Coupled Electromagnetics- Multiphase Porous Media Model for Microwave Combination Heating

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Abstract: Combining microwaves with other heating modes provides an excellent method to speed up cooking processes and potentially provide automated custom-cooking ability. A physics-based computational model that captures spatial and temporal temperature and moisture patterns in the heated sample would provide valuable insight into the nature of combination heating. This work investigated combination heating in a novel microwave combination system that heats the sample through a combination of microwaves and hot air using a coupled electromagnetics-multiphase porous media model to determine the effect of combining different modes on heating patterns. Temperature, moisture, pressure and evaporation rates in the sample were obtained as a function of location and time. It was concluded that the different heating modes complement each other increasing the efficiency of the combination heating process. Combination heating can also overcome the problem of surface sogginess reported in microwave only heating. The results can be used in further development of combination heating methods for different food processes.

Keywords: combination microwave heating, multiphase porous media.

1. Introduction and Objectives

Combining microwaves with other heating modes such as infrared and hot air provides an excellent method to speed up cooking processes and potentially provide automated custom-cooking ability by implementing temperature and moisture profiles needed for specific processes. Although microwave heating has been studied in great detail [1, 2], microwave combination heating has not been extensively studied with most of the work in the area being related to drying [3] where spatial distributions of temperature and moisture are not critical and were therefore not reported. However, in the cooking process, the quality of the final product such as texture (e.g., sogginess) or flavor (e.g., browning) is a multifaceted attribute that depends on the temperature and moisture distribution. Through improved understanding of the combination heating process, overheating, underheating, overdrying and sogginess of food can be minimized while enhancing its quality. Quality would be more predictable, which would in turn allow increased automation and reduce the drudgery and frustration of food product and process development. This work proposes to study combination heating using a fundamental physics-based computational model of the cooking process to obtain optimum process guidelines for practical use that would provide the desired product quality in the quickest time.

2. Material and Methods

The combination oven used for heating the samples was a GE Profile Trivection oven (Model no. JT930BHBB) (Fig. 1). The oven heats the sample using a combination of microwaves and hot air (air heated by heating elements and circulated by a fan) as shown in the Fig. 1. The microwaves, three heating elements and the fan can be turned on or off to heat the samples using a desired combination of heating modes. Two different settings of the oven were selected for this study, one without microwaves and the other with microwaves, as shown in Table 1 (in Appendix). Two different model products were used: 1) TX151 powder mixed with water and preconditioned to form the gel; 2) Restructured potato samples.

(a)

(b)

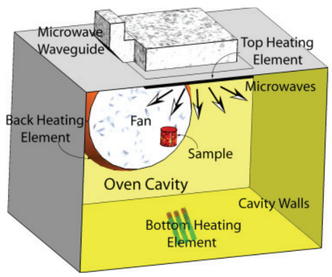

Figure 1. (a) GE Profile Single Wall Oven (Model JT930BHBB) used in this study (b) Geometry of the oven used in the computations. Microwaves are launched from the top. The upper, lower and back elements provide heat and the fan circulates the hot air inside the oven.

The Maxwell's equations of electromagnetics were solved to obtain the electric field inside the oven cavity and sample [6] and coupled with a multiphase porous media model [7] to obtain temperature and moisture distribution in 3D inside the restructured potato samples, as shown in Fig. 2. The fundamental physics based mechanistic model includes the effects of phase change (evaporation/ condensation) and pressure driven flow needed to describe the cooking phenomena for food processes undergoing rapid evaporation [4]. For the gel samples, Maxwell's equations were coupled with heat transfer only as there was insignificant moisture transport.

2.1 Governing Equations: Electromagnetics

The electromagnetic field distribution inside the microwave cavity including the load is governed by the Maxwell's equations. The Maxwell's equations of electromagnetics were solved in the three dimensions to obtain the electric field inside the oven cavity and the sample. The Maxwell's equations with no sources can be written as:

$$\begin{aligned} \nabla \times \mathbf{E} &= -j\omega\mu\mathbf{H} \\ \nabla \times \mathbf{H} &= j\omega\varepsilon\varepsilon_0\mathbf{E} \\ \nabla \cdot (\varepsilon\mathbf{E}) &= 0 \\ \nabla \cdot \mathbf{H} &= 0 \end{aligned} \tag{1}$$

