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Mathematical model for intermittent microwave convective drying of food materials.
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A Mathematical Model for Intermittent Microwave Convective (IMCD) Drying of Food Materials

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1 ABSTRACT

Intermittent microwave convective drying (IMCD) is an advanced technology that improves both energy efficiency and food quality in drying. Modelling of IMCD is essential to understand the physics of this advanced drying process and to optimize the microwave power level and intermittency during drying. However, there is still a lack of modelling studies dedicated to IMCD. In this study, a mathematical model for IMCD was developed and validated with experimental data. The model showed that the interior temperature of the material was higher than the surface in IMCD, and that the temperatures fluctuated and redistributed due to the intermittency of the microwave power. This redistribution of temperature could significantly contribute to the improvement of product quality during IMCD. Limitations when using Lambert's Law for microwave heat generation were identified and discussed.

2 INTRODUCTION

Currently, 1.3 billion tonnes of foodstuffs are lost annually due to a lack of proper processing and preservation[1]. Drying is a method of removing moisture for the purpose of preserving food from microbial spoilage. Conventional convective drying is a very lengthy and energy intensive process[2]. Higher drying temperatures reduce the drying times, however under such conditions food quality and nutritional value is reduced and more energy is wasted as exhaust. To overcome these latter problems, convective drying can be combined with microwave drying. Microwaves interact with water molecules inside the food and heat up samples volumetrically, thus increasing the moisture diffusion rate and significantly

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reducing the drying time and improving energy efficiency[3]. Microwaves are often combined with other drying processes, for example, vacuum-microwave dried sour cherries were superior to convective drying and competitive with freeze drying[4]. There was a problem, however, with the continuous application of microwaves in the drying process, as high product temperatures and uneven heating resulted[3]. As noted above, high drying temperatures can cause quality degradation in heat sensitive materials, such as fruits and vegetables[5, 6]. This problem can potentially be overcome by applying microwave power intermittently. Research has shown that intermittent microwave convective drying increases both energy efficiency and product quality[3, 7].

Microwave related heating processes have many advantages compared to conventional methods[8]. The main advantages of intermittent microwave assisted drying are: (1) Volumetric Heating: Microwave energy interacts with water molecules within the food leading to volumetric heating and increased moisture diffusion[8], thus significantly reduce drying times[9]; (2) Quality Improvement: The quality of the dried product can be improved by combining intermittent microwave heating with other drying technologies[10]; (3) Controlled Heating: The fidelity of heating can be controlled using microwave energy as it can be applied in a pulsed manner[11].

Soysal *et al*.[12] experimentally investigated intermittent microwave-convective drying (IMCD), and the results were compared with continuous microwave-convective drying (CMCD), and traditional convective drying for oregano. They observed that IMCD was 4.7–11.2 times more energy efficient when compared to convective drying. Furthermore, the drying time of the convective drying process was about 4.7–17.3 times longer when compared with the IMCD drying. Zhao *et al*.[13] found that intermitted microwave assisted hot air drying was a promising method for industrial application because of lower energy consumption and improved quality of the dried food. Ahrné *et al*.[14] compared CMCD and IMCD for bananas, as these were a heat sensitive food product. They reported that drying using variable microwave power was a more suitable process. They also reported that IMCD produced better outcomes in that it reduced the charring of the product. Esturk[15] studied IMCD of sage leaves and compared the result with convective air-drying and CMCD. Although CMCD provided the fastest drying rate, it yielded the lowest quality (in terms of oil content). Esturk[15] also noted that in IMCD, the intermittency and the microwave power level significantly impacted the energy consumption and the quality of dried product[15]. Therefore, the microwave power level and pulse ratio should be carefully chosen to achieve the best outcomes.

Mathematical modelling can help us to understand the heat and mass transfer involved in IMCD and thereby be used to determine the optimum pulse ratio and power levels for drying[3]. The previously mentioned work related to IMCD has been limited to experimental analysis. To date, relatively few studies have presented theoretical models of the IMCD of food.

Recently, Bhattacharya *et al*.[16] and Esturk[15] developed a purely empirical model for CMCD (not IMCD) of oyster mushroom (*pleurotus ostreatus*) and sage, respectively. However, these empirical models did not provide physical insight into the process and were only applicable to a specific experimental range[17-19]. Some diffusion-based single phase models exist for CMCD[20, 21], however, none of them considered intermittency of the microwave energy applied. For this reason, they cannot be applied to IMCD, and are not capable of investigating the temperature redistribution which occurs due to the intermittency of the microwave. However, there are some simulation models that considered intermittency of microwave power[11, 22-25]; but the mass transfer was neglected in those models. In other words, these are only heating models, not drying models.

Some models of intermittent heating have used constant dielectric properties[26]. However, dielectric properties vary with moisture content, in particular, for fruits and vegetables because they contain a large amount of moisture. Moisture content has a significant effect on dielectric properties of fruits and vegetables[27]. Therefore, constant dielectric properties cannot be considered in the case of drying of fruits and vegetables.

Taken together, it can be concluded that, although extensive research has been carried out on microwave convective heating, there are very limited studies dealing with modelling the IMCD of food, that considers the entire drying period, as well as variable material properties. Furthermore, the temperature redistribution due to the intermittency of the microwaves, which is crucial in IMCD for quality improvement, has not been properly investigated.

In the current study, we present a model of IMCD of food that accounts for the intermittency of the microwave power, and variable thermo-physical and dielectric properties of the material. COMSOL Multiphysics 4.4, a finite element based engineering simulation software, was used to model coupled heat and mass transfer model equations. The outcomes of the model are presented and discussed, and validated with experimental data.

3 MATHEMATICAL MODELLING

We considered a 2D axisymmetric geometry of a cylindrical slice of apple as presented in Figure 1. The following assumptions were applied when developing the mathematical model:

- A homogeneous domain having a single temperature was considered;
- The initial temperature and moisture distribution within the slice were uniform;
- The thermo-physical and dielectric properties varied with moisture content of the sample;
- Only single-phase water was present in the domain. This characterized the moisture concentration of the apple. Furthermore, moisture was transported by diffusion towards the surface.
- It was assumed that the volume of the sample did not change.

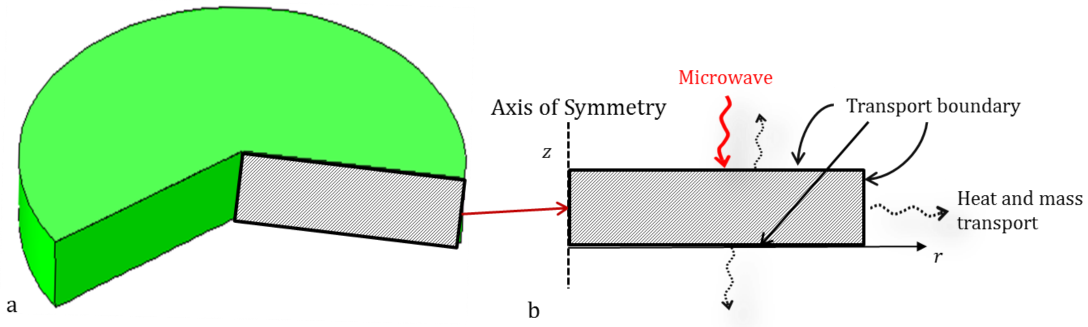

Figure 1. 3D apple slice and 2D axisymmetric domain showing symmetry boundary and transfer boundary (arrow)

Governing equations

Heat transfer:

The energy balance was characterized by a Fourier flux with a heat generation term due to microwave heating, Q_{mic} (W/m^3).

$$\rho c_p \frac{\partial T}{\partial t} = \nabla.(k\nabla T) + Q_{mic} f(t) \quad (1)$$

where, T is the temperature (^{0}K), ρ is the density of sample (kg/m^3), c_p is the specific heat (J/kg/K), and k is the thermal conductivity (W/m/K). The heat generation, Q_{mic} (W/m^3), was calculated using Lambert's Law[20, 21, 28, 29] and f(t) is the intermittency function as discussed in the later section.

