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Computational modelling of the impact of polystyrene containers on radio frequency heating uniformity improvement for dried soybeans

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ABSTRACT

Radio frequency (RF) heating has been explored as a new method for postharvest pasteurization and disinfestations, but the non-uniform heating problem needs to be solved. In this study, an experimentally validated simulation model was developed to investigate effects of applying a surrounding polystyrene container on RF heating uniformity improvement in dried soybeans. The computer model was built for soybeans with both low and high moisture contents placed in the rectangular shaped polypropylene and polystyrene containers and heated in a parallel plate RF system. Results showed that the temperature uniformity was greatly improved by placing soybean samples in the polystyrene container other than the polypropylene one. The maximum temperature difference and uniformity index (UI) were reduced. The inner corner radius of 8 cm combined with container thickness of 8 cm could provide the best heating uniformity for soybeans. This newly developed technique can be easily implemented to improve the RF heating uniformity of other low-moisture legumes for industrial applications.

Industrial relevance: Radio frequency (RF) heating has been explored as a new method for postharvest pasteurization and disinfestations of low-moisture granular legumes, but the non-uniform heating problem needs to be solved before being applied in industry. A validated simulation model was used to demonstrate the better container material and design for ensuring good temperature distributions in practical RF treatments. The optimal parameters from computer simulation may save time and reduce the cost to facilitate the design and scaling-up of the RF treatment protocols.

1. Introduction

Although more than 50 countries in the world cultivate soybeans, the United States, Brazil, Argentina and China are the four main soybean producers, contributing more than 90% of the total soybean production in the world (FAO, 2013). Current world production of soybeans far exceeds that of any other edible oilseed, with about 85% of the world's soybeans processed into meal and vegetable oil (Gunstone, 2011). Continuous and rapid growths of soybean consumptions last for the past twenty years in China, with oil production increased by 600%, and edible or industrial consumptions increased by 78% from 1996 to 2013 (Zhu & Jiang, 2014). Infestation by insects may make soybeans totally inedible through associated microbial spoilage caused by their metabolic activities and contaminations (Acasio, 2007; Neethirajan, Karunakaran, Jayas, & White, 2007). Another problem associated with soybeans storage is the putrefactive spoilage caused by fungi, which would cause serious quality loss and food safety concern. Therefore, controlling internal insects and reducing the number of fungi colony in soybeans are important measures for ensuring long storage shelf life and food safety.

Several methods have been developed to control hidden insects and reduce the number of fungi colony inside the food products, such as the conventional heat treatment, chemical fumigation, and irradiation (Feng, Hansen, Biasi, Tang, & Mitcham, 2004; Mohapatra, Kar, & Giri, 2015). However, all these methods show varying degrees of consumer acceptance due to the reduced quality from long treatment time, negative environmental pollutions and harmful effects on human health in their applications (Gao, Tang, Wang, Powers, & Wang, 2010; Wang & Tang, 2001). Therefore, there is a critical need to develop novel and effective technologies that would control the insects and fungi without adverse physical or chemical changes in the product.

Radio frequency (RF) energy has been proposed as a new alternative treatment method for postharvest pasteurization and disinfestations of agricultural products, and refers to the dielectric heating of material using electromagnetic waves ranging from 3 kHz to 300 MHz. With main advantages of rapid and volumetric heating, this RF treatment has been successfully applied in controlling insects and microorganisms in bulk materials (Gao, Tang, Villa-Rojas, Wang, & Wang, 2011; Jiao, Deng, Zhong, Wang, & Zhao, 2015a; Jiao, Johnson, Tang, & Wang, 2012; Luechapattanaporn et al., 2004; Mohapatra et al., 2015; Wang,

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Notation

B	magnetic flux density (Wb m^{-2})
C_p	heat capacity (J kg^{-1} K^{-1})
D	electric flux density (C m^{-2})
E	electric field intensity (V m^{-1}).
E_r	root mean square value of the electric field (V m^{-1})
f	frequency (Hz)
H	magnetic field intensity (A m^{-1})
h	heat transfer coefficient (W m^{-2} K^{-1})
I_a	the measured anode current (A)
J	total current density (A m^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
Q	density of power generated by electric field distribution (W m^{-3})
t	time (s)
T	sample temperature (K)
v	volume fraction
V	electric potential (V)
V_{vol}	sample volume (m^3)
ε	complex permittivity of the mixture (F m^{-1})
ε_1	complex permittivity of the air (F m^{-1})
ε_2	complex permittivity of particles (F m^{-1})
ε_0	free space permittivity (F m^{-1})
ε'	dielectric constant (dimensionless)
ε''	dielectric loss factor (dimensionless)
∇	gradient operator
ρ	density (kg m^{-3})
ρ_e	total electric charge density (C m^{-3})
μ	magnetic permeability (H m^{-1})
ω	angular frequency (rad s^{-1})

Subscripts

avg	average
ini	initial
min	minimum
max	maximum
sd	standard deviation
vol	volume

Tiwari, Jiao, Johnson, & Tang, 2010). But the major challenge of this heating method is overheating in corners and edges within the treated materials, especially in foods with intermediate and high moisture contents (Birla, Wang, & Tang, 2008; Farag, Marra, Lyng, Morgan, & Cronin, 2010; Fu, 2004; Tiwari, Wang, Tang, & Birla, 2011a, 2011b). Higher temperatures would effectively kill the insects or microorganisms, but might result in serious deteriorations in product quality (Birla, Wang, Tang, & Hallman, 2004; Geveke, Brunkhorst, & Fan, 2007; Geveke, Kozempel, Scullen, & Brunkhorst, 2002; Wang, Yue, Tang, & Chen, 2005). To ensure product safety and meet regulatory requirements, it is essential to improve the RF heating uniformity and the temperature distributions within products.

A number of studies have been explored to reduce the edge or corner RF overheating for maintaining good sensory quality of agricultural products. These include hot water immersion (Feng et al., 2004; Ikediala, Hansen, Tang, Drake, & Wang, 2002; Kirmaci & Singh, 2012; Tiwari, Wang, Birla, & Tang, 2008), hot air assisted surface heating (Wang et al., 2014; Zhou, Ling, Zheng, Zhang, & Wang, 2015), combining with moving or rotating method (Birla et al., 2004, 2008; Jiao et al., 2012; Wang, Birla, Tang, & Hansen, 2006), intermittent mixing (Wang et al., 2005; Zhou et al., 2015), electrode modification (Tiwari et al., 2011b; Wang, Luechapattanaporn, & Tang, 2008), and plastic sheets surrounding methods (Huang, Zhu, Yan, & Wang, 2015; Jiao, Shi, Tang, Li, & Wang, 2015b; Jiao, Tang, & Wang, 2014; Tiwari et al., 2011b). Extensive experiments to explore the behaviour of RF heating or to develop new techniques in improving heating uniformity are time consuming and very expensive. Latest advances in computer simulation technology allow for solving the problems and great progresses in improving heating uniformity have been made to facilitate the design and scaling-up of an RF system (Chan, Tang, & Younce, 2004; Llave, Liu, Fukuoka, & Sakai, 2015; Marra, Lyng, Romano, & McKenna, 2007; Romano & Marra, 2008). For example, Birla et al. (2008) analyzed the effects of sample relative position and surrounding media on temperature distribution within a spherical object by using the validated computer model. Tiwari et al. (2011b) developed a simulation model based on COMSOL software to investigate the effect of sample size, shape, and its relative vertical position, surrounding materials, electrode gap and upper electrode configuration on RF power density distributions. Alfaifi et al. (2014) also developed a computer model for RF heating of raisins and validated the model by experimental results, and further utilized the model to analyze the influence of different factors on RF heating uniformity. Moreover, according to the simulated results of Huang, Zhu, Yan et al. (2015), the RF heating uniformity could be improved by using a similar dielectric material around the samples, a smaller upper plate area, and placing the samples in the middle of two plate electrodes. Amongst these factors, placing a surrounding material with similar dielectric constant to that of the treated product and negligible loss factor is one of the most effective methods to improve RF heating uniformity (Birla et al., 2004; Huang, Zhu, Yan et al., 2015; Jiao et al., 2014; Tiwari et al., 2011b). A simulation method of adding Polyetherimide (PEI) cylindrical blocks on top of and at the bottom of peanut butter samples in a cylindrical jar has been evaluated, showing effective results to improve the RF heating uniformity (Jiao et al., 2015b). However, the PEI material with density of 1270 kg m^{-3} used in Jiao et al. (2015b) is too heavy to be used in industrial applications and so far there is no available computer simulation model to investigate the influence of container material and wall thickness on RF heating uniformity of dry products with different moisture content in the literature.

The general purpose of this study was to investigate overheating that may occur at corners and edges of the RF treated products for better understanding the causes of non-uniform temperature distributions in soybeans and provide an optimal solution for improving the RF heating uniformity in low moisture granular legumes. The specific objectives of this study were 1) to establish a computer simulation model for predicting the temperature distribution of soybeans with different moisture content placed in the polypropylene and polystyrene containers, respectively, 2) to validate the simulation model by comparing with the transient experimental temperature profiles of soybeans with different moisture content, 3) to compare the temperature distribution and heating uniformity of soybeans placed in different size of the polystyrene container by both experimental and simulation methods, and 4) to optimize the best combination of parameters in adjusting the thickness and corner radius of the polystyrene container for heating uniformity improvement using the validated simulation model.

2. Materials and methods

2.1. Sample handling and preparation

Soybeans (Glycine max) were purchased from a local supermarket in Yangling, Shaanxi, China. The initial moisture content of soybean seeds was 4.64% on wet basis (w.b.) determined by oven methods. Moisture content is the most important physical parameter of seeds that affects thermal and dielectric properties, and in turn the RF heating behaviour. For example, the dielectric and thermal properties of agricultural products generally increase with increasing moisture content (Huang, Zhu, Yan et al., 2015). To cover the higher moisture level of soybeans, another moisture content of 7.86% w.b. was selected based on the market standard for trading and safe storage of soybean grains (Alencar, Faroni, Lacerda, Ferreira, & Meneghitti, 2006). To prohibit germinating, soybean seeds were conditioned by direct addition of a predetermined amount of distilled water. Then seeds were gently mixed and shaken manually for 25 min. The samples were exposed in saturated air in an isolated air-tight plastic bag at 4 °C for 4 days in a refrigerator to allow the moisture to equilibrate, and the bags were shaken 4 times per day (Guo, Wang, Tiwari, Johnson, & Tang, 2010; Rani, Chelladurai, Jayas, White, & Kavitha-Abirami, 2013). After obtaining the samples with the given moisture levels, they were taken out from the refrigerator and stored with mesh bags for 2 days in the thermostatic and humidity controlled chamber (BSC-150, Shanghai BoXun Industrial & Commerce Co., LTD., Shanghai, China) at mild conditions of 57% and 74% RH (20 °C), respectively, prior to RF experiments (Wang, Zhu, Chen, Li, & Wang, 2015).