The complex relative permittivity, ε, is defined as:

$$\varepsilon = \varepsilon' - j\varepsilon'' \tag{2}$$

Power absorbed per unit volume from the microwaves at any location of the sample was calculated from the electric field distribution inside the sample:

$$Q_{mic} = \frac{1}{2}\omega\varepsilon_0\varepsilon''|\mathbf{E}|^2 \tag{3}$$

Boundary Conditions The walls of the oven were assumed to be perfect electric conductors and hence the tangential component of the electric field was set to zero:

$$E_{tangential\,,oven\,wall} = 0 \tag{4}$$

2.2 Governing Equations: Multiphase Porous Media Model

A 3D multiphase porous media model was formulated that describes the momentum, heat and mass transfer inside the sample. The three phases included in the porous media model were solid, liquid water and gas. The gas phase had two components: water vapor and air. The mass conservation equation for the different transportable phases included the effects of diffusion, capillary flow and convection. The porous media model included the change of phase between liquid water and vapor (evaporation/ condensation) throughout the domain. The energy conservation equation was solved for the mixture and the effect of microwave heating was included as a source term obtained from the electromagnetics model. For momentum balance, Darcy's equation was used for each phase in the porous media.

$$u_i = -\frac{kk_{r,i}}{\mu}\nabla P \tag{5}$$

$$\frac{\partial c_w}{\partial t} + \nabla\cdot(u_w\rho_w) = \nabla\cdot(D_w\nabla c_w) - \dot{I} \tag{6}$$

$$\frac{\partial c_v}{\partial t} + \nabla\cdot(u_g\rho_v\omega_v) = \nabla\cdot\left(\frac{C^2}{\rho_g}M_aM_vD_{eff,g}\nabla x_v\right) + \dot{I} \tag{7}$$