Mass transfer:

We assume that the mass flux of moisture was due to Fickian diffusion; therefore,

$$\frac{\partial c}{\partial t} + \nabla.\left(-D_{eff}\nabla c\right) = 0 \qquad (2)$$

where, c is the moisture concentration (mol/m^3), D_{eff} is the effective diffusion coefficient (m^2/s) discussed further in the input parameters section.

Initial and boundary conditions

The initial conditions for heat and mass transfer were given by,

$$T_{(t=0)} = 20^0C, \qquad (3)$$

and

$$c_{w(t=0)} = c_0, \qquad (4)$$

respectively. Here c_0 is the initial moisture concentration of the apple (mol/m^3).

The boundary conditions for the heat and mass transfer equations at the transport boundaries (as shown in Figure 1) were given by,

$$-(k\nabla T) = h_T(T - T_{air}) + h_m \frac{\left(p_{v,eq} - p_{v\,air}\right)}{RT} h_{fg}, \qquad (5)$$

and $$\left(-D_{eff}\nabla c\right) = h_m \frac{\left(p_{v,eq} - p_{v\,air}\right)}{RT}, \qquad (6)$$

respectively. Here, h_T is the heat transfer coefficient (W/m^2/K) and T_{air} is the drying air temperature (^{0}C), $p_{v,air}$ vapour pressure of ambient air (Pa), $p_{v,eq}$ is the equilibrium vapour pressure (Pa), h_{fg} is the latent heat of evaporation (J/kg) , R is the universal gas constant (J/mol/K), and h_m is the mass transfer coefficient (m/s).

The boundary conditions for heat and mass transfer of the symmetry boundary (as shown in Figure 1) were given by

$$-(k\nabla T)=0\,, \tag{7}$$

and

$$\left(-D_{eff}\nabla c\right)=0\,. \tag{8}$$

Modelling of microwave power absorption using Lambert's Law

Budd & Hill[30] compared power absorption modelled by Lambert's Law and Maxwell's equation, and showed that for thicker material the power absorption according to both approaches was similar.

Many researchers have used Lambert's Law for microwave energy distribution in food products during drying[20, 21, 28, 29, 31]. Therefore, in this study, Lambert's Law has been used to calculate microwave energy absorption inside the food samples. It considered exponential attenuation of microwave absorption within the product, as expressed by the following equation:

$$P_{mic}=P_0\,\exp^{-2\alpha(h-z)}\,. \tag{9}$$

Here, P_0 is the incident power at the surface (W), α is the attenuation constant (1/m), and h is the thickness of the sample (m) and (h-z) represents the distance from surface (m). The measurement of P_0 via experiments is presented in the following section4.

The attenuation constant, α is given by

$$\alpha=\frac{2\pi}{\lambda}\sqrt{\varepsilon'\left[\frac{\sqrt{\left(1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right)}-1}{2}\right]}\,, \tag{10}$$

where λ is the wavelength of the microwave in free space ($\lambda=12.24cm$ at 2450MHz and air temperature 20^0C) and ε' and ε'' are the dielectric constant and dielectric loss, respectively.

The dielectric constant and dielectric loss of the material are the most important parameters in microwave heating and drying applications, because these properties define how materials interact with electromagnetic energy[32]. The evaluation of dielectric properties is critical in modelling and product and process development[33]. Dielectric properties of materials define how much microwave energy will be converted to heat[34].

Here we use the data of Martín-Esparza *et al.*[35] in a quadratic regression analysis in which the intercept of the ε' and ε'' versus M_{wb} graph was set to 0.1 in order to avoid numerical singularity in ε' and ε'' when M_{wb} is zero. The resulting quadratic expressions were found to be:

$$\varepsilon' = 36.638 M_{wb}^{2} + 30.289 M_{wb} + 0.1 \tag{11}$$

and $$\varepsilon'' = -13.543 M_{wb}^{2} + 26.8150. M_{wb} + 0.1. \tag{12}$$

The volumetric heat generation, Q_{mic} (*W/m*^{3}) in Equation 1 was then calculated by:

$$Q_{mic} = \frac{P_{mic}}{V}, \tag{13}$$

where, V is the volume of Apple sample (m^3).

Input parameters

The input parameters of the model are listed in Table 1 and some of these values are further discussed later in this section.

Table 1. *Input properties of the model*

Parameters	**Value[Unit]**	**Reference**
Initial moisture content (db), M_0	6.14[kg/kg]	This work
Initial temperature, T_i	20[°C]	This work
Molecular weight of water, M_w	18[g/mol]	[36]
Latent heat of evaporation, h_{fg}	2358600[J/kg]	[36]
Drying air temperature, T_{air}	60°C	This work

Parameters	**Value[Unit]**	**Reference**
Vapour pressure of ambient air, p_{vair}	2.7[kPa]	Calculated
Diameter of the sample	40[mm]	This work
Thickness of the sample	10[mm]	This work
Reference diffusivity, D_{ref}	3.24e-9 [m^2/s]	Calculated
Heat transfer coefficient, h_T	16.746 [W/(m^2·K)]	[37]
Mass transfer coefficient, h_m	0.067904 [m/s]	[37]

Microwave incident power absorption

The incident power at the surface, P_0, can be determined by calculating the heat absorbed by distilled water of same volume, with the sample placed in the microwave oven[21, 38, 39].This is one of the most difficult aspects of microwave heating[40]. Arballo *et al*.[20] determined P_0 *via* the application of the formula,

$$P_0 = m_w C_{pw} \frac{\Delta T}{\Delta t}, \tag{14}$$

where, m_w is the mass of water (kg), C_{pw} is the specific heat of water (*J/kg/K*), ΔT is the temperature rise of water (^{0}C) and ΔT is the heating time (s).

A major drawback of equation (14) was that it did not account for the evaporation heat loss. The evaporation of water is not negligible at higher microwave power. This evaporative heat loss was also taken into account in some studies[29]. Then the absorbed power considering evaporative heat loss can be calculated by

$$P_0 = m_w C_{pw} \frac{\Delta T}{\Delta t} + h_{fg} \frac{\Delta m_w}{\Delta t}. \tag{15}$$

Here, Δm_w is the evaporated mass (kg) of water and h_{fg} is the latent heat of evaporation (J/kg).

Auxiliary Equations

The moisture content (wb), M_{wb}, can be calculated from the water concentration by the formula:

$$M_{wb} = \frac{cM_w}{\rho}. \tag{16}$$

Here M_w is the molecular weight of water (kg/mol).

The relationship between dry basis moisture content, M_{db}, and wet basis moisture content, M_{wb}, was given by:

$$M_{db} = \frac{M_{wb}}{1 - M_{wb}}. \tag{17}$$

Equilibrium vapour pressure

The vapour pressure of the food was assumed to be always in equilibrium with the vapour pressure given by an appropriate sorption isotherm. For Apple, the correlation of equilibrium vapour pressure with moisture and temperature is given by[41],

$$P_{v,eq} = P_{v,sat}(T)\exp\left(-0.182M_{db}^{-0.696} + 0.232e^{-43.949M}M_{db}^{0.0411}\ln[P_{sat}(T)]\right). \tag{18}$$

Here, M_{db} is the moisture content dry basis and $P_{v,sat}$ is the saturated vapour pressure given by[42],

$$P_{v,sat} = \exp\begin{bmatrix} -5800.2206/T + 1.3915 - 0.0486T + 0.4176x10^{-4}T^2 \\ -0.01445x10^{-7}T^3 + 6.656\ln(T) \end{bmatrix}. \tag{19}$$

Effective diffusivity

For effective diffusivity, D_{eff}, we adopted an expression that was developed in the previous work[37] that was a function of both temperature and moisture, namely,

$$D_{eff} = \frac{\left(D_0 e^{-\frac{E_a}{RT}} + D_{ref}\left(\frac{b}{b_0}\right)^2\right)}{2}. \tag{20}$$

Here D_{ref} is reference diffusivity (m^2/s), E_a is activation energy of diffusion of water (J/mol), b is the half thickness of the material (m), b_0 is the initial thickness (m), and D_0 is an integration constant and is usually referred to as a frequency factor when discussing Arrhenius equation (m^2/sec). The activation energy was calculated from the slope of a $\ln(D_{ref})$ versus (1/T) graph resulting in the values D_0 =0.09 and E_a = 50 kJ/mol.

