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**Modeling heat and mass transport during microwave heating of frozen food rotating on
a turntable**

Jiajia Chen ^a, Krishnamoorthy Pitchai ^{a, b}, Sohan Birla ^{a, c},

David Jones ^a, Mehrdad Negahban ^d, Jeyamkondan Subbiah ^{a, b, *}

^aDepartment of Biological Systems Engineering, University of Nebraska-Lincoln, Lincoln,
NE 68583, USA

^bDepartment of Food Science and Technology, University of Nebraska-Lincoln, Lincoln,
NE 68583, USA

^cConAgra Foods, Inc., Omaha, NE 68102, USA

^dDepartment of Mechanical and Materials Engineering, University of Nebraska-Lincoln,
Lincoln, NE 68588, USA

*Corresponding author: Jeyamkondan Subbiah, Kenneth E Morrison Distinguished
Professor of Food Engineering, Departments of Food Science & Technology and Biological
Systems Engineering, 210, L.W. Chase Hall, East Campus, University of Nebraska-Lincoln, NE-
68583-0726

Email address: jeyam.subbiah@unl.edu; Phone: +1 402-472-4944; Fax: +1 402-472-6338

Abstract

Microwave heating of frozen foods involves multiple physics and food product development has been trial-and-error in the food industry. Multiphysics models can be used to understand microwave interactions and can assist in design of food that can be heated more uniformly. A comprehensive three-dimensional finite element model for describing microwave heating of a food product on a rotating turntable is developed including multiphysics of Maxwell's electromagnetic heating, energy conservation, Darcy's velocity, mass conservations of water and gas, and phase change of melting and evaporation of water. The necessity of incorporating mass transfer physics was investigated and confirmed. Twelve discrete rotational steps were used in one rotational cycle. Two approaches of updating dielectric properties at each rotational step (typical) and each cycle (simplified) were evaluated. The models using typical and simplified approaches were developed and validated for heating of a 550 g tray of frozen mashed potato for 6 minutes in a 1250 W microwave oven on a rotating turntable. The spatial variation of the top surface temperatures of the mashed potato acquired by an infrared camera, the transient temperatures at six locations recorded by fiber optic sensors, and the total moisture loss during heating all showed good agreement with the simulation results for both approaches. The typical and simplified approaches had similar RMSE values of transient temperatures of, respectively, 13.1 and 13.2 °C, while the RMSE values between experimental replications was 8.0 °C. The RMSE values of total moisture loss of were similar (2.2 and 2.4 g) for both approaches. With 83% reduction in computation time for the simplified approach, this method can be used to evaluate the microwave heating of food products and accelerate microwaveable food products development.

Keywords: microwave heating, heat transfer, mass transfer, finite element analysis, rotation, updating dielectric properties.

1 Introduction

In general, microwaveable foods are perceived as lower quality food by consumers. This perception is primarily due to uneven cooking of frozen foods in domestic microwave oven rather than the quality of food ingredients used in the food product. Microwave heating of frozen foods involves multiple physics and food product development has been trial-and-error in the food industry (Pitchai et al., 2012). This process is time consuming and expensive. Recently, multiphysics models have been developed to characterize the heating of food products in domestic microwave ovens. These models can enhance the understanding of interactions between the microwaves and the food products, and serve as an excellent tool for the food product developers in designing a food product that cooks more uniformly across a range of microwave ovens (Datta and Anantheswaran, 2001). This has a potential to change the negative perception of microwaveable foods and increase the market share of these products (American Frozen Food Institute, 2016).

Several microwave models for thawing of frozen food products have been reported (Basak and Ayappa, 2001; Campañone and Zaritzky, 2009; Chamchong and Datta, 1999a, 1999b; Liu et al., 2005; Tilford et al., 2007). However, most of these models only couple electromagnetics (EM) heating and heat transfer to simulate the microwave heating process for a short heating time or with cycled microwave power. In these models, the food products are assumed to be a single phase solid food product where evaporation and moisture movement in the food were ignored. These assumptions surely limit the ability of these models to fully characterize a real

microwave heating process. Therefore, the necessity of incorporating mass transfer physics for longer microwave heating needs to be evaluated.

