Journal of Stored Products Research 65 (2016) 19–29

Contents lists available at ScienceDirect

Journal of Stored Products Research

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

Simulation of heating uniformity in a heating block system modified for controlled atmosphere treatments

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ARTICLE INFO

Article history:
Received 9 October 2015
Received in revised form
15 November 2015
Accepted 15 November 2015
Available online 10 December 2015

Keywords:
Controlled atmosphere
Heating block system
Heating rate
Insects
Simulation
Temperature distribution

ABSTRACT

Reliable and repeatable insect thermal mortality data rely on the performance of a heating device. Computer simulation has been widely used to optimize structures, design parameters and process conditions. To improve the temperature uniformity of a heating block system (HBS), a computer model was developed using finite element software COMSOL. Good agreement was obtained between the simulated and experimental block surface temperatures at three positions of the HBS and three heating rates. The validated computer model was further used to predict the effects of heating rates, the position of test insects and the addition of gases on the block and air temperature distributions. Simulation results showed that increasing heating rate reduced heating uniformity. The position of test insects in the treatment chamber largely affected their heating rate, with a position closer to the surface of the heat block providing a better temperature match between test insects and the HBS. When gas was added, block temperatures within the treatment chamber, particularly near the gas inlet, were influenced by gas speeds, temperatures and the gas channel design. The heating uniformity in the treatment chamber of the HBS was improved by heating the gas before adding it to the HBS, by routing the gas channel through the heating block to preheat the gas, and by using a relatively slow gas speed. The simulation results demonstrated that the validated computer model could be a reliable tool to evaluate the heating performance of the HBS for studying insect thermal death kinetics and optimize treatment conditions for the HBS when modified to include controlled atmospheres.

1. Introduction

Production in China of stored cereals and beans reached 539.3 and 17.3 million tons in 2012, respectively (National Bureau of Statistics of China [NBS], 2013). The main quality loss during storage is from damage due to insect pests. For example, the losses caused by pests in postharvest rice and wheat can be as high as 20% and 30%, respectively (FAO, 2013; FAOSTAT, 2013). Pest infestations cause reductions of product weight, quality, nutritional content and commercial value, and create a threat to consumer health. Chemical fumigations are widely used to control insects in stored products. To reduce chemical residues and environmental pollution, non-chemical thermal treatment methods, such as hot air, microwave and radio frequency (RF) heating, have been widely studied for disinfesting agricultural products (Tilley et al., 2007; Wang et al., 2010; Hansen et al., 2011; Opit et al., 2011).

Developing effective thermal treatment methods depends on the thermal death kinetics of target insects. A heating block system (HBS) has been successfully used as a unique device to determine the thermal death kinetics of many insects (Wang et al., 2002a, 2002b; Johnson et al., 2003, 2004; Hallman et al., 2005; Yan et al., 2014; Hou et al., 2015; Li et al., 2015). Thermal death results obtained with the HBS have been confirmed for navel orangeworm (*Amyelois transitella*) in walnuts (Wang et al., 2002c), yellow peach moth (*Conogethes punctiferalis*) in chestnuts (Hou et al., 2015) and cowpea weevil (*Callosobruchus maculatus*) in lentils (Jiao et al., 2012). The HBS can be programmed to simulate the heating rate of the interior of agricultural products (Wang et al., 2005) when subjected to different heating methods, such as hot air, hot water and RF treatments (Wang et al., 2006). However, variability in insect mortality using the HBS suggests that a systematic study of the

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http://dx.doi.org/10.1016/j.jspr.2015.11.003
0022-474X/

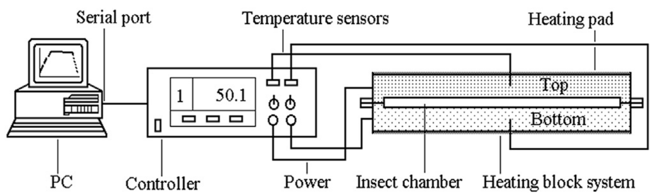

Fig. 1. Heating block system for insect mortality studies (Yin et al., 2006).

heating behaviour of the HBS with and without insects would be needed.

Controlled atmosphere (CA) treatments to control insects in agricultural products typically involve lowering O_2 and raising CO_2 concentrations (Neven and Rehfield-Ray, 2006a, 2006b; Son et al., 2012; Neven et al., 2014). The susceptibility of insects to CA increases with increasing temperature due to enhanced respiratory demand. Using heat treatments reduces the exposure time needed when using modified or controlled atmospheres (Neven and Mitcham, 1996; Shellie et al., 1997). To analyse the effects of combined heat and CA treatment on insect mortality, the HBS was modified to allow the addition of different gases (Neven et al., 2012; Li et al., 2015). However, before insect thermal death kinetic tests are determined, the effect that added gas may have on the heating rate and temperature uniformity of the HBS must be understood.

