



Computer simulation model development and validation for radio frequency (RF) heating of dry food materials

G. Tiwari^a, S. Wang^a, J. Tang^{a,*}, S.L. Birla^b

^a Department of Biological Systems Engineering, Washington State University, 213 LJ Smith Hall, Pullman, WA 99164-6120, USA

^b Department of Biological Systems Engineering, University of Nebraska, Lincoln, NE 68583, USA

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ABSTRACT

Radio frequency (RF) heat treatment has been identified as a novel pasteurization and non-chemical quarantine method for dry food materials. But the major obstacle of this treatment is non-uniform heating in these food materials. The objective of this study was to help understand RF heating process by developing a computer simulation model. A finite element based commercial software FEMLAB was used to develop the computer model for a 12 kW, 27.12 MHz parallel plate RF system. Wheat flour was selected as a model food to represent dry food materials. Dielectric properties of wheat flour were measured using an open-ended coaxial probe connected with impedance analyzer, whereas thermal properties were determined using a duel needle probe method. Simulated and experimented temperature profiles (°C) of wheat flour were compared in four different horizontal layers after 3 min of RF heating, with a fixed electrode gap of 155 mm. Both, simulated and experimental results showed that temperature values were higher at the mid layers followed by top and bottom layers. Corners were more heated than centers in each layer. Sensitivity analysis showed that temperature uniformity in the sample was most affected by top electrode voltage and sample dielectric properties. The developed model can further be used to study the effect of some important parameters such as sample size, position, shape, and dielectric properties on RF heating of dry food materials.

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1. Introduction

Dry products such as grains (cereals, oil seeds, and legumes), nuts, herbs, spices, bakery products, and infant formulas are generally regarded as shelf stable foods and can be stored for a long time due to their low moisture contents. Presence of pathogens and insect pests, nevertheless, may cause considerable qualitative and quantitative losses in these products. For example, in lentils, if not stored properly, losses can be reached as high as 50% due to insect damages (Ghosh et al., 2007). Wheat flour infested with *Rhyzopertha dominica* greatly affects baking and rheological properties of bread made by the flour (Sánchez-Mariñez et al., 1997). International trade of dry nuts such as walnuts and almonds may require complete elimination of targeted insect pests in these commodities in certain countries such as Japan, South Korea, and European countries (Wang et al., 2007a,b). Contamination of pathogens *Enterobacter sakazakii* and *Salmonella* spp. in infant formulas (Breeuwer et al., 2003; Friedemann, 2007), and *Bacillus cereus* and *Clostridium perfringens* in spices (Banerjee and Sarkar, 2003) may even pose a serious threat to consumer health.

Radio frequency (RF) heat treatment has been explored to investigate its potential applications in dry food products and to control targeted pathogens and insects in several dry products, such as disinfestations of navel orangeworm (*Amyelois transitella*), codling moth (*Cydia pomonella*), Indianmeal moth (*Plodia interpunctella*) and red flour beetle (*Tribolium castaneum*) in in-shell walnuts (Wang et al., 2001a, 2002, 2007a,b), grain borers and Angoumois grain moth in rice (Lagunas-Solar et al., 2007), and *Salmonella* spp. and *Escherichia coli* O157: H57 in fishmeal (Lagunas-Solar et al., 2005). But the major hurdle for RF heating technology to be commercially applicable is its non-uniform heating. Severe uneven heating has been reported for several dry agricultural commodities, such as alfalfa seeds (Yang et al., 2003), walnuts (Wang et al., 2007a,b), and legumes (Wang et al., 2010). Non-uniform temperature distribution may cause quality loss or insect/pathogen survival due to either over or under heating in different parts of a food product. To make this technology commercially feasible, it is essential to understand the complex mechanism of RF heating.

Computer simulation has been effectively used to help understand RF heating process. Neophyту and Metaxas (1998, 1999) used finite element method to simulate electric field inside RF applicators by solving both wave and Laplace equations. Yang et al. (2003) modeled RF heating of alfalfa and radish seeds packed inside rectangular polypropylene boxes in a 1 kW RF system using

* Corresponding author. Tel.: +1 509 335 2140; fax: +1 509 335 2722.