2.2. Physical properties of samples

Bulk density of soybeans at room temperature was measured with a basic volume method using a $30 \times 22 \times 6$ cm^3 polypropylene rectangular container and determined to be 743 ± 1 and 736 ± 2 kg m^{-3} with moisture contents of 4.64 and 7.86% w.b. based on three replicates. These values were close to those reported by Guo et al. (2010). Bulk density of soybeans was assumed as constant and temperature independent during the simulated process. The bulk thermal conductivity and heat capacity values of soybeans were measured and reported by Deshpande, Bal, and Ojha (1996) and Deshpande and Bal (1999). Dielectric properties of soybeans at its particle density and 27 MHz were obtained from Guo et al. (2010) in the range of 20–80 °C. This temperature range should be practically applicable for the heat disinfestations of soybeans without affecting their quality (Johnson, Wang, & Tang, 2010). To simplify the computer simulation model, soybeans in the rectangular container were assumed as a whole. Dielectric mixture equations were used to estimate the dielectric properties of air–particle mixtures (Nelson, 1996). In this study, the Complex Refractive Index mixture equation was used to calculate the dielectric properties (relative dielectric constant and relative dielectric loss factor) of soybeans in the temperature range of 20–80 °C.

The Complex Refractive Index mixture equation (CRIME) is described as (Kraszewski, 1977):

$$\varepsilon^{\frac{1}{2}} = v_1(\varepsilon_1)^{\frac{1}{2}} + v_2(\varepsilon_2)^{\frac{1}{2}} \quad (1)$$

where ε is the complex permittivity of the mixture, ε_1 is the complex permittivity of the air, and ε_2 is the complex permittivity of particles (soybeans), v_1 is the volume fraction of the air, and v_2 is the volume fractions of particles, where $v_1 + v_2 = 1$.

2.3. Surrounding material selection

To study effects of different surrounding materials on the RF heating uniformity of soybeans, two kinds of materials (polystyrene and polypropylene) have been selected both for simulation and experiment. Dielectric properties of polystyrene and polypropylene at a frequency of 1 MHz, which is close to the RF heating frequency, were taken from the literature and summarized in Table 1 (Brandrup, Immergut, Grulke, Abe, & Bloch, 1999; von Hippel, 1954). Compared to polypropylene container, polystyrene has the closest dielectric constant (2.6) to that of soybeans (average value of 2.5 and 2.7 with moisture contents of 4.64 and 7.86% w.b.) and a lower dielectric loss factor (0.0003), so that the better heating uniformity may be obtained (Huang, Zhu, Yan et al., 2015; Jiao et al., 2014). Polystyrene container was widely used in protective packaging, or disposable cutlery, which can also be processed by heating, bending, and vacuum forming (Marsh & Bugusu, 2007), with the cheap, stable, high heat resistance and quality portable characteristics (Donald, Rosato, & Rosato, 2004). Therefore, polystyrene container was chosen as the surrounding material of soybeans for RF heating uniformity improvement.

2.4. Computer simulation

2.4.1. Physical model

The RF machine used was a parallel plate RF system (COMBI 6-S, Strayfield International Limited, Wokingham, UK) with a 6 kW RF generator and 27.12 MHz oscillator. This system included a metallic enclosure, generator, and RF applicator with a pair of RF electrodes, a power amplifier and a matching unit. The RF power was supplied via the middle of the upper electrode. The RF upper electrode position could be changed with the aid of adjustable screws to regulate the power. Soybeans were placed inside the plastic (polypropylene and polystyrene) rectangular container ($30 \times 22 \times 6$ cm^3) with a bottom container thickness of 2 cm placed above at the bottom electrode to prevent direct contact between the electrode and the samples (Fig. 1).

2.4.2. Governing equations

To predict the temperature distribution of soybeans generated by dielectric heating, a multi-physics model based on simultaneous solution of heat transfer and electro-magnetic field displacement in the multi-domains (food products and the surrounding environment) inside the RF cavity was set and solved. Electromagnetic field distribution inside the RF applicator was described by four fundamental equations (Maxwell's equations) of electromagnetism in differential forms, which could be expressed in terms of the electric field (E) and magnetic intensity (H) as follows (Balanis, 1989):

$$\nabla \cdot \vec{D} = \rho_e \quad (2)$$

$$\nabla \cdot \vec{B} = 0 \quad (3)$$

$$\nabla \times \vec{E} = \frac{\partial \vec{B}}{\partial t} = -\mu \frac{\partial \vec{H}}{\partial t} \quad (4)$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t} = \varepsilon \frac{\partial \vec{E}}{\partial t} + \varepsilon_0 \varepsilon'' \omega \vec{E} \quad (5)$$

where D is the electric flux density (C m^{-2}), B is the magnetic flux density (Wb m^{-2}), ρ_e is the total electric charge density (C m^{-3}), E is the electric field intensity (V m^{-1}), H is the magnetic field intensity (Am^{-1}), μ is the magnetic permeability (H m^{-1}), J is the total current density (A m^{-2}), ω is the angular frequency (rad s^{-1}), and ε is the complex relative permittivity of the dielectric material (F m^{-1}), which can be expressed in terms of the relative (to air) dielectric constant (ε') and the relative loss factor (ε'') of the material ($\varepsilon = \varepsilon' - j\varepsilon''$).

The absorbed RF power density at any point inside the material is proportional to the square of the electric field strength and directly

Table 1
Electrical and thermo-physical properties of polystyrene, polypropylene and air used in mathematical modelling.

Container material	Density (kg m^{-3})	Thermal conductivity (W m^{-1} K^{-1})	Heat capacity (J kg^{-1} K^{-1})	Dielectric constant	Loss factor
Polystyrene	25[a]	0.036[a]	1300[a]	2.6[b]	0.0003[b]
Polypropylene[c]	900	0.26	1800	2.0	0.0023
Air[d]	1.2	0.025	1200	1	0

[a] Source: Juran (1991).
[b] Brandrup et al. (1999).
[c] von Hippel (1954).
[d] COMSOL material library (2012).

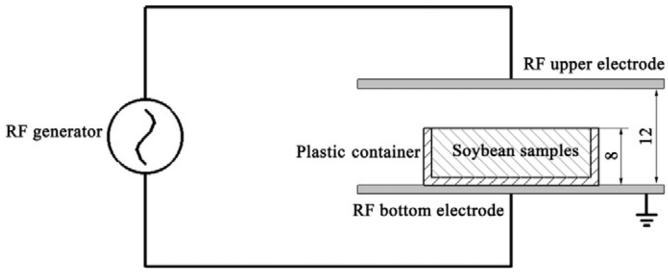

Fig. 1. Scheme of soybeans placed in a rectangular container in a 6 kW, 27.12 MHz RF system (all dimensions are in cm).

proportional to the dielectric loss factor and the frequency as follows (Choi & Konrad, 1991):

$$Q = 2\pi f \varepsilon_0 \varepsilon'' E_r{}^2 = \pi f \varepsilon_0 \varepsilon'' \left|\vec{E}\right|^2 \quad (6)$$

where Q is the power conversion to thermal energy in foods (W m^{-3}), f is the frequency (Hz), ε_0 is the permittivity of electromagnetic wave in free space (8.86×10^{-12} F m^{-1}), ε'' is the loss factor of food material, E_r is the root mean square value of the electric field (V m^{-1}), and the scalar voltage potential (V) is related to the electric field as $\vec{E} = -\vec{\nabla} V$.

In the proposed model, solution of a Fourier heat transfer equation plus a generation term solved in the multi-domain constituted by the food product (soybeans, sub-domain 1) and coupled with the quasi-static electro-magnetic field equations (solved in both the food product and the surrounding air, which is the sub-domain 2) was considered sufficiently accurate to determine temperature distributions within the food product (soybeans) sandwiched between two electrodes (Nelson, 1996). In this specific case, the following equation was solved in the sub-domain 1 (food product).

$$\rho C_P \frac{\partial T}{\partial t} = \vec{\nabla} \cdot k \vec{\nabla} T + Q \quad (7)$$

where ρ is the density of soybeans (kg m^{-3}), C_p and k are respectively their specific heat (J kg^{-1} K^{-1}) and thermal conductivity (W m^{-1} K^{-1}), T is the temperature within the food sample (K), and t is the process time (s).

In both the sub-domains 1 and 2 (food and air), the distribution of the electromagnetic field was determined by the solution of the following equation, given by Gauss law derived from the quasi-static approximation of Maxwell's equations (Romano & Marra, 2008):

$$\vec{\nabla} \varepsilon_i \cdot \vec{E} = 0 \quad (8)$$

where ε_i is in turn the permittivity of the food product (in sub-domain 1) and of the surrounding air (in sub-domain 2). At sub-domain interfaces, continuity of electrical potential was followed. Simultaneous solutions of PDE system made by Eqs. (7) and (8) required the statement of initial and boundary conditions (Fig. 2). In details, the solution of heat transfer equation (Eq. (7)) required the statement of initial condition and conditions at boundary only of the food product (interfaces between the sub-domain 1 and the sub-domain 2). The solution of Eq. (8) required the statement of conditions at the boundary of the whole domain, which are the upper and lower electrodes, and all the side walls of the RF cavity.

Convective heat transfer was considered on the external surfaces of soybeans, which can be described as (Huang, Zhu, Yan et al., 2015):

$$-k \vec{\nabla} T \vec{n} = h(T - T_{\text{air}}) \quad (9)$$

where h is the convective heat transfer coefficient (h = 20 W m^{-2} K^{-1} for forced convection), T_{air} is the air temperature inside the RF cavity (≈20 °C) and $\vec{n}$ is the vector of the surface crossed by the heat flux.

Although the voltage varies widely across the surface of the upper electrode, it was assumed to be uniform because 30% of the RF wavelength (11 m) is larger than the dimension of the upper electrode (83 × 40 cm^2) in the operating RF system and voltage variation is less than 10% (Wang, Chen, Li, & Wang, 2015). The anode current or the directly measured current could be applied to precisely and quickly estimate the upper electrode voltage as the upper electrode voltage is linearly proportional to these currents (Wang, Zhu et al., 2015). Thus, the upper electrode voltage was estimated by the following equation with the measured anode current (I_a) (Zhu, Huang, & Wang, 2014):

$$V = 11,242 \times I_a + 2029.9 \quad (10)$$

A constant electric field strength was assumed and applied at the upper electrode during the processing time, which was set as the electromagnetic source since it introduced high frequency electromagnetic energy from the generator to the heating cavity (Birla et al., 2008). Since electric potential varied with different treated materials (Jiao et al., 2014, 2015b), the estimated voltages in simulation were 6320 and 5940 V with soybeans moisture contents of 4.64% w.b. in 2 cm thick polypropylene and polystyrene containers, respectively, based on these measured anode currents.

