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Microwave-Convective Drying of Food Materials: A Critical Review

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Abstract

Microwave convective drying (MCD) is gaining increasing interest due to its unique volumetric heating capability and ability to significantly reduce drying time and improve food quality. The main objective of this paper is to discuss, critically analyze and evaluate the recent advances in MCD and suggest the future directions in this field. The main focus of this paper is the mathematical modeling and experimental investigations in microwave convective drying of food materials. Recent developments in mathematical modeling of MCD is discussed and existing experimental setup and their advantages and disadvantages are discussed and analysed. Long drying time is a concern in food industries. Reductions in drying time by applying MCD compared to convection drying are calculated and discussed. It was apparent that the proper integration of mathematical modeling and experimental technique is the best way to maximize the advantages of this drying method. Although a plethora of research is being carried out on this topic, there is still need for research to develop fundamental modeling to optimize the process parameters and scale up this technology for the industrial application. Overall, the review provides an in-depth insight into the latest development of MCD and its mathematical modeling approaches and will hopefully serve to inspire future work in the field.

Keywords

Microwave, modeling, drying time, experiments, energy efficiency

1. Introduction

Energy efficiency, product quality and drying time are three main concerns in food drying. Drying research evolved to optimize these three parameters. Based on the available drying technologies, drying methods can be divided into four generations. First and second generation include different convective drying methods. Cabinet, kiln, belt, conveyor dryer are considered as the first generation, and spray and drum drier are considered as second generation drying. Then the freeze and osmotic drying are considered as the third generation. Microwave and RF related drying are referred to as innovative and fourth generation drying technology (Malafronte et al. 2012, Vega-Mercado, Marcela Góngora-Nieto, and Barbosa-Cánovas 2001). Microwave related drying is gaining increasing interest due to the following reasons: (a)volumetric heating: microwave energy heats up volumetrically and pumps moisture to surface the product thus case hardening of the product could be eliminated (Turner, Puiggali, and Jomaa 1998); (b)increase drying rate: microwave increase diffusion of heat and mass thus significantly reduce the drying time (Mujumdar 2004, Zhang et al. 2006); (c) quality improvement: quality of the dried product can be improved by combining microwave with other drying method(Dev et al. 2011); (d) applying MW energy in a pulsed manner to maximize drying efficiency when the process is mass transfer controlled; (e) Bound water molecules which are difficult to remove can also be excited by microwaves (Gunasekaran 1999).

To improve the performance, microwave is generally combined with hot air drying, freeze drying, vacuum drying, spouted bed drying and osmotic drying. Since freeze and vacuum drying involve higher capital and operating cost, convection drying is most widely combined with microwave (Andrés, Bilbao, and Fito 2004). Moreover, the main drawbacks of convective drying are longer drying times and formation of a crust on the surface due to the elevated temperature. Microwaves can mitigate these problems by increasing the diffusion rate and supplying enough moisture to the surface. Thus, combining microwave with convection drying can significantly shorten the drying time and improve product quality and energy efficiency (Zhang et al. 2006). Internal heat generated by the microwave increase pressure within the pores and drives the moisture to the surface. The convective air takes the moisture by evaporation, and sometimes evaporative cooling occurs at the surface (Kumar, Millar, and Karim 2016)..

There have been tremendous progress in experimental investigation and mathematical modeling of MCD in the last few decades. However, there is no comprehensive review of the recent advances in this field to analyze the progress systematically and prospect future direction. This paper presents a comprehensive review of the current developments in MCD of food materials. This work focuses on mathematical modeling of MCD, experimental methods and drying time savings in MCD. First, a review on MCD method was critically discussed by categorizing the literature into two broad divisions: (1) continuous microwave-convective drying (CMCD) and, (2) intermittent microwave-convective drying (IMCD). In this section, the drying time savings and food quality in MCD are discussed. Then the current experimental process and their advantages and limitation were presented and discussed. Finally, an extensive review of the mathematical models available for MCD are critically analysed with relevant analysis and reasoning.

2. Principle of microwave heating

Microwave refers electromagnetic radiation in the frequency range of 300 MHz-300GHz with a wavelength 1mm-1m. Electromagnetic energy propagates through spaces by means of time-varying electric and magnetic fields (Feng, Yin, and Tang 2012). Microwave penetrates the material until moisture is located and heats up the material volumetrically thus facilitates higher diffusion rate and pressure gradient to drive off the moisture from inside of the material (Turner and Jolly 1991). There are two main mechanisms of MW heating: dipolar reorientation and ionic conduction. Water molecules are dipolar in nature and try to follow the electric field which alternates at very high frequency. For a commonly used microwave frequency of 2450 MHz, the electric field changes directions 2.45 billion times a second, making the dipoles move with it (Kumar 2015). Such rotation of molecules produces friction and generate heat inside the food material (Zhang, Jiang, and Lim 2010). Food materials, especially fruits and vegetables, contain about 80% of dipolar water. Therefore, microwave can generate significant volumetric heat. The second major mechanism is ionic conduction. The ions, particularly in salty foods, migrate under the influence of electric field migrate and generate heat. Figure 1 shows the two heating mechanism in the frequency region used in industry for heating and drying.