E-mail address: jtang@wsu.edu (J. Tang).

commercial software TLM-FOOD HEATING based on transmission line and finite different time domain method. Chan et al. (2004) solved wave equations to simulate electric field patterns in 1% carboxymethyl cellulose (CMC) solution, placed in a 6 kW, 27.12 MHz RF system using finite element method. They compared simulated electric field patterns with the experimentally determined temperature patterns in CMC solutions using five load positions and container sizes. Marra et al. (2007) successfully simulated the temperature distribution and heating uniformity inside a cylindrical meat roll subjected to a 600 W RF heating using a commercially available finite element based software FEMLAB. They reported differences in temperature uniformity inside a meat roll sample at different power levels. A computer simulation using FEMLAB was also successfully performed to study various factors causing heating non uniformity in fresh fruits, when subjected to RF heating inside a 12 kW, 27.12 MHz RF system (Birla et al., 2008a,b). Simulation results showed that dielectric properties, shape, and position of fruit inside the RF applicator greatly influenced heating uniformity of fresh fruits. Romano and Marra (2008) studied the effect of regular sample shapes (cube, cylinder, and sphere) and their orientations on RF heating behavior in meat samples using a computer model and predicted that cubes should have better heating uniformity than cylinders and spheres. Wang et al. (2008) simulated and validated a computer model to study the influence of dielectric properties of mashed potato and circulating water on the electric field distribution, heating rate, and temperature distribution in a 6 kW RF system. Simulation results confirmed that increase in salt content (loss factor) did not guarantee increase in RF power density.

Very few studies on the computer simulation of the RF heating of dry food products are reported in the literature. Yang et al. (2003) simulated the RF heating of alfalfa and radish seeds. But this study was based on a small RF cavity and reported discrepancies in temperature distributions between simulation and experimental results. Therefore, it is necessary to systematically study the RF heating characteristics in dry food materials and design parameters to improve the RF heating uniformity in these materials, based on the validated computer simulation model.

The overall objective of this study was to investigate the behavior of RF heating in dry food materials using computer simulation model. Specific objectives were to (1) determine the dielectric and thermal properties of the wheat flour as a representative of dry food products, (2) develop a computer simulation model for a 12 kW, 27.12 MHz RF system using commercial finite element software FEMLAB, and (3) validate the computer model by comparing with the transient experimental temperature profiles of wheat flour.

2. Materials and methods

2.1. Material selection

Hard red spring wheat flour, *bronze chief*, was selected as a representative dry food material. The selection of wheat flour was based on its better structural uniformity and consistency as compared to other dry food materials, such as food grains, legumes, and bakery products. The flour was procured from Wheat Montana farms, Three Forks, Montana, USA and stored at room temperature prior to RF experiments. The initial moisture content of wheat flour was 8.8% on wet basis (w.b.).

2.2. Dielectric and thermal properties measurement

Dielectric properties (DPs) of wheat flour samples at a normal bulk density (without further compression) of 800 kg m^{-3} were

measured with an open-ended coaxial-line probe (HP 85070B) connected to an impedance analyzer (HP 4291B, Hewlett Packard Corp., Santa Clara, CA, USA). This normal bulk density of wheat flour was similar to that (785 kg m^{-3}) reported by Rahman (1995). Sample was placed in a cylindrical test cell, with circulating ethylene glycol and water solution through the jacket of the test cell. The circulating ethylene glycol and water solution was used to raise the sample temperature from 20 to 70 °C in every 10 °C increment. The details of the measurement system and procedure can be found elsewhere (Wang et al., 2003; Guo et al., 2008). The selected temperature range is practically applicable for the heat disinfestations of dry food materials without affecting their quality.

Thermal properties (thermal conductivity and specific heat), at a bulk density of 800 kg m^{-3} were measured by a dual needle probe method (KD2 Pro, Decagon Devices, Pullman, WA, USA) at every 10 °C interval from 20 to 70 °C.

2.3. Development of computer model

2.3.1. Physical model

A 12 kW, 27.12 MHz parallel plate RF heating system (Strayfield Fastran with E-200, Strayfield International Limited, Wokingham, UK) was used in this study. The RF system included metallic enclosure, generator, and RF applicator with a pair of RF electrodes. A schematic diagram of the RF applicator is shown in Fig. 1. The bottom electrode is the integral part of metallic enclosure. Top electrode position could be changed with the help of adjustable screws. RF power from the generator was fed in the middle of top electrode. A dielectric material (wheat flour) in a container was placed on the bottom (ground) electrode.