$$\omega_v + \omega_a = 1 \tag{8}$$

$$\frac{\partial c_g}{\partial t} + \nabla\cdot(u_g\rho_g) = \dot{I} \tag{9}$$

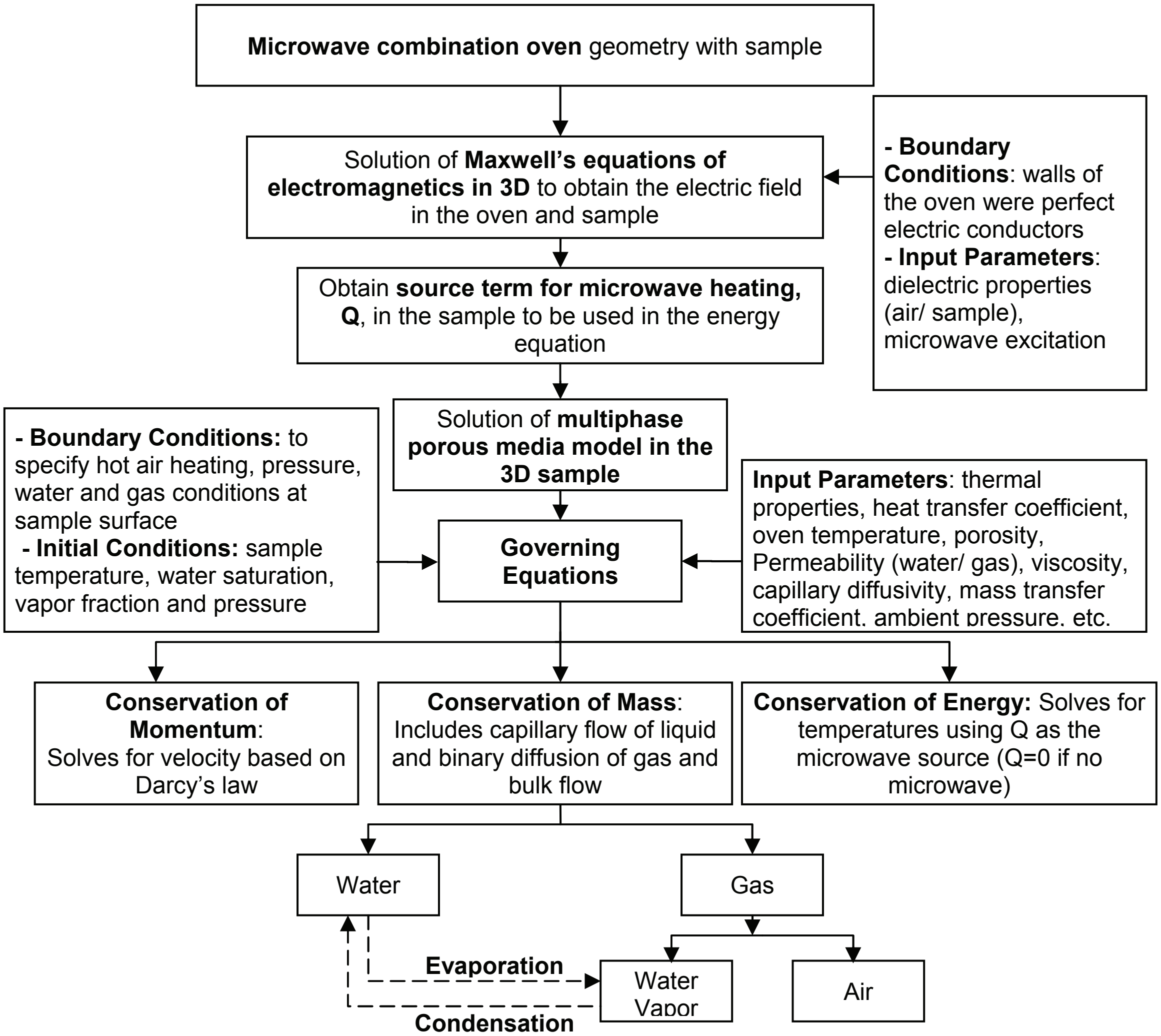

Figure 2. Flow chart showing the sequence of steps followed to develop the computational model.

$$\frac{\partial}{\partial t}\left(\rho_{eff} c_{p,eff} T\right) + \nabla\cdot\left[\left(c_{pv}\vec{n}_v + c_{pa}\vec{n}_a + c_{pw}\vec{n}_w\right)T\right] = \nabla\left(k_{eff}\nabla T\right) - \lambda \dot{I} + Q_{mic} \qquad (10)$$

$$\dot{I} = K\left(\rho_{v,eq} - \rho_v\right) \qquad (11)$$

Boundary Conditions The contribution due to hot air was incorporated as a boundary condition using a surface heat transfer coefficient measured experimentally. Only the top surface of the sample was open for mass transfer and the other surfaces were insulated.

$$P\big|_{top\,surface} = P_{amb} \qquad (12)$$

$$n_w\big|_{surface} = 0$$

$$n_v\big|_{surface} = h_m c_v \qquad (13)$$

$$-k\nabla T = h_c(T - T_a) - h_m c_v c_{p,v} T \qquad (14)$$

2.3 Input Parameters

Dielectric properties of the samples as functions of temperature and moisture content were determined experimentally using the HP85070 open ended coaxial high temperature probe (Agilent Technologies, Inc., Palo Alto, CA). Thermal properties were measured using the KD2 Pro probe (KD2, Decagon Devices, Inc., Pullman, WA). Other input parameters such as porosity, permeability (water/ gas), viscosity, capillary diffusivity and mass transfer coefficients were obtained from literature [4, 5].

2.4 Numerical Solution

The electromagnetics and the multiphase porous media were fully coupled as the dielectric properties of the sample, which were also measured experimentally, were a function of temperature and moisture content. The coupling procedure is shown in Fig. 2. All the equations were solved using COMSOL Script in a Windows workstation with 16 Gb of memory. The GMRES solver was used with the Geometric Multigrid preconditioner to solve the Maxwell's equations. The number of elements in the mesh (including the oven and the sample) used to solve the Maxwell's equations was 367,082. For the restructured potato sample, energy, momentum and mass balance equations (multiphase porous media model) were solved using the UMFPACK solver. The multiphase porous media model was solved using 28,229 elements in the sample. The computation time was approximately 3 days for 2 min of heating time with a maximum time step size of 0.01 s. For the gel sample, only the heat transfer equation was solved and coupled with the Maxwell's equations of electromagnetics.

