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Temperature redistribution modelling during intermittent microwave convective heating

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Abstract

Microwave power is used for heating and drying processes because of its faster and volumetric heating capability. Non-uniform temperature distribution during microwave application is a major drawback of these processes. Intermittent application of microwave potentially reduces the impact of non-uniformity and improves energy efficiency by redistributing the temperature. However, temperature re-distribution during intermittent microwave heating has not been investigated adequately. Consequently, in this study, a coupled electromagnetic with heat and mass transfer model was developed using the finite element method embedded in COMSOL-Multyphysics software. Particularly, the temperature redistribution due to intermittent heating was investigated. A series of experiments were performed to validate the simulation. The test specimen was an apple and the temperature distribution was closely monitored by a TIC (Thermal Imaging Camera). The simulated temperature profile matched closely with thermal images obtained from experiments.

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Keywords: Intermittent microwave convective heating; drying; temperature redistribution; modelling; microwave; convective;

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1. Introduction

Microwave penetrates a material until moisture is located and heats up the material volumetrically. Thus a rapid and convenient heating method is offered by microwave application. This unique heating capability has resulted in considerable interest in heating and drying related commercial situations. However, the major drawback associated with microwave heating is the non-uniform temperature distribution, resulting in hot and cold spots in the heated product[1]. This non-uniformity of temperature is due to (1) interference of electromagnetic waves inside the microwave cavity resulting in hot and cold spots, and (2) variation in dielectric, physical, and thermal properties of food components during heating. Temperature uniformity is critical for ensuring food safety because the cold spot can be a source of pathogens [2]. Vadivambal and Jayas [1] mentioned that the non-uniform temperature distribution not only affects the quality of the food but also raises the issue of food safety when the microorganisms may not be destroyed in the cold spots. For this reason, our research group has accepted the challenge to reduce this non-uniformity. One of the potential solutions to reduce non-uniformity is to apply microwave intermittently. Gunasekaran and Yang [3] argues that pulse or intermittent microwave heating is preferred over continuous heating when uniform temperature distribution is important.

An appropriate theoretical model to describe the heat and mass transfer process during intermittent microwave heating has to be developed to facilitate an improved strategy for applying this intermittency[4]. Extensive modelling efforts have been made to simulate microwave heating but none of them consider intermittency and temperature redistribution. Moreover, the complex nature of food structure and variability in properties during the drying process complicate the modeling of drying of fruits and vegetables [5, 6]. Inclusion of microwave heating further complicates the model. Several authors[7, 8] considered Lamberts law to calculate microwave heating of food product. However, Lambert's Law does not accurately predict the heating situation and electric field distribution [9]. Chandrasekaran et al. [9] reviewed the comparison between Lambert's law and Maxwell's equation, they reported that Maxwell's equation provided a more accurate solution for microwave propagation in samples. Recently, Malafronte et al. [10] developed a simulation model for combined microwave convective drying for food wherein they considered moisture and temperature dependent dielectric properties. These latter authors solved both heat and mass transport equations and Maxwell equations in transient regime. Maxwell's equation has also been considered for modelling puffing of potato [11], combined drying [12] and combined heating[13]. However, none of the previous studies considered the intermittent heating nor did they investigate spatial temperature redistribution due to cycled microwave. The objectives of this study were to:

1. Develop an intermittent microwave heating model considering Maxwell equations and variable dielectric properties
2. Validate the model comparing the temperature distribution obtained from a TIC (Thermal Imaging Camera) and simulation
3. Investigate the temperature redistribution due to intermittency

Nomenclature

E	electric field intensity (V/m)	ρ	density
ε'	dielectric constant	C_p	specific heat
ε''	dielectric loss	k	thermal conductivity
ω	angular wave frequency ($2\pi f$, rad/sec)	M	Moiture content dry basis
μ'	relative permeability of the material	h_T	heat transfer coefficient
i	imaginary unit	h_m	mass transfer coefficient
c	speed of light in free space (3×10^8, m/s)	μ	Dynamic viscosity, (Pa.s)
Q_e	electromagnetic losses/heat sources	T	temperature
Q_{rh}	resistive losses	c	concentration(mol/m^3)
Q_{ml}	magnetic losses	u	domain velocity
D	diffusion coefficient	MC	moisture content wet basis

2. Materials and method

The experiments were carried out using a Panasonic 1100W inverter microwave oven (Model NN-SD691S). The microwave oven had a cavity dimension of 355mm (W) x251mm (H) x365mm (D) as shown in Fig.1. An apple sample was placed at the center of the glass tray. The intermittent heating was achieved by heating the sample in a microwave for 60s and then drying with a convection dryer for 150s at 40^0C. A thermal imaging camera (FLIR i7) was used to obtain the temperature distribution after 60s (heating) and 150s (tempering).

