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Investigation into heat transfer and fluid flow characteristics of liquid two-layer and emulsion in microwave processing☆

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ABSTRACT

Numerical study of fluid flow and heat transfer within two types of liquid (liquid two-layer and oil–water emulsion) when subjected to microwave energy are discussed. In order to obtain the simulation of microwave heating from room temperature, a 2D comprehensive model was integrated with electromagnetic field, incompressible laminar flow and heat transfer. The effects of layered configuration, layered thickness and dispersed fraction of emulsions were investigated. Temporal profiles obtained using fiber optic sensors at four discrete points were compared with the simulated temperature profiles. The simulated outlet temperatures of liquid had a good agreement with experimental data within the maximum prediction error of 5%. The theory presented in this paper can be effectively used to explain fluid transport during microwave heating system using the rectangular waveguide.

1. Introduction

The major advantages of microwave heating are rapid and volumetric heating. Microwave can penetrate the surface and produce volumetric heat generation within materials, thus leading to high energy efficiency and short process time. However, non-uniform heating is a disadvantage of microwave heating. The complex interaction of microwaves with sample properties produces non-uniform heating. A particular microwave oven can behave differently for the same sample depending on its physical state such as liquid two-layer and emulsion. This non-uniform heating in a microwave oven not only affects food safety but also influences food quality [1].

Most of the work on microwave heating system design and processes has been done based on only experience and perception of engineers. In addition, experimental study alone is quite difficult to gain the reasons behind non-uniform heating in a microwave oven. A modeling technique is powerful tool can provide a complete platform to study the effects of microwave oven design and food properties on non-uniform heating. Coupled electromagnetic and multi-physics (momentum and heat) equations can describe microwave heating and would help in design microwave ovens and optimize process parameters to minimize non-uniformity issues [2].

Refer to the literature, there were many the theoretical studies on combined microwave and thermal transport [3–20]. The various kinds of dielectric materials are chosen to illustrate microwave heating phenomena.

For liquid sample, Zhang et al. [9] proposed a 3D mathematical model for the heating of water and oil layer with time dependent dielectric properties in microwave cavity. Zhu et al. [16] presented the numerical modeling of continuous flow microwave heating of liquids layer. The results revealed that the heating pattern strongly depends on the dielectric properties of liquids and geometry of the microwave system. Cha-um et al. [19] studied heating process of liquids using microwave with a rectangular waveguide numerically and experimentally. The effects of sample sizes, placement of sample inside the guide, and microwave power were considered in detail. The numerical results agreed well with experimental data. Salvi et al. [21] developed model to simulate temperature profiles in Newtonian and non-Newtonian fluids for continuous flow microwave heating by COMSOL Multiphysics. Recently, Yousefi et al. [22] investigated on microwave heating of flowing water in ANSYS Multiphysics. Various factors were examined; namely, the effects of inlet velocity, applicator height and applicator diameter on the temperature field. A 2D numerical model using COMSOL was developed by Choi et al. [23]. It was to validate uniform heating of particulate foods in a continuous flow microwave and ohmic combination heater. The developed model was included with an electric field, electromagnetic field, incompressible laminar flow, forced-coupling method, heat transfer and arbitrary Langrangian–Eulerian (ALE) moving mesh technique. The simulated outlet temperature of particulate foods was compared with experimental data. The maximum prediction error was 4%.

For layered sample, Rattanadecho [24] investigated the thawing of layered sample using microwave oven. It is shown that, the variation of layered configurations and layer thickness affected to thawing rate

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Nomenclature

A	area (m^2)
C_p	specific heat capacity (J/(kg K))
E	electric fields intensity (V/m)
f	frequency of incident wave (Hz)
g	gravitational constant (m/s^2)
h_c	local heat transfer coefficient (W/m^2K)
H	magnetic field intensity (A/m)
k	thermal conductivity (W/mK)
L_x	width of the rectangular waveguide (m)
P	power (W)
p	pressure (Pa)
Q	local electromagnetic heat generation term (W/m^3)
T	temperature (°C)
t	time (s)
$\tan\ \delta$	dielectric loss coefficient (−)
u,w	velocity component (m/s)
Z_H	wave impedance (Ω)
Z_I	intrinsic impedance (Ω)

Greek letters

φ	volume fraction of dispersed phase (−)
α	thermal diffusivity (m^2/s)
β	coefficient of thermal expansion (1/K)
η	dynamic viscosity (Pa/s)
ε	permittivity (F/m)
λ	wavelength (m)
μ	magnetic permeability (H/m)
υ	velocity of propagation (m/s)
ν	kinematics viscosity (m^2/s)
ρ	density (kg/m^3)
σ	electric conductivity (S/m)
ω	angular frequency (rad/s)
ξ	surface tension (N/m)