3. Continuous microwave-convective drying (CMCD)

An extensive compilation of literature regarding microwave assisted convective drying of food is presented in Table 1. The second column of Table 1 represents the drying time savings for different studies when compared to convective drying. The percentage of drying time savings were calculated by dividing the reduction in drying time compared to convective drying with the total convection drying time. A substantial drying time saving was reported by (Sadeghi, Mirzabeigi Kesbi, and Mireei 2013), where they reported that the convection drying of lemon slice at 50^0C took 1850 min, whereas microwave convective drying with specific microwave power 2.04 W/g took only 44 min. This is an enormous saving in drying time, accounting 97%. Another considerable drying time saving was reported by McMinn et al. (2003) which is approximately 96% for lemon slice drying using MCD. Other significant drying time savings using MCD was reported by Prabhanjan et al. (1995) for carrot (82%), Bantle et al. (2013) for clipfish (90%), Gowen et al. (2008) for soybean (62.5%). Nevertheless, the drying time savings may differ with the microwave power level. The higher the microwave power, the more the drying time savings. However, the higher power level can damage or overheat the product and eventually degrade the food quality. Therefore, the microwave power should be taken into consideration when applying CMCD drying. In summary, it can be concluded that substantial reduction in the drying time (25–90%) have been achieved in MCD drying when compared with convection drying (Prabhanjan, Ramaswamy, and Raghavan 1995, Izli and Isik 2014, Cinquanta et al. 2013). However, as mentioned earlier, heat sensitive food materials like banana may char due to overheating. In that case, the microwave should be applied carefully to avoid quality degradation in CMCD.

Microwave assisted drying also applied to non-food material like wood (Lehne, Barton, and Langrish 1999), kaolin (Kowalski, Musielak, and Banaszak 2010), brick (Turner and Jolly 1991), agglomerated sand (Hassini, Peczalski, and Gelet 2013) and found to be helpful in terms of energy efficiency and product quality. Regarding quality of non-food materials, MCD dried products resulted in superior quality when compared to hot air drying (Argyropoulos, Heindl, and Müller 2011, Cinquanta et al. 2013). Jindarat et al. (2011) also found that using microwave energy in drying of a non-hygroscopic porous packed bed reduced drying time by five times when compared to convective drying method. From the above discussion, it can be said that MCD is a potential option to achieve a better quality of dried food and a reduction in drying time.

The third column of Table 1 indicates the availability of modeling work of the relevant study and types of model, i.e. whether they applied Lambert's law or Maxwell's equation for microwave power absorption. More details of the modeling work including Lambert's Law and Maxwell's equation are discussed in the modeling section of this paper presented in section 5.

However, supplying continuous microwave energy to heat sensitive material like food may cause uneven heating or overheating or even create hot spots and cold spots (Kumar et al. 2014). Heat and mass transfer should be carefully balanced to avoid such overheating (Gunasekaran 1999). This problem could be overcome by applying microwave energy intermittently. Intermittency also allows limiting the temperature rise and moisture redistribution which improves product quality and energy efficiency (Soysal et al. 2009a).

4. Intermittent Microwave-Convective Drying (IMCD)

Table 2 summarizes the studies relevant to Intermittent Microwave-Convective Drying (IMCD). Intermittent application of microwave energy in convective drying is more advantageous than continuous application and can overcome the problems of overheating and

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uneven heating. This has been demonstrated in different studies shown on Table 2. For instance, Soysal et al. (2009a) reported that IMCD of red pepper produced better sensory attributes, appearance, color, texture and overall liking, than MCD and commercial drying. Soysal et al. (2009b) compared IMCD and convective drying for oregano and found that the IMCD was 4.7–11.2 times more energy efficient compared to convective drying and was able to provide better quality dried food.

Advantages of IMCD in terms of improving energy efficiency and product quality, and significantly reducing drying time have been found in many other products such as Oregano (Soysal, Arslan, and Keskin 2009b), Pineapple (Botha, Oliveira, and Ahrné 2012), Red Pepper (Soysal et al. 2009a), Sage Leaves (Esturk 2012, Esturk et al. 2011), Bananas (Ahrné et al. 2007), and Carrots and Mushrooms (Orsat et al. 2007).

The second and third column of Table 2 presents an overview of modeling studies regarding IMCD. It can be seen from the table that there are very limited studies regarding modeling of IMCD, which has been discussed more details in section 7.

5. Mathematical Modeling of MCD

Mathematical models can be used to predict the internal temperature that is difficult to measure and control the microwave power to avoid overheating. As discussed in section 2 that microwave generate volumetric heat inside the sample and this heat generation needs to be added in energy equation when modeling MCD process. Thus the theoretical investigation of MCD consists of two parts. The first part is the calculation of microwave power absorption that converted into

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heat and the second part is solving the conjugate heat and mass transfer for drying. This section discusses both microwave power absorption and heat and mass transfer during MCD drying.

5.1 Modeling of MW power absorption

In MCD model, heat generation analysis is crucial for accurate estimation of the temperature of the sample. Volumetric heat generation depends on the dielectric properties of the material, and the frequency and intensity of the applied microwave. There is plethora of studies regarding calculation of power distribution or heat generation due to microwave. In the previous studies electromagnetic field inside the product was assumed to be (i)uniform; (ii) exponentially decayed; (iii)decayed following empirical relations; (iv)decayed following Lambert’s relation and (v)decayed calculated by solving electric field equations (Maxwell’s equations). Among them, Lambert’s Law and Maxwell’s equations are most commonly used in microwave assisted drying.

5.1.1 Lambert’s Law

Microwave energy distribution in food products with basic geometries (slabs, spheres, and cylinders) is calculated by using Lambert’s Law. Especially in drying, application of this law is more common (Arballo, Campanone, and Mascheroni 2012, Mihoubi and Bellagi 2009, Zhou et al. 1995, Salagnac, Glouannec, and Lecharpentier 2004, Abbasi Souraki and Mowla 2008, Hemis, Choudhary, and Watson 2012, Khraisheh, Cooper, and Magee 1997).

Lambert’s Law considers exponential attenuation of microwave absorption within the product, via the following relationship.

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$$\mathrm{P}(\mathrm{x})=\mathrm{P_0}\exp^{(-2\alpha\mathrm{x})} \qquad (1)$$

Here, P_0 the incident power at the surface (W), α is he attenuation constant (1/m), and x represents the distance from surface (m). The measurement of P_0 is generally obtained via experimentation.