A three-dimensional (3-D) model considering food as a multiphase porous media has been developed to simulate microwave heating of fresh mashed potato that combines convective and radiant heating (Rakesh et al., 2012). Recently, Chen et al. (2014) developed a 3-D multiphase model considering heat and mass transfer and phase change of evaporation for microwave heating of fresh mashed potato in a domestic microwave oven. However, most of the microwaveable foods in North America are frozen. Modeling frozen food is complex which needs to consider complex moving phase change interface and dramatic changes in properties (Handbook of Frozen Food Processing and Packaging, Second Edition, 2011; Leung et al., 2005). During microwave heating process, portion of the frozen sample will thaw first and reach melting point, forming phase-change interface; as microwave heating continues, the phase change interface moves (Handbook of Frozen Food Processing and Packaging, Second Edition, 2011; Leung et al., 2005). Frozen products cook more unevenly in a domestic microwave oven, when compared to refrigerated or fresh products. Cooking of frozen products takes longer time and results in larger temperature gradients between the edges and the center. Therefore it is also important to consider mass transfer physics to understand evaporation on edges and moisture movement. A multiphysics model incorporating mass transfer physics could provide better understanding of moisture movement which is critical for food quality (Rakesh and Datta, 2011). However, these models are considerably more computationally intensive and time consuming.

Most microwave ovens manufactured today have turntables that rotate the food during heating to improve the microwave heating uniformity. There is a significant variation in EM field distribution within the cavity at different locations (Risman et al., 1987). Thus, the rotation

of the turntable needs to be included in the modelling process. However, only few studies included rotation of the turntable when modeling microwave heating (Geedipalli et al., 2007; Liu et al., 2013; Pitchai et al., 2014). Because of difficulty in implementation of the rotation, and the resulting long computation times needed for capturing continuous rotation, discrete rotating steps are often used. Because a fully coupled multiphysics model (solving all dependent variables together) is computationally intensive, two segregated steps are often used for solving the microwave heating model at each rotational step. The first segregated step calculates the EM field, and the second segregated step solves for the temperature field. Because of the temperature-dependent dielectric properties, the second segregated step typically involves updating of the dielectric properties, which, in turn, influences the EM field calculated in the first segregated step. We will refer to this approach of updating dielectric properties at each rotation step as the typical approach. Liu et al. used this typical approach for evaluating the microwave heating of rotating fresh mashed potato and found that the dielectric properties need not to be updated frequently if the penetration depth does not change considerably with temperature change (Liu et al., 2013). However, the dielectric properties and penetration depth change considerably with temperature for a frozen food product especially during phase change. Therefore, it is necessary to determine the frequency of updating the dielectric properties during microwave heating. Multiphysics models are computationally intensive (Liu et al., 2013), which deters food industry in adopting these models for food design. This investigation of effect of model simplification (less frequent updating of dielectric properties) on model accuracy may provide information that helps the industry in using appropriate models at different stages of food design.

The objectives of this study are:

(1) to develop a 3-D model for microwaving frozen mashed potato with multiphysics incorporating electromagnetics, heat and mass transfer, Darcy's velocity, and phase change of melting and evaporation of water;

(2) to investigate the necessity of incorporating mass transfer physics; and

(3) to evaluate the effect of updating dielectric properties at each rotational cycle on model prediction accuracy and computation time.

2 Mathematical model development and experimental validation

2.1 Multiphysics of microwave heating of frozen food products

Governing equations and boundary conditions of the models without mass transfer physics were described in Pitchai et al. (2014). Governing equations and boundary conditions of the models with mass transfer physics were reported in our earlier study (Chen et al., 2014) of the development of microwave heating of fresh mashed potato. This study extends the model with mass transfer physics to frozen mashed potato by incorporating the apparent specific heat capacity to incorporate latent heat of melting. All the same model assumptions and property values used by Chen et al. (2014) were used in this study. Microwave heating of a frozen food product is a comprehensive process that involves EM heating, phase change during melting and evaporation, pressure driven flow, and heat and mass transport in a multiphase porous product. An overview of schematic of multiphysics coupling with governing equations and boundary conditions is shown in Fig. 1.

Electromagnetics: When the food product is exposed to microwaves in an oven, the interaction between the food product and the EM waves is described by Maxwell's equations (Eqns. 1-4),

and it results in heat generation governed by Eqn. 5. The boundary conditions are defined by perfect electric conductors at the cavity walls (Eqn. 6). Input to this EM physics is temperature from the energy conservation, while the output is the heating source. This was implemented in COMSOL Multiphysics 4.3a (COMSOL Inc., Boston, Mass., U.S.A.) with using the Radio Frequency Module.

Phase change of melting: Initially, the frozen mashed potato is considered as a single phased solid. The specific heat capacity and thermal conductivity of frozen mashed potato was reported in an earlier work (Chen et al., 2013) and used in the model. Upon thawing, the mashed potato was considered as porous media, including a solid phase of potato granules, a liquid phase of water, and a gaseous phase of vapor and air. The porosity is defined as the fraction of volume of pores (filled with water and gas) to the total volume (Eqn. 7). The saturation of water and gas is defined as the volume of water and gas to the volume of pores (Eqns. 8-9), respectively. The effective density, specific heat capacity, and thermal conductivity can be calculated based on volume or mass fractions of the compositions (Eqns. 20-22) using the methods described in (Choi and Okos, 1986).