2.4.3. Geometric, initial and boundary conditions

A 3D geometric model was constructed using COMSOL (V4.3a COMSOL Multiphysics, CnTech Co., LTD., Wuhan, China) software based on the actual structure and size of the RF system in the simulation (Fig. 2). Gap between the upper and bottom electrodes was set as 12 cm to heat the sample centre from 20 to 50 °C at a heating rate of 4–6 °C/min for complete control of the insects in soybeans (Huang, Zhu, Yan et al., 2015). All the metallic casings except for the upper electrode were grounded (V = 0 V). Electrical insulation $\vec{\nabla} \cdot \vec{E} = 0$ was considered for the external walls of the RF cavity. The surrounding air was considered in the inlet and outlet of the system with condition of $T = T_{air}$ (T_{air} is the ambient temperature). The initial temperature of all domains in the system, including the air, plastic container, soybeans, upper and bottom electrodes was set at room temperature (20 °C). The convective heat transfer boundary conditions were assigned at the outer sample surfaces exposed to air with heat transfer coefficient of h = 20 W m^{-2} K^{-1}.

2.4.4. Meshing size selection

After plotting the geometry based on the actual size of soybeans and the RF cavity, all domains were meshed to obtain a numerical solution to determine the temperature distribution inside the heating system. The COMSOL software has the built-in different types of meshes, including extremely coarse, extra coarse, coarser, coarse, normal, fine, finer, extra fine, and extremely fine. The accuracy of the results is affected by the meshing size, and generally the small element size would result in more accurate results, but a considerable increase in computing time. The criteria of meshing were obtained when the predicted maximum temperature difference between the two sequential sets of mesh was less than 0.1% (Tiwari et al., 2011a). Simulation tests were performed to benchmark the modelling results and identify the best mesh-describing domains. In this study, the soybeans, container and the upper electrode were meshed with extremely fine tetrahedral meshes, and all other domains were meshed with normal size meshes based on the mesh convergence study. Numbers of elements in the whole geometry after meshing were shown in Table 2, and used in subsequent simulation runs.

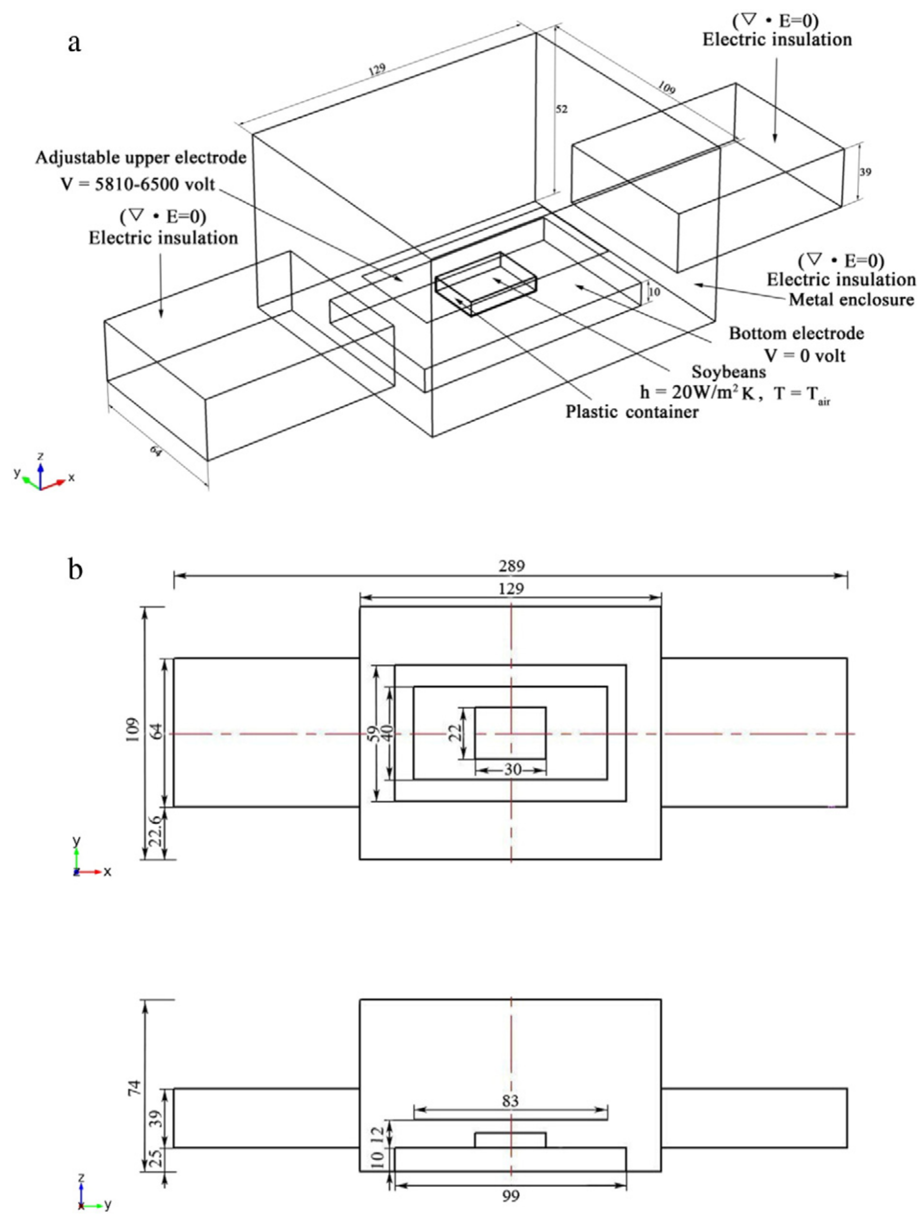

Fig. 2. 3-D geometry (a) and dimensions (b) of the 6 kW, 27.12 MHz RF system used in simulations (all dimensions are in cm).

2.4.5. Solution methodology and procedure

Commercialized software COMSOL based on finite element method was widely used for providing numerical solutions to predict the temperature distribution in the heat transfer model. The joule heating module was employed to solve the coupled quasi-static electromagnetic and heat transfer equations. All computer simulations were performed on a Dell workstation with an Intel® Core™ i5-2400, 3.10-GHz processor and 8 GB RAM running a Windows 8.1 64-bit operating system. By simultaneously solving Eqs. (6)–(8), the heating pattern in foods within a certain time period could be obtained in a reliable and fast way. The direct linear system solver (UMFPACK) was used with a relative tolerance and absolute tolerance of 0.01 and 0.001, respectively. The

Table 2
Number of different type of mesh generated in all domains in computer simulation with soybeans moisture content of 4.64 and 7.86% w.b. in polypropylene container after 7 min RF heating and the corresponding solution time (electrode gap of 12 cm and sample size of 30 × 22 × 6 cm^3).

Moisture content (w.b.)	Meshing	Type of mesh				
		Normal	Fine	Finer	Extra fine	Extremely fine
4.64%	Triangular elements	1260	2048	2894	4913	10,574
	Tetrahedral elements	4062	7613	12,768	30,912	122,707
	Degree of freedom	12,438	22,776	37,624	89,164	343,824
	Solution time (min)	48	76	120	231	719
7.86%	Triangular elements	1258	2,056	2892	4,919	10,562
	Tetrahedral elements	4082	7520	12,809	31,168	122,576
	Degree of freedom	12,484	22,562	37,730	89,804	343,444
	Solution time (s)	46	69	108	285	788

convergence test was used to analyse the convergence of the whole solving process until the desired convergence test tolerance (calculation error) was approached. Simulation of a 7 min RF heating process with determination of the heat transfer phenomenon at 10 s intervals required computer time varied between 20 and 40 min, depending on the simulation sequence. The initial and maximum time steps were 0.001 s and 0.1 s, respectively. The main solution steps for the development of computer simulation model are shown in Fig. 3.

2.4.6. Heating uniformity evaluation

The effectiveness of several heating uniformity improvement methods was compared in all of the simulation sequences to evaluate the temperature uniformity (UI) inside the samples after 7 min RF heating (Alfaifi et al., 2014):

$$UI = \frac{\frac{1}{V_{vol}}\int_{V_{vol}}\sqrt{(T-T_{avg})^2}dV_{vol}}{T_{avg}-T_{\text{initial}}} \quad (11)$$

where T and T_{avg} are the local and average temperatures (°C) inside the dielectric material over the volume (V_{vol}, m^3), respectively. A smaller index corresponds to a better heating uniformity.

2.5. Model validation

2.5.1. Container material and dimensions

To validate the developed simulation model, 3 kg soybeans were filled in each container (inner dimension of 30 × 22 × 6 cm^3 with the wall thickness of the container of 2 cm) to maintain bulk density of 743 and 736 kg m^{-3} at moisture content of 4.64 and 7.86% w.b. both in experiment and simulation. After that, the rectangular polystyrene container with thickness of 4, 6, 8, 10, and 12 cm was chosen for the subsequent experiment. Thickness of the polystyrene container was determined from the preliminary experimental results to better fit in the RF electrode gap and to provide a reasonable heating rate in soybeans. The polystyrene container with different thickness of surrounding walls was manufactured from polystyrene sheets by the mechanical mould. Soybean samples were divided into three different layers (upper, middle and bottom layers) parallel to electrodes to represent the temperature distribution inside the sample as shown in Fig. 4a. The heights of each layer were 2, 4, and 6 cm, respectively. The thin plastic film (thickness of 0.28 mm) was used to split the layers so as to obtain the sample surface temperature distributions in each layer.

2.5.2. RF experiments

The 6 kW, 27.12 MHz free-running oscillator RF heating system was used in experiments to validate the computer simulation model. In experiments, soybean samples with the moisture content of 4.64 and 7.86% w.b. were placed in the polypropylene and polystyrene containers, respectively. Soybeans in the rectangular container were positioned coaxially in the centre of the RF cavity with an electrode gap of 12 cm. Temperature profile at the geometric centre of soybeans was recorded at each 5 s by the fibre optical sensor (HQ-FTS-D120, Xi 'an HeQi Opo-Electronic Technology Co., LTD, Shaanxi, China) with an accuracy of ±1 °C, which was inserted with 3 cm deep from the top sample layer during RF heating. Tip of the fibre optical sensors (d = 2 mm) was