The attenuation constant, α is given by the following equations

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

where λ is the wavelength of microwave in free space ($\lambda = 12.24 cm$ at 2450 MHz and air temperature 20^0C) and ε' and ε'' are the dielectric constant and dielectric loss, respectively. The volumetric heat generation, Q_{mic} (W/m^3) in Equation (3) is then calculated by:

$$Q_{mic} = \frac{P_{mic}}{V}, \qquad (3)$$

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

However, Lambert's Law does not accurately predict the heating situation and electric field distribution (Rakesh et al. 2009, Chandrasekaran, Ramanathan, and Basak 2012). Recently, Kumar et al. (2015) developed a mathematical model for IMCD drying using Lambert's law and highlighted the limitations of Lambert's law. They mentioned that the microwave absorption should reduce with decreasing moisture content, but the Lambert's Law fails to take this into account, giving highest power at the surface irrespective of moisture content.

During the 1970s and 1980s most of the power absorption calculation was based on Lambert's law. However, during the early 1990s, theoretical foundation of combined electromagnetic and thermal transport using Maxwell's equations has been established. Chandrasekaran, Ramanathan et al. (2012) reviewed the comparison between Lambert's law and Maxwell's equation; they reported that Maxwell's equation give exact and more accurate solution for microwave propagation in samples.

5.1.2 Maxwell's Equations

Maxwell's equations are a set of partial differential equations of electrodynamics which represent a fundamental unification of electric and magnetic fields for predicting electromagnetic wave propagation. Physicist and engineers use computers ranging from simple desktop machines to massively parallel supercomputing arrays for solving these equations to investigate waveguiding, radiation, scattering, and heating(Zhao 1997).

Maxwell's equations that govern the propagation and microwave heating of material are given below:

$$\nabla \times E = \frac{\partial B}{\partial t} \quad (4)$$

$$\nabla \times H = \frac{\partial D}{\partial t} + J_c \quad (5)$$

$$\nabla . B = 0 \quad (6)$$

$$\nabla . D = \rho \quad (7)$$

Where E is electric field distribution (V/m), D is electric flux density distribution (C/m^2), H is magnetic field distribution (A/m), B is magnetic flux density distribution (W/m^2), J_c current density (A/m^2), ρ is volume charge density (C/m^3).

In frequency domain time harmonic Maxwell's equations can be written as

$$\nabla \times \left(\frac{1}{\mu'} \nabla \times E \right) - \frac{\omega^2}{c} \left(\varepsilon' - i \varepsilon'' \right) E = 0 \quad (8)$$

where $\vec{E}$ is the electric field strength (V/m), f is the microwave frequency (Hz), c is the speed of light (m/s), $\varepsilon', \varepsilon'', \mu$ are the dielectric constant, dielectric loss factor, and electromagnetic permeability of the material, respectively.

The heat generation due to microwave, Q_m (W/m^3), given by (COMSOL 2012),

$$Q_m = Q_{rh} + Q_{ml} .. \quad (9)$$

Here, Q_{rh} is the resistive loss (W/m^3) and Q_{ml} is the magnetic loss (W/m^3). For food products the magnetic losses are negligible, i.e. $Q_{ml} = 0$ (Chen et al. 2014).

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The resistive loss can be calculated as (Chen et al. 2014, Wentworth 2004)

$$Q_{rh} = 0.5 \cdot \vec{J} \cdot \vec{E}^{*} \qquad (10)$$

where $\vec{E}^{*}$ is the conjugate of $\vec{E}$ and the electric current density $\vec{J}$ (A/m^2) is given by,

$$\vec{J} = \sigma \cdot \vec{E} = 2\pi f \varepsilon_0 \varepsilon'' \cdot \vec{E}, \qquad (11)$$

where, σ is the electrical conductivity (S/m), ε'' is the dielectric loss factor and ε_0 is permittivity in free space.

Substituting the above into equation (12), the microwave heat generation due to can be written as,

$$Q_m = \pi f \varepsilon_0 \varepsilon'' |E|^2 \qquad (12)$$

which conforms with the heat generations equation derived by Metaxas (1996a).

5.2 Dielectric properties

Dielectric properties such as dielectric constant and dielectric loss factor define how materials interact with electromagnetic energy. These properties of materials define how much microwave energy will be converted to heat (Chandrasekaran, Ramanathan, and Basak 2013). As can be seen from the heat generation formulation above, the dielectric properties of the material are one of the most important parameters in calculating microwave heat generation during drying (Sosa-Morales et al. 2010). Therefore, the evaluation of dielectric properties is critical in modeling and product and process development (Ikediala et al. 2000).

5.3 Heat and mass transfer modeling in MCD

Heat and mass transfer models are necessary for evaluating the effect of process parameters on energy efficiency and drying time, and optimizing the drying process (Kumar et al. 2012a, Kumar, Karim, and Joardder 2014). Developing a physics based drying model for agricultural products is a challenging task due to the complex structural nature of agricultural products and changes in the thermo-physical properties during drying. Moreover, the heat generation due to microwave in MCD makes the modeling more challenging. Therefore, some assumptions are indispensable if mathematical models are to be developed, but these should be carefully made to represent the physical phenomena during the process. In this section, the modeling approaches of heat and mass transfer in MCD are discussed, and their limitation are highlighted. The MCD drying models available in literature can be classified into two categories: empirical models, fundamental models. The fundamentals models again then categorized into three divisions based on their water transport mechanisms: 1) single phase, 2) double phase and 3) multiphase models as shown in Figure 2.. In the following sections, the model based on these classification are discussed and analysed.