Phase change of evaporation: In the thawed mashed potato, water may either evaporate or condense until the equilibrium between liquid and vapor is achieved at that temperature and moisture content (Eqns. 10-12).

Darcy's velocity: The increase of vapor concentration (C_v) due to evaporation generates higher vapor pressure in the food product. The pressure driven flow of liquid water and gas (combination of vapor and air) in the solid is described by Darcy's Law (Eqn. 13). The total gas pressure is the sum of air pressure and vapor pressure (Eqn. 14), which can be calculated based on the concentrations of air and vapor using the ideal gas law. On food boundaries (only the top

surface which is exposed to air, but not on the sides), the total pressure of air and vapor was defined to be the ambient pressure (Eqn. 15).

Mass conservation equation: The change in concentration of species (liquid water, water vapor, and air) with time is determined by the diffusion due to concentration gradient (Fick's Law), convection due to pressure driven flow (Darcy's Law), and reaction due to non-equilibrium condition between liquid water and water vapor (Phase change of evaporation), as described by the mass conservation equation (Eqn. 16). Water vapor generated within the food domain can move out of the food product by convection and diffusion, which is given as a boundary condition on the top surface of the food (Eqn. 17). Liquid water can move out of the boundary as vapor after evaporation (Eqn. 18). This was implemented in COMSOL with using the Chemical Species Transport Module.

Energy conservation equation: The energy conservation equation includes energy convection due to mass transport, conduction due to temperature gradient (Fourier's Law), phase change of melting and evaporation, and from the microwave heating source (Eqn. 19). Along with the mass flux of the vapor, the food boundaries also lose heat because of the vapor lost, as well as cooling by convection at room temperature due to the air domain (Eqn. 23). This was implemented in COMSOL with using the Heat Transfer Module.

Fig. 1. Schematic of multiphysics coupling for microwave heating of porous media product.

2.2 Model assumptions

Besides the assumptions stated in our previous work (Chen et al., 2014), the additional following assumption was included in this study. Considering there is a temperature range during phase change of melting around 0 °C (Chen et al., 2013; Pham, 2006), the mashed potato was assumed to be frozen below 10 °C and completely thawed above 10 °C. In the frozen state, the mashed potato is solid, and therefore components of water (ice) and gas cannot move freely. In the thawed state, the mashed potato is assumed to be a multiphase porous media including a solid (potato), a liquid (water), and gases (vapor and air), where the components of liquid and gas can transport due to the concentration and pressure gradients.

2.3 Model parameters

The initial conditions of temperature and water, vapor and air concentrations, and other input parameters (porosity, density, specific heat capacity, thermal conductivity, intrinsic permeability, relative permeability, diffusion coefficient, viscosity, latent heat of evaporation, evaporation rate constant, mass transfer coefficient, heat transfer coefficient and dielectric properties have been discussed in a previous work in detail (Chen et al., 2014). The latent heat of melting of water is 334 kJ·kg⁻¹.

2.4 Geometric model and meshing scheme

A geometric model was developed for a domestic microwave oven (Model no: NN – SD9675; Panasonic Corporation, Shanghai, China) rated at 1250 W and a tray of 550 g frozen mashed potato. In the geometric model, important details of oven cavity, magnetron, waveguide, turntable, crevices and a metal bump were included as shown in Fig. 2(a).

The entire domain was discretized into tetrahedral and prism shaped elements. Boundary layers were created at the food boundaries (Fig. 2b) to improve the convergence. The mesh sizes were determined according to the normalized power absorption method described in Geedipalli et al. (2007) and Chen et al. (2014). It was found that the numbers of elements in the entire domains and food domain of, respectively, 546960 and 190985 were sufficient to get mesh-size independent results. The simulations were performed on a Microway E2600 workstation with an available memory of 96 GB RAM running two twelve-core Intel Xeon E5-2667 processors at 2.9 GHz frequency (Microway Inc., Plymouth, MA).

Fig.2. Geometric model of microwave oven and the food product (a) and the mesh used for a quarter of food product showing the boundary layers (b).

2.5 Simulation strategy

Rotation of the food product was incorporated in the model. Instead of continuous rotation of the turntable, discrete step rotation was used in the simulation. Liu et al. used a more complex geometry setup in which the sample, container and a middle-hollow cylindrical surrounding air were united together and rotated with turntable to minimize the interpolation errors (Liu et al., 2013). In this study, we rotated the oven cavity instead of the food product. The advantage of

rotating the oven cavity is that the food product location does not change during rotation, which simplifies the interpolations in food product domain between the different rotational steps. A discrete rotation angle of 30° for each rotational step (12 steps for one full rotation) was found to be accurate enough to simulate the microwave heating process including rotation (Liu et al., 2013).

