 25 cm diameter and 2.5 cm height.

#### 3.2. Tempering

A halogen lamp–microwave combination oven (Advantium oven®, General Electric Company, Louisville, KY, USA) was used for both microwave tempering and infrared assisted microwave tempering. The power of microwave oven has been determined as 706 W by using IMPI 2-1 test (Buffler, 1993). Three different microwave power levels (30%, 40%, and 50%) were used for microwave tempering. For infrared assisted microwave tempering, lower halogen lamp was not used, and three different upper halogen lamp power levels (10%, 20%, and 30%) were used in combination with the microwave power levels.

#### 3.3. Measurement of temperature

Temperature was measured with a fiber optic temperature probe (FOT-L/2M, FISO, Canada) at three different points (0.5 cm, 1.5 cm, and 2.5 cm far from the surface). The temperature data was collected every 10 s.

#### 3.4. Measurement of density

The volume of the potato puree with a known weight was measured, and the density was calculated by the following density formula:

\[
\rho = \frac{m}{V}
\]

#### 3.5. Measurement of heat capacity

Step scan alternating differential scanning calorimeter (DSC) (Perkin-Elmer Diamond DSC, Perkin-Elmer, USA) was used to measure the heat capacity of the sample. Hermetically sealed aluminum pans were used to avoid any moisture loss during the test. In the experiment, unfrozen potato puree samples (10–15 mg) were put into the pan, and the pans were sealed. They were cooled to −30 °C, held at that temperature for 15 min, and then warmed at heating rate of 10 °C/min from −30 °C to −10 °C. The equation is then extrapolated to −2 °C.

#### 3.6. Measurement of dielectric properties

A vector network analyzer (Model: Agilent 8722ES, Agilent Technology, Palo Alto, CA) with an open-ended coaxial cable (Nos. 8120-6192, Hewlett Packard) connected to a probe
(85070C, Agilent Technology, Palo Alto, CA) was used to measure dielectric properties of potato puree. The built-in S-parameter test set provided a full range of magnitude and phase measurements in both the forward and reverse directions. The instrument was calibrated by measuring the properties of air, short-circuit block, and water at 25 °C. To obtain uniform readings, the instrument was turned on at least 2 h before the calibration and measurements were made. The network analyzer probe and the cable were fixed together so that there could be no movement during sample measurement and data acquisition. The dielectric properties of the potato puree were measured in the temperature range of −30 °C to 10 °C for every 2 °C intervals. A thermocouple temperature sensor (BK Precision 390A, Taiwan) was used to monitor the temperature during the study and the temperature variation within the sample was minimal, ±0.5 °C. The dielectric properties of the potato puree were measured at 2450 MHz. The dielectric spectra of the samples (dielectric constant \( \varepsilon' \), and dielectric loss factor \( \varepsilon'' \)) were automatically computed and recorded with the manufacturer supplied computer software (Version 85070 D1.00, Agilent Technologies, Palo Alto, CA).

3.7. Data analysis

Microsoft Excel software package (Microsoft Corporation, USA) was used to carry out the statistical analysis and linear regressions of experimental data. MATLAB was used for finite difference modeling.

4. Results and discussion

4.1. Heat capacity

The specific heat capacity is the amount of heat required to change a unit mass of a substance by 1 °C in temperature. Heat capacity of food is important for heat transfer since it determines how fast a food can be heated. The heat capacity of potato puree was observed to increase with increasing temperature. Predictive equation for the heat capacity obtained from this result \((r^2 = 0.99)\) and used for the modeling is given as follows:

\[
C_p(T) = 2087.8 + 21.058 \times T + 0.2224 \times T^2. \tag{17}
\]

4.2. Dielectric properties

Figs. 2 and 3 show the change of dielectric constant \((\varepsilon')\) and loss factor \((\varepsilon'')\) of the frozen potato puree with respect to temperature, respectively. Results indicated that the dielectric constant and loss factor of potato puree samples increased exponentially as the temperature increased. Both dielectric parameters were found to be very low (3–10 for dielectric constant and 0–3 for loss factor) up to −10 °C and level off at above −2 °C. During thawing, both dielectric constant and loss factor show large increases with temperature. After thawing, dielectric properties of foods are known to decrease with increasing temperature (Sahin and Sumnu, 2006). Free and bound moisture content affect the rate of change of dielectric constant and loss factor with temperature. If the water is in bound form, the increase in temperature increases the dielectric properties. However, in the presence of free water, dielectric properties of free water decrease as temperature increases. At high temperatures, hydrogen bonds become rare. Less energy is required to overcome intermolecular bond at higher temperatures that results in lower dielectric properties. Therefore, the rate of variation of dielectric properties depends on the ratio of bound to free moisture content (Sahin and Sumnu, 2006). The values of both dielectric constant and loss factor were found to be rather small for mashed potatoes at 2450 MHz (Regier et al., 2001). Ice has a low dielectric constant and loss factor when compared to that of water (Schiffmann, 1986). The dielectric constant and loss factor of ice is 3.2 and 0.0029, and the dielectric constant and loss factor of water is 78 and 12.48 at 2450 MHz.