The thickness ratio obtained by the following equation:

$$\frac{b}{b_0} = \left[\frac{\rho_w + M_{wb}\rho}{\rho_w + M_0\rho} \right] \quad (21)$$

where ρ_w is the density of water (kg/m^3), ρ is density of sample (kg/m^3), M_{wb} is moisture content wet basis and M_0 is initial moisture content kg/kg (wb).

Thermo-physical properties of apple

Thermal conductivity and specific heat of apple can be expressed as a functions of moisture content[43],

$$k = 0.148 + 0.00493 M_{wb} \quad (22)$$

and $$c_p = 1000(1.4 + 3.22 M_{wb}), \quad (23)$$

respectively.

Moreover, the density of Apple, ρ, during drying changes with moisture content, M_{wb}. In this study, we measured the density change with moisture content of apple by a solid displacement method[44, 45] using a cylindrical vial and 57 µm glass beads. The relationship between ρ and M_{wb} was determined to be,

$$\rho = 569.01 M_{wb} + 415.94 . \quad (24)$$

Heat and mass transfer coefficient

The heat and mass transfer coefficients were calculated based on the empirical relationship discussed in a previous paper[37] and found to be h_T =16.746 W/(m^2·K) and h_m =0.067904 m/s, respectively.

4 MATERIALS AND METHODS

Sample preparation

Fresh Granny Smith apples used for the intermittent microwave drying experiments were obtained from local supermarkets. The samples were stored at 5±1^{0}C to keep them as fresh as possible before they were used in the experiments. The apples taken from the storage unit were washed and put aside for one hour to allow their temperature to elevate to room temperature prior to each drying experiment. The samples were cut to a thickness of 10mm and a diameter of approximately 40mm. The initial moisture content of the apple slices was approximately 0.868 kg/kg (wet basis).

IMCD and convection drying

The IMCD drying was achieved by heating the sample in a microwave for 60s and then drying for 120s in the convection dryer. The experiments were conducted with a Panasonic Microwave Oven having inverter technology with cavity dimension 355mm (W) x251mm (H) x365mm (D). The inverter technology enabled accurate and continuous power supply at lower power settings. Whereas, with conventional microwave oven supply, lower power was achieved by turning the microwave on and off while running at maximum rated power of the oven[46]. The microwave oven supplied 10 accurate power levels with a maximum of 1100W at 2.45GHz frequency. The apple slices were placed in the centre of the microwave cavity, to facilitate an even absorption of microwave energy. The moisture loss was recorded at regular intervals at the end of power-off times by placing the apple slices on a digital balance (specification: 0.001g accuracy).

Convection drying was conducted to compare the results with IMCD. For convection drying, the same samples were placed in a convection dryer where the temperature was set to 60^0C. The moisture loss was recorded at regular intervals of 10 mins with the digital balance (specification: 0.001g accuracy). All experiments were repeated three times for repeatability and comparison, and the standard deviation was calculated.

Thermal imaging

A Flir i7 thermal imaging camera was used to measure the temperature distribution on the sample surface. Accurate measurement of temperature by thermal imaging cameras depends on the emissivity values. The emissivity value for apple was found in the range between 0.94 and 0.97[47] and 0.95 was set in the camera before taking images.

Determination of incident power (P_0) for Lambert's Law

The Panasonic Inverter microwave oven was used in the experiments to determine the power absorption. The tests were conducted at three power levels, namely; 100W, 200W and 300W with a water sample. The volume of water sample was taken as the same volume of apple to obtain accurate power absorption. Water was heated for 60s and thermal images were taken by the thermal imaging camera (Flir i7) before and after heating. The water was properly agitated to measure the average rise of temperature. The absorbed power, P_0, was calculated by equation (15) for various load volume and applied microwave power.

5 SIMULATION PROCEDURE

COMSOL Multiphysics, an advanced software for modelling and simulation, was used to implement the numerical solution of the model introduced in Section 3.

Combinations of a rectangular function and an analytic function in COMSOL Multiphysics were used to develop an intermittency function as shown in Figure 2. The mathematical expression for the intermittency function is given below:

$$f(t) = \begin{cases} 1 & \text{if} \quad n \le t \le n+60 \\ 0 & \text{if} \quad n+60 < t < n+180 \end{cases} \tag{25}$$

where n=0, 180, 360, 540,720………………3960, 4140, 4320.

Then the function was multiplied with the heat generation term in the energy equations to implement intermittency of the microwave heat source.

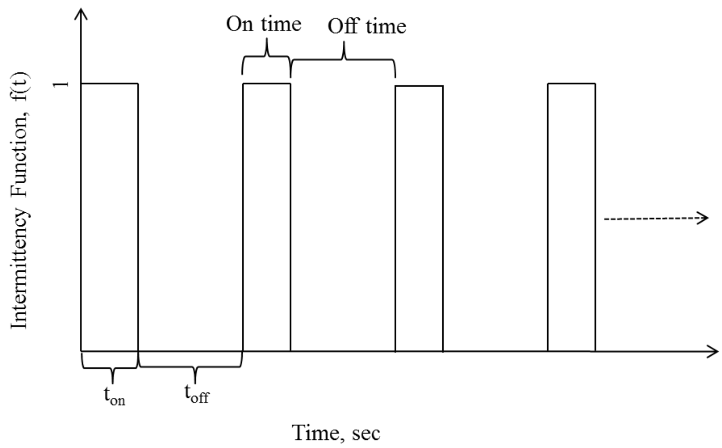

Figure 2. Intermittency function

Figure 3 below shows the flow chart of the simulation procedure. It shows that the moisture dependent material properties, microwave source term, and input properties were updated at the beginning of each iteration.

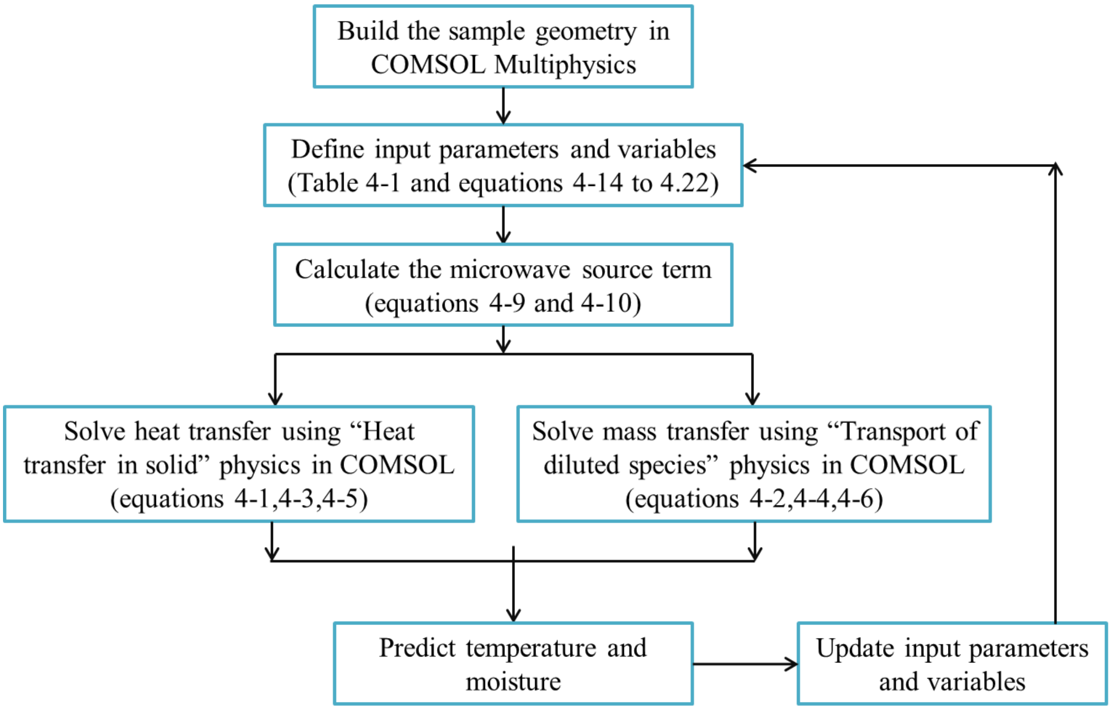

Figure 3. Flow chart showing the modelling strategy in COMSOL Multiphysics

6 RESULTS AND DISCUSSIONS

Incident power absorption by experiments

The incident power absorbed by the sample (P_0) was calculated for three different power levels for various loads. Absorbed power was calculated by using equation (15) and then converted to power absorption ratio defined as the ratio of absorbed power by sample (P_0) and microwave set power (P_{set}). Table 2 shows the power absorption ratio obtained for three different microwave set power values, namely, 100W, 200W and 300W.