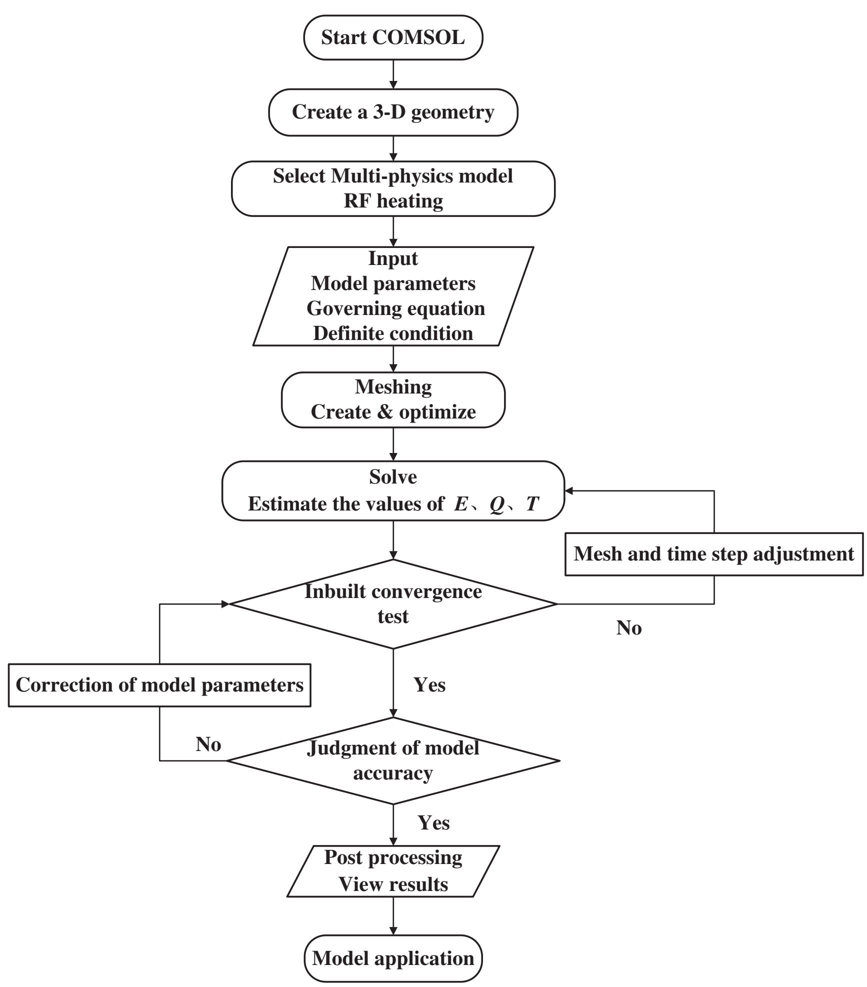

Fig. 3. The procedures and steps of building computer simulation model for RF heating by using COMSOL software.

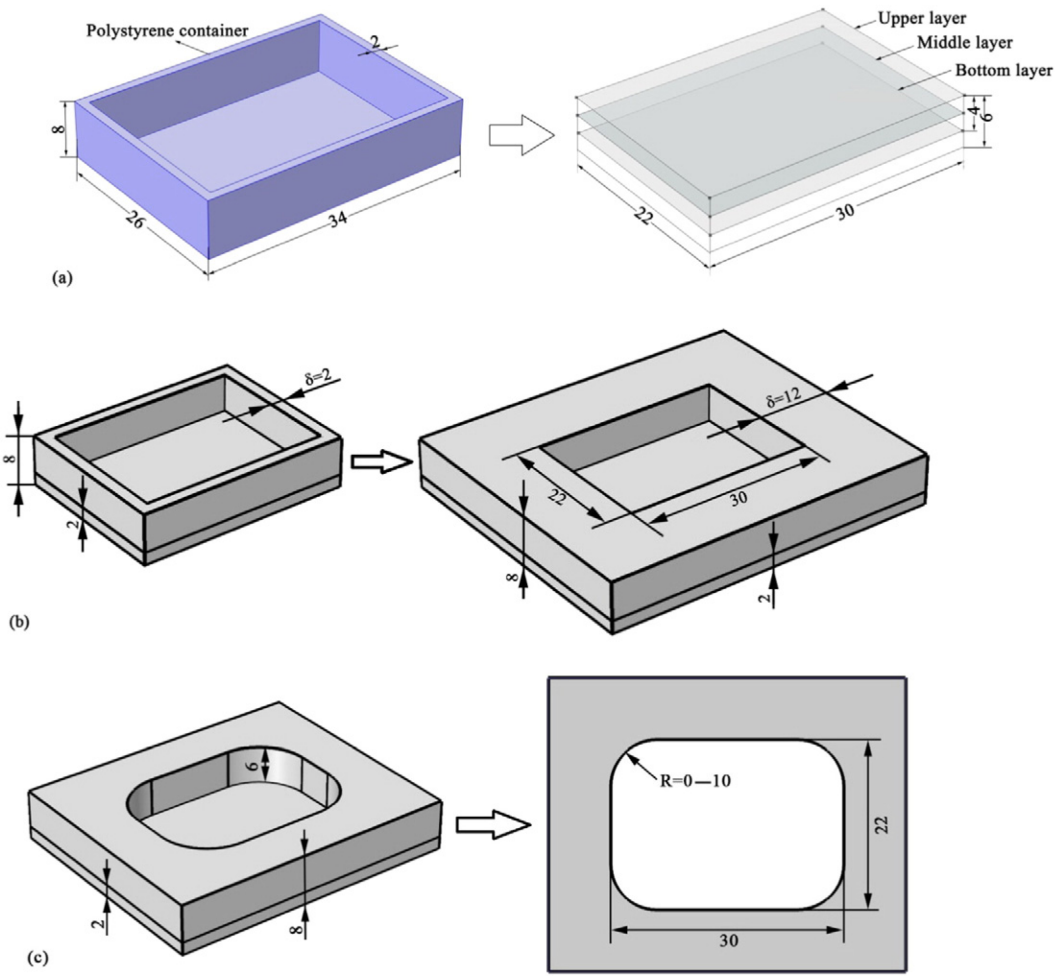

Fig. 4. Geometry of the rectangular shaped polystyrene container (a) split into three layers for temperature measurements, (b) with thickness (δ) increased from 2 to 12 cm and bottom thickness fixed at 2 cm, and (c) corner radius (R) ranged from 0 to 10 cm at the fixed container thickness used in the simulation (all dimensions are in cm).

fixed in contact with the surface of soybean samples. The surface and centre temperature of soybean was assumed to be uniform due to the small particle size (d < 5 mm). The air gap amongst soybean seeds was smaller (<1 mm) than the tip size of fibre optical sensors, so the accuracy of each measurement could be guaranteed. The same methods have been also used in other materials treated in RF system, such as raisins (Alfaifi et al., 2014), rice (Zhou et al., 2015), soybean (Wang, Zhu et al., 2015), and wheat (Chen, Wang, Li, & Wang, 2015; Jiao et al., 2015a). The cold spot temperature (50 °C) was used as the target one by considering the potential application of RF energy to control insects, and 7 min of RF heating was needed for the geometric centre (cold spot) from ambient temperature (20 °C) to 50 °C with soybeans moisture content of 4.64% w.b. based on our preliminary tests (Huang, Chen, & Wang, 2015). Therefore, for all cases with different moisture content of soybeans placed in various thicknesses of polypropylene and polystyrene containers, 7 min RF heating was selected and used in the following computer simulation study to make it easy for comparison and analysis. The obtained temperature profiles were further used to validate the computer simulation model. The container was immediately removed from the heating system after 7 min RF treatments. The surface temperatures of soybeans in all three layers were recorded using an infrared camera (DM63-S, DaLi Science and Technology Co., LTD, Zhejiang, China) with an accuracy of ±2 °C, starting from the upper to the bottom layer. Therefore, the surface temperature distribution of soybeans in three different layers could represent the RF heating uniformity over the whole volume of soybeans. All three thermal imaging measurements were completed within 30 s. Each experiment was replicated five times. Experimental and simulated surface temperature distributions were compared in all three different layers.

2.6. Model applications

2.6.1. Heating uniformity evaluation of different container material

After the computer simulation model was validated by low moisture content (4.64% w.b.) soybeans placed in the polypropylene and polystyrene containers, the surface temperature uniformity of soybean samples obtained from both experiment and simulation was analysed in each layer. The high moisture content (7.86% w.b.) soybeans were used to study the RF heating uniformity of different container material and better illustrate the significant effect of polystyrene material on RF heating uniformity improvement. Finally, the effectiveness of heating uniformity improvement for soybeans placed in polypropylene and polystyrene containers was compared by obtaining the temperature uniformity index from computer simulation results.

2.6.2. Heating uniformity of soybeans with different container thickness

To further improve the heating uniformity in high moisture content (7.86% w.b.) soybeans, the optimal thickness of the polystyrene container was determined using computer simulation. With a fixed bottom thickness of 2 cm, the surrounding thickness of the polystyrene container for the side walls was swept from 2 to 12 cm with an interval of 2 cm (Fig. 4b). All the simulation cases were run

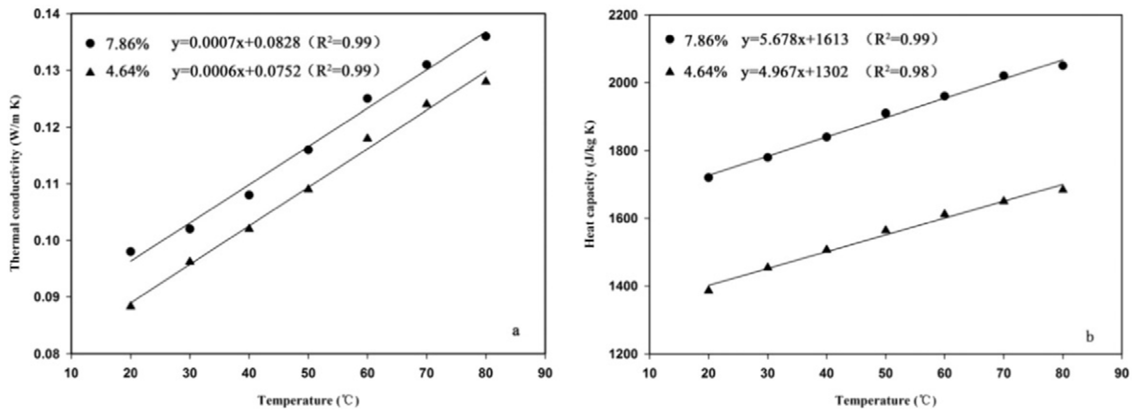

Fig. 5. Thermal conductivity (a) and heat capacity (b) of soybeans with moisture contents of 4.64 and 7.86% w.b. at temperature range of 20–80 °C.

under an electrode gap of 12 cm and RF heating time of 7 min for comparison. The selection of the thickness range was based on the preliminary simulation and experiment results. These container sizes were applied to simulate the different heating conditions of soybeans. Uniformity indexes were calculated and the temperature distributions were compared in three horizontal layers within the rectangular shaped sample.

2.6.3. Effect of rounded corner of polystyrene container on heating uniformity

Simulation runs were designed to study the overheating behaviours that commonly occur in corners and edges of the rectangular shaped samples. Six corner radius values (ranged from 0 to 10 cm) of the polystyrene container were used to investigate the effects of rounded corners on the temperature distribution and heating uniformity of soybeans packed in a rectangular shaped polystyrene container after 7 min RF heating. These dimensions were determined according to the actual sizes of the polystyrene container ($30 \times 22 \times 6$ cm^3), which was illustrated in Fig. 4c. Heating uniformity in each simulation was compared by determining the temperature profiles of soybeans in the middle layer.

2.7. Statistical analysis

The mean values of temperatures measured by infrared camera over five replicates were analysed by SigmaPlot 12.0 (Systat Software, Inc., San Jose, CA, USA). All the statistically significant comparisons were made at a significance level of $P = 0.05$.