2.3.2. Governing equations

Quasi static approximation for the RF electric field is a valid assumption inside the RF cavity due to its long wavelength ($\sim 11 \text{ m}$) compared to cavity size ($1.8 \times 1.4 \times 1.0 \text{ m}$). Wave length of a wave in a non-magnetic homogeneous dielectric material (λ_m) can be expressed as:

$$\lambda_m = \lambda / \sqrt{\epsilon'_m} \quad (1)$$

where ϵ'_m is the material dielectric constant and λ is the wavelength (m) in air (Besser and Gilmore, 2003). Since dry food materials have low dielectric constant values, assumption of quasi-static RF electric field inside dry food materials should also be valid. Quasi-static electric field inside the RF cavity can be obtained by solving Laplace equation:

$$\nabla(\sigma + j2\pi f \epsilon_0 \epsilon_m) \nabla V = 0 \quad (2)$$

where $j = \sqrt{-1}$, V is the voltage between the two electrodes (V), related to the electric field ($E = -\nabla V$), f is the frequency (Hz), ϵ_0 is the permittivity of free space ($8.86 \times 10^{-12} \text{ F m}^{-1}$), σ and ϵ_m are the electrical conductivity (S m^{-1}) and the complex relative permittivity of the material, respectively. The complex relative permittivity ϵ_m can be expressed in terms of dielectric constant ϵ'_m and loss factor ϵ''_m of the material ($\epsilon_m = \epsilon'_m - j^* \epsilon''_m$). When a dielectric material is placed inside the RF applicator, RF power density (Q , W m^{-3}) in the material is governed by:

$$Q = 2\pi f \epsilon_0 \epsilon''_m |E|^2 \quad (3)$$

The RF power density acts as a heat source and results in unsteady conductive heat transfer inside the material. The unsteady heat transfer equation is governed by Fourier Eq.:

$$\frac{\partial T}{\partial t} = \nabla \alpha \nabla T + \frac{Q}{\rho C_p} \quad (4)$$

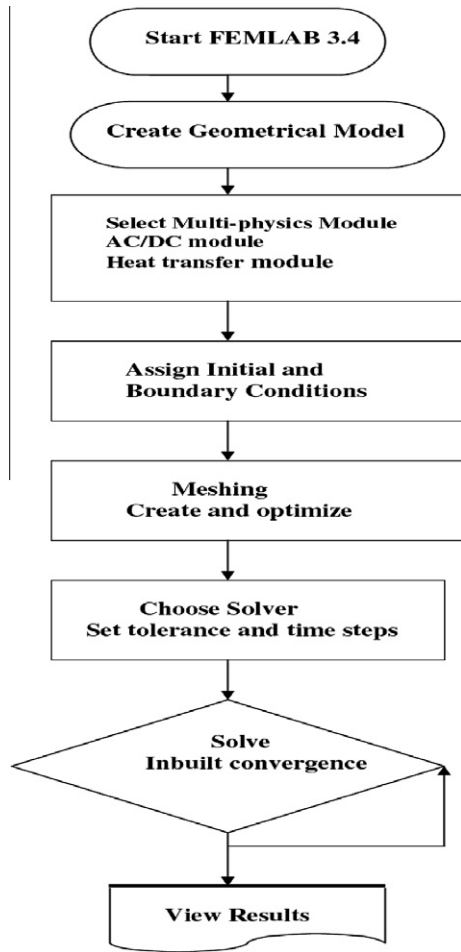


Fig. 3. Flow chart of modeling using FEMLAB 3.4.

where T and T_{av} are local and average temperatures ($^{\circ}\text{C}$) inside the dielectric material over the volume (V_{vol} , m^3), respectively. Subdomain integration scheme of FEMLAB was used to integrate Eq. (5). The results were expressed by ratio of percentage change in STU to the corresponding percent change in input parameters.

2.4. Model validation

2.4.1. Container material selection

Three trays of polypropylene (each having inner dimension $300 \times 220 \times 20 \text{ mm}^3$) stacked one over other to form a container

Table 1

Dielectric and thermal properties of hard red spring wheat flour at a bulk density of 800 kg m^{-3} and moisture content of 8.8% w.b. The data represent the mean of two replicates.