Table 2. *Power absorption ratio for microwave power (100W, 200W and 300W) for different sample volume*

Sample volume (cc)	Power absorption ratio (%), P_0/P_{set}				Standard deviation
	100W	200W	300W	Average	
15	25	25.3	26	25.43	0.51
35	38	43	41	40.67	2.52
55	59	66	59	61.33	4.04

It was interesting to note that the power absorption ratios were the same for a certain volume of sample irrespective of the microwave power. Therefore, the average power absorption ratios in percentage were plotted against the sample volume in Figure 4 with the error bar showing standard deviations. Figure 4 can be used to find absorbed microwave power (P_0) when the sample volume and microwave set power (P_{set}) is known.

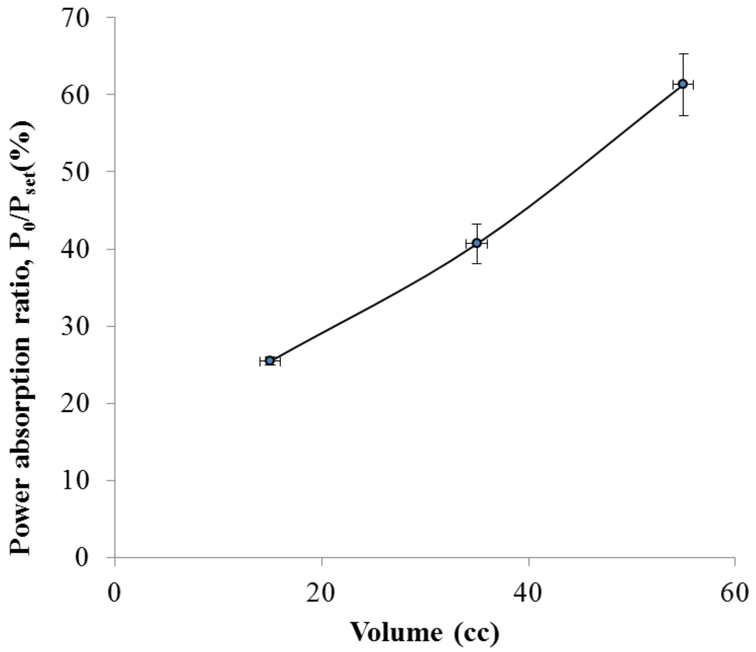

Figure 4. Microwave power absorption for different loading volume

The above results correlated well with those of Mudgett[48] who also investigated the power absorption ratio and found a similar trend.

Average moisture curve

The comparison of moisture content obtained from experiments and simulation is shown in Figure 5. A Pearson correlation coefficients, R^2, was used to determine the goodness of fit of the model. We observed that a high correlation was obtained between the model and experimental values with R^2=0.997623. This good agreement between experimental data and model calculations supported the suitability of the model to describe the drying kinetics and moisture content obtained during the IMCD drying process.

The drying curves for both processes were also plotted in Figure 5 to demonstrate the advantage of IMCD drying over convection drying. It was found that, after 75 minutes of drying, convection drying reduced the moisture content to 3 kg/kg db, whereas by using IMCD reduced the moisture content to 0.4 kg/kg db. Thus, IMCD significantly reduced the drying time. To reduce the moisture content to 0.4 kg/kg db by convection drying took around 300min, which was four times longer than the IMCD with intermittency 60s on and 120s off.

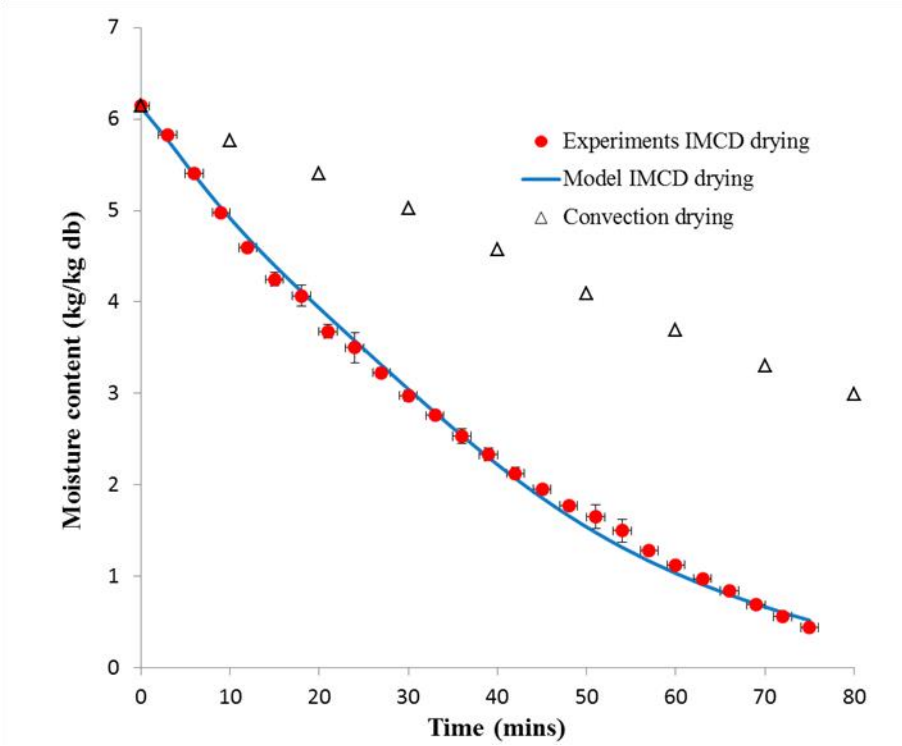

Figure 5. Drying curve for IMCD (experiments and model) and convective drying

Temperature

Figure 6 shows the temperature at the centre of the top surface predicted from our model whilst Figure 7 shows the temperature distribution of the surface obtained experimentally from thermal imaging. The thermal images were taken immediately after microwave heating for 60s and after tempering for 120s in the convection dryer. Thus, this measurement allowed the investigation of temperature rise during microwave heating and drops during tempering in the process of IMCD.