Two segregated steps were used for solving the microwave heating model with mass transfer physics. The first segregated step calculated the EM field by solving Eqns. 1-4 and 6, and heat source by solving Eqn. 5 using an iterative generalized minimal residual method solver (GMRES). The second segregated step calculated heat and mass transport by solving Eqns. 7-23, and updated the dielectric properties which in turn influenced the EM field calculations in the first segregated step. For this second segregated step, a fully coupled nonlinear Newton solver was used to simultaneously solve heat and mass transfer equations and determine temperature, water, vapor and air concentrations using the heat source calculated in the first segregated step. The Jacobian Matrix (the change of basis transformation that provides the mapping between derivatives of the physical and reference element) was updated at each iteration to improve the convergence.

To couple the two segregated steps, two frequencies of updating dielectric properties were evaluated in this study: updating at each rotational step (Typical approach) and updating at each rotational cycle (Simplified approach), as shown in Fig. 3. The simulation of rotation was performed in COMSOL live linked with MALAB (MathWorks®, Inc., Natick, MA).

(a) Updating at each rotational step (Typical)

(b) Updating at each rotational cycle (Simplified)

Fig. 3. Flow chart depicting microwave heating simulation and strategy for updating dielectric properties during rotation (a. typical approach of updating at each rotational step, b. simplified approach of updating at each rotational cycle).

(1) Updating at each rotational step (Typical approach):

Both segregated steps were performed for each rotational time step sequentially as depicted in Fig. 3(a). During one rotational step (30° rotational angle, 0.83 s of actual microwave cooking time), the dielectric properties were assumed to be constant. After performing calculations of two segregated steps (EM field and microwave power density in first segregated step and heat and mass transfer in second segregated step for 0.83 s of microwave cooking), the oven cavity was rotated by 30° . The dielectric properties were updated based on the current temperature from the previous location (rotational step) and then EM field, heat and mass transport equations were solved for the next location. A turntable rotating at a speed of 6 rpm makes 36 rotational cycles in 6 min of microwave heating. For each rotational cycle, the turntable was assumed to be at 12 discrete locations with 30° step angle. Therefore, the EM field and the heat-mass transfer were analyzed for 432 time steps to simulate the entire heating process.

(2) Updating at each rotational cycle (Simplified approach):

Liu et al. (Liu et al., 2013) reported that the dielectric properties (heat source) need not to be updated frequently, when the dielectric properties do not change considerably. Therefore, instead of updating dielectric properties of the food product at each rotational step, the dielectric properties were assumed to be constant during one rotational cycle (10 s) in this simplified approach. As shown in Fig.3 (b), for each rotation cycle, the electric field distributions at 12 discrete locations were calculated using segregated step 1 based on the dielectric properties using the temperature from the previous rotational cycle. The heat sources of the 12 discrete locations were averaged and the average heat source was then used for a 10 s duration heat and mass transfer analysis. The dielectric properties

were updated after one rotational cycle based on the new temperature and used for next rotational cycle. Because this method averaged the calculated heat source in 12 orientations, the variability of EM field within the cavity is still considered in this simplified approach. Only, the dielectric properties were less frequently updated (10 s instead of 0.83 s). For a 6 min microwave heating process, the EM fields were solved 432 times for both the simplified and typical approaches; however heat and mass transfer analysis was computed for 432 times for 0.83s each in the typical approach, while heat and mass transfer were only analyzed 36 times, each for a 10 s interval.

2.6 Experimental validation

Mashed potato was prepared as described in our previous work (Chen et al., 2013) by mixing dry potato flakes, whole milk, deionized water and margarine,. The prepared mashed potato in a tray was covered with a shrink wrap film and kept in a -10 °C freezer until used for the experiment.

The mashed potato tray set at the center of a rotating turntable was heated for 6 minutes. Six fiber optic sensors (8-channel signal conditioner, FISO Technologies Inc., Quebec, Canada) recorded transient temperatures of six points inside the sample, as shown in Fig. 4. An infrared camera (SC640, accuracy $\pm 2^{\circ}\text{C}$, 640×480 pixels, FLIR systems, Boston, MA) was used to acquire temperature profiles on the top surface of the mashed potato after 2, 4, and 6 min of microwave heating. The total weights of the food product before and after microwave heating was recorded to determine the total moisture loss. The experiments were performed in triplicates.

Fig. 4. Locations of fiber-optic sensor for transient temperature measurement in the center plane (15 mm from the top surface) of the food (top view).