The dielectric constant decreased slightly whereas loss factor increased significantly as the frequency was increased (Fig. 3.1 and 3.2). The same trend was observed for frozen tylose samples in literature (Chamchong, 1997). These results are important for microwave thawing and tempering of frozen potato puree studies and can be used for modeling purposes to estimate the thawing or tempering time and temperature distribution during microwave heating.

The penetration depth of frozen potato puree was calculated by using Eq. (2). As microwaves move through the slab at any point, the rate of heat generated per unit volume decreases. For materials having high loss factor, the rate of heat generated decreases rapidly and microwave energy does not penetrate deeply. A parameter called penetration depth indicates the distance that microwaves will penetrate into the material before it is reduced to 1/e of its initial value (Sahin and Sumnu, 2006). The penetration depth \((D_p)\) of the frozen samples decreased as a function of temperature. The decrease was more significant at lower temperatures and the penetration depth became almost constant after −6 °C. An equation was fitted to penetration depth data to use in modeling and given as:

\[
D_p = 0.0137 + 0.0032 \times T + 0.0004 \times T^2 \quad r^2 = 0.99. \tag{18}
\]

4.3. Modeling

In this study, tempering time is defined as the time needed for the surface temperature of frozen potato puree sample to reach
The microwave tempering times of frozen potato puree are given in Table 1. When the microwave power was increased, the tempering time got shorter as expected.

The temperature distribution within the frozen potato puree during tempering is modeled by using finite difference method. Fig. 4 shows the variation of temperature at different positions as a function of time for 40% microwave power. Different markers indicate different thermocouple positions inside the frozen potato puree sample. The predicted temperatures show good agreement with the experimental results. The $r^2$ values ranged between 0.989 and 0.998. The bottom of the sample was heated slower (Fig. 4) since microwave power flux decreases as an exponential decay. The temperature distribution was more uniform at lower microwave powers since tempering time was longer at lower microwave powers allowing also conduction to take place.

Times necessary to temper frozen potato puree in infrared assisted microwave oven are also given in Table 1. As can be seen from the table, using infrared heating in combination with microwaves decreased the tempering time. In addition, increasing halogen power level resulted in lower tempering times.

Finite difference method was used to model the temperature distribution during infrared assisted microwave tempering. Fig. 5 compares the measured and simulated temperature distribution during infrared assisted microwave tempering with 30% microwave power and 20% infrared power combination. Different markers indicate different thermocouple positions inside the frozen potato puree sample. As can be observed from the figure below, the heating pattern seems to be different from microwave tempering (Figs. 4 and 5). The stepwise changes seen in temperature profile are due to on–off cycling of infrared heating depending on the halogen lamp power. Actually, microwave heating also has on–off cycling, but due to very low dielectric properties of frozen sample the effect of cycling cannot be observed on temperature profile of frozen potato puree during microwave tempering.

Fig. 6 represents the effect of halogen power on variation of temperature during microwave tempering and infrared assisted microwave tempering. Infrared heating provided an additional flux as illustrated in Fig. 6. Using infrared heating in combination with microwave heating decreased the tempering time and changed the heating pattern. It can also be seen that increasing the halogen power decreased the tempering time. Considering the experimental data and the model, the match between the two is very good. The $r^2$ values ranged between 0.985 and 0.998. It is worth to note that how the model well predicted the onset and the offset of the heating profile.

The effect of microwave power during infrared assisted microwave tempering is shown in Fig. 7. As the microwave power increases, tempering time also decreases in infrared assisted microwave tempering (Fig. 7). It was observed that at the same microwave power level, increasing the infrared power increases the height of the steps in stepwise changes on the temperature profile, resulting in a more non-uniform temperature distribution since when the infrared power increased, the halogen lamp (the source of infrared heating) is on for a longer time, i.e., the sample is exposed to infrared heating more. Also, at the same infrared power level, increasing the microwave power level increased the non-uniformity in the temperature distribution during tempering. At 30% microwave plus 10% infrared level, the temperature profile is the most uniform one. The effect of infrared heating is observed as more dominant at the lowest microwave power level, but infrared heating adds non-uniformity to the temperature distribution.

| Table 1 |
| Tempering times for microwave and infrared assisted microwave tempering. |
| Microwave power | 30% | 40% | 50% |
| Microwave power | 30% | 40% | 50% |
| Infrared power | 0% | 10% | 20% | 30% | 0% | 10% | 20% | 30% | 0% | 10% | 20% | 30% |
| Tempering time (s) | 630 | 320 | 240 | 200 | 440 | 250 | 210 | 170 | 330 | 210 | 170 | 150 |
References


Fig. 7. Effect of microwave power on variation of temperature during tempering of frozen potato puree at 1.5 cm depth with 20% halogen power. (○) Experimental data at 30% microwave power, (□) experimental data at 40% microwave power, (△) experimental data at 50% microwave power, (—) model.