3. Results and discussions

3.1. Model parameters

It has been well known that the thermal and dielectric properties of the treated products might vary during heating via the temperature increase, and this behaviour changes the heating rate accordingly. Fig. 5 shows the temperature dependent thermal conductivity (Fig. 5a) and heat capacity (Fig. 5b) of soybeans, which increased with increasing temperature at moisture contents of 4.64 and 7.86% w.b. (Deshpande & Bal, 1999; Deshpande et al., 1996). These data were subjected to linear regression analysis ($R^2 > 0.99$) at temperature range of 20–80 °C for using these properties in the simulation model. The same method has been used in simulation of other products during RF heating, such as beef (Uyar et al., 2015), wheat (Tiwari et al., 2011a), raisins (Alfaifi et al., 2014) and mung beans (Huang, Zhu, & Wang, 2015).

Dielectric properties of soybeans at the bulk density of 743 and 736 kg m^{-3} calculated from the mixture equations are presented in Fig. 6. Both dielectric constant (Fig. 6a) and loss factor (Fig. 6b) increased slightly with an increase in temperature from 20 to 80 °C. The calculated dielectric properties of soybeans were reduced as compared to these properties at particle density (0% air) due to the presence of air (Alfaifi et al., 2014; Jiao et al., 2015a; Uyar et al., 2015). These values were in good agreement and comparable with the data reported by Guo et al. (2010). The calculated dielectric properties were further used in the computer simulation model and inputted using linear interpolation functions in the COMSOL software (Alfaifi et al., 2014; Jiao et al., 2015a).

The estimated voltages used in the computer simulation are listed in Table 3. Based on these preliminary experimental results, the

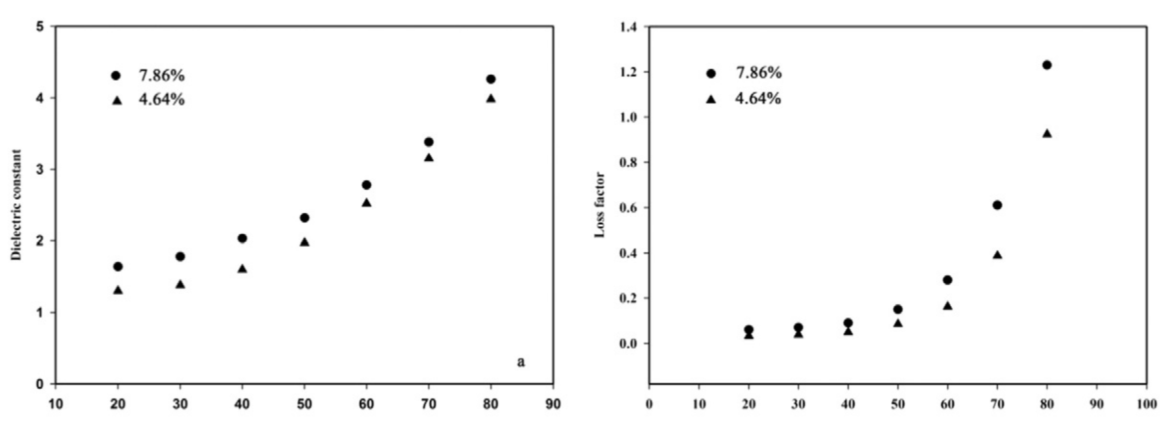

Fig. 6. Relative dielectric properties: (a) dielectric constant; (b) dielectric loss factor of soybeans with moisture contents of 4.64 and 7.86% w.b. at bulk densities of 743 and 736 kg m^{-3} within the temperature range of 20–80 °C.

Table 3
The upper electrode voltage estimation for soybeans at two moisture levels (% w.b.) placed in polypropylene and polystyrene containers with various thicknesses during 7 min RF heating with a fixed electrode gap of 12 cm.

Container material	Polypropylene		Polystyrene						
Moisture content (w.b.)	4.64%	7.86%	4.64%	7.86%					
Container thickness (cm)	2	2	2	2	4	6	8	10	12
Anode current (A)	0.381	0.397	0.348	0.362	0.378	0.352	0.336	0.341	0.345
Estimated voltage (V)	6320	6500	5940	6100	6280	5990	5810	5870	5910

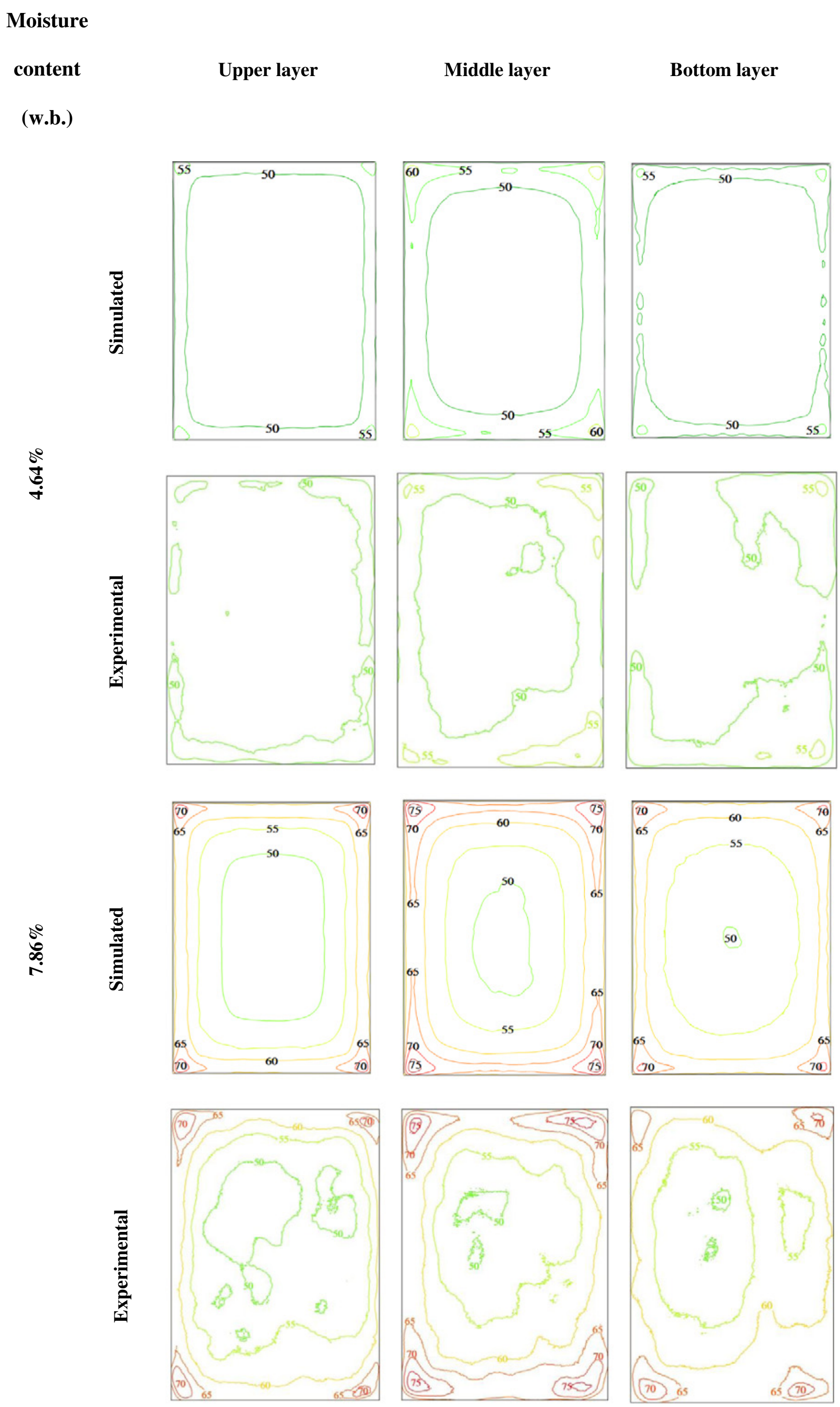

Fig. 7. Simulated and experimental temperature distributions (°C) of soybeans with moisture contents of 4.64 and 7.86% w.b. in upper, middle and bottom layers (6, 4 and 2 cm from the bottom of sample) placed in the polypropylene container (thickness of 2 cm) on the centre of bottom electrode after 7 min RF heating with a fixed electrode gap of 12 cm and an initial temperature of 20 °C.

corresponding anode current increased from 0.336 to 0.397 A. The estimated voltage was in a range of 5810–6500 V while the thickness of the walls of the container increased from 2 to 12 cm and soybeans moisture content varied from 4.64 to 7.86% w.b. The reason for the unclear trend of estimated voltage with thickness change of the walls of the container was probably caused by the increased volume of the treated material, which provided a better impedance match between the work circuit and the tank circuit, so that the inputted power changed (Jiao et al., 2014).

3.2. Model validation

The surface temperature contours of soybeans with moisture contents of 4.64 and 7.86% w.b. placed in the polypropylene container