3. Results and Discussions

3.1 Speed of heating and uniformity

Speed of heating is quantified by the rate of increase of average temperature with time, and temperature non-uniformity, using coefficient of variation (COV) [6], which is defined as the ratio of the standard deviation to the mean of a data set. From Fig. 3a, it is observed that heating speed is significantly greater when microwaves are used (heating mode 2) in combination with other methods. Fig. 3b shows that COV for both the heating modes are similar. This indicates that contrary to the notion that microwaves cause non-uniformity in temperatures [4], if a proper combination of heating modes (including cycling of microwaves) is selected, similar heating uniformity compared to conventional means (mode 1) can be obtained and at the same time the speed of heating can be increased significantly.

3.2 Temperature distribution

Fig. 4 shows the temperature distribution in the sample heated without (mode 1) and with (mode 2) microwaves. Higher temperatures are observed at the outer walls and the top boundary due to hot air heating in both cases. However, in case of mode 2, heating by the focusing effect of the microwaves is also observed near the center of the sample. The different heating modes, therefore, complement each other when microwaves are used increasing the efficiency of the combination heating process.

3.3 Moisture distribution

The spatial moisture distributions in samples heated by different heating modes (Table 1) are shown in Fig. 5. The moisture content is lower on the top open surface of the sample as the moisture is carried away in form of water vapor due to high oven temperature (80^{o}C). Combination heating can, therefore overcome the problem of surface sogginess reported in microwave only heating [4].

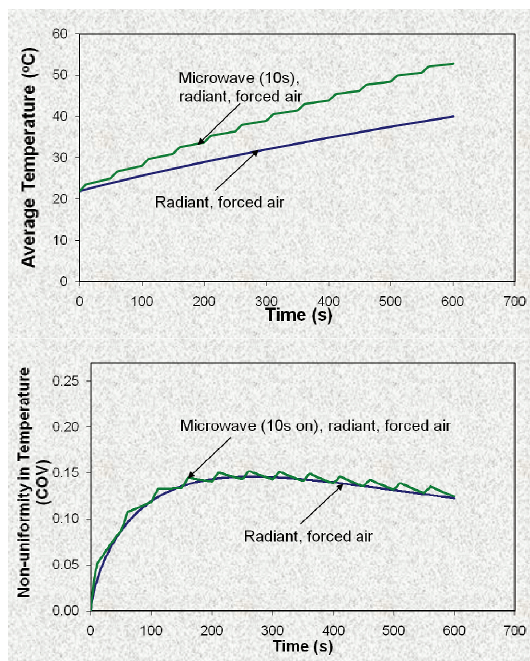

Figure 3. Computed average temperatures and non-uniformity in temperatures (with coefficient of variation or COV as the measure) of the gel samples as functions of time for the two modes of heating.

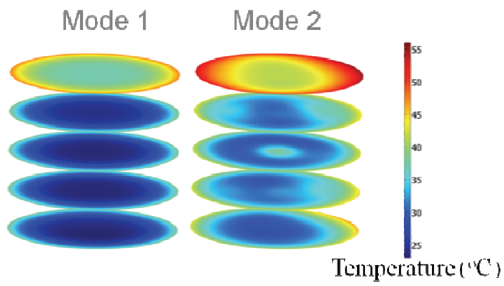

Figure 4. Spatial distribution of temperature inside the restructured potato samples heated for 2 min by heating modes 1 and 2 (see Table 1). The initial temperature of the sample was 22°C.

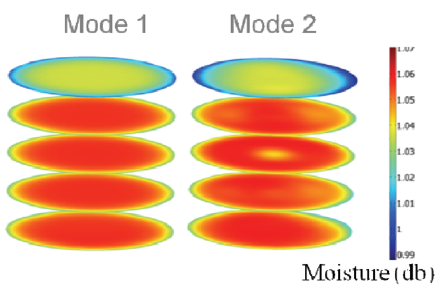

Figure 5. Spatial distribution of moisture inside the restructured potato samples heated for 2 min by heating modes 1 and 2 (see Table 1). The initial moisture content of the sample was 1.05 db.

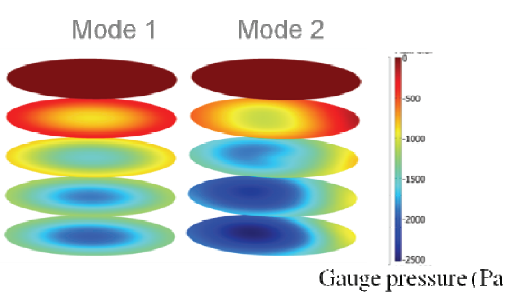

Figure 6. Spatial distribution of pressure inside the restructured potato samples heated for 2 min by heating modes 1 and 2 (see Table 1). The sample was initially at atmospheric pressure.

