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Research Paper

Simulation and prediction of radio frequency heating in dry soybeans

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Radio frequency (RF) heating is considered as a potential postharvest technology for disinfesting legumes. However, the non-uniformity in RF heating is still a major problem in developing effective RF heat treatments for pest control and other applications. A computer simulation model was developed with a finite element-based commercial software, COMSOL, to analyse the temperature distributions. Dry soybeans packed in a rectangular plastic container were used to determine the heating uniformity and validate the simulation model using a 27.12 MHz, 6 kW RF system. Both simulated and experimental results showed similar heating patterns in RF treated soybeans, in which corners and edges were more heated and the temperature values were higher in the lower part of the container. The simulation results demonstrated that the RF heating uniformity could be improved using a similar dielectric material around the samples, a smaller top plate area (similar to the sample size), and placing the samples in the middle of the two plate electrodes. The simulation model developed in this study could be applied to improve the RF heating uniformity and to optimise the treatment parameters.

1. Introduction

Soybean (*Glycine max*) is a leading oilseed crop produced and consumed worldwide because of its broad uses for human and animal food, industrial and medical applications (Wilcox, 2004). But a major problem in storage, production and marketing of soybeans is infestation by insect pests (USADPLC, 2007). These pests degrade the soybean quality by direct damage through feeding and webbing the production, and indirect damage through induction of diseases, which may pose a critical threat to consumer health. To meet phytosanitary and quarantine regulations for international trade, there is an urgent need in developing non-chemical postharvest pest control methods for dry soybeans.

Radio frequency (RF) energy is an electromagnetic wave with a frequency of 1–300 MHz, which provides rapid and volumetric heating, and has been studied as a non-chemical alternative for postharvest insect control in dry products (Halverson, Burkholder, Bigelow, Nordheim, & Misenheimer, 1996; Nelson, 1973; Tang, Ikediala, Wang, Hansen, & Cavalieri, 2000), such as alfalfa seed (Yang, Zhao, & Wells,

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Notation

A	top plate area (mm^2)
c_p	heat capacity (J kg^{-1} K^{-1})
d	distance (m)
E	electric field intensity (V m^{-1}).
f	frequency (Hz)
k	thermal conductivity (W m^{-1} K^{-1})
m	moisture content (w.b.)
Q	density of power generated by electric field distribution (W m^{-3})
t	time (s)
T	sample temperature (K)
V	electric potential (V)
V_{vol}	sample volume (m^3)
z	vertical co-ordinates or vertical position (m)
α	thermal diffusivity (m^2 s^{-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})
σ	electric conductivity (S m^{-1})

Subscripts

mat	material
av	average
vol	volume

2003), grain (Nelson, 1996), legume (Jiao, Tang, Johnson, Tiwari, & Wang, 2011; Wang, Tiwari, Jiao, Johnson, & Tang, 2010), lentil (Jiao, Johnson, Tang, & Wang, 2012), rice (Lagunas-Solar et al., 2007; Zhao, Qiu, Xiong, & Cheng, 2007), walnut (Mitcham et al., 2004; Wang et al., 2001; Wang, Monzon, Johnson, Mitcham, & Tang, 2007a, b; Wang et al., 2006), and wheat (Halverson et al., 1996). The relatively long wavelength of RF usually results in deep penetration depth and predictable temperature profiles in foods, but the non-uniform heating is still a problem for RF heating technology to be applicable in the food industry (Tang et al., 2000; Wang et al., 2007a). The different temperature distribution among and within products may cause quality loss or insect survival due to overheating in corners and edges, and under-heating in centre parts, especially in foods with intermediate and high water contents (Fu, 2004). It is essential to understand the complex mechanism of RF heating and improve the heating uniformity in RF treated products so as to ensure complete insect mortality and maintain product quality throughout the whole product volume.

Computer simulation and mathematical modelling serve as a valuable tool for rapid analysis of RF heating process without the necessity of extensive time consumed in experiments. Computer simulation has also been conducted to study the RF heating uniformity in various food materials, such as alfalfa and radish seeds (Yang et al., 2003), 1% carboxy methyl cellulose solution (Chan, Tang, & Younce, 2004), cylindrical meat batters (Marra, Lyng, Romano, & McKenna, 2007), meat (Romano & Marra, 2008), fresh fruits (Birla, Wang, & Tang, 2008; Birla, Wang, Tang, & Tiwari, 2008), mashed potato (Wang, Olsen, Tang, & Tang, 2008), wheat flour (Tiwari, Wang, Tang, & Birla, 2011a), and raisins (Alfaifi et al., 2014). Neophytou and Metaxas (1996, 1998, 1999) attempted to model the electrical field for industrial-scale RF heating systems by solving the coupled Laplace and wave equations. The well-developed computer simulation model makes it possible to obtain accurate results from various agricultural products. Different criteria and indexes have been used to study, evaluate, and compare the RF power and temperature uniformity in food samples, such as the normalised RF power density (Neophytou & Metaxas, 1998), the heating uniformity index (Wang, Yue, Tang, & Chen, 2005), the RF power uniformity index (Tiwari, Wang, Tang, & Birla, 2011b), and the temperature uniformity index (Alfaifi et al., 2014). Since the sample temperatures are the main targets in RF heating for disinfestations or pasteurization and quality evaluations, the simulated temperatures in dry food samples are accessed and compared under different conditions using the simulated temperature uniformity index (STUI) in this study.

There are few reports on the computer simulation and prediction about effects of related parameters on the RF heating uniformity in dry soybeans for thermal disinfestations. Therefore, it is necessary to systematically study the RF heating characteristics and evaluate treatment parameters to improve the RF heating uniformity in dry soybeans based on the validated computer simulation model. Specific objectives were to (1) develop a computer simulation model for dry soybeans when subjected to a 6 kW, 27.12 MHz RF system using commercial finite element software COMSOL, (2) validate the computer simulation model by comparing with the transient experimental temperature profiles of dry soybeans at three different layers after 6 min RF heating, and (3) apply the validated computer simulation model to predict the effects of sample moisture content, top electrode area, sample vertical position, and special dielectric container materials around samples on the behaviour of RF heating uniformity in dry soybeans.

2. Materials and methods

2.1. *Sample preparation*

Seeds of soybean were purchased from a local grocery store in Yangling, Shaanxi, China and stored at the constant temperature (25 °C) of a thermostatic and humidity controlled chamber (BSC-150, Shanghai BoXun Industrial & Commerce Co., LTD., Shanghai, China) prior to RF experiments. The composition of soybean was reported on the label as: 11.2 g (100 g)$^{-1}$ fat, 35.1 g (100 g)$^{-1}$ protein, 5.0 g (100 g)$^{-1}$ ash, 41.1 g (100 g)$^{-1}$ sodium, and 41.1 g (100 g)$^{-1}$ carbohydrate (Guo, Wang, Tiwari, Johnson, & Tang, 2010). The initial moisture content of dry soybean was 5.13 ± 0.11% on wet basis. The bulk density of dry soybean at room temperature was measured by a basic volume method using a 30 × 22 × 6 cm^3 plastic rectangular container and obtained to be 748 ± 4 kg m^{-3} over three replicates.