Temperature (T , $^{\circ}\text{C}$)	Dielectric constant (ϵ'_m)	Loss factor (ϵ''_m)	Thermal conductivity (k , $\text{W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$)	Specific heat (C_p , $\text{J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$)
20	3.27 ± 0.03	0.23 ± 0.01	0.12 ± 0.003	1229.37 ± 36.23
30	3.34 ± 0.03	0.31 ± 0.00	0.14 ± 0.005	1644.38 ± 38.00
40	3.49 ± 0.02	0.31 ± 0.02	0.15 ± 0.003	1661.25 ± 35.23
50	3.73 ± 0.06	0.31 ± 0.01	0.17 ± 0.006	1823.75 ± 60.10
60	4.09 ± 0.01	0.34 ± 0.01	0.20 ± 0.007	1950.64 ± 13.25
70	4.77 ± 0.10	0.42 ± 0.01	0.27 ± 0.004	2188.75 ± 21.21

Table 2

Dielectric and thermo-physical properties of wheat flour, polypropylene and air used in computer simulation as a function of temperature (T , $^{\circ}\text{C}$).

	Wheat flour	Polypropylene	Air
Dielectric constant (ϵ'_m)	$3.72 - 0.0345T + 0.0007T^2$	2	1
Loss factor (ϵ''_m)	0.33	0.0023	0
Specific heat (C_p , $\text{J kg}^{-1} \text{ }^{\circ}\text{C}^{-1}$)	$23T + 757$	1800	–
Thermal conductivity (k , $\text{W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$)	$1.36 \times 10^{-4}T^2 - 0.0094T + 0.2819$	0.2	–
Density (ρ , kg m^{-3})	800	900	–

for holding wheat flour. This was designed to facilitate temperature mapping at multiple layers. The bottoms of the top two trays were made of polypropylene mesh (thickness 2 mm with mesh opening of 6 mm). The purpose of using mesh as a bottom was to minimize air gap between two adjacent trays, when stacked one above another. The lower tray bottom and side walls of the trays were made of 7 mm thick polypropylene sheet.

2.4.2. Experimental procedure

About one kg wheat flour was filled in each tray to maintain bulk density of 800 kg m^{-3} in experiments as used in simulation. A very thin polypropylene film was placed on the perforated bottom of each tray, prior to loading flour into trays. This was done to prevent flour particles falling, while taking out the trays for thermal imaging. The container (stacked trays) was put at the center of the bottom electrode. The wheat sample was subjected to 3 min RF heating in 155 mm electrodes gap. Immediately after heating, the container was removed and the surface temperatures of all three trays were recorded using an infra-red image camera (ThermaCAM™ Researcher 2001, FL-IR Systems, Portland, OR, USA) with an accuracy $\pm 2 \text{ }^{\circ}\text{C}$, starting from the top to the bottom tray. Finally, wheat flour of the third (bottom) tray was carefully overturned on another polypropylene sheet to record the bottom surface

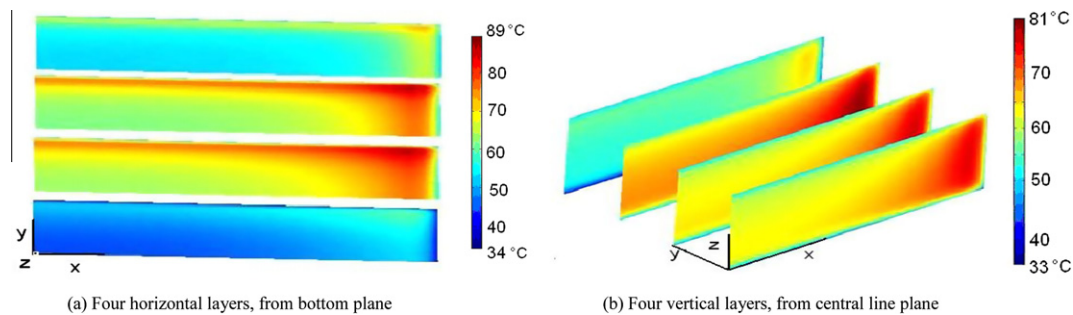


Fig. 4. Simulated temperature ($^{\circ}\text{C}$) profiles of one quadrant wheat flour sample ($150 \times 110 \times 60 \text{ mm}^3$) at (a) four different horizontal layers (0, 20, 40, and 60 mm) from the bottom (b) four different vertical layers (0, 36, 72, and 110 mm) from the vertical center plane of sample after 3 min RF heating with an electrode gap 155 mm and initial temperature $23 \text{ }^{\circ}\text{C}$.