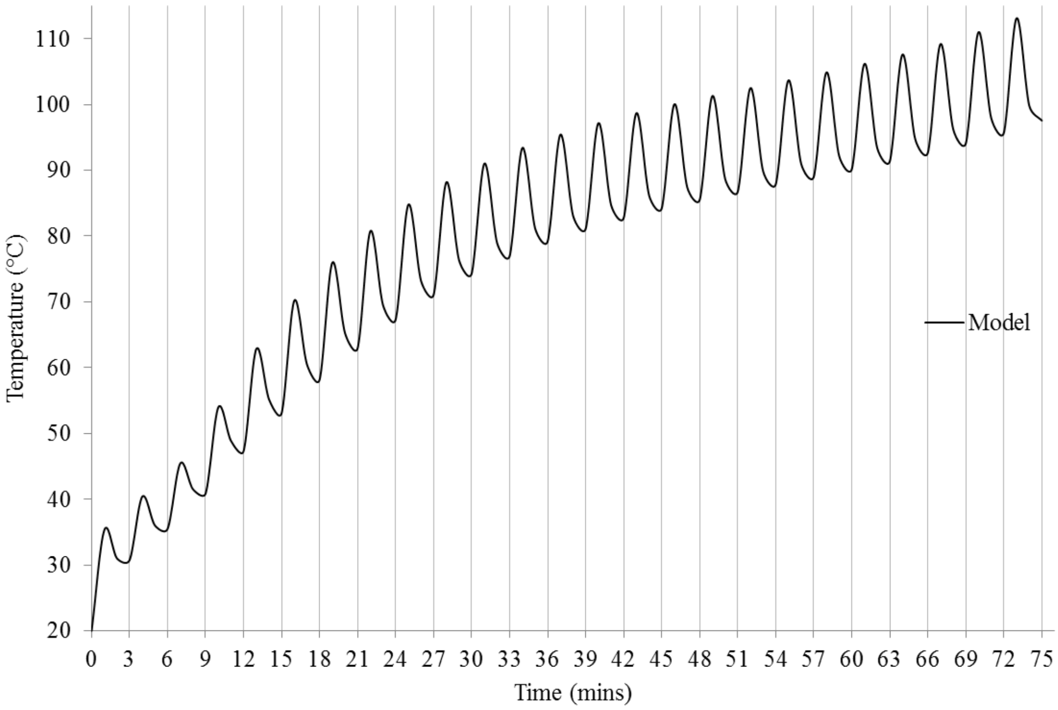

Figure 6. Temperature curve obtained from the model

The temperature profile from the model showed that the temperature rose after each heating cycle. The temperature then fell (at the centre of the surface) during the 120s convection drying phase (when the microwave was turned off). Similar fluctuating temperature profiles were obtained under oscillating infrared irradiation[49].

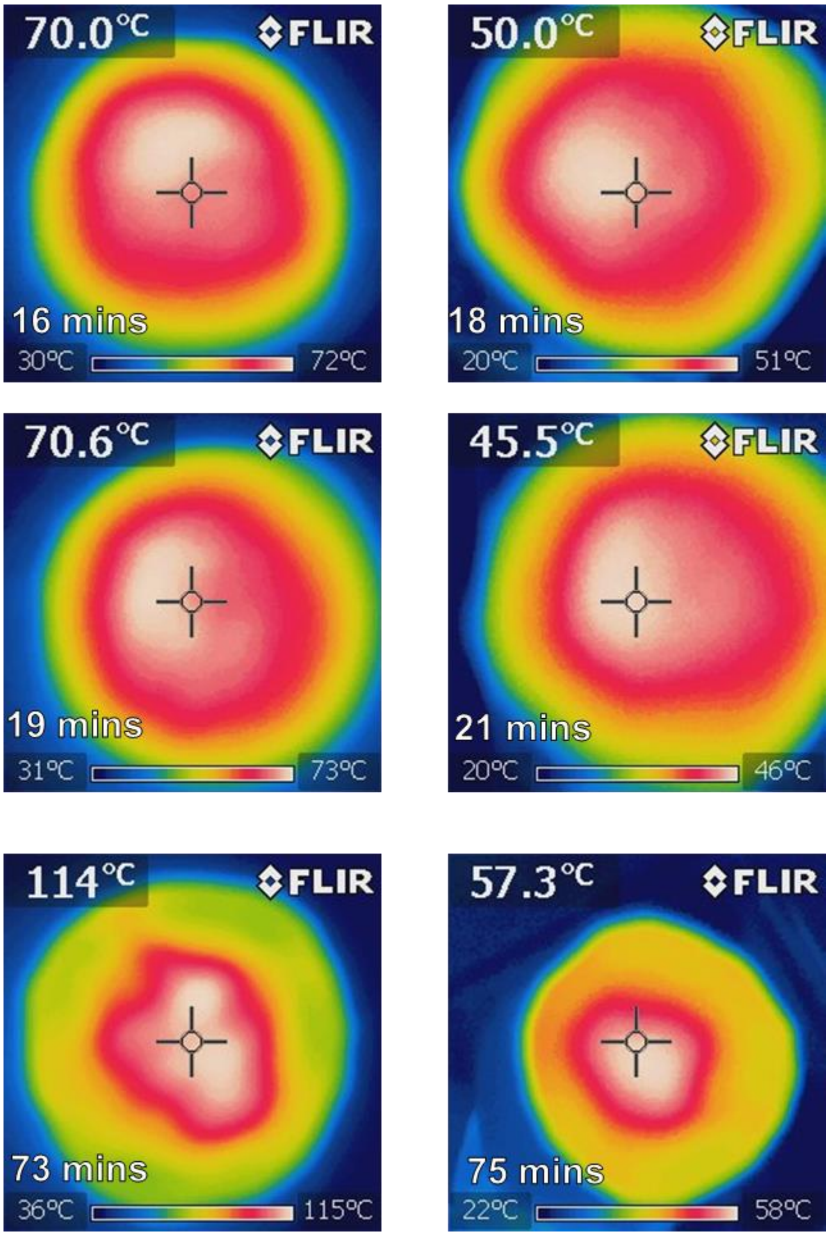

Figure 7. Thermal images of top surface at selected times

The thermal images also showed a similar pattern. To illustrate this more clearly, the centre temperatures measured on the surface and the analogous model prediction for the selected time are presented in Table 3.

Table 3: *Centre temperature of apple surface from experiment and model*

Time (mins)	**16**	**18**	**19**	**21**	**73**	**75**
Microwave	On	Off	On	On	Off	On
Experimental temperature	70	50	70.6	45.5	114	57.3
Model temperature	70.5	57	76.5	61	114.5	95.4

We observed that there was a reasonable correlation between the observed and predicted temperatures. Certainly the periodic pattern of heating and cooling was captured by the model. There were, however, some discrepancies observed in Table 3. Generally, the model seemed to predict higher temperatures than those observed. We believe that this was due to the fact that the thermal images were taken after removing the sample from the microwave oven and placing them in an ambient environment (~20^0C) for a short time.

It can be seen from the above figures (Figure 6 and Figure 7) that the temperature reached as high as 114°C at the end of the drying process. This was because the temperature continued to rise after each cycle while it fluctuated. We note that a similar rise in temperature with cycled microwave heating was found by Rakesh *et al*.[50] and Yang *et al*.[26].

In light of these findings, it can be said that the temperature of the sample should be controlled, particularly, at the later stages of drying. Since the higher temperature may reduce the food quality or even burn the product, the microwave power should be reduced or the tempering period increased to avoid burning at the final stage of drying.

Although the above results were taken at a single point in the sample, it is reasonable to assume that heat energy was being dissipated during tempering *via* conduction as opposed to purely convective cooling. This redistribution of temperature could significantly contribute in the improvement of product quality during IMCD by selecting an optimum tempering time.

Moisture and temperature distribution

Moisture distribution inside the sample is shown in Figure 8. We observed that the moisture content of the surface reduced to nearly zero after about 20mins of drying, whereas at that time the moisture content at the centre was still at its maximum.