5.3.1 Empirical model

The empirical models are generally derived from Newton's law of cooling and Fick's law of diffusions (Erbay and Icier 2010). These are simpler to apply and often used to describe the drying curve. The drying constant and coefficients in the empirical models are developed with regression analysis. Page model and exponential model are frequently used in microwave convective drying. Table 1 and Table 2 present the empirical model of CMCD and IMCD available in the literature. There are many different empirical models often referred as thin layer drying models such as Newton, Page, Henderson Pabis, Logarithmic, two term, two-term exponential, and Wang and Sing models. The acceptability of these models are usually determined by the coefficient of determination R^2, and the reduced value of the mean square of deviation χ^2. They do not provide physical insight into the process. Also, these models are only valid for specific process condition and material. In contrast to empirical models, the physics-based models can capture the inherent drying mechanism better (Chou et al. 2000, Ho et al. 2002, Chua, Mujumdar, and Chou 2003). The theoretical models often can be used for wide range of process parameter and can be used for parametric analysis and optimization.

5.3.2 Single phase model

The single phase models consider only one phase in food domain i.e. liquid water diffusion through the solid media. These are often called diffusion-based models and are very popular because of their simplicity and good predictive capability (Arballo, Campañone, and Mascheroni 2010, Perussello et al. 2014, Kumar et al. 2012b). Maybe due to this reason, most of the model related to microwave assisted drying are single phase. These models assume conductive heat transfer for energy and diffusive transport for moisture.

The single phase model considers only diffusive water transport as shown in the equation (13).

$$\frac{\partial c_w}{\partial t} + \nabla \cdot (-\mathrm{D}_{\mathrm{eff}} \nabla c_w) + \mathrm{u} \cdot \nabla c_w = 0 \qquad (13)$$

where, c_w is the moisture concentration (mol/m^3), D_{eff} is the effective diffusion coefficient (m^2/s) and u is the convective flow. The effective diffusion coefficient, D_{eff} , in those models has to be determined experimentally. Thus this model can be said as a semi-empirical model.

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The energy balance was characterized by a Fourier flux with a heat generation term due to microwave heating, Q_{mic} (W/m3).

$$\rho c_p \frac{\partial T}{\partial t} = \nabla.(k\nabla T) + Q_{mic} \qquad (14)$$

where, T is the temperature (^{0}K), ρ is the density of sample (kg/m^3), c_p is the specific heat (J/kgK), and k is the thermal conductivity (W/mK). The heat generation, Q_{mic} (W/m^3), was calculated using Lambert's Law.

In the case of microwave heating or drying, the effective diffusivity increases due to volumetric heating which cause pressure driven flow. This pressure driven flow is lumped together with diffusion in case of single phase models. Therefore it can be said that although this model can provide a good match with experimental results, it cannot provide an understanding of other transport mechanisms such as pressure driven flow and evaporation. This is because all water are lumped in one parameter, diffusion coefficient, cannot provide individual contribution of the water flux. The drawbacks of these kinds of models are discussed in detail in the work of Zhang and Datta (2004). Lumping all the water transport as diffusion cannot be justified under all situations. Therefore, multiphase models considering transport of liquid water, vapour, air inside the food materials are considered to be more realistic.

5.3.3 Double phase model

Double phase models consider two species, namely water vapour and liquid water for mass transfer during the modeling process. These models are comparatively more realistic and comprehensive than single-phase models because of the incorporation of evaporation or phase change between liquid water and water vapour. The general governing equation for double phase model is presented in Eq. (15) and (16).

$$\text{Liquidphase of water}: \frac{\partial c_l}{\partial t} + \nabla \cdot \left(-D_l \nabla c_l \right) + u_l \cdot \nabla c_l = -R \quad (15)$$

$$\text{Vapour phase of water}: \frac{\partial c_v}{\partial t} + \nabla \cdot \left(-D_v \nabla c_v \right) + u_v \cdot \nabla c_v = R \quad (16)$$

Here the c_l and c_v are the concentration of liquid water and water vapour, D_l and D_v are the diffusion coefficient for liquid water and water vapour and u_l and u_v are the convective flow of liquid water and vapour. The R is the production or consumption of species (i.e. evaporation or condensation). Malafronte et al. (2012) estimated the evaporation rate as,

$$R = \begin{Bmatrix} k_c \left(c_{sat}(T) - c_v \right) \\ 0 \end{Bmatrix} \text{when,} \quad \begin{matrix} c_{sat} > c_v \\ c_{sat} \le c_v \end{matrix} \quad (17)$$

Where $c_{sat}(T) = \frac{MP_v(T)}{RT}$ and vapour pressure was calculated from Antoine's equation.

There are some two phase models in MCD drying process. For example, Malafronte et al. (2012) developed a two phase models for combined microwave convective drying. The strong point of the model is that they took moisture and temperature dependent dielectric properties. Moreover, they solved both heat and mass transport equations and Maxwell's equations in transient regime. Marra et al. (2010) also developed a two phase model for combined microwave convective drying. The main strong point of their model is that they considered conjugate approach of heat and mass transfer, which enabled to calculate realistic heat and mass transfer coefficient without requiring empirical average based calculations. Jindarat et al. (2011) also considered two phase transport. However, the deformation or shrinkage have not been considered in all these models. Moreover, the available model considering two phase neglected the Darcy or pressure driven flow i.e. bulk flow. Multiphase models discussed below have considered bulk flow.

5.3.4 Multiphase porous media model

The multiphase models consider all phases inside the food materials namely water, air, water vapour and solid matrix. Multiphase models can be categorised into two groups: equilibrium and non-equilibrium approach of vapour pressure. In equilibrium formulations, the vapour pressure, p_v, is assumed to be equal to equilibrium vapour pressure, $p_{v,eq}$, and vice versa. There are some multiphase models considering equilibrium approach applied in vacuum drying of wood (Turner and Perré 2004) and convection drying of wood and clay (Stanish, Schajer, and Kayihan 1986) (Chemkhi, Jomaa, and Zagrouba 2009), microwave spouted bed drying of apple (Feng et al. 2001) and large bagasse stockpiles (Farrell et al. 2012). Some multiphase porous media models combine the liquid water and vapour equations together to eliminate the evaporation rate term (Ratanadecho, Aoki, and Akahori 2001, Farrell et al. 2012, Suwannapum and Rattanadecho 2011). By doing this, the concentrations of liquid water and vapour cannot be determined separately (Kumar et al. 2016).

