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A finite element method based flow and heat transfer model of continuous flow microwave and ohmic combination heating for particulate foods

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ABSTRACT

A 2D numerical model using COMSOL codes was developed to validate uniform heating of particulate foods in a continuous flow microwave (MW) and ohmic (OH) combination heater. The developed model was integrated with an electric field, electromagnetic field, incompressible laminar flow, forced-coupling method (FCM), heat transfer and arbitrary Langrangian–Eulerian (ALE) moving mesh technique. Three representative solid particles were simulated to experience hydrodynamic viscous drag and pressure forces resulting from their motions relative to fluid. The stress tensors of forces exerted on the particle surfaces were successfully formulated by use of the FCM module. The large deformation and movement of geometric mesh containing trajectories of particles inside the feeding tube were accurately predicted in an unsteady state. The simulated outlet temperatures of particulate foods had a good agreement with experimental data within the maximum prediction error of 4%.

1. Introduction

Individual ohmic and microwave heating techniques can heat-treat various foods during a short time depending upon their electrical conductivities and relative permittivities, respectively. However, under-processed foods could increase microbiological risks. On the other hand, over-processed foods may cause serious nutritional losses and reduce down sensory values. Uniform heating of particulate foods is a serious challenge because individual solids and liquids are so discrepant in terms of thermal, electrical, and dielectric properties. To achieve the challengeable uniformity in heating of particulate foods, a new cylindrical microwave chamber equipped with an ohmic tube was designed and fabricated for testing in a continuous flow mode. Over the past few decades, there have been many studies using numerical methods to validate continuous flow microwave and ohmic heaters. Prediction of thermal behavior of solids or liquid inside the heat exchanging units, along with the dynamic flow patterns is crucial for system optimization and validation. In general, simulation for microwave heating is more complicated than ohmic heating since the numerical approach permits hyperbolic partial differential equations to address propagation characteristics of waves in x, y, and z coordinates.

The Lambert's law estimates the dissipation energy of microwave power by assuming that it decreases exponentially from food surface to its center (Campanone and Zaritzky, 2005; Chamchong and Datta, 1999a, 1999b; Chen et al., 1993; Khraisheh et al., 1997; Swami, 1982; Zhou et al., 1995). Because the Lambert's law could not calculate the real electromagnetic field inside the cavity, the simulation showed reasonable results in the case that the volume of the object is relatively large (Datta and Anantheswaran, 2001). Romano et al. (2005) discussed the relationship between the energy absorption of microwave and the dimensions of cylindrical samples applying the Lambert's law. By approximating the penetration depth in the Lambert's law as a linear function of temperature, Chatterjee et al. (2007) tried to describe the complex flow and temperature patterns due to microwave heating of containerized liquids in the presence of rotating turntables. Marra et al. (2010) fully combined the energy transfer equation, phase transition model for liquid water and water vapor, and incompressible standard k–ε turbulent model for air using finite element codes by assuming that the volumetric power absorption energy of microwave followed the Lambert's law.

The Maxwell's equations consisting of topological and constitutive relationships can be solved numerically by the FDTD method

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Nomenclature

f	microwave frequency (GHz)
P	microwave power (W)
V	ohmic voltage (V)
V_0	applied ohmic voltage (V)
k	thermal conductivity (W/m K)
C_p	specific heat (kJ/kg K)
λ	electrical conductivity (S/m)
ε_r	relative permittivity
ρ	density (kg/m^3)
U_0	inlet velocity (m/s)
μ	dynamic viscosity (Pa s)
D	particle diameter (m)
T_0	initial temperature (°C)
E	electric field (V/m)
H	magnetic field (A/m)
ω	angular frequency (rad/s)
μ_0	free space permeability (H/m)
ε_0	free space permittivity (F/m)
T	temperature (K)
t	time (s)
u	velocity (m/s)
q	heat source (J)
ε''	dielectric loss (J/s)
σ	stress tensor (N/m^2)
b	body force (N/m^3)
p	pressure (Pa)
v	kinematic viscosity (m^2/s)
n	unit normal vector
g	gravity (m/s^2)
I	identity tensor
T	transpose of a matrix
x	position vector of solution
Y	position vector of particle
N	total number of particles
F	force
$\Delta(x)$	Gaussian envelope function
σ_n	length scale of n th particle
r_n	radius of n th particle
S	surface of particle
m	mass
d	distance
Δh	mesh size
δ	range of repulsive force
ε	positive stiffness parameter
Re_p	particle Reynolds number
D_t	diameter of the tube
C_D	drag coefficient
F_D	drag force
r	radius of tube

Subscripts

0	initial value
MW	microwave
OH	ohmic
P	particle

Superscripts

n	nth particle
m	mth particle
ext	external force
ine	inertia
R	repulsive force
W	wall
$'$	imaginary particle

or FEM. The FDTD method is to solve the partial differential equation (PDE) directly through approximation. But the FDTD method is difficult to apply for complex domain and can require long computational time because it is based on finite difference method (FDM). On the other hand, Maxwell's equations can be converted into 'weak' form for the finite element method that is flexible enough to integrate with different physics phenomenon. In the field of microwave heating, the weak form derived from Maxwell's equations can especially make great harmony with linear and non-linear equations related to thermal physics. Because Maxwell's equations are based on a dynamical theory of the electromagnetic field, it can also deal with time and space simultaneously.

The FDTD is a time stepping algorithm to solve problems related to electromagnetics (Inan and Marshall, 2011). It applied a finite difference method (FDM) with time because the change in the electric field (E-field) with respect to time is dependent on the change (curl) in the magnetic field (H-field), and the physics phenomenon can be reversed in the same way (Yee, 1966). However, the FDTD requires excessively large memory especially in the case of complex geometry because the concept of the FDTD is based on the FDM logistics; the domain should be sufficiently discretized to solve for electromagnetic wavelengths and geometrical features, which leads to lots of the computational time (Inan and Marshall, 2011). A majority of research related with the Mur absorbing boundary condition (ABC), the Liao ABC and a various perfectly matched layer (PML) were focused on reducing truncation errors occurred by inserting artificial boundaries which were created to decrease the computational time (Berenger, 1994; Deinega and Valuev, 2011; Gedney, 1996; Taflove and Hagness, 2005). The other researchers (Harms et al., 1992; Madsen and Ziolkowski, 1988) attempted to improve the original algorithm of the conventional FDTD method. Because a general FDTD method gives better accuracy when structured (rectangular) mesh is used, Dincov et al. (2004) developed two-phase porous media model under intensive microwave heating to predict the heating mechanism including heat transfer, liquid saturation and dynamic pressure. Zhu et al. (2007) developed a numerical model to simulate the forced convection of liquid flowing inside a circular applicator subjected to microwave heating. To simulate the temperature distribution of moving packages under microwave heating process, whey protein gels sealed in a polymeric tray as a food model for moving package were prepared and the dielectric properties were measured. The conformal FDTD method to model the irregularities without excessive memory overheads was applied assuming that its steady state was setup before the thermal reaction took place and the field intensity of microwave within the food model was constant until it was moved to its subsequent position (Chen et al., 2008). Pitchai et al. (2012) included a rotating turntable in a domestic oven, and simulated temperature distribution of the sample using commercial software.

Compared with previous studies, the finite element method (FEM) has no restrictions in arbitrary and irregular geometries, and can deal with any types of boundary conditions. Non-homogeneity and non-linear behavior can be included in the FEM. Hence, it is a general formulation to combine partial differential equations to govern targeted multi-domains in a wide range of fields in engineering and physics (Logan, 2007). Oliveira and Franca (2002) simulated the heat transfer in microwaved foodstuffs using