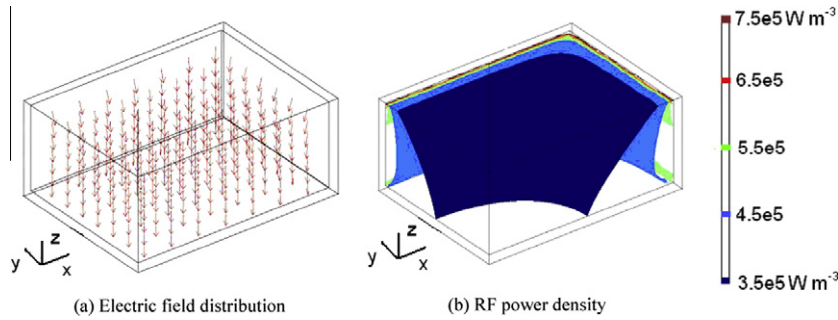


Fig. 5. Simulated electric field distribution (a) and RF power density distribution ($W m^{-3}$) of one quadrant wheat flour sample ($150 \times 110 \times 60 mm^3$) after 3 min RF heating with an electrode gap of 155 mm.

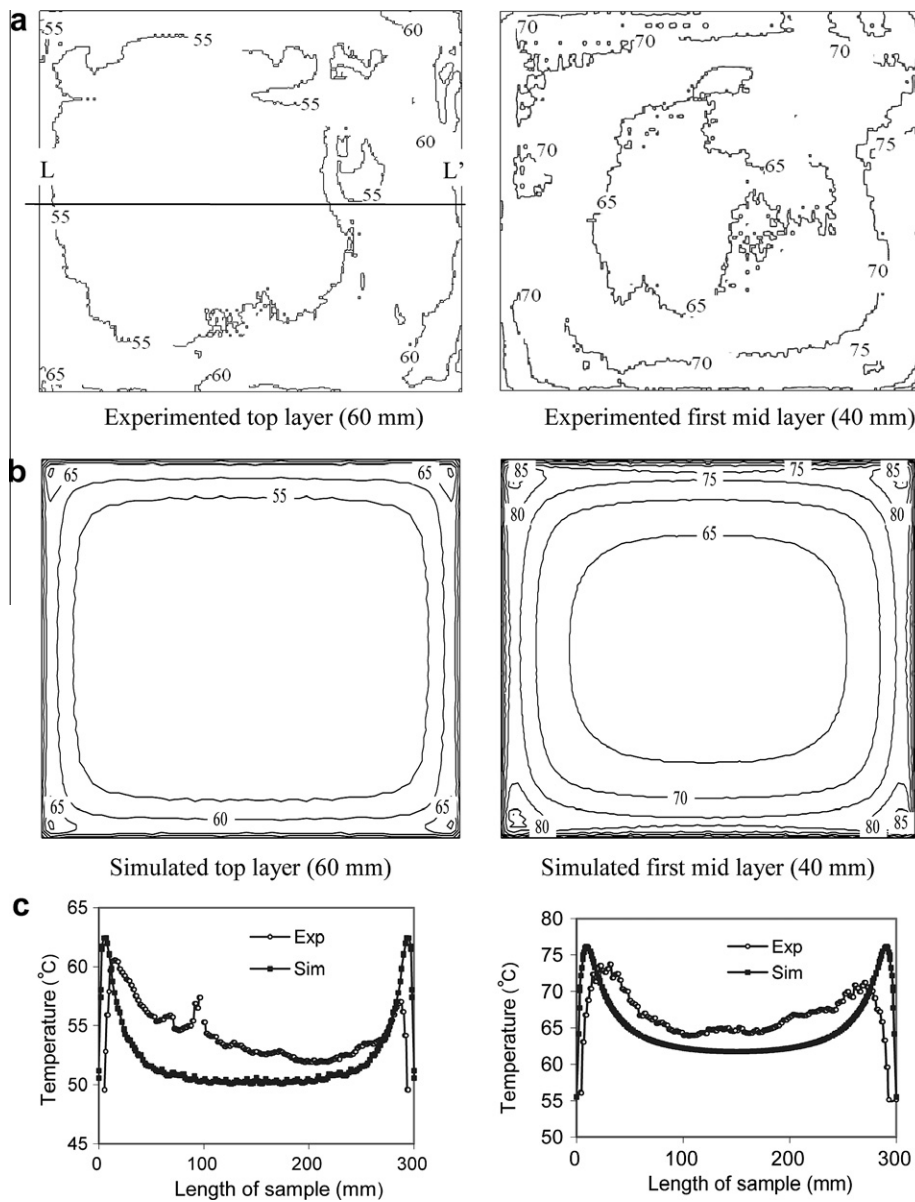


Fig. 6. Experimental (a) and simulated (b) temperature distributions ($^{\circ}C$) of hard red spring wheat flour in top and first mid layers (60 and 40 mm from the bottom of sample) placed in a polypropylene container ($300 \times 220 \times 60 mm^3$) on the top of the bottom electrode with the comparison of the temperature profiles (c) along the line LL', after 3 min RF heating with an initial temperature of $23^{\circ}C$ and a fixed electrode gap of 155 mm.

temperature of the sample. All the four thermal imaging recordings were completed within 30 s. A fiber-optic sensor (UMI, FISO Tech-

nologies Inc., Quebec, Canada) was also inserted 40 mm from the bottom of the container to measure the temperature profile at

