Journal of Food Engineering 116 (2013) 65–71

Contents lists available at SciVerse ScienceDirect

Journal of Food Engineering

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

Exploring the heating patterns of multiphase foods in a continuous flow, simultaneous microwave and ohmic combination heater

Loc T. Nguyen [a], Won Choi [b], Seung Hyun Lee [c], Soojin Jun [b],*

[a] Department of Food Technology, Ho Chi Minh International University, Thu Duc District, HCMC, Vietnam
[b] Department of Human Nutrition, Food and Animal Sciences, University of Hawaii, Honolulu, HI 96822, USA
[c] Department of Molecular Biosciences and Bioengineering, University of Hawaii, Honolulu, HI 96822, USA

ARTICLE INFO

Article history:
Received 8 August 2012
Received in revised form 26 September 2012
Accepted 20 November 2012
Available online 28 November 2012

Keywords:
Combination heating
Hurdle
Uniformity
Microwave
Ohmic heating
Dielectric properties
Electrical conductivity

ABSTRACT

A continuous flow, simultaneous microwave and ohmic combination heater was designed and fabricated to heat treat particulate foods without leaving solids under-processed. Heating uniformity of the combination heater was examined by numerically analyzing the electric field distribution under microwave and ohmic heating. In addition, to minimize the reflection of microwave power, impedance matching of the microwave cavity was conducted with a vector network analyzer. Performance of the heater was studied using food mixtures containing sodium chloride solutions (0.2–0.5%) and carrot particulates. Heating patterns of liquid–particle mixtures were investigated and compared under individual and combination heating modes. Energy efficiencies were also determined for corresponding heating methods. The results showed that maximum solid–liquid temperature differences under microwave and ohmic heating were about 8.1 and 8.0 °C, respectively. However when microwave and ohmic heating techniques were applied simultaneously, there was no significant temperature difference between solid and liquid phases. Energy efficiency of combination heating was higher than microwave heating and a maximum increase in energy conversion of 12.8% was obtained. The findings opened new and very promising opportunities to thermally process particulate foods with improved uniformity, organoleptic, and nutritional quality in addition to reduced food safety problems.

1. Introduction

Non-uniformity is the key issue in conventional thermal processing of foods containing solid–liquid mixtures. The liquid usually gets heated faster and then heat is transferred to particles by convection and conduction. Temperature difference between solid and liquid phases can be due to low convective heat transfer coefficient on the particle surface and low thermal diffusivity of the particles (Sandeep and Puri, 2009). Consequently, under-processed food particles may risk food safety. On the other hand, over-processing to overcome thermal lag of particles could result in loss of nutrients and sensory values of foods. Therefore, continued efforts have been made to improve uniformity of thermal treatments. Recent advances in volumetric heating such as microwave or ohmic heating have made considerable contribution to uniformity improvement. However, these technologies have their inherent limitations. Ohmic heating, internal heat generation by passage of an electric current, generally has superior energy efficiency close to 100% and uniform temperature distribution (Ghnimi et al., 2007; Jun and Sastry, 2005; Salengke, 2000). Nonetheless, ohmic heating depends on electrical conductivities of foods and it is desirable that liquid and particles should have equal conductivities to achieve uniform heating (Wang and Sastry, 1993). Several studies on electrical conductivities of foods were conducted and foods were usually found to have different electrical conductivities (Castro et al., 2004; Halden et al., 1990; Icer and Ilicali, 2005; Kim et al., 1996; Mitchell and de Alwis, 1989; Palaniappan and Sastry, 1991; Saif et al., 2004; Sarang et al., 2008; Shirsat et al., 2004; Tulsiyan et al., 2008). If food particles of low conductivities are surrounded by high conductive media, the particles will thermally lag the fluid after ohmic treatment (Sastry, 1992). Differences in electrical conductivities of liquid and particles can be lessened by pretreatments such as blanching or soaking. Disadvantages of these approaches are additional energy consumption, increased processing time or changes in composition and sensory values of treated foods (Palaniappan and Sastry, 1991; Wang and Sastry, 1993).

Microwave heating can reduce come-up-time and better preserve thermo-labile constituents (Coronel et al., 2003). Significant retention of quality attributes of foods treated by continuous flow microwave systems was reported (Coronel et al., 2003; Gentry and Roberts, 2005). However, microwave heating has several inherent problems such as non-uniform heating, edge over-heating and thereby, concerns about incomplete microbial destruction. In

---

* Corresponding author. Tel.: +1 808 956 8283; fax: +1 808 956 4024.
E-mail address: soojin@hawaii.edu (S. Jun).

0260-8774/$ - see front matter Published by Elsevier Ltd.
http://dx.doi.org/10.1016/j.jfoodeng.2012.11.011

Nomenclature

A	internal cross-sectional area of the test cell (m^2)
a	temperature coefficient of conductivity (S/m °C).
C_p	specific heat (kJ/kg °C)
I	electric current (A)
L	distance between two electrodes (m)
m	mass flow rate (kg/s)
Q	heat absorbed by tested foods (kJ)
T	temperature (°C)
V	voltage (V)
σ	electrical conductivity (S/m)
σ_0	reference value of electrical conductivity (S/m)

addition, energy efficiency of microwave heating can go up to 65% at 2.45 GHz (Saltiel and Datta, 1999). To reduce the non-uniform temperature distribution, microwave heating has been supplemented with additional treatments such as infrared or convection heating (Geedipalli et al., 2008; Ni and Datta, 2002). Nevertheless, the aforementioned combination approaches are limited because they mainly focused on improvement of surface heating by means of convective or low depth radiative aids.