2.7 Data analysis

To investigate the necessity of incorporating mass transfer physics, the simulated temperature profiles at three layers (top, middle, and bottom) after six minutes of heating were compared between the models with and without mass transfer physics. The total power absorption for the two approaches in updating dielectric properties was analyzed for the food domain. The spatial temperature on the top surface and the transient point temperatures at the selected six locations in the simulations for the two approaches were compared to the three replications of experimental results. The simulated transient point temperatures were compared with the experimental result using the root mean square errors (RMSE) given by Eqn. 24:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (T_s - T_e)^2} \quad (24)$$

where T_s and T_e are, respectively, the simulated and experimental transient point temperatures, and n is the total number of time steps recorded during heating. Similarly, the RMSE between the simulation and the experiment were calculated for the total moisture loss at three time points. The simulation results using the two proposed

approaches for updating the dielectric properties were compared with each other and the experimental results.

3 Results and discussions

3.1 Investigation of necessity of incorporating mass transfer physics

The simulated temperature profiles after six minutes of heating at three layers (top, middle, and bottom) were compared between the models with and without mass transfer physics, as shown in Fig. 5. Two models showed similar heating patterns, but the temperature scale is considerably different especially for the top layer. Generally, neglecting mass transfer physics resulted in higher temperature prediction, when compared to experimental result (Fig. 7 in Section 3.2) and the model that incorporated mass transfer physics. Most of the locations on the top layer of the model without mass transfer model are even higher than 100 °C. Similar results were reported by Liu et al. (2013) and Geedipalli et al. (2007), where the mass transfer physics was not included even just for 150 s of microwave heating.

The higher temperature in the model without mass transfer physics can be attributed to the ignorance of moisture movement out of the top surface of the food product, which took away a large amount of thermal energy on the surface. The latent heat of evaporation was considered in the apparent specific heat capacity term for the model that did not incorporate mass transfer; however once the temperature increased beyond the latent heat region, the temperature will continue to increase rapidly. However in reality, the evaporated moisture escapes the food surface taking away some thermal energy,

while the moisture from interior moves to the drier area and continues to maintain the temperature at around 100 C.

Therefore, it is necessary to incorporate mass transfer physics to model longer duration microwave heating process.

Fig. 5. Comparison of simulated temperature profiles after six minutes heating at different layers with and without mass transfer physics.

Based on these results, further discussions were presented only for the models that incorporated mass transfer physics.

3.2 Total power absorption

The total power absorption for the two proposed approaches, of updating dielectric properties at each rotational step (typical) and at each rotational cycle (simplified), and the 12-point moving average power absorption of the typical approach during the microwave heating process is shown in Fig. 6(a). The total power absorption for updating at each rotational cycle showed an increasing trend at the beginning of microwave heating. After 30 s of microwave heating, the total power absorption stabilized at about 1040 W. This is because the slightly thawed top layer of the food product dramatically changed the power absorption (Chen et al., 2015). The total power absorption during the heating is related to temperature-dependent dielectric properties of mashed potato from the frozen to the cooked state. At the beginning of the heating, the complex dielectric properties of frozen mashed potato were as low as $5 - 2i$ at $-10\text{ }^{\circ}\text{C}$ (Chen et al., 2013). After some heating time, the complex dielectric properties of the thawed mashed potato increased considerably to be $47 - 21i$ at $0\text{ }^{\circ}\text{C}$. Frozen food generally absorbs less energy than thawed food (Zhang and Datta, 2003) because water molecules in the frozen food product are in the crystalized state. However, due to high penetration depth, the frozen mashed potato also absorbed a relatively large amount of microwave energy (about 83% of the thawed product), which was also observed by Zhang and Datta (2003). After thawing, the microwave power absorption increased slightly (Venkatesh and Raghavan, 2004).

(a) Total power absorption of two approaches

(b) Total power absorption at different locations in one cycle

(c) Food location on a turntable

Fig. 6. Total microwave power absorption during microwave heating of mashed potato for two approaches of updating dielectric properties and food location on a turntable.

The approach of updating at each rotational step (typical approach) also showed a similar trend that, the total power absorption increased first and then stabilized, but with cyclic variations within each rotation cycle (10 s). The moving average of the typical approach showed similar total power absorption to the simplified approach. The cyclic variations can be attributed to the rotation of the non-symmetric mashed potato and the nonuniform electric field distribution. In one rotation cycle (10 s), the mashed potato tray

was rotated for 12 orientations. At different orientations, the non-symmetric food product absorbed different microwave power due to nonuniform standing wave pattern inside the cavity, as shown in Fig. 6(b). When food orientation changes with respect to magnetron position, the food interacts with microwaves differently. Because the food is located at the center of the turntable (Fig. 6c), the total power absorption curve is symmetric within a one rotation cycle. For example, the total power absorption at location 1 is similar to that of location 7 because the food product was placed at the same position but only with 180° rotation. The consistent cyclic pattern also indicates that the standing wave pattern of the EM waves within the cavity did not change considerably during the heating time.