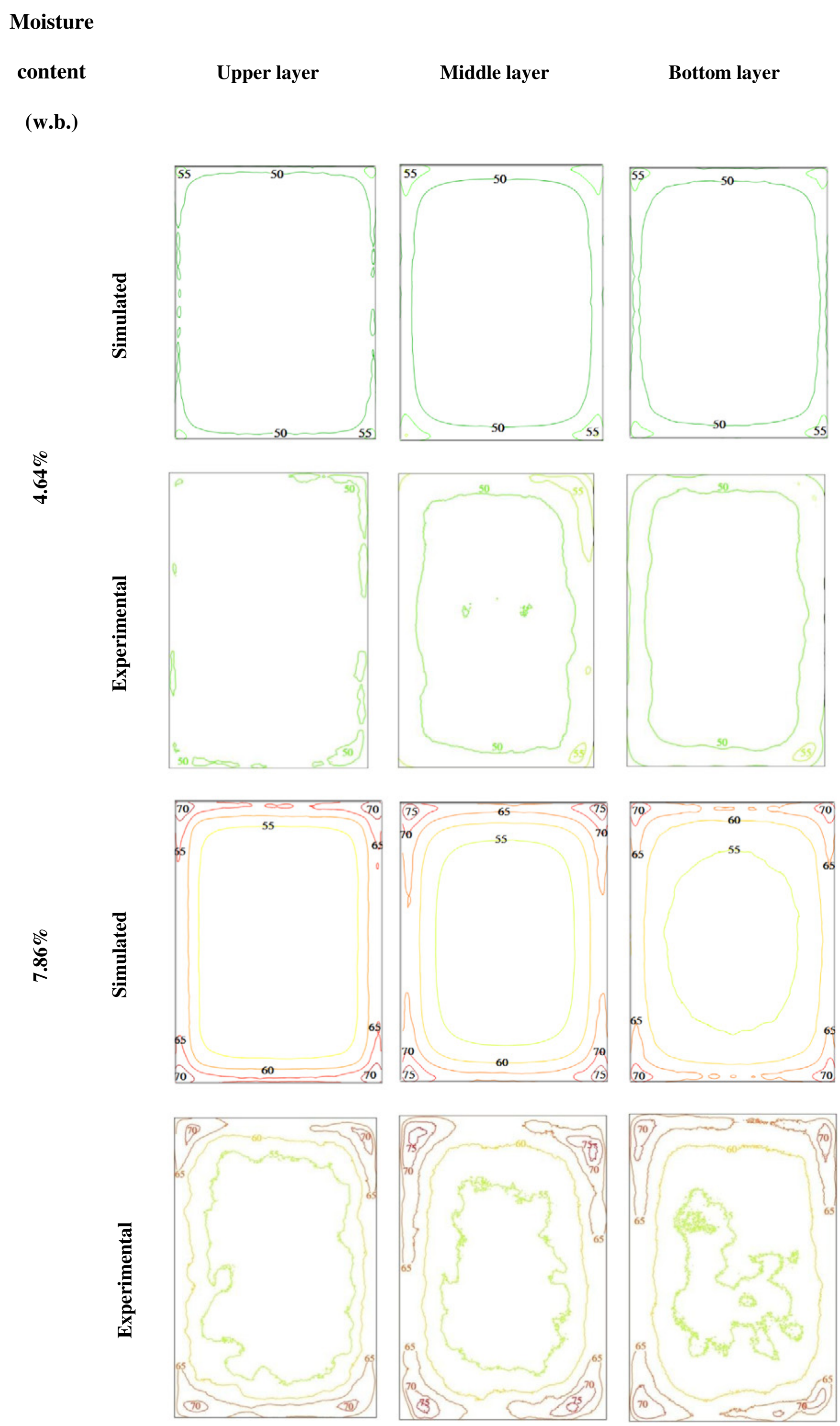

Fig. 8. Simulated and experimental temperature distributions (°C) of soybeans with moisture contents of 4.64 and 7.86% w.b. in upper, middle and bottom layers (6, 4 and 2 cm from the bottom of sample) placed in the polystyrene container (thickness of 2 cm) on the centre of bottom electrode after 7 min RF heating with a fixed electrode gap of 12 cm and an initial temperature of 20 °C.

Table 4
Simulated and experimental temperatures (Avg ± SD, °C) in three different horizontal layers of soybeans with moisture contents of 4.64 and 7.86% w.b. in polypropylene and polystyrene container ($30 \times 22 \times 6$ cm^3) at a fixed electrode gap of 12 cm and initial temperature of 20 °C.

Moisture content (w.b.)	Container	Layer	Simulated (°C)	Experimental (°C)
			Avg ± SD	Avg ± SD
4.64%	Polypropylene	Upper	50.35 ± 4.40	50.30 ± 3.39
		Middle	53.27 ± 5.68	52.12 ± 3.96
		Bottom	52.61 ± 5.65	51.68 ± 3.85
	Polystyrene	Upper	50.33 ± 3.21	50.13 ± 3.06
		Middle	53.19 ± 4.57	51.91 ± 3.80
		Bottom	51.14 ± 4.46	50.95 ± 2.69
7.86%	Polypropylene	Upper	58.18 ± 5.94	57.45 ± 5.73
		Middle	61.18 ± 6.86	59.44 ± 6.55
		Bottom	59.07 ± 4.93	58.31 ± 4.81
	Polystyrene	Upper	57.61 ± 4.98	57.13 ± 4.80
		Middle	60.17 ± 5.91	58.87 ± 5.42
		Bottom	59.24 ± 4.44	58.05 ± 4.50

obtained from both experiment and simulation were shown in Fig. 7. Because of the limitation of available experimental data, only temperature data in three horizontal layers (as demonstrated in Fig. 4a) were used for the validation studies. Temperature distribution patterns for all three layers of soybeans with moisture contents of 4.64 and 7.86% w.b. were in good agreement both from simulated and experimental results. The maximum temperature difference was about 13 °C in the middle layer of soybeans with moisture content of 4.64% w.b. obtained both by experiment and simulation. The higher temperature values in the upper (70 °C), middle (75 °C), and bottom (70 °C) layers of soybeans with moisture content of 7.86% w.b. were found in the areas of edges and corners of the rectangular polypropylene container, when compared to the lower temperatures (50 °C) in the central areas of each layer (Fig. 7). The maximum temperature difference was observed in the middle layer (25 °C), and followed by the upper and bottom layers (20 °C). Higher moisture content level (7.86% w.b.) resulted in poor heating uniformity of soybeans in this study. The uneven temperature distribution in the centre area of the middle layer could be due to the result of field bending all-around of the sample and concentrating in the middle part (Jiao et al., 2014; Tiwari et al., 2011a). This non-uniform heating behaviour has also been reported in other literatures (Alfaifi et al., 2014; Birla et al., 2008; Fu, 2004; Jiao et al., 2015a; Marra et al., 2007).

The comparison between simulation results and experimental data obtained in the free-running oscillating system for soybeans with moisture contents of 4.64 and 7.86% w.b. in the polystyrene container is shown in Fig. 8. From the surface temperature comparison of three layers, the computer simulation results matched well with the experimental ones. The maximum temperature difference of soybeans with moisture content of 4.64% w.b. in the middle layer decreased from 13 to 7 °C due to container material changes as shown in Figs. 7 and 8. Therefore, the good heating uniformity could be achieved by using the 2 cm thickness of polystyrene container other than the polypropylene container. The highest temperature value was observed at corners and edges of the middle layer of soybeans, which maintained the same as 75 °C both from experiment and simulation. More uniform temperature distribution was obtained in the central area of upper (55–70 °C) layer with less uniformity observed in middle (55–75 °C) and bottom (55–70 °C) layers. The non-uniform heating was generally happened at

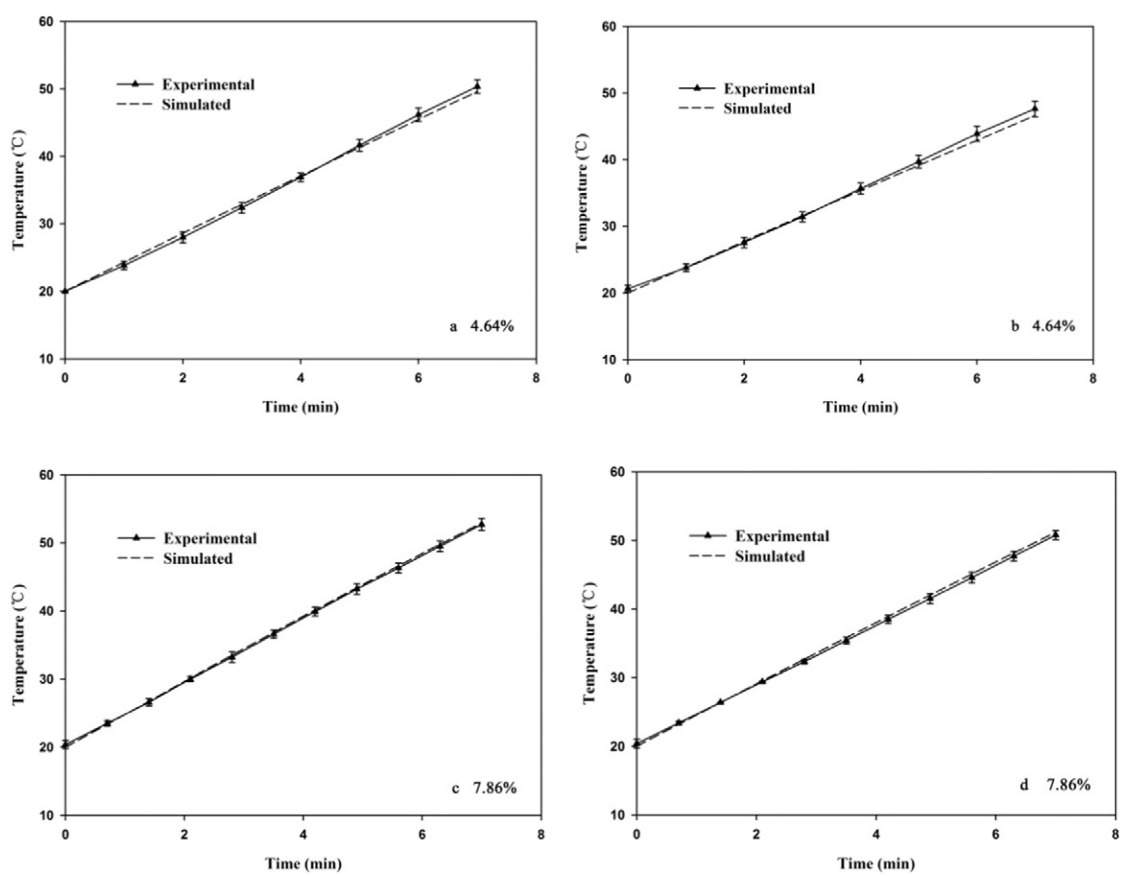

Fig. 9. Experimental and simulated temperature-time histories of soybeans with moisture contents of 4.64% w.b. (a) and 7.86% w.b. (c) at the geometric centre of polypropylene container and moisture contents of 4.64% w.b. (b) and 7.86% w.b. (d) at the geometric centre of polystyrene container (3 cm deep from the top sample layer), placed on the centre of bottom electrode during 7 min RF heating with an electrode gap of 12 cm.

lower sections of the sample since electric fields might refract and reflect or focus frequently at those parts where contacted with the bottom electrode (Tiwari et al., 2011a). The uniform temperature distribution at the upper surfaces of soybeans might be attributed to the evaporative cooling. Dielectric properties of polystyrene container limited its heat absorbance during 7 min RF heating, which may make heat focus more on soybeans (Jiao et al., 2014). So the temperature curve of intermediate section increased from 50 to 55 °C as compared with soybeans placed in the polypropylene container with thickness of 2 cm. The maximum temperature difference in the middle layer was reduced gradually from 25 to 20 °C with soybeans moisture content of 7.86% w.b., indicating that the heating uniformity was improved by using the same thickness of polystyrene container. Results demonstrated that simulated and experimental temperature distribution patterns for all layers of soybeans placed in the polystyrene container were found more uniform than those in the polypropylene container.