However, equilibrium condition may be valid at the surface with lower moisture content because equilibrium condition may not be achieved due to lower moisture content at the surface during drying. Therefore, the non-equilibrium approach is a more realistic representation of the physical

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situation during drying (Zhang and Datta 2004). Moreover, the non-equilibrium formulation for evaporation can be used to express explicit formulation of evaporation, thus allowing calculation of each phase separately. Furthermore, non-equilibrium multiphase models are computationally effective and applied to wide range of food processing such as frying (Ni and Datta 1999, Bansal, Takhar, and Maneerote 2014), microwave heating (Rakesh et al. 2010, Chen et al. 2014), puffing (Rakesh and Datta 2013) baking (Zhang, Datta, and Mukherjee 2005), meat cooking (Dhall and Datta 2011) etc. However, application of these non-equilibrium models in drying of food materials is very limited.

There are some multiphase models in MCD process. Most recently, Kumar et al. (2016) developed a multiphase model for IMCD of apple. They considered non-equilibrium approach and applied Lambert's law to calculate microwave heat generation. Dinčov et al. (2004) developed a Finite volume multiphase porous media model where the coupling was achieved by considering dielectric properties as a function of moisture and temperature. Zhu et al. (2015) developed a comprehensive multiphase model of microwave drying of sphere. The governing equation used to develop the multiphase model are summarised in Table 3 (Kumar et al. 2016).

6. Experiments in MCD drying

This section discusses the experimental procedures used in literature for MCD. The limitation and strength of the experimental facilities are analysed and recommendations for future experimental setup and challenges in scaling up MCD experimental facility are suggested.

The main components of an MCD drying test facility are: 1 variable power microwave generator (magnetron), 2. waveguide, 3. microwave cavity and 4. A heating source for hot air supply (Tulasidas 1995). Microwave generator can be a variety of devices such as magnetrons, klystrons, power grid tubes, traveling wave tubes, and gyrotrons, but the most commonly used source is the magnetron, which is more efficient, reliable, and available at lower cost than other sources (National Research Council 1994). Microwave generated in magnetron is guided through waveguides to the cavity where the materials are placed. At the same time hot air needs to be supplied to the cavity to combine with the convective drying. The MCD drying set ups can be classified into two main categories based on the cavity type: single mode cavity and multimode cavity (Chandrasekaran et al., 2011).

6.4 Experimental process with single mode cavity

Single mode cavities are used when precise focus at a given location is needed. For these cavities, the transverse electric (TE or H) waves and transverse magnetic (TM or E) waves are commonly used which are designed either rectangular or circular cross section. The electric intensity in the direction of propagation is zero for the TE wave whereas, for the TM wave, the magnetic intensity in the direction of propagation is zero (Chandrasekaran, Ramanathan, and Basak 2012). Single mode applicators are used extensively where the load conditions can be kept constant (and thus repeated tuning is not required). These conditions are present in heating a fluid stream, for example, whereby the fluid flows through the applicator such that its properties are relatively constant.

A basic single mode applicator setup has been shown in Figure 3.. The waveguide circulator (as in Figure 3) is a three-port device ideally having no power attenuation capability. Because circulators are not designed to absorb power, a separate "dummy" load is connected to the circulator and used to absorb reverse power that may otherwise damage the magnetron (Gerling, 2000).

Impedance matching is usually achieved using three manual stub tuners, which are used to alter the capacitance of the waveguide system (Gerling, 2000). As an example, two strawberries of slightly different shape would require different stub tuner settings (position and penetration depth) for optimum impedance matching. Furthermore, the same strawberry at different drying stages (and thus different moisture contents) may require a drastic change in stub tuner settings to keep the strawberry matched with the load. Failure to match two impedances results in poor microwave power coupling with the load.

There are many other studies that used specially designed single mode applicator in their study (Holtz et al. 2009, Holtz et al. 2010, Malafronte et al. 2012). The drying equipment (as shown in Figure 4) comprised of a straight aluminum waveguide (8643 mm) fitted with an air-cooled magnetron (2.45 GHz, 2M244-M16, Panasonic, Cwmbran, U.K.). The drying cavity was situated inside the waveguide. Between the magnetron and waveguide a three-stub tuner (stainless steel) were incorporated, and the far end of the waveguide was adjustable, enabling the length of the waveguide to be adjusted.

Jindarat et al. (2011) analysed energy efficiency of microwave convective drying using a TE_{10} mode microwave convective dryer for porous packed bed. Figure 5 shows the experimental setup using a rectangular waveguide with dimension of 110mm ×55mm. The isolator was used to trap microwave reflection from sample to save magnetron. The temperature at various point of sample was measured by fiber optic probes.

In conclusion of single of cavity discussion, it can be said that the experimental setup with a single model cavity are mainly designed for studying the physics involved rather than being optimized for a drying process. In these setups, coupling microwave power to a load requires the respective complex impedances between the load and the microwave power source to be matched. This is the greatest disadvantage of a single mode applicator, since the complex impedance of the load changes with geometry, chemical composition and temperature (Gerling, 2000). Precision control or target heating can be achieved with single mode applicator. However, the multimode applicator is being widely used in the industrial system.