The two approaches of updating dielectric properties showed little difference on total power absorption during the whole heating period. For the first couple of rotations, the total power absorption predicted using the simplified approach (846 W for 1st rotation) was slightly lower than the average total power absorption of 12 orientations using the typical approach (895 W for 1st rotation). This is due to the lower power absorption of the frozen (-10 °C) food product. The simplified approach used the same frozen dielectric properties during the first rotation; while the typical approach used temperature-dependent dielectric properties at each step which are continuously increasing during heating. However, after a portion of the food product was thawed, the two approaches of updating dielectric properties showed similar total power absorption values for each rotation. This is because the dielectric properties do not change considerably during one rotation, as the thawed portion of the food product absorbs the majority of the microwave energy (Oliveira and Franca, 2002). The total power absorption of the simplified approach is slightly higher than that of the moving average of the typical approach for

most of the time of heating. Similarly, the average temperature in the food domain for the simplified approach was found to be 0.9 °C higher than that of the typical approach after 6 min of heating.

3.2 Spatial temperature profiles

Figure 7 shows the comparison between experimental spatial temperature profiles collected after 2, 4, and 6 min of microwave heating and simulated profiles with the two approaches of updating dielectric properties. After 2 min of microwave heating, the top layer of the mashed potato showed hot spots on the edges and a hot ring around the center area. With increasing heating time, the hot spots expanded from the edges to the center. Both simulated results using the two approaches showed similar hot and cold spot locations on the top layer when compared to the observed thermal images. Slight discrepancy between simulated and experimental results can be attributed to the assumptions in the model development, such as single frequency (2.45 GHz) (Pitchai et al., 2012), using discrete rotational steps (12 steps per rotation), and model parameters from literatures (diffusion coefficient, permeability, evaporation rate constant, and moisture-isotherm). Both experiments and simulations showed that the mashed potato was not heated uniformly. Similar edge heating were also reported in the microwave heating of a rotating potato (Geedipalli et al., 2007; Liu et al., 2013).

In summary, the temperature-dependent dielectric properties did not change considerably within one rotation and therefore the two approaches of updating dielectric properties showed similar temperature predictions on the top surface at different time steps.

Fig. 7. Spatial temperature profiles on the top surface of mashed potato after 2, 4, and 6 min of microwave heating for simulations and experiments.

3.3 Point temperature profiles

Figure 8 summarizes transient point temperatures at six locations during microwave heating of mashed potato. These were used to further validate the accuracy of the model. Three replications of experiment showed divergence in the transient temperature profiles, which was also reported by Pitchai et al. (2012) and Liu et al. (2013). The RMSE values of three experimental replications for six locations ranged from 3.9 to 13.9 °C (with an average of 8.0 °C) as shown in Table 1. The discrepancy between experimental replications can be attributed to the difficulty in maintaining the fiber optic probes at the same consistent locations in the mashed potato in the experimental validation. Because of the nonuniform EM field and power density distribution, a small shift in probe location causes a significant temperature differences (Pitchai et al., 2012).

Fig. 8. Transient point temperature profile comparison between simulations (2 updating approaches) and experimental values at six locations during 6 minutes of microwave heating of mashed potato (..... Experiment, - - - updating at each rotational step (Typical) , — updating at each rotational cycle (Simplified)).

Table 1. The RMSE of two simulated updating approaches and experiment results at 6 locations

Location	RMSE, °C		
	Experimental replications	Updating at each rotational step (Typical)	Updating at each rotational cycle (Simplified)
1 (Corner)	13.9	18.8	20.1
2	4.1	7.5	8.3
3	11.8	11.4	9.1
4 (Center)	1.9	5.5	5.6
5	12.4	12.5	12.1
6	3.9	22.8	24.1
Average	8.0	13.1	13.2

Generally, both approaches of updating dielectric properties matched well with the experiment for most of the points. Location 6 was the worst prediction point, which was primarily attributed to the poor prediction of thawing process at that location. In this study, many simplifications in the model development such as using a single frequency (2.45 GHz) (Pitchai et al., 2012) and using discrete rotational steps (12 steps per rotation) may influence the EM field distribution prediction, and therefore the heat source power density distribution. The discrepancy between the experimental and simulated results may be partly attributed to the inaccurate EM heat source prediction in the simulation. A false prediction of hot and cold spots caused by the inaccurate EM heat source prediction may influence the point temperature prediction considerably (Pitchai et al., 2012).

