International Journal of Heat and Mass Transfer 90 (2015) 406–417

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Computer simulation of radio frequency selective heating of insects in soybeans

Zhi Huang [a], Long Chen [a], Shaojin Wang [a,b,*]

[a] College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, Shaanxi 712100, China
[b] Department of Biological Systems Engineering, Washington State University, Pullman, WA 99164-6120, USA

ARTICLE INFO

Article history:
Received 2 February 2015
Received in revised form 23 June 2015
Accepted 23 June 2015

Keywords:
Computer simulation
Insect control
RF energy
Differential heating
Soybean

ABSTRACT

Radio frequency (RF) treatments have potential as alternatives to chemical fumigation for disinfesting legumes. This study was conducted to investigate the feasibility of RF selective heating of insect larvae in 3 kg soybeans packed in a rectangular plastic container ($30 \times 22 \times 6\ cm^3$) using a 6 kW, 27.12 MHz RF heating system. A finite element based computer simulation program-COMSOL was used to solve the coupled electromagnetic and heat transfer equations for developing a simulation model. Indianmeal moth larvae were selected as the target insect for experimental validation of the simulation results. Simulated and experimental temperatures of insects and soybeans after 6 min RF heating were compared in top, middle, and bottom layers within the container. Both results showed that insect larvae were differentially heated with 5.9–6.6 °C higher than host soybeans when RF heated from 25 to 50 °C. These results revealed that the heating rate of insects was 1.4 times greater than that of soybeans. The validated simulation results demonstrated that placing the insect on the cold spot of each layer, or horizontally, and large insect size may cause less selective heating within the insect bodies. Dielectric properties of insects may also influence the preferential heating patterns. The selective heating of insects in soybeans may provide potential benefits in developing practical RF treatments to ensure reliable control of insect pests without adverse effects on product quality.

1. Introduction

Soybeans are one of important legumes in current international market, with an annual production of 241 million metric tons in 2012 and 91 million tons were exported in 2011 by the 9 leading countries for a value of US$51 million [1]. Preservation of soybeans for long-term storage has always been a challenge due to infestation by various insects. The major pest for concern is the Indianmeal moth, *Plodia interpunctella* and other internal pests are the cowpea weevil, *Callosobruchus maculatus*, and red flour beetle, *Tribolium castaneum*, respectively. These insects reduce the quality of products and promote mold growth or toxin production, which may create technical barriers to export and even pose a serious threat to consumer health. The total postharvest product losses due to insect damages are conservatively estimated to be between 10% and 40% worldwide [2]. The most common method for postharvest insect control in soybeans is chemical fumigation with methyl bromide (MeBr), which is a broad spectrum pesticide with low cost and high effectiveness. However, the major problem of MeBr fumigation is the negative impact on environment due to depleting ozone layer [3]. With actions taken by the Montreal Protocol, MeBr is no longer available to the legumes industry for postharvest phytosanitary treatments. In addition, because of the rapidly growing market for organic soybeans, there is an urgent need to find environmentally friendly and effective alternatives to chemical fumigation for soybeans.

Radio frequency (RF) technology with a frequency of 1–300 MHz has long been proposed as a potential alternative to chemical fumigation and applied for control of different insects for various agricultural products [4,5]. Recently, RF treatment protocols have been developed to effectively control cowpea weevil in legumes (chickpea, lentil and green pea) with acceptable product quality [6,7]. RF heating relies on vibration of polar molecules and movement of ions, which result in heat generation. The interaction of RF electromagnetic field with any material depends on its dielectric properties [8]. It has been established that the insect has higher dielectric properties than the host material they infest, which would lead to faster heating of the insect when compared with the treated samples [9–13]. Insects might reach a lethal

* Corresponding author at: College of Mechanical and Electronic Engineering, Northwest A&F University, Yangling, Shaanxi 712100, China. Tel.: +86 2987092391; fax: +86 2987091737.

E-mail address: shaojinwang@nwsuaf.edu.cn (S. Wang).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.06.071
0017-9310/© 2015 Elsevier Ltd. All rights reserved.