3.4 Pressure distribution

Fig. 6 shows that there is pressure build up near the surface whereas pressure (gauge) in the interior of the sample becomes negative as water vapor condenses. The pressure distribution is a function of the microwave heating pattern in case of the heating mode using microwaves.

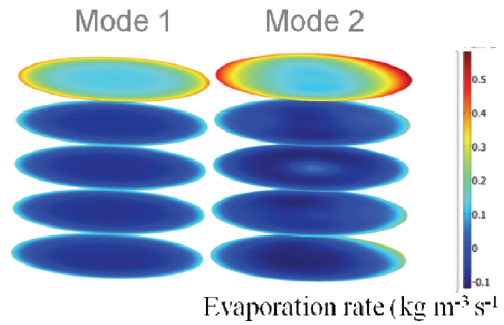

Figure 7. Spatial distribution of evaporation rate inside the restructured potato samples heated for 2 min by heating modes 1 and 2 (see Table 1).

3.5 Evaporation

Fig. 7 shows that greater evaporation occurs at the top and the sides where temperatures are higher. Negative values indicate condensation and it occurs where temperatures are lower at locations of the sample that are not heated by the microwaves or the hot air. In case of mode 2 that uses microwaves, evaporation also occurs at the center of the sample. These results are available for the first time for the combination heating process.

4. Summary and Conclusions

This is the first study that uses complex coupling of Maxwell's equations of electromagnetics with a multiphase porous media model to study microwave combination heating comprehensively. The coupling of different physics presents unmatched computational challenges. The use of such a technique is, however, a requisite in the study of combination heating processes otherwise predictions of critical cooking parameters such as microwave energy deposition, temperature, moisture content and evaporation rate in space and time are not possible. Knowledge of these factors, in turn lead to a quantum improvement in speed, quality and safety of food preparation, increased ability of automation, retention of food nutrition and organoleptic qualities, reduction of food wastage, and increase of energy efficiency. The results can also be used to develop design recommendations for combination heating for different thermal processes.

5. References

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6. Acknowledgements

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7. Appendix

Table 1: Different heating modes of the oven used in the study.

Mode	Heating Method
1	Radiant, Hot Air
2	Microwave (Cycling: 10 s on, 40 s off), Radiant, Hot Air

7.1 Nomenclature

Symbol	Description and unit
c	concentration, kg m^{-3}
c_p	specific heat capacity, J kg^{-1}K^{-1}
C	molar density, kmol m^{-3}
$D_{eff,\, g}$	effective gas diffusivity, m^{2}s^{-1}
D	diffusivity, m^{2}s^{-1}
E	electric field intensity, V m^{-1}
h	heat transfer coefficient, W m^{-2}K^{-1}
h_m	mass transfer coefficient of vapor, ms^{-1}
H	magnetic field intensity, A m^{-1}
$\dot{I}$	volumetric evaporation rate, kgm^{-3}s^{-1}
k	thermal conductivity, Wm^{-2}K^{-1}
k_p	permeability, m^2
K	non-equilibrium evaporation constant
m	overall mass fraction
M	moisture content, d.b.
M_a, M_v	molecular weight of air and vapor
n	total flux, kg m^{-2}s^{-1}
P, p	total pressure and partial pressure, respectively, Pa
Q_{mic}	microwave source term, Jm^{-3}s^{-1}
R	universal gas constant, J kmol^{-1} K^{-1}
S	saturation
t	time, s
T	Temperature
u	velocity, m s^{-1}
V	volume, m^3
x	mole fraction

Greek Symbols

ρ	density, kg m^{-3}
λ	latent heat of vaporization, J kg^{-1}
ω_a, ω_v	mass fraction of vapor and air in relation to total gas
π	porosity
μ_d	dynamic viscosity, Pa s
ε_o	permittivity of free space, 8.854 x 10^{-12} Fm^{-1}
μ	permeability of free space, 4π x 10^{-7} Hm^{-1}
ε	complex relative permittivity
ε'	dielectric constant
ε''	dielectric loss
ω	angular frequency, rad s^{-1}