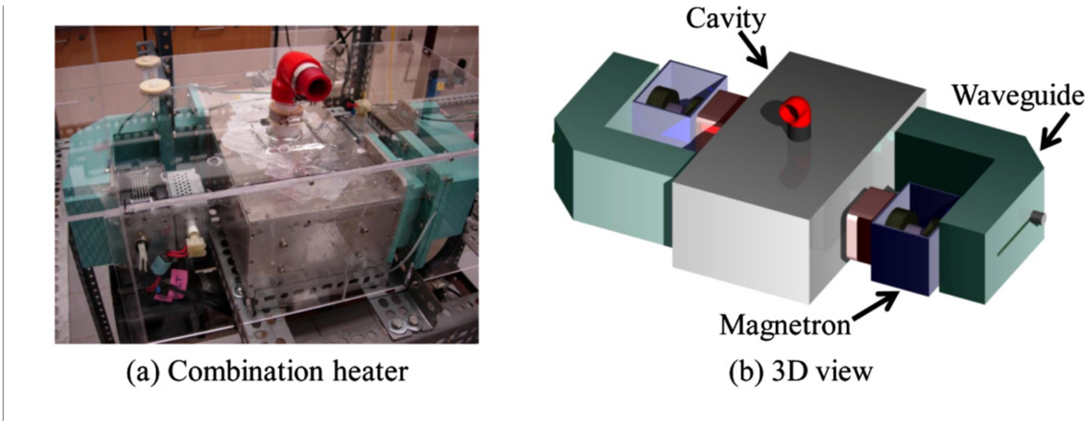
A simultaneous microwave and ohmic combination heating technique proposes that food particles are heated by microwave independent of their electrical conductivity and liquid phase is heated via electric current, which will eventually eliminate the drawbacks of individual technologies and enhance heating uniformity. In addition, as ohmic heating has high electric energy conversion efficiency, the overall efficiency of the combination system can therefore be significantly improved. The concept of microwave and ohmic combination heating has never been reported to the authors' knowledge.

The objectives of this study were (a) to design and fabricate a continuous flow, simultaneous microwave and ohmic combination heater; (b) to experimentally explore heating patterns of the solid–liquid food mixtures under individual and combination heating; (c) to evaluate and compare the overall energy efficiencies of the given experimental set-up for corresponding heating methods.

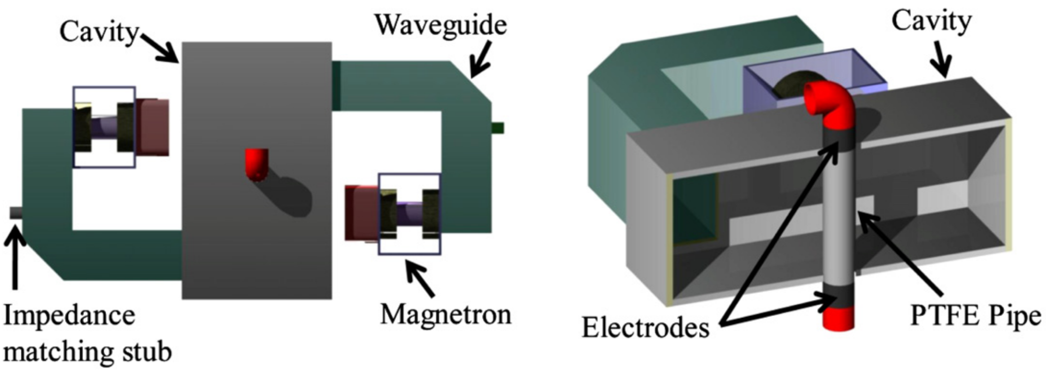
2. Materials and methods

2.1. Experimental set-up

A rectangular microwave heating chamber (internal dimensions: 0.12 m length × 0.18 m width × 0.31 m height) was fabricated from aluminum sheets (McMasterCarr, Santa Fe Springs, CA). The chamber has two transmission ports connected to the waveguide (type WR-430) that was built with right-angled nickel-coated brass to make the whole unit compact and space saving. Two dual magnetrons that could deliver 0.9 kW per each (2450 MHz, Model OM75S, Samsung) were mounted on the sides of the chamber (Fig. 1). One polytetrafluoroethylene tube (0.18 m long and 0.024 m inner diameter, Virgin electrical grade Teflon ®PTFE, Santa Fe Springs, CA) was fed through the cavity and used as a combination applicator. The PTFE was considered to be transparent to microwave, hence leading to negligible dielectric heating. The applicator as an ohmic heating chamber included two titanium ring-typed electrodes (0.024 m inner diameter and 0.032 m length,



(a) Combination heater (b) 3D view



(c) Upper view (d) Internal view

Fig. 1. Schematic diagram of the microwave and ohmic combination heater.