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Effect of changes in microwave frequency on heating patterns of foods in a microwave assisted thermal sterilization system

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ABSTRACT

This research studied the influence of frequency variation on heating patterns within prepackaged foods in a 915 MHz single-mode microwave assisted sterilization (MATS) system consisting of four microwave heating cavities. The frequencies of the four generators powering the MATS system at Washington State University were measured at different power levels over one year. The effect of frequency shifts in the generators on heating patterns within a model food (whey protein gel, WPG) was studied through computer simulation. The simulated heating patterns were experimentally validated using a chemical marker. Our measurement results showed that a 0.5 kW increase in the microwave power caused the operating frequencies of the generators to increase by 0.25–0.75 MHz. The simulation results suggested that the heating pattern of WPG processed by the MATS system was not affected by the varying frequencies of generators within the operating frequency bandwidth (900–920 MHz). In addition, the simulation results revealed that using deionized water as the circulation medium in the MATS system resulted in a 23–37% increase in the temperature of WPG as compared with that when using normal tap water, but did not alter the heating pattern.

1. Introduction

The Federal Communications Commission (FCC) of the United States designated 915 ± 13 MHz and 2450 ± 50 MHz for industrial, scientific, and medical uses other than telecommunications. However, the operating peak frequency of a magnetron may vary within or beyond the allocated bandwidth. The variations are caused by differences in design and manufacture of magnetrons and the generators. A magnetron may also experience frequency shifts as it ages (Cooper, 2009). An important reason for the frequency shift would be the reduction of strength of the permanent magnet in the magnetron (Decareau, 1985). Finally, the operating frequency of a microwave generator also changes with the power setting during operation.

The heating pattern of food in a microwave heating system is determined by the microwave propagations and resonant modes within the microwave heating cavities. Each mode has a matched frequency. In a multimode microwave heating cavity with fixed dimension, the mode type is determined by the microwave frequency. A small shift in frequency may result in a different mode type (Dibben, 2001), which can lead to unpredictable heating patterns. For industrial microwave assisted thermal processes that require regulatory acceptance for food safety purposes, it is highly desirable that the systems provide predictable and repeatable heating patterns in the processed foods to allow accurate monitoring of temperature history at the cold spots. A 915 MHz single mode microwave assisted thermal sterilization (MATS) system was developed at Washington State University (WSU) with the ultimate goal for industrial implementation (Tang et al., 2006). The MATS system was powered by four high-power magnetron generators. Since its inception, several MATS processes for different foods in either rigid trays or flexible pouches were developed by the WSU research team and accepted by the United States Food and Drug Administration (FDA) or the United States Department of Agriculture Food Safety and Inspection Service (USDA, FSIS). After monitoring the operating frequencies of the four generators of the MATS system over one year (2009–2010), we noticed changes in their peak frequencies. Although no change in the heating patterns were observed during microwave processing, it is necessary to systematically investigate the effect of the operation peak frequency on microwave heating of foods and determine the

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frequency boundaries of the current system design without causing a change in the heating pattern. Such information is needed to guide future development of system operation and calibration protocols that assure consistent industrial production of safe foods using the MATS systems. Computer simulation was used in this study to systematically evaluate the limits for microwave operation frequency shift that would not potentially alter heating patterns during thermal processing in the WSU MATS system and guide future design and operations of similar industrial systems.

Microwave heating systems have been modeled using various numerical methods including the Finite Difference Time Domain (FDTD) method (Sundberg et al., 1996; Chen et al., 2008) and Finite Element Method (Zhou et al., 1995; Romano et al., 2005; Hossan et al., 2010). A typical assumption of such simulation models considered that microwave energy was transmitted at a fixed operating frequency. No study was conducted to quantify the effect of frequency shift of microwave on food heating patterns.

Therefore, the objectives of this study were to evaluate the factors responsible for possible changes in the peak frequency of microwave generators and determine the boundary of the frequency shift to ensure that no change in heating patterns would occur during microwave heating using the MATS and similar systems.

2. Materials and methods

2.1. MATS system

The MATS system developed and installed at WSU was used in this study (Resurreccion et al., 2013). It consisted of four sections, i.e., preheating, heating, holding and cooling, arranged in series representing the four sequential processing steps. In operation, the system was pressurized while the circulating water in each section was set at a certain temperature. A pocketed mesh conveyor belt made of non-metallic material extending from the start of the preheating section to the end of the cooling section conveyed the food trays or pouches through the MATS system.

