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Investigation and modeling of temperature changes in food heated in a flatbed microwave oven

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ABSTRACT

The flatbed microwave oven, unlike a turntable-equipped one, has a stationary ceramic plate inside the cavity, which allows more space for rectangular or larger dishes and is easier to clean. This newly designed microwave oven contains an aluminum antenna with irregularly shaped holes in the base that rotates during heating to achieve relatively uniform heating. Therefore, the complex configuration increases the difficulty of modeling the heating process, and no information has been available on this.

This study investigated the heating characteristics of the domestic flatbed microwave oven by observing the temperature distributions in different foods during processing. A computational model based on the finite element method was also successfully established for predicting the temperature distributions in food by coupling an analysis of the electromagnetic field and heat transfer with a consideration of the rotation of the antenna during heating. Methods for optimizing the simulations to minimize the computational time using a geometric model and the food's dielectric properties were proposed. Finally, the simulations were compared with the experiments, and the *RRMSE* (relative root mean square error) and *MRE* (maximum relative error) values (material A of 2.27% and 6.53%, material B of 1.92% and 5.88%) demonstrated that they are in good agreement.

1. Introduction

Because of its advantages of rapid speed and great convenience, microwave heating technology has dramatically changed the food industry. Microwave has also been widely used globally for domestic food heating, reheating, cooking, and even grilling since Raytheon demonstrated the world's first microwave oven, which was called a Radarange, in 1947.

However, problems including non-uniform temperature distribution are associated with the use of microwave energy (Zhou et al., 1995). This problem is due to differences in the intensity of the electromagnetic field distribution inside the food during heating, which result in heat generation differences. Non-uniform heating or cooking is the source of other problems during processing (Basak and Meenakshi, 2006), for example producing both hot spots as well as undercooked areas, which will cause burns or fail to destroy bacteria or pathogens leading to foodborne illnesses. Therefore, efforts have been made to greatly improve the uniformity of microwave heating, and methods such as using variable-frequency microwaves (Bows, 1999), adding a mode-stirrer near the waveguide (Plaza-Gonzalez et al., 2004), and rotating the waveguide or moving food in the cavity (Pedreño-Molina et al., 2007) have been studied.

Most domestic microwave ovens made before 2005 were designed with a turntable in the cavity for rotating the food during heating to obtain a relatively uniform final temperature. This improvement helped fuel the expansion of microwave oven use, and now the total annual manufacture of domestic microwave ovens worldwide has reached more than 70 million; they are almost as common as refrigerators. The popularity of microwave ovens also promoted their development, and an advanced model called a flatbed microwave oven was designed without a turntable to provide more space for food while achieving a temperature distribution similar to that of turntable models. Some models with complex setting functions and those that combined microwaves with other heating techniques such as infrared, convection, ohmic, or jet impingement for food processing have even been explored recently to achieve better heating (Geedipalli et al., 2008; Choi et al., 2011).

In addition to the spread of microwave ovens, more and more food manufacturers have also responded to consumer demand for convenience by developing products specifically designed for microwave heating in recent decades. Products developed for domestic and fast-food restaurant consumers such as pizza, pasta,

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Nomenclature

Latin letters

a, b	length and width of rectangular waveguide (0.1092×0.0546 m^2)
$\vec{B}$	magnetic induction (Wb m^{-2})
C_p	specific heat (J kg^{-1} K^{-1})
C	speed for light in free space (3×10^8 m s^{-1})
$\vec{D}$	electric displacement (C m^{-2})
d	distance of node from nearest width edge inside the waveguide (m)
d_p	penetration depth of microwaves (m)
$\vec{E}$	electric field intensity (V m^{-1})
E_1	original electric field strength at feeding port (V m^{-1})
E_2	corrected electric field strength at feeding port (V m^{-1})
E_{max}	maximum electric intensity inside waveguide (V m^{-1})
E_{rms}	root mean square value of electric field (V m^{-1})
E_y	electric intensity inside waveguide along y direction (V m^{-1})
f	frequency of microwaves (Hz)
$\vec{H}$	magnetic field intensity (A m^{-1})
h	edge length of cubic element (m)
J	current flux (A m^{-2})
j	complex number operator
k	thermal conductivity (W m^{-1} K^{-1})
n	number of points
P_M	absorbed power measured experimentally (W)
P_s	absorbed power estimated by simulation (W)
P_t	transmitted peak microwave power (W)
P_0	active microwave power (W)
Q	volumetric internal heat generation term (J s^{-1} m^{-3})
r	distance from a point to the central axis (m)
r_1	inner radius of coaxial space (m)
r_2	outer radius of coaxial space (m)
T	initial temperature (°C)
T_{cal}	predicted temperature (°C)
T_{exp}	measured temperature (°C)
T_i	predicted internal temperature at node i (°C)
t	heating time (s)
t'	interval at which the gap passes the same area or point twice (s)
t_{stay}	dwell time of each heat generation update interval in simulation (s)
t_{total}	total heating time of a specified area or point (s)
V_r	voltage of different points related to their positions (V)
x, y	coordinates of points in coaxial space
Z_0	wave characteristic impedance (Ω)