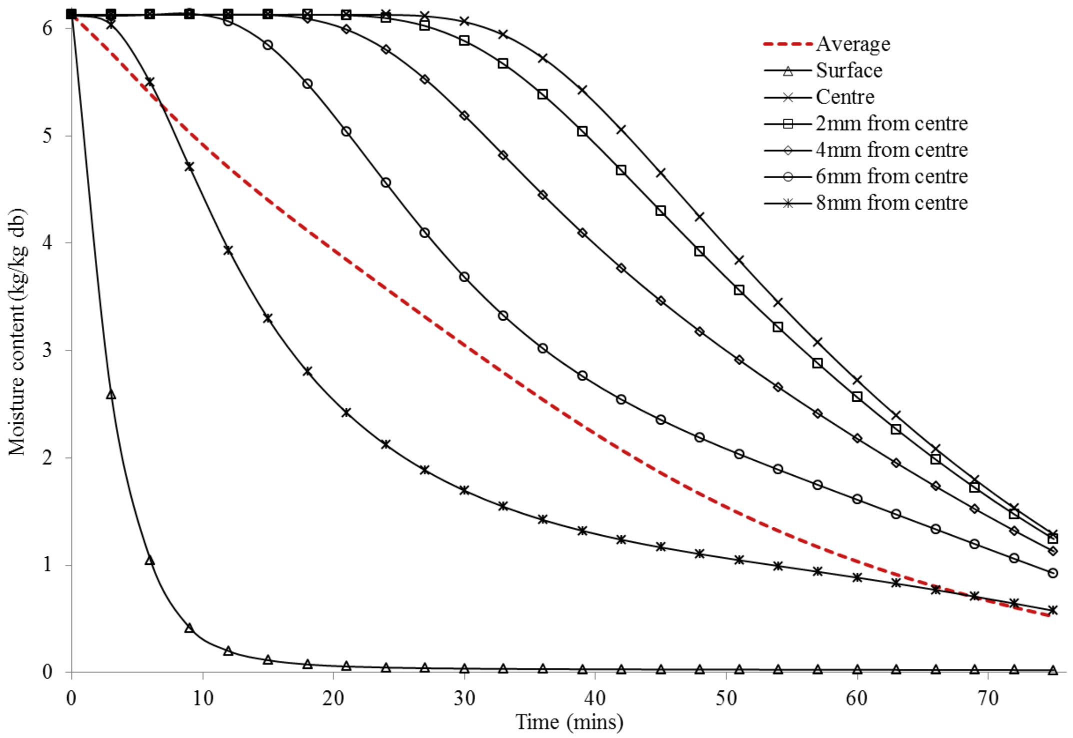

Figure 8. Moisture distribution inside the sample

Another observation to note from the figure was that the moisture content was always higher in the inner part of the sample and decreased as drying progressed. These results were consistent with the idea that the surface of the sample dried first and then the moisture from the centre was removed.

Figure 9 shows the simulated temperature profile at the surface, centre and 8mm beneath the surface. It showed that the temperature was always higher in the interior of the apple than the surface, despite the fact that microwave power absorption was higher at the surface, according to Lambert's Law. This was due to the internal heating characteristics of the microwave. Although the heating was higher near the surface, the convection and evaporative cooling reduced the temperature of the surface. A similar pattern (higher centre temperature) has been observed during microwave heating[50, 51]. The temperature difference between surface and centre increased as drying progressed. This was because the thermal conductivity was considered to be a function of moisture content, and it decreased with moisture content.

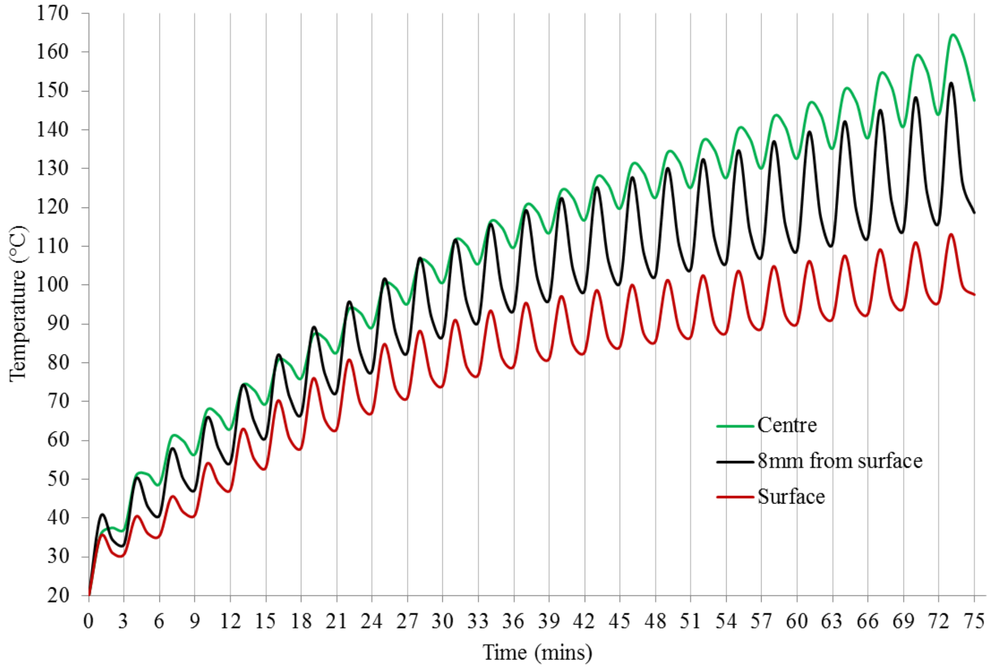

Figure 9. Temperature distribution inside the sample

Equilibrium vapour pressure

Equilibrium vapour pressure, $P_{v,eq}$, is an important parameter for surface evaporation and thus moisture loss. The equilibrium vapour pressure at the surface was determined from Equation (18) and plotted in Figure 10. We observed that $P_{v,eq}$ initially increased rapidly because of increase in temperature and the higher moisture content. However, when the material became drier, near the end of the drying period, the equilibrium vapour pressure decreased. This behaviour indicated that initially the moisture loss was higher and that the drying rate started to decrease when the equilibrium vapour pressure decreased at about 15 mins. From the moisture distribution curve (Figure 8), it could be seen that the surface moisture content became close to zero after 15 mins of drying time, and after that time the vapour pressure did not rise. However, due to diffusion the vapour pressure was still higher than the ambient vapour pressure, $P_{v,air}$, and evaporation occurred.

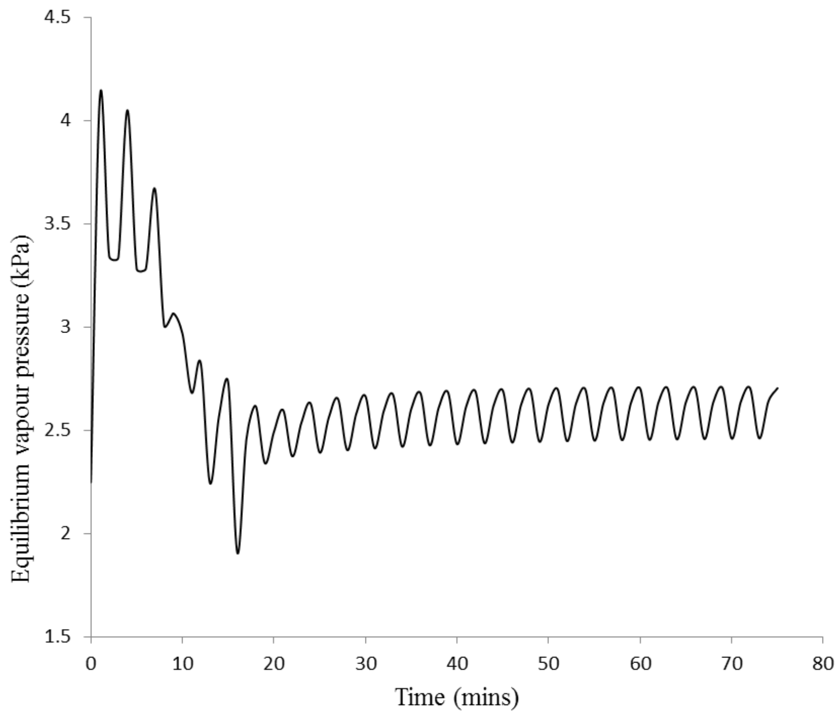

Figure 10. Evolutions of equilibrium vapour pressure at the surface of the sample

Absorbed power distribution

Absorbed power along the depth of the sample at the end of drying is shown in Figure 11. According to Lambert's Law, the power absorbed was maximum at the surface and decreased exponentially inside the sample. Therefore, Figure 11 showed that the absorbed power at the top surface was the highest (25W) which was calculated in Table 2. The power decreased with depth of the sample to a minimum of 10W at the bottom of the surface. A similar trend of theoretical power absorption was found by Budd *et al*.[30] and they also showed that the power absorption was higher at the surface and decayed exponentially with depth in the sample. Although microwave power absorption was higher near the surface, the convection and evaporative cooling led to a reduction of the temperature of the surface.