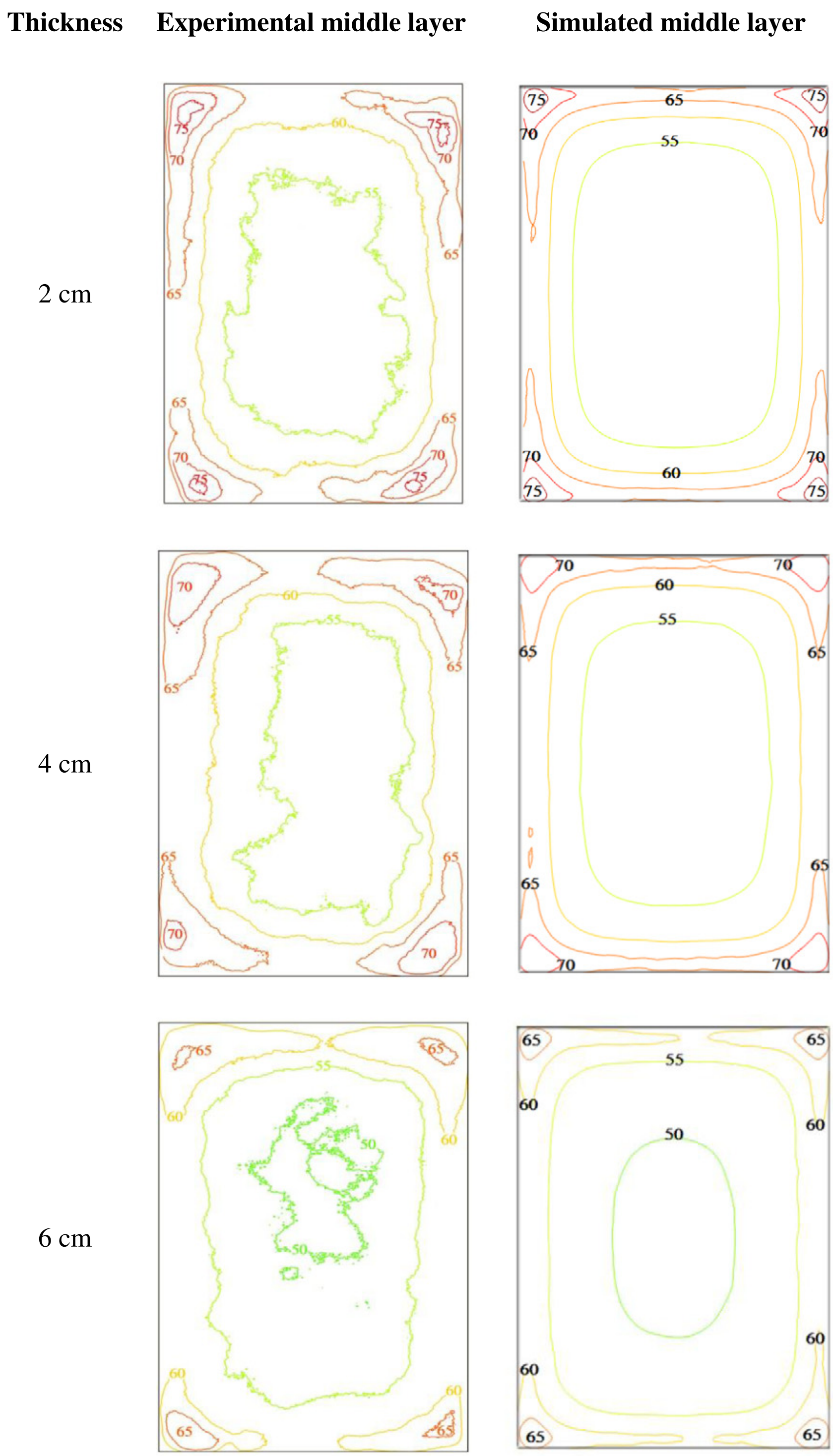

Fig. 10. Temperature distribution in the middle layer of soybeans with moisture content of 7.86% w.b. from experiment and computer simulation with various thicknesses of polystyrene container ($30 \times 22 \times 6$ cm^3) after 7 min RF heating at a fixed electrode gap of 12 cm and initial temperature of 20 °C.

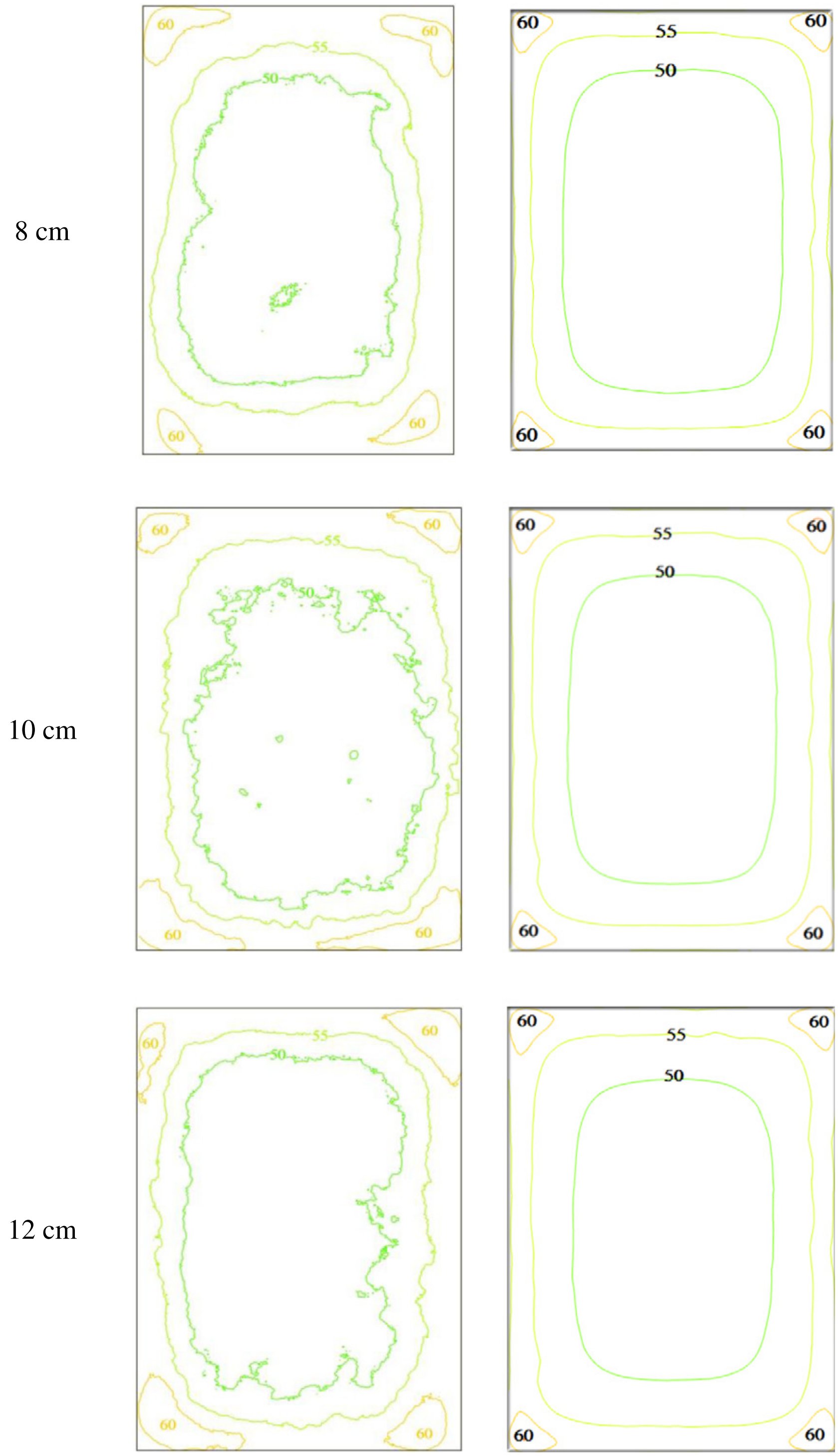

Fig. 10 (*continued*).

About 0.58 and 0.55 °C differences were obtained between simulated and experimental average temperatures in all layers with soybeans moisture content of 4.64% w.b. placed in the polypropylene and polystyrene container, respectively (Table 4). The simulated average temperatures were comparatively higher than those determined by experiments with soybeans moisture contents of 4.64 and 7.86% w.b. This was probably caused by heat loss to the ambient air due to the time delay when removing the container from the RF cavity to the infrared camera in the experiment. The lower standard deviation of soybeans with moisture contents of 4.64 and 7.86% w.b. placed in the polystyrene container indicated better heating uniformity than that placed in the polypropylene container. Soybeans with low moisture content heated more uniform due to the low standard deviation of soybeans (Table 4). Simulated and experimental temperature profiles measured at the geometry centre of soybeans were also in good agreement (Fig. 9). The similar heating rates of 4.46 (Fig. 9a), 3.80 (Fig. 9b), 4.72 (Fig. 9c), and 4.23 °C/min (Fig. 9d) and the small RMSE values of 0.0047, 0.0051, 0.0038, and 0.0041 °C were observed for RF treated soybeans with moisture contents of 4.64 and 7.86% w.b. placed in the polypropylene and polystyrene containers, respectively.

Table 5
Simulated minimum (Min), maximum (Max), average (Avg) and standard deviation (SD) temperatures (°C) of soybeans with moisture content of 7.86% w.b. in three horizontal layers (6, 4, and 2 cm from the bottom of container) with various thicknesses of polystyrene container ($30 \times 22 \times 6$ cm^3) after 7 min RF heating with a fixed electrode gap of 12 cm and initial temperature of 20 °C.

Container thickness (cm)		2	4	6	8	10	12
Min (°C)	Upper	49.63	49.36	48.65	47.93	48.47	48.86
	Middle	53.09	52.57	49.49	48.65	49.13	49.44
	Bottom	54.37	52.39	49.06	48.05	48.66	48.90
Max (°C)	Upper	72.12	63.77	58.80	55.60	56.26	56.66
	Middle	76.14	70.70	65.27	60.01	60.77	61.19
	Bottom	70.45	67.21	60.41	56.37	57.09	57.47
Max-Min (°C)	Upper	22.49	14.41	10.15	7.67	7.79	7.80
	Middle	23.05	18.13	15.78	11.36	11.64	11.75
	Bottom	16.08	14.82	11.35	8.32	8.43	8.57
Avg (°C)	Upper	57.61	55.46	52.03	50.00	50.58	50.91
	Middle	60.17	58.46	54.26	51.41	52.16	52.42
	Bottom	59.24	58.32	53.78	51.10	51.23	51.33
SD (°C)	Upper	4.98	4.74	4.11	3.58	3.60	3.61
	Middle	5.91	5.44	4.58	3.90	3.91	3.92
	Bottom	4.44	4.34	3.46	2.85	2.86	2.87

3.3. Effect of polystyrene container thickness on temperature distribution of soybeans

Fig. 10 shows the experimental and simulated middle temperature distributions of soybeans with moisture content of 7.86% w.b. placed in various thicknesses of polystyrene container treated in RF systems. The highest temperature value at corners of RF treated soybeans decreased from 75 to 60 °C and then kept constant at 60 °C with the thickness of polystyrene container increased from 2 to 12 cm. The maximum temperature difference was reduced from 20 to 10 °C when using the polystyrene container with the thickness of the walls increased from 2 to 8 cm. The average temperature of soybeans with moisture content of 7.86% w.b. in middle layers calculated from the validated simulation model decreased from 60.17 to 51.41 °C when thickness of polystyrene container increased from 2 to 8 cm (Table 5). With thickness of the polystyrene container increased from 8 to 12 cm, the average temperature of soybeans started increasing gradually to 52.42 °C. The difference between maximum and minimum temperatures in the middle layers reduced from 23.05 to 11.36 °C with the wall thickness of the container increased from 2 to 8 cm. The similar trends were also observed in standard deviation of soybeans in the upper, middle and bottom layers (Table 5). The lower voltage inputted to the upper electrode (Table 3) resulted in lower RF power supply as shown in Eq. (6). So the average temperature decreased with increasing container thickness from 2 to 8 cm. According to our previously published RF heating uniformity recommendations, the better temperature uniformity of samples can be achieved when the surrounding material thickness was in a reasonable range (Huang, Zhu, Yan et al., 2015). This behaviour has also been observed for peanut butter (Jiao et al., 2015b) and wheat flour (Tiwari et al., 2011b) subjected to RF treatments.