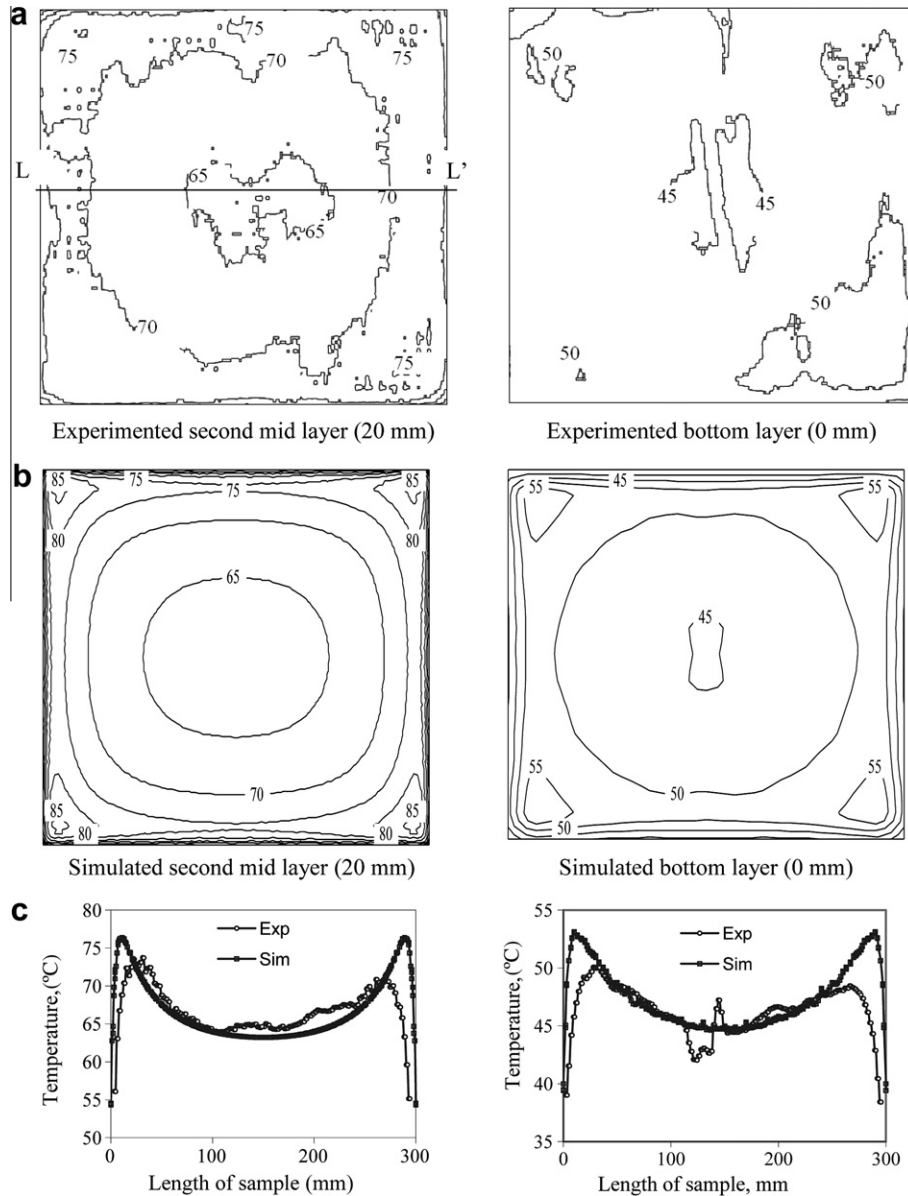


Fig. 7. Experimental (a) and simulated (b) temperature distributions (°C) of hard red spring wheat flour in second mid and bottom layers (20 and 0 mm from the bottom of sample) placed in a polypropylene container (300 × 220 × 60 mm³) on the top of the bottom electrode with the comparison of the temperature profiles (c) along the line LL' after 3 min RF heating with an initial temperature of 23 °C and a fixed electrode gap of 155 mm.

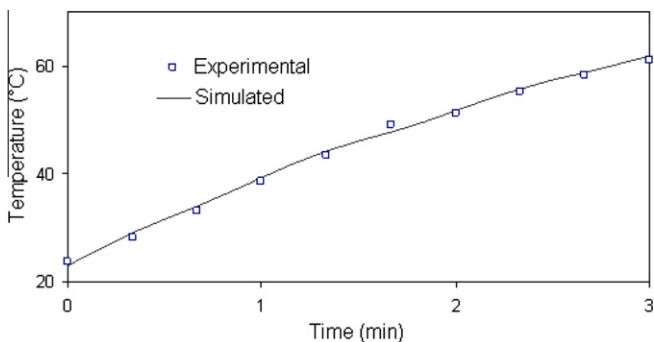


Fig. 8. Experimental and simulated temperature–time histories of hard red spring wheat flour at the center of first mid layer (40 mm) from the bottom of sample (300 × 220 × 60 mm³), placed in a polypropylene container on the top of grounded electrode during 3 min RF heating with an electrode gap of 155 mm.

the center of the second tray during 3-min RF heating. Experimental and simulated surface temperature distributions were compared at four different heights (0, 20, 40, and 60 mm) from the bottom of the container.

3. Results and discussions

3.1. Dielectric and thermal properties of wheat flour

Table 1 shows the temperature dependent dielectric and thermal properties of wheat flour at 27.12 MHz. Both, dielectric constant and loss factor increased slightly with an increase in temperature. Nelson and Trabelsi (2006) also reported slight increase in dielectric properties of hard red winter flour at moisture content of 11% d.b. within the temperature range from 5 to 55 °C. Thermal conductivity and specific heat of wheat flour also increased with increasing temperature. Increases in thermal