This study was primarily concerned with general heating patterns in pre-packaged food in the microwave heating section of the MATS system. The microwave heating section consisted of four connected rectangular cavities. The cavities were specially designed to operate in single mode (*i.e.*, only one pattern of electromagnetic field distribution in each cavity) (Tang et al., 2006). Each cavity (Fig. 1) had two windows (top and bottom) made of high temperature resistant polymer. The microwaves were delivered to the cavity through the windows that were connected to two horn microwave applicators. The horn was a tapered shape with the wide end connected to the window and the narrow end having the same inner cross sectional dimension as that of a standard WR975 waveguide (247.7 mm by 123.8 mm). The microwaves were directed from generators to the horn applicators through WR975 rectangular waveguides consisting of six 90° E-bend waveguide elbows, a 90° H-bend waveguide elbow, and a tee junction. Incident microwaves were bifurcated at the tee junction wherein two equal portions propagating to the top and bottom horns and merging in the cavity without phase shift. In the MATS system, cavity 1, 2, 3, and 4 were connected to generator 1, 2, 3, and 4, respectively.

2.2. Computer simulation model for the MATS system

The geometry and dimension of the microwave heating section, including the heating cavities and horn applicators, was incorporated in computer simulation model (Fig. 2). Since a pseudo location for microwave input port can be drawn anywhere within the waveguide (*i.e.*, as long as it is parallel to the cross section of the waveguide), port locations were selected just above and below the narrow ends of the horns (Fig. 2a). The selected location of microwave input ports allowed for the exclusion of the waveguides connecting the applicators to the microwave generators. Doing so could reduce the dimension of the simulation model and minimize the computational resources.

The power setting of each port was based on the net output power of each generator. The generator output powers were measured by directional couplers (Ferrite Microwave Technologies, Inc., Nashua, NH 03060) installed along the waveguides through an automated feedback mechanism. The power settings of the four microwave heating cavities were 6.4, 5.6, 2.5, 2.6 kW, respectively. In the simulation model, the net input power of each cavity was evenly distributed to the two ports.

The finite difference time domain (FDTD) method was used to numerically solve the coupled electromagnetic and heat transfer equations during microwave processing. The simulation was conducted using a commercial software of Quickwave version 7.5 64-bit (QWED, Warsaw, Poland). The FDTD cell size in this study was 4, 4 and 1 mm in *x*, *y*, and *z* direction (Fig. 2), respectively. It followed a general rule by thumb that the discrete cell dimension

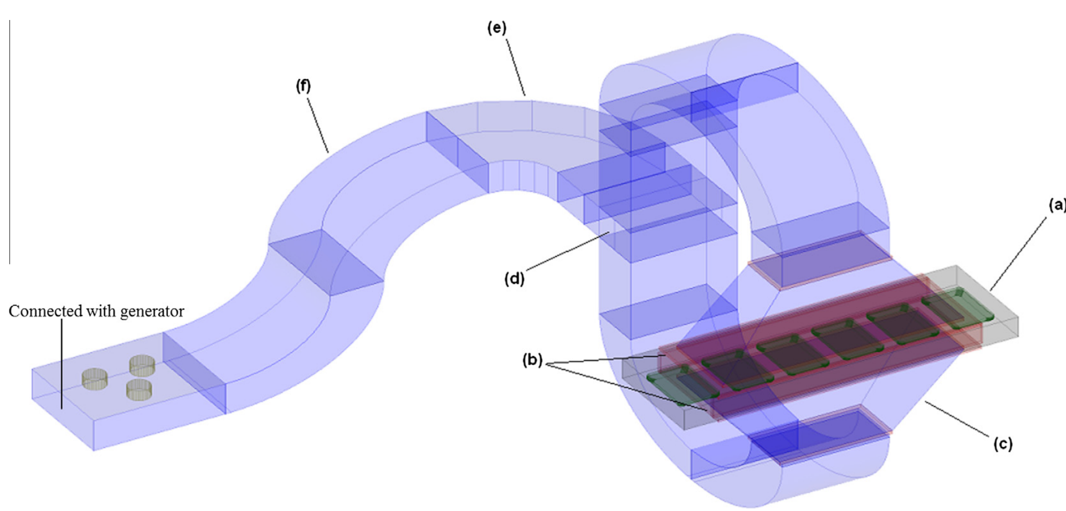

Fig. 1. A typical microwave heating cavity and its attachments of the MATS system. (a) A single mode cavity, (b) two microwave transparent windows at the top and bottom of the cavity, (c) one of the two horns at bottom, (d) a tee waveguide junction, (e) a 90° H-bend waveguide elbow, (f) one of the six 90° E-bend waveguide elbow.