However, the assumption of Lambert's Law suggested that the power absorption was always highest at the surface, irrespective of the moisture content of the sample. It is well known that moisture or dipolar materials are mainly responsible for microwave absorption [52]. Therefore, when the surface became dry, the microwave absorption should be less. Lambert's Law fails to take this into account, giving always highest power at the surface, irrespective of moisture content. This could be one possible error in the temperature prediction from the model.

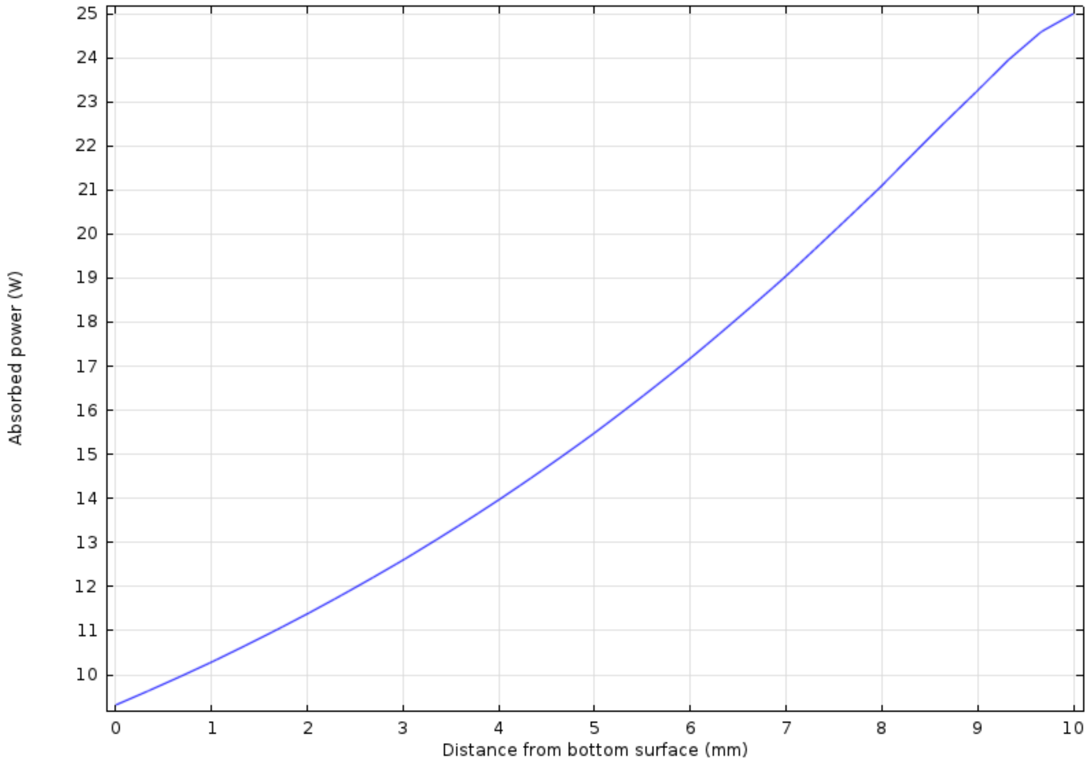

Figure 11. Absorption of microwave power along the length of the sample at 75mins

7 CONCLUSIONS

In this study, a novel model of IMCD has been developed and compared with experimental data collected from a sample of apple. The predicted moisture content showed good agreement with experimental data. The IMCD (with microwave 60s on and 120s off) was four times faster as compared to convection drying. The intermittency of microwaves in IMCD allowed the temperature to re-distribute and drop. Thus, IMCD helped to limit the temperature and improved product quality. Unlike convection drying, the temperature at the centre of the sample was higher in IMCD, which was due to the volumetric heating capability of microwave. The moisture distribution from the model showed that the moisture content was always higher in the inner part of the sample and decreased as drying progressed. The primary limitation of using Lambert's Law in modelling of microwave heat generation in IMCD was that the sample surface always absorbed higher microwave power irrespective of its moisture content. This could be one possible source of error in the over-prediction of temperature. Consideration of a multiphase porous media model for transport and Maxwell's equations for microwave heat generation may improve the accuracy of the model.

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8 REFERENCES

1. Gustavsson, J., C. Cederberg, U. Sonesson, R.v. Otterdijk, and A. Meybeck. *Global food losses and food waste*. 2011 2 October 2012]; Available from: http://www.fao.org/ag/ags/ags-division/publications/publication/en/c/74045/.
2. Karim, M.A. and M.N.A. Hawlader, *Drying characteristics of banana: theoretical modelling and experimental validation.* Journal of Food Engineering, 2005b. **70**(1): p. 35-45.
3. Kumar, C., M.A. Karim, and M.U.H. Joardder, *Intermittent drying of food products: A critical review*. Journal of Food Engineering, 2014. **121**(0): p. 48-57.
4. Wojdyło, A., A. Figiel, K. Lech, P. Nowicka, and J. Oszmiański, *Effect of Convective and Vacuum–Microwave Drying on the Bioactive Compounds, Color, and Antioxidant Capacity of Sour Cherries.* Food and Bioprocess Technology, 2014. **7**(3): p. 829-841.
5. Joardder, M.U.H., A. Karim, and C. Kumar, *Effect of temperature distribution on predicting quality of microwave dehydrated food.* Journal of Mechanical Engineering and Sciences, 2013. **5**: p. 562-568.
6. Joardder, M.U.H., R.J. Brown, C. Kumar, and M.A. Karim, *Effect of Cell Wall Properties on Porosity and Shrinkage of Dried Apple.* International Journal of Food Properties, 2015. **18**(10): p. 2327-2337.
7. Musielak, G. and A. Kieca, *Influence of Varying Microwave Power during Microwave–Vacuum Drying on the Drying Time and Quality of Beetroot and Carrot Slices.* Drying Technology, 2014. **32**(11): p. 1326-1333.
8. Rattanadecho, P. and N. Makul, *Microwave-Assisted Drying: A Review of the State-of-the-Art.* Drying Technology, 2015: p. null-null.
9. Zhang, M., J. Tang, A.S. Mujumdar, and S. Wang, *Trends in microwave-related drying of fruits and vegetables.* Trends in Food Science andTechnology, 2006. **17**(10): p. 524-534.
10. Dev, S.R.S., P. Geetha, V. Orsat, Y. Gariépy, and G.S.V. Raghavan, *Effects of Microwave-Assisted Hot Air Drying and Conventional Hot Air Drying on the Drying Kinetics, Color, Rehydration, and Volatiles of Moringa oleifera.* Drying Technology, 2011. **29**(12): p. 1452-1458.
11. Gunasekaran, S., *Pulsed microwave-vacuum drying of food materials.* Drying Technology, 1999. **17**(3): p. 395-412.
12. Soysal, Y., M. Arslan, and M. Keskin, *Intermittent Microwave-convective Air Drying of Oregano.* Food Science and Technology International, 2009b. **15**(4): p. 397-406.
13. Zhao, D., K. An, S. Ding, L. Liu, Z. Xu, and Z. Wang, *Two-Stage Intermittent Microwave Coupled with Hot-Air Drying of Carrot Slices: Drying Kinetics and Physical Quality*. Food and Bioprocess Technology, 2014. **7**(8): p. 2308-2318.
14. Ahrné, L.M., N.R. Pereira, N. Staack, and P. Floberg, *Microwave Convective Drying of Plant Foods at Constant and Variable Microwave Power.* Drying Technology, 2007. **25**(7-8): p. 1149-1153.