conductivity and specific heat with temperature were reported in literature for many other dry products, such as rice flour, milk powder (Muramatsu et al., 2006), wheat flour (Rahman, 1995), lentils (Tang et al., 1991), and gram (Dutta et al., 1998). These data were subjected to linear regression analysis (Table 2) for using these properties in simulation model. Since the increase in loss factor of wheat flour with temperature was trivial, an average loss factor value of 0.33 was used in the simulation. Dielectric and thermal properties of polypropylene container and air were adapted from Birla et al. (2008a).

3.2. Simulated temperature profiles of wheat flour

Fig. 4 shows simulated temperature profiles of one quadrant of the wheat flour sample in four different horizontal and vertical layers. Horizontally, temperature values were highest at the lower sections of the wheat flour except at the bottom layer, which was in contact with the container bottom. Vertically, temperature increased from symmetrical (central) layer to outer layers of the wheat sample, except at the outer most layer, which was in contact with the container side walls. The temperature non uniformity in the sample could be attributed to electric field behavior. Though electric field was normal to the central parts of top sample, it was deflected at the sample corners and edges (Fig. 5a). As a result, net electric field increased at the corners, edges, and lower sections of the sample. Since RF power density at any sample location is proportional to the square of electric field, it also increased (Fig. 5b), resulting in higher temperature values at these parts. These findings are corroborated by overheating at edges and lower sections of the cylindrical meat batters subjected to RF heating (Marra et al., 2007). Computer simulation of RF heating of model fruit, placed on the bottom electrode also showed higher heating at the lower part of the fruit (Birla et al., 2008a). Similar heating patterns were reported in seven polyurethane foam sheets, subjected to an industrial-scale RF heating (Wang et al., 2007a,b).