6.5 Experimental process with multimode mode cavity

Multimode microwave applicators are closed volume, totally surrounded by conducting walls and have a large cavity to permit more than one mode (pattern) of the electric field (Funebo and Ohlsson 1998). Unlike single mode applicators, multimode applicators are less sensitive to product position or geometry (Chandrasekaran, Ramanathan, and Basak 2013). Figure 6 shows a multimode cavity with hot air inlet and outlet for drying of pumpkin (Wang, Wang, and Yu 2007). Many drying researches used modified household microwave oven as a multimode applicator. Wang et al. (2007) used a laboratory microwave oven with an outlet at the upper left side of the oven to allow exhaust of moist air as shown in Figure 6. One dish, containing the sample, was placed at the center of a turntable fitted inside (bottom) the microwave cavity.

Moisture loss was recorded at 5 min intervals during drying, measured by taking out and weighing the dish on the digital balance (JY1000, 1 000 ± 0.01 g). However, taking the sample out may cause some error in moisture measurement. The major limitation of this study was that there was no temperature measurement of the sample. Therefore, it was difficult to monitor the overheating of the samples.

Figure 7 shows a modified microwave (900 W, 2450MHz), having an inside chamber with dimensions of (345 × 335 × 220) which was used to dry Oregano (Soysal, Arslan, and Keskin 2009b, Soysal et al. 2009a). Two rectangular opening (10 × 8cm^2) was made on the back and top wall to supply and exit hot air respectively. The heated air was forced into the drying chamber by a radial fan (100 W, 180m^3/h). A potentiometer was used to control the speed of the fan. Continuous monitoring of the weight was done with a digital balance (Sartorius TE3102S, Germany, 3100±0.01 g) that was placed under the rotating glass tray (diameter: 314 mm, mass: 1150 g). A programmable logic controller (PLC) system was used to control the intermittence time, the fan and the glass turntable. The temperature of the air inside the air duct was measured using a PT100 platinum resistance temperature sensor. The glass turntable on which the material was placed continuously turned (5 rpm) during the drying procedure to obtain a uniform distribution of the microwave energy in the material, and to assure homogenized drying. This drying system is impressive because it is equipped with temperature, moisture, and air velocity measurement system. However, one limitation could be the uneven airflow distribution in the drying chamber. As the air enters at the bottom and exit at the top, this may result in uneven airflow or poor airflow distribution over the product. Moreover, the temperature distribution can be uneven in microwave so it is better to use thermal imaging camera in multimode cavity rather than point measurement using thermocouple.

Uprit and Mishra (2003) used a modified programmable domestic microwave oven (IBM, Model Electron), with a maximum output of 625W at 2450MHz and cavity (drying chamber) dimensions of 300 × 240 × 210mm as shown in Figure 8 for soy-fortified paneer drying. Moisture loss in the sample was measured by on-line weight recording at 3 min interval. The temperature and relative humidity of the exhaust air were measured periodically using a digital hygrometer (ALMEMO, Germany). The material is assumed to reach equilibrium moisture content when the material acquired a constant weight. They paid special attention to avoid charring of the product which is difficult without measuring the temperature of the product. Because microwave heating is fast and volumetric, their visual inspection may not be sufficient to predict the commencement of charring.

Andrés et al. (2004) performed experiments in a specially designed hot air–microwave oven equipped with continuous microwave energy (Figure 9). They varied microwave power and air temperature with constant air velocity at 1 m/s.

Ahrné et al. (2007) The drying experiments were performed in a dryer (Figure 10) specially designed in the framework of the European Union project ICA4-CT-2002-10034 by P.O. Risman in collaboration with SIK and constructed by TIVOX machine AB (TIVOX Maskin AB, Sweden). It can be operated with a temperature of 40--80^{0}C and air velocity of 0.3-0.8m/s. The product temperature was measured by fiber-optic temperature sensors (ReFLexTM, Neoptix, Canada) placed in four samples located at different positions of the dryer. The fiber optic temperature probes give temperature at a point which may sometimes deceive in microwave heating experiments since microwave generates uneven heating with hot spot and cold spot in the sample. Instead of point measurement, Kowalski, Musielak et al. (2010) used a thermal imager to measure 2D surface temperature (Figure 11) which can provide more detail information of surface temperature of the sample.

Kowalski, Musielak et al. (2010) used a microwave oven with cavity dimensions 300 × 400 × 450 which can supply maximum power of 600W. They found that temperature was higher in the middle of the sample. In their setup, air with 22^0C was supplied with installed mechanical ventilation system. However, from Figure 11, it is not clear where the ventilation system was placed and how efficiently it worked. Air flow is important because reduced airflow may results moisture accumulation at the surface of the sample which reduces drying rate and degrades sample texture for food application.

In contrast, Fu et al. (2005) developed dryer to operate at an air velocity of 1--3 m/s to provide sufficient airflow to the drying chamber (Figure 12). The air was drawn with an axial fan through cutting vent on the microwave wall. However, one should make sure that the microwave leakage is less than the allowable limit (5 mW/cm^2) through that vent.

Temperature and moisture are the two main parameters need to be measured accurately during the drying process. The efficacy of an experimental setup depends on how accurately these two parameters can be measured. Additionally, the air velocity distribution plays an important role in drying rate because it affects the heat and mass transfer coefficient which is essential for modeling.

The major problem with multimode applicators is non-uniformity of the microwave field in the load which causes non-uniform heat distribution. This problem can be minimised by providing a mode stirrer (rotating metal bladed fan) or turntable (Schiffmann 1995). The effect of mode stirrers in a multimode microwave heating applicator are investigated by Kurniawan et al. (2015) using 3D COMSOL Multiphysics Simulation. They have found that the temperature distribution is more uniform for the case with mode stirrers compared to that obtained without mode stirrers. Implementing intermittency in microwave application is another technique to reduce non-uniform heating of the sample.