Nomenclature

A	surface area (m^2)
c_p	heat capacity (J/kg °C)
d	diameter (m)
E	electric field intensity (V/m)
E_{is}	ratio of the insect-to-soybean electric field intensity
f	frequency (Hz)
h_c	heat transfer coefficient at the sample surface(W/m^2 °C)
I_a	measured anode current (A)
k	thermal conductivity (W/m °C)
Q	power density generated by electric field (W/m^3)
t	time (s)
T	sample temperature (°C)
$\partial T/\partial t$	increase rate of temperature (°C/s)
V	electric potential (V)
V	volume (m^3)
SD	standard deviation
ε	permittivity (F/m)
ε_0	free space permittivity (F/m)
ε'	dielectric constant (dimensionless)
ε''	dielectric loss factor (dimensionless)
∇	gradient operator
ρ	density (kg/m^3)

Subscripts

i	insect
s	soybean

temperature while products would be heated to a lower temperature that does not cause quality loss [14–16]. Nelson and Charity firstly suggested that it would be possible to generate differential heating between rice weevil and winter wheat based on the measured dielectric properties in a frequency range of 10–100 MHz [17]. A theoretical analysis and experimental evidence showed that codling moth larvae were heated 1.4–1.7 times faster than walnut kernels at 27.12 MHz, but no preferential heating was observed at microwave frequencies of 915 MHz [13]. Wang et al. reported, based on direct measurements using model insects made of gellan gel and from theoretical predictions, that the mean temperature differences between model insects and almond kernels were 4.7 and 6.0 °C at heating rates of 5 and 10 °C/min, respectively [18]. Studies on electromagnetic interactions with the insect and products also showed that the insect-to-wheat power dissipation factor was between 5 and 31 depending upon insect-wheat mixture temperature (15–75 °C), and wheat moisture level (12–18% wet basis) at the test frequency of 27.12 MHz [19].

Computer simulation is a very effective tool for rapid, cost-effective, and flexible analyses, and providing an insight into the dielectric heating mechanism in food materials [20–23]. To help understand the complex RF dielectric heating process and analyze RF heating uniformity, simulation has previously been used in various food materials, such as dry soybeans [24], fresh fruits [25], mashed potato [26], meat [27], peanut butter [28], raisins [29] and wheat flour [30]. Zhu et al. simulated the top electrode voltage based on finite element method using COMSOL Multiphysics to predict the correlation between electrode voltages and electrical currents [31]. Ben-Lalli et al. developed a space-and-time dependent computer simulation model including convective heating and microwave heating (915 MHz) using commercially available finite element based software, COMSOL [32]. The model was then validated by comparing simulated and experimental temperature profiles inside date fruit and the results showed a realistic magnitude and information on insect survival rates under given treatment conditions and characteristics of dates and insects. Validated simulation models are very useful to analyze the different RF heating characteristics between insect pests and dry products, reduce adverse effects on product quality, and provide a greater throughput of product in a processing plant. There are few reports on the finite element simulation to show the differential heating of insects in host soybeans when subjected to an electromagnetic field.

The objectives of this study were to: (1) develop a computer simulation model for a 6 kW, 27.12 MHz RF system using commercial finite element software COMSOL, (2) validate the computer simulation model by comparing three-layer transient experimental temperature profiles in soybeans after 6 min RF heating, and (3) apply the validated computer simulation model to predict the effects of insect positions, orientations, dielectric properties, and sizes on the behavior of differential RF heating between insects and soybeans.

2. Materials and methods

2.1. Sample preparation

2.1.1. Dry soybeans

Seeds of soybean (Glycine mux L.) were obtained from a local wholesale market in Yangling, Shaanxi, China. The seeds were stored with mesh bags in a thermostatic and humidity (65% RH) controlled chamber (BSC-150, Shanghai BoXun Industrial & Commerce Co., Ltd., Shanghai, China) at the constant temperature (25 °C) prior to RF experiments. They were taken out from the chamber 4 h before experiment and kept at ambient room temperature (25 ± 1 °C) for equilibration.

2.1.2. Insects

Larvae of Indianmeal moth were obtained from the Entomological Institute, College of Plant Protection, Northwest A&F University, Yangling, China. Larvae were kept in a glass jar containing 200 g of dry soybeans. The jars were covered by a fine mesh cloth for air exchange, and maintained in a rearing room at 25 ± 1 °C, 65% RH, and a photoperiod of 16:8 (*L*:*D*) *h* with artificial light. Only actively moving Indianmeal moth larvae were used in RF treatments and the weight of each larva was about 0.04 ± 0.003 g. The length and diameter of Indianmeal moth larvae ranged from 10 to 13 mm and from 2.2 to 2.8 mm, respectively. These insect larvae were transferred from glass jars to plastic cups (500 ml) and left at room temperature for 4 h before treatments.

2.2. Material properties measurement

Different sample moisture content may change dielectric and thermal properties of materials, which would further influence the RF heating behavior [24]. So moisture content of soybeans was determined using the oven drying method. About 10 g of ground soybeans were placed in an aluminum dish and dried in an oven (DZX-6020B, Shanghai Nanrong Co. Ltd., Shanghai, China) at 120 °C for 12 h until a substantially constant weight was obtained. The average initial moisture content of dry soybeans was 6.18 ± 0.04% on wet basis (w.b.) together with that