3.3. Comparison of simulated and experimental thermal profiles of wheat flour

Figs. 6 and 7 show a comparison between experimental and simulated surface temperature distribution of wheat flour in all four layers. Temperature profiles along the center line LL' (Figs. 6c and 7c) of each layer were also compared. Results demonstrated that simulated and experimental temperature distribution patterns for all layers were in good agreement. The values of experimentally determined temperature and the simulated one were matched well except for the corners of the sample where the simulated temperatures values were found higher than the experimental values. Along the line LL', simulated and experimented values were also in good agreement. The difference in simulated and experimentally determined temperature values, large at the corners and edges, could be due to either simplification of RF system or ignored moisture migration from outer hot sections to inner cold sections of the wheat flour during 3 min RF heating in simulation. Simulated and experimental temperature profiles measured at the center of first mid layer (40 mm from the container bottom) were also in good agreement (Fig. 8). Table 3 compares simulated and experimented average temperature values of all four layers after 3 min RF heating. It is clear that experimented average temperatures matched well with the simulated ones. But the values of simulated standard deviation were comparatively higher than those determined by experiments. As shown in Figs. 6 and 7, corners and edges were more heated in simulation and simulated standard deviations in each layer were higher.

Table 3

Experimented and simulated average temperature \pm standard deviation ($^{\circ}\text{C}$) at four different horizontal layers of wheat flour in a plastic container ($300 \times 220 \times 60 \text{ mm}^3$) after 3 min RF heating with an electrode gap of 155 mm and initial temperature of 23°C .

Position of layer (thickness from the bottom of container)	Experiment ($^{\circ}\text{C}$)	Simulation ($^{\circ}\text{C}$)
Top layer (60 mm)	55.8 ± 2.3	54.5 ± 4.3
First mid layer (40 mm)	67.9 ± 3.0	68.2 ± 5.7
Second mid layer (20 mm)	70.9 ± 2.9	70.9 ± 5.5
Bottom layer (0 mm)	48.4 ± 1.6	49.7 ± 3.6

Table 4

Relative sensitivity of simulated temperature uniformity (*STU*) of wheat sample with respect to model input parameters.

Input parameters	Nominal value	% change in input	% change in <i>STU</i> /% change in input parameters
Electrical voltage (<i>V</i> , <i>V</i>)	13,000	± 4	1.34
DPs ($\epsilon'_m - j\epsilon''_m$)	$3.27 - j0.23$	± 20	0.49
Thermal conductivity (<i>k</i> , $\text{W m}^{-1} \text{ }^{\circ}\text{C}^{-1}$)	0.2	± 50	0.12
Heat transfer coefficient of air (<i>h</i> , $\text{W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$)	10	± 100	0.03

3.4. Sensitivity analysis

Sensitivity analysis showed that *STU* was most sensitive to the top electrode voltage as percentage change in *STU* value to the corresponding percentage change in electrode voltage was highest (Table 4). DPs and thermal conductivity of wheat flour also affected *STU*. The analysis showed that heat transfer coefficient of air within the range of $0\text{--}20 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$ had negligible effect on simulated temperature uniformity.

4. Conclusions

A computer model for the RF heating of the dry products was developed for a 27.12 MHz parallel plate RF system using a finite element based commercial software, FEMLAB. The computer model was validated using wheat flour. Simulated results showed that temperature values at the mid layers were highest, followed by those of top and bottom layers. Corners were heated more than centers at each layer. Simulation results confirmed that non-uniform distribution of RF power density resulted in temperature non uniformity in the sample. Therefore, analysis of RF power distribution inside food materials can be a starting step to understand the complex RF heating process and to predict the temperature distribution in dry food materials.

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