In summary, the experimental facilities for a MCD should be equipped with continuous weight monitoring, temperature monitoring such as thermal imaging camera, and have uniform airflow distribution in the chamber. In addition, the safety of the setup is another critical issue. Because the microwave leakage can cause damage to human cell and tissues and cause cataracts. Therefore, the design of vent or any perforation should be carefully handled while designing and manufacturing microwave assisted dryer.

7. Challenges and future direction for research

The major challenge in microwave system is the non-uniformity of electric field. Future research should involve addressing this problem focusing on obtaining more uniform electric filed distribution thus to obtain uniform temperature and moisture distribution. One potential solution could be using multiple magnetrons at appropriate locations of the chamber. Mathematical modeling and simulation would be essential to do such investigations. The plant based food materials are hygroscopic in nature, containing free water and bound water. The transport mechanisms of free water and bound water are different. Therefore, the future modeling study of MCD should include a separate mechanism for the transport of free and bound water. Moreover, the models should be able to predict the effect of process parameters on drying kinetics, then the models can be used to optimize the process and suggest an appropriate strategy of applying MCD to avoid overheating and gaining maximum food quality with minimum energy usage.

8. Conclusion

The present study provides an overview of MCD process focusing on drying kinetics, experimental process and mathematical modeling. Moreover, the comparative study of drying time between microwave assisted drying and convective drying for different materials are calculated and discussed. It is clear that drying time saving can be up to 90% by applying microwave. Considering this huge drying time saving of MCD, there is enourmous potential of this process in industrial applications. The critical review of experimental facilities showed that the experimental facilities should be equipped with real time moisture and temperature measurement of the sample, and should have uniform airflow distribution. The risk and safety issues of creating vent for airflow in microwave cavity was investigated. Although the setup with a single mode cavity can provide an understanding of physics, their performance is sensitive to product position and geometry. In contrast, multimode cavities are less sensitive to product position or geometry but provide uneven heating. However, these uneven heat can be minimized by applying microwave intermittently, providing turntable or model stirrers and by suitable cavity design. Continuous microwave-convective drying may overheat and damage quality which can be overcome by intermittent microwave-convective drying by applying appropriate power level and pulse ratio. The mathematical modeling can help to optimize intermittency and power level of microwave for better product quality and energy efficiency. One major disadvantage of microwave application is the non-uniform heating due to standing wave pattern. A comprehensive multiphase mathematical model can also help in selecting magnetron size, position and cavity shape in order to obtain more uniform heating pattern. Therefore, the future research should focus on scaling up and optimizing this technology for industrial applications.

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9. References

Abbasi Souraki, B., and D. Mowla. 2008. "Experimental and theoretical investigation of drying behaviour of garlic in an inert medium fluidized bed assisted by microwave." *Journal of Food Engineering* 88 (4):438-449. doi: 10.1016/j.jfoodeng.2007.12.034.

Ahrné, L. M., N. R. Pereira, N. Staack, and P. Floberg. 2007. "Microwave Convective Drying of Plant Foods at Constant and Variable Microwave Power." *Drying Technology* 25 (7-8):1149-1153. doi: 10.1080/07373930701438436.

Andrés, Ana, Cristina Bilbao, and Pedro Fito. 2004. "Drying kinetics of apple cylinders under combined hot air–microwave dehydration." *Journal of Food Engineering* 63 (1):71-78. doi: 10.1016/s0260-8774(03)00284-x.

Arballo, J. R., L. A. Campanone, and R. H. Mascheroni. 2012. "Modeling of Microwave Drying of Fruits. Part II: Effect of Osmotic Pretreatment on the Microwave Dehydration Process." *Drying Technology* 30 (4):404-415. doi: 10.1080/07373937.2011.645100.

Arballo, Javier R., Laura A. Campañone, and Rodolfo H. Mascheroni. 2010. "Modeling of Microwave Drying of Fruits." *Drying Technology* 28 (10):1178-1184. doi: 10.1080/07373937.2010.493253.

Argyropoulos, Dimitrios, Albert Heindl, and Joachim Müller. 2011. "Assessment of convection, hot-air combined with microwave-vacuum and freeze-drying methods for mushrooms with regard to product quality." *International Journal of Food Science & Technology* 46 (2):333-342. doi: 10.1111/j.1365-2621.2010.02500.x.

 ACCEPTED MANUSCRIPT

Bansal, Harkirat S., Pawan S. Takhar, and Jirawan Maneerote. 2014. "Modeling multiscale transport mechanisms, phase changes and thermomechanics during frying." *Food Research International* 62:709-717. doi: 10.1016/j.foodres.2014.04.016.

Bantle, Michael, Timo Käfer, and Trygve M. Eikevik. 2013. "Model and process simulation of microwave assisted convective drying of clipfish." *Applied Thermal Engineering* 59 (1–2):675-682. doi: http://dx.doi.org/10.1016/j.applthermaleng.2013.05.046.

Bhattacharya, Mrittika, PremPrakash Srivastav, and HariNiwas Mishra. 2013. "Thin-layer modeling of convective and microwave-convective drying of oyster mushroom (Pleurotus ostreatus)." *Journal of Food Science and Technology*:1-10. doi: 10.1007/s13197-013-1209-2.

Botha, G. E., J. C. Oliveira, and L. Ahrné. 2011. "Quality optimisation of combined osmotic dehydration and microwave assisted air drying of pineapple using constant power emission." *Food and Bioproducts Processing* 90 (2):171-179.

Botha, G. E., J. C. Oliveira, and L. Ahrné. 2012. "Microwave assisted air drying of osmotically treated pineapple with variable power programmes." *Journal of Food Engineering* 108 (2):304-311. doi: 10.1016/j.jfoodeng.2011.08.009.

Campañone, L. A., and N. E. Zaritzky. 2005. "Mathematical analysis of microwave heating process." *Journal of Food Engineering* 69 (3):359-368. doi: 10.1016/j.jfoodeng.2004.08.027.