Because lengthy experimental methods to determine the effects of multiple factors are costly, computer simulation has been used to predict the effect of gas speeds and temperature on heat transfer under various conditions. Chung et al. (2008) developed a finite element model using the commercially available software FEMLAB to simulate transient heat transfer in a test cell. Tiwari et al. (2011) confirmed that non-uniform distribution of RF power density resulted in non-uniform heating in wheat flour using the finite element method. Ben-Lalli et al. (2012) defined 2D axial-symmetric domain during both convective and microwave heating treatments, and obtained 95% accuracy between the simulated temperatures and experimental data. Huang et al. (2015a) developed a 3-D theoretical model using COMSOL to determine differential heating of insects in soybeans when subjected to radio frequency treatments. Therefore, computer simulation may provide a useful tool in determining the effects of gas temperature and flow rates on the heating uniformity within the HBS.

Objectives of this study were as follows: 1) using the finite element software COMSOL, develop and validate a simulation model for the HBS under different heating rates without insects or adding gases; 2) simulate temperature differences between the aluminium block, air in the treatment chamber and test insects when test insects are placed in various positions without adding gases; and 3) apply the validated model to predict effects of different gas speeds, temperatures, and gas channel systems on temperature distribution of the HBS.

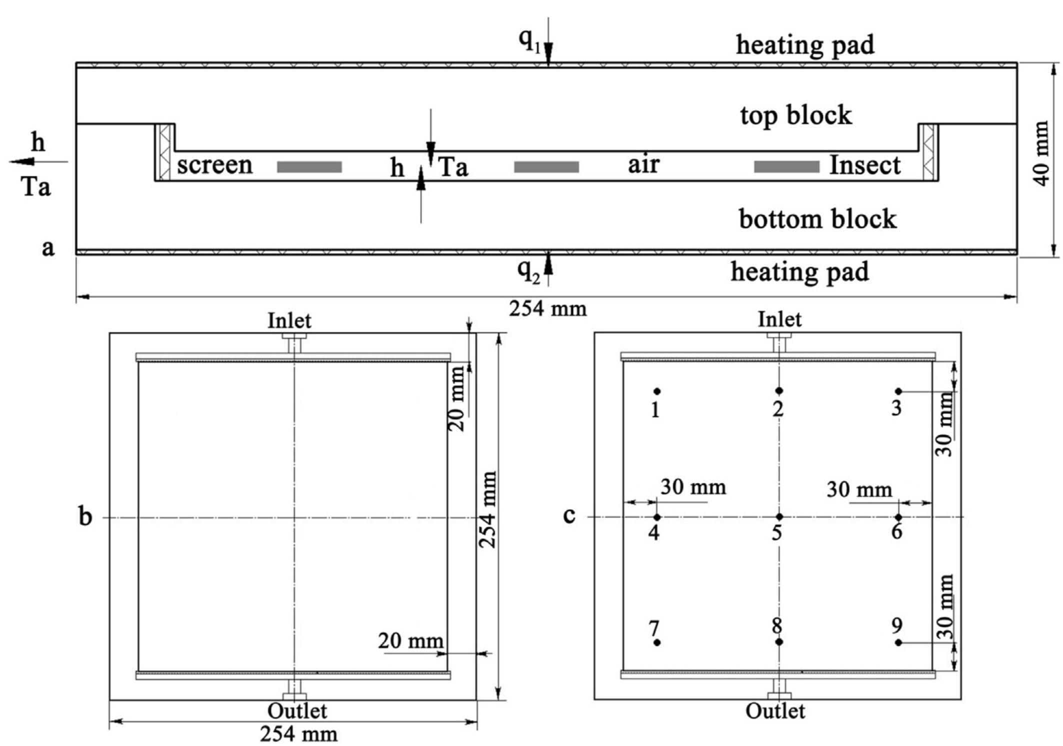

Fig. 2. Dimensions and heat transfer parameters for the model (a), dimensions of the cavity (b) used to simulate the heating block system, and positions on the bottom block surface (c) used for temperature measurement.

Table 1
Thermal properties and conditions used in the simulation (Ikediala et al., 2000).

Material	Density ρ (kg/m^3)	Specific heat c_p (J/kg°C)	Thermal conductivity k (W/m°C)
Aluminium block	2702	903	234
Insect	1036	3450	0.51
Air	1.160	1007	0.027