Journal of Food Engineering 128 (2014) 60–71

Contents lists available at ScienceDirect

Journal of Food Engineering

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

A microwave heat transfer model for a rotating multi-component meal in a domestic oven: Development and validation

K. Pitchai[a,b], J. Chen[b], S. Birla[b], R. Gonzalez[c], D. Jones[b], J. Subbiah[a,b,*]

[a] Department of Food Science and Technology, University of Nebraska-Lincoln, NE 68583, United States
[b] Department of Biological Systems Engineering, University of Nebraska-Lincoln, NE 68583, United States
[c] ConAgra Foods, Inc., Omaha, NE 68102, United States

ARTICLE INFO

Article history:
Received 3 July 2013
Received in revised form 9 December 2013
Accepted 12 December 2013
Available online 29 December 2013

Keywords:
Domestic microwave oven
Computer simulation model
Multi-component meal
Rotation
Validation
Microbial inactivation model

ABSTRACT

A finite element model coupling electromagnetic and heat transfer equations was developed to understand complex microwave interactions in food. The model simulated rotation of a frozen multi-component meal consisting of nine chicken nuggets and mashed potatoes. Temperature-dependent dielectric and thermophysical properties of chicken nuggets and mashed potatoes were measured as a function of temperature from −10 °C to 110 °C. The model included detailed cavity geometry, phase change, and rotation of the food. Effect of rotation angle on temperature predictions was studied and a 45° rotation angle was found to be sufficient. Simulated temperature profiles were compared with experimental temperature profiles obtained using a thermal imaging camera and fiber-optic sensors. Predicted spatial surface temperature profile was in good agreement with the corresponding experimental profiles in terms of hot and cold spot patterns. The root mean square error values ranged from 5.8 °C to 26.2 °C in chicken nuggets as compared 4.3–4.7 °C in mashed potatoes. The predicted and experimental temperature profiles were provided as inputs to a microbial inactivation kinetics model for *Salmonella* Heidelberg to assess food safety risks in chicken nuggets. For 90 s of cooking in a 1200 W microwave oven, at least 7-log reductions of *Salmonella* Heidelberg was not achieved completely at all locations in the chicken nuggets due to non-uniform heating. The validated model can be used to optimize the layout and food system/package modification to achieve more uniform heating.

1. Introduction

Because of rapid and convenient heating offered by the domestic microwave oven, it has become a favorite appliance to heat/cook frozen meals (Venkatesh and Raghavan, 2004). Frozen microwaveable meals may be available as not-ready-to-eat (NRTE), meaning that the product has to be thoroughly cooked by the consumer before consumption to ensure food safety. NRTE meals are available in a variety of product layouts such as single-component, multi-component and multi-compartment meals. Rapid microwave heating may enhance the overall food quality (Guan et al., 2002; Knoerzer et al., 2008). However, the microwave heating process could produce a non-uniform temperature distribution within the food, possibly resulting in over-cooked and under-cooked regions. NRTE foods may contain some raw ingredients or partially cooked meat and poultry products. When the cooked temperature does not reach the desired target temperature for inactivating microorganisms, they can survive in the cold regions and thus cause foodborne illness. This is evident from the several foodborne illness outbreaks associated with microwaveable frozen foods (CDC, 2008; Leitch, 2008; USDA-FSIS, 2007; USDA-FSIS, 2010).

There are many factors affecting microwave heating uniformity including: dielectric properties (dielectric constant and dielectric loss factor), thermal properties (specific heat capacity and thermal conductivity) and physical properties (size, shape, density, and location in the package) of foods (Zhang and Datta, 2000). These factors affect the degree of food components interaction with microwave energy and are important to consider for optimizing food design to achieve uniform heating. Microwave food product development is very time-consuming and expensive. However, use of the computer simulation tool can accelerate the product development cycle and reduce the cost of production. While endeavoring to optimize food and package design to achieve uniform heating, a mere 'cook-and-measure' experimental approach alone may not be optimal in order to understand the complex interactions of food components and the package with microwave energy and therefore simulation can be highly useful.

Over the last two decades, computer simulation is becoming a promising tool to understand complex microwave heating with the availability of powerful computational techniques and the

* Corresponding author. Address: 212 L.W. Chase Hall, East campus, Lincoln, NE-68583-0726, United States. Tel.: +1 402 472 4944; fax: +1 402 472 6338.
E-mail address: jeyam.subbiah@unl.edu (J. Subbiah).