Greek letters

β	the imaginary part (rad m^{-1})
ε	complex permittivity (dimensionless)
ε_0	permittivity of free space (8.85×10^{-12} F m^{-1})
ε'	dielectric constant (dimensionless)
ε''	dielectric loss factor (dimensionless)
ε_r	relative permittivity of the medium (F m^{-1})
μ	magnetic permeability of the material (H m^{-1})
μ_0	magnetic permeability of free space (1.256×10^{-6} H m^{-1})
λ	the wavelength of microwave in food (m)
λ_0	microwave length in free space (m)
λ_c	cutoff wavelength in a specific waveguide (m)
π	Ludolph's number (≈3.14159)
ρ	density (kg m^{-3})
ρ_m	electric volume charge density (C m^{-3})
σ	electric conductivity (S m^{-1})
ω	angular frequency (rad s^{-1})
ω_0	rotation speed of turntable (° s^{-1})
ζ	impedance of microwaves in free space (Ω)
ζ_0	impedance of microwaves in vacuum (Ω)

and hamburger are popular. To develop new products suitable for microwave heating, knowledge of the electromagnetic field and temperature distribution during treatment inside a processing unit is necessary; this knowledge is also the foundation for scale-up and development of specifications and for design and approval of the thermal process operations by government regulators (Knoerzer et al., 2008). Microwave heating results from coupling of electrical energy from an electromagnetic field in a microwave cavity and its dissipation within food (Liu et al., 2013; Resurreccion et al., 2013). This causes an instantaneous temperature rise within the product, in contrast with conventional heating processes that transfer energy from the surface with long thermal time constants and slow heat penetration. Because the distribution of the electromagnetic field during processing is affected by many factors, including the food's dielectric and physical properties and the heating conditions, our understanding of the entire microwave heating process is still somewhat empirical and speculative owing to is highly nonlinear characteristics and complex interactions with food (Vriezinga et al., 2002). Therefore, computer simulation for microwave cooking or processing has been suggested and has proven to be one of the best ways of understanding the process in detail, although such simulation is complicated (Bhattacharya and Basak, 2006; Resurreccion et al., 2013).

Domestic flatbed microwave ovens have been available to customers for many years. Instead of a turntable, a stationary ceramic plate is used in the oven to hold the food, which allows more space for placing rectangular or larger dishes and is easier to clean. Thus, it has achieved a high market share compared with turntable models. However, the waveguide, which was located at the bottom of the oven, was newly designed, and some parts, such as the rotating antenna, were irregularly shaped, increasing the difficulty of investigation or modeling. For information on or even description of the use of this type of microwave oven for heating food is still lack to date, this study did this investigation using a domestic flatbed microwave oven. And we successfully developed a computational model using the finite element method (FEM) for electromagnetic field and temperature analysis of food. The simulations were validated experimentally and were finally optimized to minimize the computational time by several methods while ensuring high accuracy.

2. Materials and methods

2.1. The model

2.1.1. Solution method

Three-dimensional geometric models were built using FEMAP (V10.3, Siemens PLM Software Inc., Plano, Texas, USA) according to the real structure and size of a flatbed microwave oven. The boundary conditions, electric intensity, and other parameters, including the dielectric and thermal properties of the samples, were set in PHOTO-Series (V7.2, PHOTON Co. Ltd., Kyoto, Japan), where a combined analysis of the electromagnetic field and heat transfer was conducted for temperature estimation. The two