Both updating approaches showed similar temperature predictions as seen in the experiments. The transient point temperatures from the two updating approaches matched well with the experimental values. As shown in Table 1, the RMSE values of the typical and simplified approach ranged from, respectively, 5.5 to 22.8 °C (with an average of 13.1 °C) and 5.6 to 24.1 °C (with average of 13.2 °C), showing similar transient point temperature predictions. Even though these errors are large, the average RMSE values between the experimental replications and experimental average was large (8.0 °C). This large experimental error is due to inconsistency in magnetron performance (Ghammaz et al., 2003; Liu et al., 2014; Pitchai et al., 2015, 2012; Yakovlev, 2006) and sensor positioning (Liu et al., 2013; Pitchai et al., 2012) during microwave heating.

3.4 Total moisture loss

It is important to consider mass transfer in a multiphysics model to describe microwave heating of a product for a longer duration. It is not only important to

understand the moisture movement, mass transfer physics has an impact on the temperature predictions. The microwave heating models that only consider heat transfer often over-predict temperature when compared to experiments, especially for longer heating duration (Pitchai et al., 2014, 2012). An apparent specific heat capacity measured by a differential scanning calorimetry is often used in the microwave-heat transfer model development. Although latent heat of vaporization is included in the apparent specific heat in the heat transfer models, the mass transfer physics of escaping vapor along with its thermal energy are not included in these models. Thus, ignoring the mass transfer in the model considerably influences the temperature prediction. In this study, we considered mass transfer physics in the model.

Water evaporation and mass transport are significant in a longer microwave heating process. The comparison of total moisture loss between experimental and simulated results is shown in Fig. 9. Both updating approaches showed good agreement with the experiments results, with the RMSE values, respectively, of 2.2 and 2.4 g. The total moisture loss for the two simulation approaches closely matched with each other (RMSE = 0.2 g). In the first 2 min of microwave heating, the total moisture loss was very low. This is because only portion of the frozen mashed potato was thawed at low temperatures. After 2 min, the total moisture loss rapidly increased with increasing time and temperatures. After 6 min of microwave heating of frozen mashed potato, 5.7% moisture of the total mass evaporated and convected out of the mashed potato, indicating the necessity of including mass transfer in the microwave heating model.

Fig. 9. Total moisture loss profile comparison between the simulated and experimental results during microwave heating of mashed potato.

3.5 Simulated temperature and pressure profiles

The simulated results from the model with updating dielectric properties at each rotational cycle were used to analyze the temperature and pressure (gauge) distributions within the food product after 2, 4, and 6 min of microwave heating, as shown in Fig. 10. Because the food sample in this study is a big block (550 g), and the thickness of the food sample (35 mm) is much bigger than the penetration depth (5.1 mm after thawing), the temperatures at the edges are higher than that at the center. Higher pressure was observed near to the edge of the food product because of evaporation of moisture due to higher temperature. The highest pressure (gauge) was found as 1.6×10^5 Pa inside the mashed potato after 6 min of heating. Similar results have been reported in a microwave puffing process that, the highest pressure (gauge) was predicted to be 3.5×10^5 Pa after 40 s of heating (Rakesh and Datta, 2012, 2011).

Fig. 10. Simulated temperature and pressure profiles after 2, 4, and 6 min of microwave heating.

3.6 Computation time

Although both updating approaches of dielectric properties showed similar simulation results, they require considerably different computation times. The comparison of computation time of the two updating approaches is shown in Table 2. In the typical approach of updating dielectric properties at each rotational step, the EM field density and heat and mass transfer were all calculated for 432 time steps, which equals to 6 min of actual heating time; while using simplified approach of updating dielectric properties at each rotational cycle, the EM field density was also calculated for 432 time steps, but the heat and mass transfer was only analyzed for 36 time intervals during heating. Two approaches need the same time for the EM field analysis. However, different computation

times were needed for the heat and mass transfer analysis, although the total heating time was the same for two approaches (6 min). In this study, the implicit method was used (“free time step”) in the time-dependent solver for the coupled heat and mass transfer analysis, where the solver can choose time steps according to the total heating time settings at that step (10 s for one rotational cycle in the simplified approach versus 0.83 s for each rotational step in the typical approach) and convergence performance. The solver typically starts with a smaller time step. Based on convergence, the solver then starts using larger and larger time steps (the maximum time step can be as high as 10% of the total heating time) during the remaining part of the heating. In case of short heating steps of 0.83 s, the solver restarts more frequently (432 times) and takes a longer time when compared to solving a relatively longer heating time (10 s) with less frequency (36 times). Generally, both approaches used about 40 h on EM analysis, and the computation time for heat and mass transfer analysis of the typical approach was 12 times of that of the simplified approach. Therefore, the simplified approach of updating at each rotational cycle used less computation time (96 h) than the typical approach of updating at each rotational step (550 h). Similarly, Liu et al. (2013) also found that the computation time could be shortened by reducing the frequency of updating dielectric properties (heat source) in microwave heating.