15. Esturk, O., *Intermittent and Continuous Microwave-Convective Air-Drying Characteristics of Sage (Salvia officinalis) Leaves.* Food and Bioprocess Technology, 2012. **5**(5): p. 1664-1673.
16. Bhattacharya, M., P. Srivastav, and H. Mishra, *Thin-layer modeling of convective and microwave-convective drying of oyster mushroom (Pleurotus ostreatus).* Journal of Food Science and Technology, 2013: p. 1-10.
17. Kumar, C., A. Karim, M.U.H. Joardder, and G.J. Miller. *Modeling Heat and Mass Transfer Process during Convection Drying of Fruit*. in *The 4th International Conference on Computational Methods*. 2012a. Gold Coast, Australia.
18. Perussello, C.A., C. Kumar, F. de Castilhos, and M.A. Karim, *Heat and mass transfer modeling of the osmo-convective drying of yacon roots (Smallanthus sonchifolius).* Applied Thermal Engineering, 2014. **63**(1): p. 23-32.
19. Kumar, C., A. Karim, S.C. Saha, M.U.H. Joardder, R.J. Brown, and D. Biswas. *Multiphysics modelling of convective drying of food materials*. in *Proceedings of the Global Engineering, Science and Technology Conference*. 2012b. Dhaka, Bangladesh.
20. Arballo, J.R., L.A. Campanone, and R.H. Mascheroni, *Modeling of Microwave Drying of Fruits. Part II: Effect of Osmotic Pretreatment on the Microwave Dehydration Process.* Drying Technology, 2012. **30**(4): p. 404-415.
21. Hemis, M., R. Choudhary, and D.G. Watson, *A coupled mathematical model for simultaneous microwave and convective drying of wheat seeds.* Biosystems Engineering, 2012. **112**(3): p. 202-209.
22. Yang, H.W. and S. Gunasekaran, *Comparison of temperature distribution in model food cylinders based on Maxwell's equations and Lambert's law during pulsed microwave heating.* Journal of Food Engineering, 2004. **64**(4): p. 445-453.
23. Gunasekaran, S. and H.-W. Yang, *Effect of experimental parameters on temperature distribution during continuous and pulsed microwave heating.* Journal of Food Engineering, 2007. **78**(4): p. 1452-1456.
24. Gunasekaran, S. and H.-W. Yang, *Optimization of pulsed microwave heating.* Journal of Food Engineering, 2007. **78**(4): p. 1457-1462.
25. Kumar, C., M.U.H. Joardder, A. Karim, G.J. Millar, and Z. Amin, *Temperature Redistribution Modelling During Intermittent Microwave Convective Heating.* Procedia Engineering, 2014. **90**(2014): p. 544-549.
26. Yang, H.W. and S. Gunasekaran, *Temperature Profiles in a Cylindrical Model Food During Pulsed Microwave Heating.* Journal of Food Science, 2001. **66**(7): p. 998-1004.
27. Feng, H., J. Tang, and R.P. Cavalieri, *Dielectric properties of dehydrated apples as affected by moisture and temperature.* T. ASAE, 2002. **45**: p. 129-135.
28. Mihoubi, D. and A. Bellagi, *Drying-Induced Stresses during Convective and Combined Microwave and Convective Drying of Saturated Porous Media.* Drying Technology, 2009. **27**(7-8): p. 851-856.
29. Abbasi Souraki, B. and D. Mowla, *Experimental and theoretical investigation of drying behaviour of garlic in an inert medium fluidized bed assisted by microwave.* Journal of Food Engineering, 2008. **88**(4): p. 438-449.
30. Budd, C.J. and A.D.C. Hill, *A comparison of models and methods for simulating the microwave heating of moist foodstuffs.* International Journal of Heat and Mass Transfer, 2011. **54**(4): p. 807-817.
31. Salagnac, P., P. Glouannec, and D. Lecharpentier, *Numerical modeling of heat and mass transfer in porous medium during combined hot air, infrared and microwaves drying.* International Journal of Heat and Mass Transfer, 2004. **47**(19-20): p. 4479-4489.

32. Sosa-Morales, M.E., L. Valerio-Junco, A. López-Malo, and H.S. García, *Dielectric properties of foods: Reported data in the 21st Century and their potential applications.* LWT - Food Science and Technology, 2010. **43**(8): p. 1169-1179.
33. Ikediala, J., J. Tang, S. Drake, and L. Neven, *Dielectric properties of apple cultivars and codling moth larvae.* Transactions of the ASAE-American Society of Agricultural Engineers, 2000. **43**(5): p. 1175-1184.
34. Chandrasekaran, S., S. Ramanathan, and T. Basak, *Microwave food processing—A review.* Food Research International, 2013. **52**(1): p. 243-261.
35. Martín-Esparza, M.E., N. Martínez-Navarrete, A. Chiralt, and P. Fito, *Dielectric behavior of apple (var. Granny Smith) at different moisture contents.* Journal of Food Engineering, 2006. **77**(1): p. 51-56.
36. Çengel, Y.A. and M.A. Boles, *Thermodynamics: an engineering approach*. 2006: McGraw-Hill Higher Education.
37. Kumar, C., G.J. Millar, and M.A. Karim, *Effective Diffusivity and Evaporative Cooling in Convective Drying of Food Material.* Drying Technology, 2015. **33**(2): p. 227-237.
38. Chandrasekaran, S., S. Ramanathan, and T. Basak, *Microwave material processing-a review.* AIChE Journal, 2012. **58**(2): p. 330-363.
39. Lin, Y.E., R.C. Anantheswaran, and V.M. Puri, *Finite element analysis of microwave heating of solid foods.* Journal of Food Engineering, 1995. **25**(1): p. 85-112.
40. Ashim, D., *Methematical Modeling of Microwave Processing of Foods*, in *Food Processing Operations Modeling*. 2001, CRC Press.
41. Ratti, C., G.H. Crapiste, and E. Rotstein, *A New Water Sorption Equilibrium Expression for Solid Foods based on Thermodynamic Considerations.* Journal of Food Science, 1989. **54**(3): p. 738-742.
42. Vega-Mercado, H., M. Marcela Góngora-Nieto, and G.V. Barbosa-Cánovas, *Advances in dehydration of foods.* Journal of Food Engineering, 2001. **49**(4): p. 271-289.
43. Sweat, V.E., *Experimental values of thermal conductivity of selected fruits and vegetables.* Journal of Food Science, 1974. **39**(6): p. 1080-1083.
44. Yan, Z., M.J. Sousa-Gallagher, and F.A.R. Oliveira, *Shrinkage and porosity of banana, pineapple and mango slices during air-drying.* Journal of Food Engineering, 2008. **84**(3): p. 430-440.
45. Joardder, M.U.H., C. Kumar, R.J. Brown, and A. Karim, *A micro-level investigation of the solid displacement method for porosity determination of dried food.* Journal of Food Engineering, 2015. **Under review**.
46. Panasonic. *Linear outpur for even cooking*. 2013 [cited 2013 12 September]; Available from: http://shop.panasonic.com/learn/microwaves/microwave-inverter/?sc_mc=vanity_inverter_01172012.
47. Hellebrand, H.J., H. Beuche, and M. Linke, *Determination of thermal emissivity and surface temperature distribution of horticultural products*, in *Sixth International Symposium on Fruit, Nut and Vegetable Production Engineering*. 2001: Potsdam, Germany.
48. Mudgett, R.E., *Microwave properties and heating characteristics of foods.* Food Technology, 1986. **40**(6): p. 84-93.
49. Rudobashta, S., G. Zueva, and N. Zuev, *Mathematical Modeling and Numerical Simulation of Seeds Drying Under Oscillating Infrared Irradiation.* Drying Technology, 2014. **32**(11): p. 1352-1359.
50. Rakesh, V., Y. Seo, A.K. Datta, K.L. McCarthy, and M.J. McCarthy, *Heat transfer during microwave combination heating: Computational modeling and MRI experiments.* AIChE Journal, 2010. **56**(9): p. 2468-2478.

51. Datta, A.K., *Mathematical modeling of microwave processing of foods: An overview*. Food Processing Operations Modeling, ed. J. Irudayaraj. 2002, New York: Marcel Dekker, Inc.
52. Joardder, M.U.H., C. Kumar, and A. Karim, *Food Structure: Its Formation and Relationships with Other Properties.* Critical Reviews in Food Science and Nutrition, 2014. **In press**.