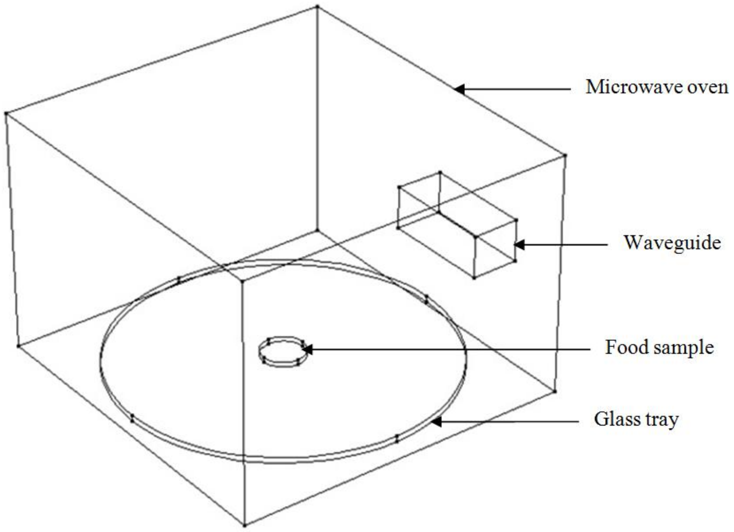

Fig. 1. The geometry with waveguide and sample.

3. Model development

In this study the model has been developed considering coupled electromagnetic and heat and mass transfer. Maxwell's equations were solved to obtain the electric field in the oven cacity and sample. The Maxwell equation for rectangular waveguide in frequency domain time can be written as Eq. 1[10].

$$\nabla\times\left(\frac{1}{\mu'}\nabla\times E\right)-\frac{\omega^2}{c}\left(\varepsilon'-i\varepsilon''\right)E=0 \tag{1}$$

The heat generated due to electromagnetic losses, Q_e (SI unit: W/m^3) then calculated by

$$Q_e=\frac{1}{2}\omega\varepsilon'\varepsilon''\left|E\right|^2 \tag{2}$$

Mass and heat transfer is considered by Eq.3 and Eq. 4 respectively

$$\frac{\partial c}{\partial t}+\nabla.(\text{-D}\nabla\text{c})+\text{u}.\nabla\text{c}=\text{R} \tag{3}$$

$$\rho c_p\frac{\partial T}{\partial t}+\rho c_p u.\nabla T=\nabla.(k\nabla T)+Q_e \tag{4}$$

3.1. Initial and boundary conditions

Uniform initial condition was considered for both the oven cavity and the sample. Initial conditions are: electric field, $E=0$; sample temperature, $T_0=20^0C$ and moisture content, $M_0=6$ *kg/kg dry basis.*

Electromagnetic boundary condition: Entrance of electromagnetic energy (port boundary) is defined as a rectangular port with TE_{10} mode and the walls were modelled with the perfect electric conductor.
Heat transfer boundary condition: Convection and evaporation has been considered in heat transfer boundary condition [14].

$$n.(k\nabla T) = h_T(T_{air} - T) - n.(D_{ref}\lambda\nabla c) \tag{5}$$

Mass transfer boundary condition: $\boldsymbol{n}.(D\nabla c) = h_m(c_b - c)$
Heat and mass transfer coefficient was assumed to be 20W/m^2 and 3.6x10^{-6} respectively.

3.2. Input parameters

Table 1. Properties of apple used in the simulation.

Property	Value	Unit	Reference
Initial moisture content	*84.89*	%	[15]
Electrical conductivity	*0*	S/m	
Dielectric constant	$e' = 0.4518MC + 1.2887$	1	[16]
Dielectric loss	$e'' = -0.0024MC^2 + 0.2912 - 1.0343$	1	[16]
Relative permeability	*1*	1	
Thermal conductivity	*0.46*	W/(m.K)	
Density	*850*	kg/m^3	
Heat capacity	*3734*	J/(kg.K)	

4. Results and discussion

4.1. Temperature redistribution

Fig. 2 compares temperature re-distribution obtained from both the theoretical model and actual experiments. It shows that the hot spot is concentrated in a region with a maximum temperature rise of 63.9^{0}C after 60s of heating. As expected, after tempering for 150s, temperature redistributes due to conduction and hot spot disperse. Thus intermittency facilitates reduction in non-uniform temperature distribution which may contribute to improve food quality. In the case of drying, the tempering period removes the accumulated moisture on the surface. Thus combining microwave with convective drying creates unique drying system with high energy efficiency. During the experimentation, it was observed that microwave power is more efficient in the initial stage of drying. As a consequence, the final stage of drying should include power reduction or tempering time should be increased to avoid burning. More involved simulation studies need to be carried out to optimize the power level and tempering time.

4.2. Maximum temperature

Maximum temperature is important in food drying as it can potentially cause burning after a certain temperature is risen. Therefore, prediction of the highest temperature achievable is of significant value as it can be employed to prevent burning, and avoid damage due to extreme temperature exposure (heat damage). Maximum temperature obtained from the simulation was compared with experimental peak temperature values measured by a thermal imaging camera [Fig. 3]. It shows that the maximum temperature drops after tempering. Thus, from the model it is possible to suggest when the microwave power should be stopped. Tracing the maximum temperature it is possible to find suitable power level or tempering period. The graph also shows that in the second cycle of heating, peak temperature is higher than the first cycle. This latter behaviour indicates microwave power “on time” should be less than that of the previous cycle in order to keep the temperature constant. Otherwise if the tempering time/pulse ratio is same throughout the process, it may cause burning, because the temperature continues to rise in the subsequent cycle.