Table 2. Comparison of physics analysis and computation time between two updating approaches

Approaches	Number of EM field analysis	Number of heat and mass transfer analysis	Total computation time, h
Updating at each rotational step (Typical)	432	432	550
Updating at each rotational cycle (Simplified)	432	36	96

Besides, the simplified approach assumed that the temperature-dependent dielectric properties were constant in one rotation cycle and the EM field density of 12 orientations were independent of each other. Thus, the EM field density at 12 orientations can be analyzed simultaneously using parallel computing techniques. The simultaneous calculation of EM field density at different orientations in the simplified approach will save more computation time.

4 Conclusions

Current microwave heating of frozen food product models have generally neglected mass transfer physics, which have resulted in higher predicted temperatures within the food matrix. It is necessary to include mass transfer physics in modeling microwave heating of frozen food products, especially when they are heated for longer durations.

This multiphysics based model, which incorporated Maxwell's electromagnetic heating, energy conservation, Darcy's velocity, mass conservations of water and gas, and phase change of melting and evaporation of water, could provide better understanding of moisture evaporation and movement which is critical for food quality. The simplified approach (updating dielectric properties at each rotational cycle) in the developed multiphysics model showed similar predictions to the typical approach (updating at each step), but with 83% reduction in computation time. This saving in the computation time is considerable and may allow the coupled comprehensive multiphysics model to be used to understand the microwave heating of frozen food products and assist microwaveable food product development. Simultaneous calculation of EM field density at different

orientations based on the simplified approach using parallel computing will further save computation time.

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Nomenclature

E	electric field intensity, $\text{V}\cdot\text{m}^{-1}$
H	magnetic field intensity, $\text{A}\cdot\text{m}^{-1}$
f	frequency, Hz
P_v	electromagnetic power dissipation density, $\text{W}\cdot\text{m}^{-3}$
Δv	volume of an element
S	saturation rate
C	concentration, $\text{mol}\cdot\text{m}^{-3}$
D	diffusion coefficient, $\text{m}^2\cdot\text{s}^{-1}$
u	Darcy's velocity, $\text{m}\cdot\text{s}^{-1}$
r	water evaporation rate in mole, $\text{mol}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$
I	water evaporation rate in quality, $\text{kg}\cdot\text{m}^{-3}\cdot\text{s}^{-1}$
M_w	water (vapor) molecular weight, $18\text{ g}\cdot\text{mol}^{-1}$
C_p	specific heat capacity, $\text{kJ}\cdot\text{kg}^{-1}\cdot^{\circ}\text{C}^{-1}$
k	thermal conductivity, $\text{W}\cdot\text{m}^{-1}\cdot^{\circ}\text{C}^{-1}$
T	temperature, $^{\circ}\text{C}$
u_i	fluid velocity, $\text{m}\cdot\text{s}^{-1}$
k_{eff}	effective thermal conductivity, $\text{W}\cdot\text{m}^{-1}\cdot^{\circ}\text{C}^{-1}$
p_{v,eq}	equilibrium vapor pressure, Pa
p_{sat}(T)	saturated vapor pressure of pure water, Pa
m	mass fraction
M	moisture content (dry basis)
K	evaporation rate constant, s^{-1}

R	ideal gas constant, $8.314 \text{ J}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}$
k_{in}	intrinsic permeability, m^2
k_r	relative permeability
$n_{\text{v,sur}}$	boundary vapor flux, $\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$
h	surface convective heat transfer coefficient, $\text{W}\cdot\text{m}^{-2}\cdot^{\circ}\text{C}^{-1}$
q_n	outward normal heat flux, $\text{W}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$
T_a	ambient temperature, $^{\circ}\text{C}$
RMSE	root mean square error, $^{\circ}\text{C}$
T_s	simulated point temperature, $^{\circ}\text{C}$
T_e	experimental point temperature, $^{\circ}\text{C}$

Greek symbols

ω	angular frequency, $\text{rad}\cdot\text{s}^{-1}$
μ	electromagnetic permeability
ε	complex relative permittivity
ε'	dielectric constant
ε''	dielectric loss factor
ε_0	free space permittivity, $8.854\times 10^{-12} \text{ F}\cdot\text{m}^{-1}$
Φ	porosity
ρ	density, $\text{kg}\cdot\text{m}^{-3}$
λ	latent heat of vaporization, $2.26\times 10^6 \text{ J}\cdot\text{kg}^{-1}$
ν	viscosity, $\text{Pa}\cdot\text{s}$