0260-8774/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jfoodeng.2013.12.015

Nomenclature

$\lvert\vec{\mathbf{E}}\rvert$	the time-harmonic electric field strength (V/m)	T_a	ambient temperature (°C)
μ_r	relative permeability	Δt	simulation time step (s)
ϵ_r	relative permittivity	h_{es}	best element mesh size in dielectric material, mm
k_o	wave number	λ	free space wavelength, cm
σ	electrical conductivity (S/m)	RMSE	root mean square error (°C)
ω	angular frequency (rad/s)	T_p	simulated point temperature (°C)
ε_0	free space permittivity (8.854×10^{-12} F/m)	T_o	averaged experimental point temperature (°C)
P_v	dissipated power per unit volume (W/m^3)	F	thermal death time (min)
f	frequency (Hz)	T_t	Transient point temperature (°C) at particular time t
ε''	relative dielectric loss factor	T_{Ref}	Reference temperature (°C) at which microorganism inactivated
ρ	density (kg/m^3)		
C_p	specific heat capacity at constant pressure (kJ/kg °C)	dt	time interval between two consecutive temperature points (s)
k	thermal conductivity (W/m °C)		
T	temperature (°C) at simulation time t	z	Temperature required to reduce microbial population by 1 log (°C)
n	normal to the direction		
h	surface convective heat transfer coefficient (W/m^2 °C)		

development of efficient numerical methods. A computer-based simulation of microwave heating of foods can assist in optimizing design of food systems and packages to improve food quality and safety. Computer-based simulations that couple electromagnetic and thermal equations to calculate the temperature field of microwave-heated foods have been reported (Dinčov et al., 2004; Geedipalli et al., 2007; Pitchai et al., 2012; Wäppling-Raaholt et al., 2002; Zhang and Datta, 2003; Zhang and Datta, 2000). These models are solved iteratively using various numerical methods such as finite-difference time-domain (Pitchai et al., 2012; Tilford et al., 2007; Kopyt and Celuch-Marcysiak, 2003) and finite element methods (Akarapu et al., 2004; Campanone and Zaritzky, 2005; Curcio et al., 2008; Hamoud-Agha et al., 2013; Zhang and Datta, 2000).

Most of the simulation models in the literature do not consider one or more of the following: (i) phase change from frozen to thawing, (ii) rotation of the turntable, (iii) detailed geometry of the cavity, and (iv) integration of the microwave model with the microbial inactivation model to assess food safety.

Most reported studies in the literature consider cooking of refrigerated meals and do not consider the phase change of thawing of frozen foods (Geedipalli et al., 2007; Ma et al., 1995; Ryynänen and Ohlsson,1996; Ryynänen et al., 2004). Because NRTE meals contain raw and/or partially cooked ingredients, they need to be stored below 41°F (5 °C) to prevent microorganism from growing during storage. In North America, most of the NRTE meals are available in the market as frozen meals. Therefore, it is important to consider the phase change characteristics of NRTE foods in the model. One of the challenges of modeling phase change is that the dielectric properties dramatically change between frozen and thawed states and this can cause numerical convergence issues during simulation.

Currently, almost all microwave ovens have turntables. Thus, it is important to simulate the rotation of the food on the turntable. Researchers have developed a computer simulation model using FDTD method based software QuickWave™ to calculate the electromagnetic and heat transfer field distribution in horizontally moving packages that were placed in a microwave assisted thermal sterilization system (Chen et al., 2008; Resurreccion et al., 2013). In most cases, FDTD based solvers are limited in simulation applications because of their inability to handle irregular geometries and boundary conditions. Whereas, FEM based solvers have been used extensively in simulating microwave heating that includes the complex geometries and boundary conditions (Liu et al., 2013). Geedipalli et al. (2007) developed a microwave heat transfer model to rotate raw potato slab kept at the center of the turntable. They demonstrated that the rotation of the turntable can improve heating uniformity by 40%. The limitations of their model include: the phase change effect was not considered as the potato was heated from room temperature; temperature-dependent dielectric properties were not considered; and a simplified geometry of the oven cavity was used. Chatterjee et al. (2007) developed a rotational mathematical model for microwave heating of containerized liquid. In their study, electromagnetic power density inside the containerized liquid was calculated using Lambert's law, which represents electromagnetic energy as planar waves. Maxwell's equations must be solved to understand hot and cold spots (multi-modes) inside the cavity.

A solution of coupled electromagnetic and heat transfer models in 3D space and time requires a great deal of computational resources. Thus far, researchers have made several simplifications in their model development approach. For example, in order to reduce the number of mesh elements required to solve the equations, many researchers have assumed the microwave cavity and waveguide as a simple geometry without considering some of the special features of microwave design, such as dents in the cavity and metal bumps in the waveguide (Geedipalli et al., 2007; Ma et al., 1995; Wäppling-Raaholt et al., 2006; Yakovlev, 2001). The modern day microwave ovens are carefully designed to include many special geometric features such as metal bumps in the waveguide, dents in the cavity, and a turntable in order to improve heating uniformity. Each of these features available inside the cavity can have a dramatic effect on electric field distribution. Electric field distribution is an important factor as it is the input heat source term in the heat transfer equations. Pitchai et al. (2012) have included all these features of microwave design into the model and demonstrated the importance of including these features in modeling accuracy. Despite including all features of the microwave oven design, their work considered a homogeneous model food and did not include the rotation of food on the turntable.

As some foodborne illness outbreaks were associated with microwavable NRTE foods in the past, thermal process calculation can be useful to determine microbial inactivation during microwave heating. There have not been many published studies that attempted to integrate a microbial inactivation kinetics model and a microwave heat transfer model. As a new initiative, Hamoud-Agha et al. (2013) integrated a microwave heat transfer model with a microbial inactivation kinetics model to calculate survival of *Escherichia coli* K12 CIP 54.117 in a calcium alginate gel medium subjected to