Subscripts

0	free space
∞	ambient condition
c	continuous phase
d	dispersed phase
eff	effective
r	relative
in	input
x,y,z	axis

due to its dielectric properties of phase change materials during microwave thawing process. Promas et al. [25] concerned with the energy and exergy analyses in the drying process of non-hygroscopic porous packed bed using a combined multi-feed microwave-convective air and continuous belt (CMCB). The results showed that using the CMCB had the several advantages over the conventional method. Klinbun and Rattanadecho [20] studied numerically the heating of multilayer porous packed bed which subjected to microwave power. This study aimed to understand effects of layered configuration, layered thickness and operating frequency. The results were presented in electric field distribution, heat transfer and velocity flow.

The layered liquids and emulsions are the common food systems, such as milk, salad dressing, mayonnaise, sauces, and many more [18]. Therefore, understanding the influences of various parameters during microwave processing of layered liquid and emulsions are required because of the wide usage of microwave systems.

The most emulsions are considered as oil-in-water (o/w) and water-in-oil (w/o). An earlier investigation on microwave heating of multiphase system and emulsions was reported by Barringer et al. [26]. They studied experimentally for various oil–water fractions and layered system with fixed beaker radii in a household microwave oven. They found the dielectric properties and sample size determined in which sample resonant absorption occurred. Chan and Chen [27], Rajaković and Skala [28], and Nour et al. [29] carried out experimental studies on the conditions of demulsification of water-in-oil emulsions by microwave technology. After that, Samanta and Basak [18] carried out the preliminary theoretical analysis on efficient microwave processing of 1D oil–water emulsion (o/w and w/o) placed on ceramic plates (alumina, SiC). The results were shown that an alumina support at the left side may be recommended as the optimal heating strategy for both o/w and w/o emulsion samples whereas SiC support may be favored for o/w emulsion sample due to lesser thermal runaway. In addition, microwave energy was applied to separate or demulsify of emulsions. For example, Palou et al. [30] studied the demulsification of an o/w emulsion prepared with Mexican heavy crude oil. A comparative study was carried out between microwave and oil bath heating with regard to water separation time. From the results, microwave dielectric heating used less time than conventional oil bath heating. Water separation of O/W emulsions increased with microwave power and salt content of the aqueous phase, and in the presence of a chemical demulsifier. Binner et al. [31] was investigated the separation of water-in-oil emulsions using natural gravity settling and microwave heating techniques. The result was found that the thermal effect of microwave heating leads to improvements in settling times.

Due to the large amount of past studies are primarily considered on microwave heating of pure substance or layered system. There are a few works which investigate of microwave processing of multiphase system, especially emulsions. Therefore, the various parameters are still not fully understood and a number of critical issues still remain unsolved. The characteristics of microwave heating of emulsions and layered materials are very complicated, thus the study in more detail should be systemically studied.

This research was to develop a comprehensive fully coupled multiphysics model that includes heat and momentum transfer in model liquid system. In this article, the simulated results were compared with experimental heating profiles of a model. The effects of layered configuration, layered thickness, dispersed phase fraction, and dielectric properties of emulsion are studied. The results presented here provide a basis for fundamental understanding of microwave heating of layered liquid and oil–water emulsions.

2. Experimental study

2.1. Sample preparation

The two-layer and emulsion of oil–water were studied. The oil-in-water emulsion, designated as o/w emulsion and water-in-oil emulsion, designated as w/o emulsions. In case of two-layer is considered in two models: w-o bed (water layer on oil layer), and o-w bed (oil layer on water layer). The sample size is chosen to be 109.22 × 54.61 × 50 mm.

2.2. Apparatus

Fig. 1 shows the experimental apparatus for microwave heating using a rectangular waveguide system. It was a monochromatic wave of TE_{10} mode operating at a frequency of 2.45 GHz. The magnetron (Micro Denshi Co., model UM-1500) generated microwave energy that was transmitted along the z-direction of the rectangular waveguide with inside dimensions of 110 × 55 mm toward a water load that was situated at the end of the guide. The water load ensured that only a minimal amount of microwave was reflected back to the sample. An isolator on the upstream side of sample is used to trap microwave was reflected from the sample in order to prevent the microwave from damaging the magnetron. The sample heated was liquid layer of 50 mm in thickness,