3.4. Effect of container thickness on heating uniformity of soybeans

The uniformity index (UI) was reduced from 0.122 to 0.106 and 0.132 to 0.122 over the volume with soybeans moisture contents of 4.64 and 7.86% w.b., respectively, placed in the polystyrene and polypropylene containers (Table 6). These results confirm that the non-uniform temperature distribution (mainly dominated by the electric field) within the treated product could be improved by minimizing the difference between dielectric constant of food sample and the surrounding material (Jiao et al., 2014; Tiwari et al., 2011b). The average temperature of soybeans within the whole volume was reduced from 57.88 to 51.17 °C and then increased to 51.65 °C with the wall thickness of the polystyrene container increased from 2 to 8 cm and finally reached to 12 cm. These results are concordant with the calculated upper electrode voltage used in the simulation model. The significantly changed UI values (0.122–0.095) showed that the temperature uniformity improved volumetrically with container thickness increased from 2 to 8 cm. This is due to the automatic adjustment of RF matching circuits, and because a larger volume usually results in a small UI under the same RF treatment condition as shown in Eq. (11). With a further increase of the container thickness from 8 to 12 cm, width of the polystyrene container would be larger than that of the upper electrode, and the non-uniform heating would be enhanced again with UI increased from 0.095 to 0.098. It was found that most of the electric field entered obliquely into the sample when the size of upper electrode was larger than that of the treated material (Jiao et al., 2014; Jiao et al., 2015b). This is in accordance with Llave et al. (2015) and Tiwari et al. (2011b), who reported that the increase in size of the treated material beyond the electrode length improved RF power uniformity. When size of the whole treated material increased similar to the upper electrode, the electric field started entering normally into the sample, and thus the RF heating uniformity could be largely improved (Huang, Zhu, Yan et al., 2015). As observed, a rather uniform temperature is obtained with the smallest UI value of 0.095, demonstrating that the 8 cm thickness of polystyrene container would obtain the best heating uniformity within the products. Therefore, the 8 cm thickness of polystyrene container was selected for further testing.

3.5. Effect of rounded corners of polystyrene container on heating uniformity

The simulated maximum temperature of soybeans with moisture content of 7.86% w.b. after a heating period of 7 min was reduced to 55 °C with rounded edges and corners, and lower than the temperatures (60 °C) at the sharp edges as exhibited in Fig. 11. The maximum temperature difference in the middle layer decreased from 10 to 5 °C. When using the 8 cm thickness of polystyrene container with corner radius ranged from 0 to 10 cm, the temperatures difference between maximum and minimum was reduced from 14.39 to 10.30 °C over the volume (Table 7). The UI was reduced from 0.095 to 0.085, suggesting a better heating uniformity due to the reduced sharp areas in edges and corners. The rectangular shaped polystyrene container with rounded

Table 6
Simulated minimum (Min), maximum (Max), average (Avg) temperatures (°C) and uniformity index (UI) over the volume of soybeans with moisture content of 4.64 and 7.86% w.b. placed in different thickness of polypropylene and polystyrene container ($30 \times 22 \times 6$ cm^3) after 7 min RF heating with a fixed electrode gap of 12 cm and initial temperature of 20 °C.

Container material		Polypropylene		Polystyrene						
Container thickness (cm)		2		2		4	6	8	10	12
Moisture content (w.b.)		4.64%	7.86%	4.64%	7.86%					
Min (°C)		45.86	49.72	45.04	49.07	48.17	48.96	47.45	47.55	47.55
Max (°C)		64.11	78.37	56.73	76.18	74.06	69.17	61.84	63.84	64.18
Max–Min (°C)		18.25	28.65	11.69	27.11	25.89	20.21	14.39	16.29	16.63
Avg (°C)		50.96	58.55	50.42	57.88	56.65	53.56	51.17	51.52	51.65
UI	Upper	0.103	0.128	0.074	0.114	0.102	0.101	0.099	0.101	0.101
	Middle	0.114	0.137	0.092	0.119	0.118	0.112	0.101	0.102	0.103
	Bottom	0.088	0.101	0.071	0.090	0.088	0.085	0.072	0.077	0.079
	Volume	0.112	0.132	0.106	0.122	0.115	0.104	0.095	0.096	0.098

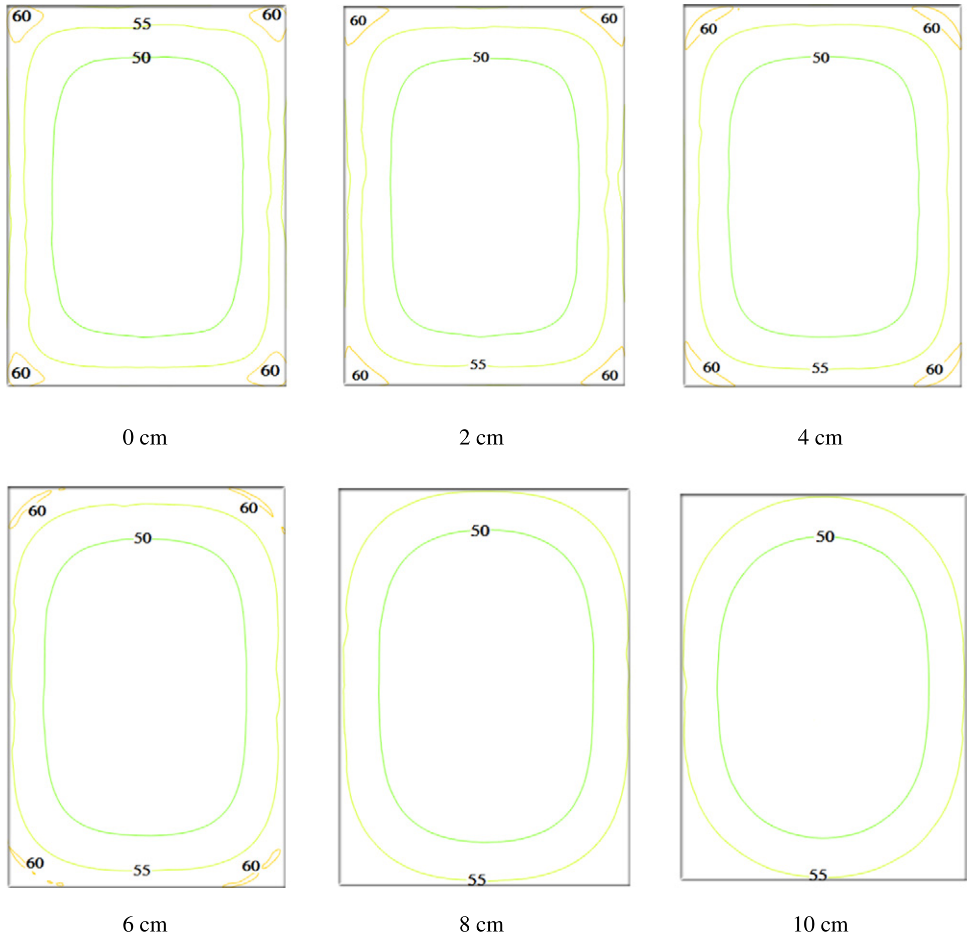

Fig. 11. Simulated temperature distributions of soybeans with moisture content of 7.86% w.b. in the middle layer placed in the polystyrene container ($30 \times 22 \times 6$ cm^3) with corner radius increased from 0 to 10 cm at the fixed container thickness of 8 cm after 7 min RF heating with a fixed electrode gap of 12 cm and initial temperature of 20 °C.

edges and corners showed more uniform temperature distributions as discussed above. Based on the study conducted by Birla et al. (2008), the spherical object was expected to heat more evenly as the electric field variation was only 37% in sphere compared to 151% and 173% variations in the cylindrical and the cubical objects, respectively. This behaviour can be explained as the electric field lines enter the rounded edges from one direction, rather than converge from two or three directions in the sharp edges of the rectangular shaped container (Llave et al., 2015; Zhang & Datta, 2001). As a result, the electric field concentration at the rounded corners and edges was reduced. Therefore, the 8 cm thickness of polystyrene container combined with the corner radius of 8 cm could obtain the best heating uniformity for soybeans heated by RF energy. Similar results were also reported in other literatures (Huang, Zhu, Yan et al., 2015; Jiao et al., 2015b; Tiwari et al., 2011b). For designing and scaling up of efficient RF systems for insects control in legumes, some extra methods (movement, rotation, electrode modification, or hot air surface heating) could be combined to further improve the heating uniformity.

Table 7
Simulated minimum (Min), maximum (Max), average (Avg) temperatures (°C) and uniformity index (UI) of soybeans with moisture content of 7.86% w.b. over the volume placed in the polystyrene container (thickness of 8 cm) with corner radius increased from 0 to 10 cm, after 7 min RF heating with a fixed electrode gap of 12 cm and initial temperature of 20 °C.

Corner radius (cm)	Min (°C)	Max (°C)	Max-Min (°C)	Avg (°C)	UI			
					Upper	Middle	Bottom	Volume
0	47.45	61.84	14.39	51.17	0.099	0.101	0.072	0.095
2	46.85	59.12	12.27	51.08	0.094	0.100	0.071	0.093
4	46.80	58.71	11.91	51.05	0.090	0.098	0.068	0.092
6	46.75	57.68	10.93	51.03	0.088	0.096	0.066	0.089
8	46.73	56.94	10.21	51.01	0.087	0.095	0.065	0.085
10	46.80	57.10	10.30	51.08	0.088	0.097	0.066	0.086

4. Conclusions

In this study, the computational model based on commercial software COMSOL was developed to investigate the effect of polystyrene container on the RF heating uniformity of soybeans with different moisture content for disinfestations. Good agreement of sample temperatures in three layers was obtained between the model simulation and experimental measurement using the infrared photography technique. Low moisture (4.64% w.b.) soybeans heated more uniform compared to the high moisture (7.86% w.b.) soybeans placed either in the polypropylene or polystyrene container. Both the experimental and simulated results showed that the RF heating uniformity could be effectively improved by increasing the wall thickness of the polystyrene container from 2 to 8 cm. Using the container thickness of 8 cm, combined with corner radius of 8 cm significantly improved the RF heating uniformity as compared to a single method. Treatment protocols with polystyrene container and rounded edges for ensuring good temperature distributions can be developed based upon these simulation findings. Results generated from this study are valuable for exploring the potential industrial applications of using RF energy to control insects and maintain good product quality.

Acknowledgments

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