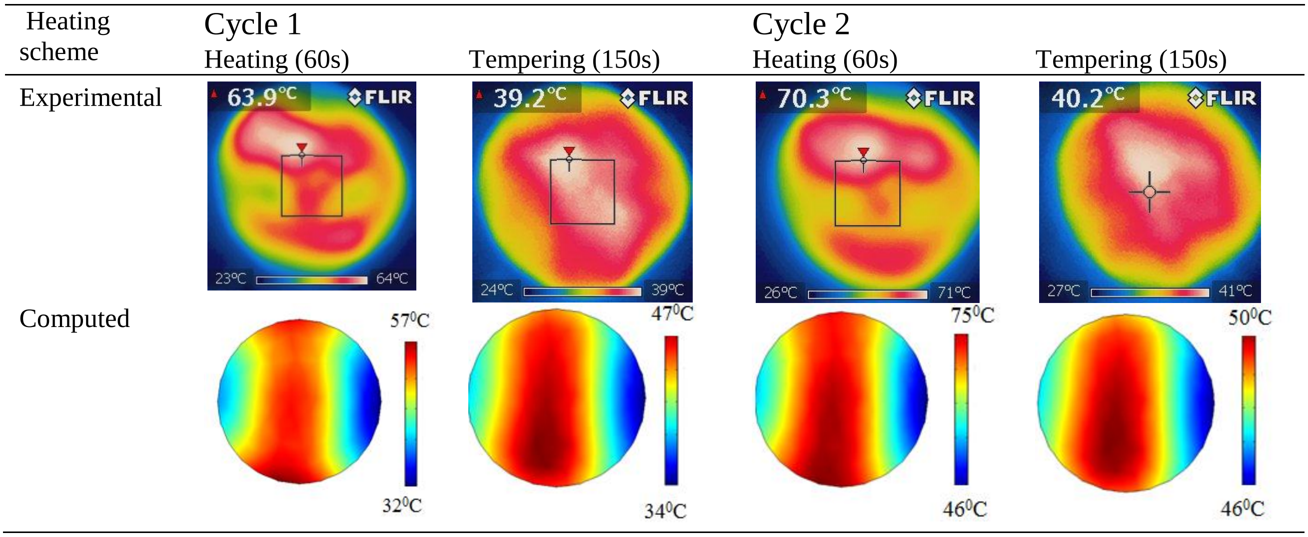

Fig. 2. Temperature distribution comparing the experimental and simulation for 100MW power with 60s on 150s off

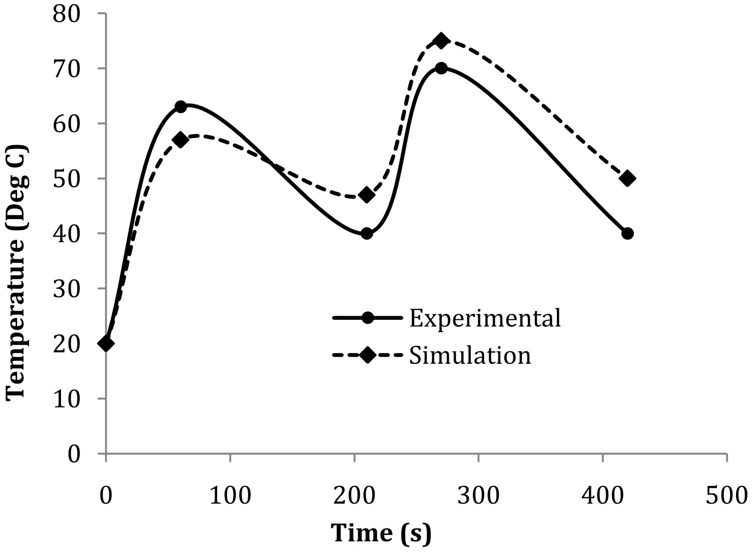

Fig. 3. Maximum temperature for 100 W with 60s on and 150s off

5. Conclusions

In this study a theoretical model for intermittent microwave convective drying has been developed to investigate temperature redistribution. This model correlated well with the experimental results. A key observation of this research is that, intermittency helps to reduce the non-uniformity of temperature in the material of interest. Intermittent heating reduces the temperature difference between hot and cold spots. Intermittent heating also can limit the maximum temperature , which can in turn prevent burning or scorching of product. The model can help to find the suitable power level or tempering period to avoid overheating of the product. Moreover, the model can help to understand the microwave heating process inside an oven which thus contribute to design of a microwave cavity characterized by more uniform heating. The model developed in this research can predict the optimum intermittency and power level for enhanced product quality.

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