Chandrasekaran, S., S. Ramanathan, and T. Basak. 2012. "Microwave material processing-a review." *AIChE Journal* 58 (2):330-363.

ACCEPTED MANUSCRIPT

Chandrasekaran, S., S. Ramanathan, and Tanmay Basak. 2013. "Microwave food processing—A review." *Food Research International* 52 (1):243-261.

Chemkhi, Saber, Wahbi Jomaa, and Féthi Zagrouba. 2009. "Application of a Coupled Thermo-Hydro-Mechanical Model to Simulate the Drying of Nonsaturated Porous Media." *Drying Technology* 27 (7-8):842-850. doi: 10.1080/07373930903021477.

Chen, Jiajia, Krishnamoorthy Pitchai, Sohan Birla, Mehrdad Negahban, David Jones, and Jeyamkondan Subbiah. 2014. "Heat and Mass Transport during Microwave Heating of Mashed Potato in Domestic Oven—Model Development, Validation, and Sensitivity Analysis." *Journal of Food Science* 79 (10):E1991-E2004. doi: 10.1111/1750-3841.12636.

Chong, ChienHwa, Adam Figiel, ChungLim Law, and Aneta Wojdyło. 2014. "Combined Drying of Apple Cubes by Using of Heat Pump, Vacuum-Microwave, and Intermittent Techniques." *Food and Bioprocess Technology* 7 (4):975-989. doi: 10.1007/s11947-013-1123-7.

Chou, S. K., K. J. Chua, A. S. Mujumdar, M. N. A. Hawlader, and J. C. Ho. 2000. "On the Intermittent Drying of an Agricultural Product." *Food and Bioproducts Processing* 78 (4):193-203. doi: 10.1205/09603080051065296.

Chua, K. J., A. S. Mujumdar, and S. K. Chou. 2003. "Intermittent drying of bioproducts—an overview." *Bioresource Technology* 90 (3):285-295. doi: 10.1016/s0960-8524(03)00133-0.

Cinquanta, L., D. Albanese, A. Fratianni, G. La Fianza, and M. Di Matteo. 2013. "Antioxidant activity and sensory attributes of tomatoes dehydrated by combination of microwave and convective heating." *Agro Food Industry Hi-Tech* 24 (6):35-38.

COMSOL. 2012. "RF Module User's Guide."

Darvishi, H., M. H. Khoshtaghaza, G. Najafi, and F. Nargesi. 2013a. "Mathematical modeling of green Pepper Drying in microwave-convective dryer." *Journal of agricultural science and technology* 15 (3):457.

Darvishi, H., M. H. Khoshtaghaza, G. Najafi, and F. Nargesi. 2013b. "Mathematical Modeling of Green Pepper Drying in Microwave-convective Dryer." *Journal of Agricultural Science and Technology* 15 (3):457-465.

Dev, S. R. S., P. Geetha, V. Orsat, Y. Gariépy, and G. S. V. Raghavan. 2011. "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* 29 (12):1452-1458. doi: 10.1080/07373937.2011.587926.

Dhall, Ashish, and Ashim K. Datta. 2011. "Transport in deformable food materials: A poromechanics approach." *Chemical Engineering Science* 66 (24):6482-6497. doi: http://dx.doi.org/10.1016/j.ces.2011.09.001.

Dinčov, D. D., K. A. Parrott, and K. A. Pericleous. 2004. "Heat and mass transfer in two-phase porous materials under intensive microwave heating." *Journal of Food Engineering* 65 (3):403-412. doi: 10.1016/j.jfoodeng.2004.02.011.

Erbay, Z., and F. Icier. 2010. "A Review of Thin Layer Drying of Foods: Theory, Modeling, and Experimental Results." *Critical Reviews in Food Science and Nutrition* 50 (5):441-464. doi: 10.1080/10408390802437063.

Esturk, O. 2012. "Intermittent and Continuous Microwave-Convective Air-Drying Characteristics of Sage (Salvia officinalis) Leaves." *Food and Bioprocess Technology* 5 (5):1664-1673. doi: 10.1007/s11947-010-0462-x.

Esturk, O., M. Arslan, Y. Soysal, I. Uremis, and Z. Ayhan. 2011. "Drying of sage (Salvia officinalis L.) inflorescences by intermittent and continuous microwave-convective air combination." *Research on Crops* 12 (2):607-615.

Esturk, O., and Y. Soysal. 2010. "Drying Properties and Quality Parameters of Dill Dried with Intermittent and Continuous Microwave-convective Air Treatments." *Tarim Bilimleri Dergisi-Journal of Agricultural Sciences* 16 (1):26-36.

Fang, Shuzheng, Zhengfu Wang, Xiaosong Hu, Fang Chen, Guanghua Zhao, Xiaojun Liao, Jihong Wu, and Y. A. N. Zhang. 2011. "Energy requirement and quality aspects of chinese jujube (zizyphus jujuba miller) in hot air drying followed by microwave drying." *Journal of Food Process Engineering* 34 (2):491-510. doi: 10.1111/j.1745-4530.2009.00372.x.

Farrell, Troy W, John H Knight, Timothy J Moroney, Philip A Hobson, Ian W Turner, and Glenn R Fulford. 2012. "The mathematical modeling of large-scale bagasse stockpiles."

Feng, H., J. Tang, R. P. Cavalieri, and O. A. Plumb. 2001. "Heat and mass transport in microwave drying of porous materials in a spouted bed." *AIChE Journal* 47 (7):1499-1512. doi: 10.1002/aic.690470704.

Feng, Hao, Yun Yin, and Juming Tang. 2012. "Microwave Drying of Food and Agricultural Materials: Basics and Heat and Mass Transfer Modeling." *Food Engineering Reviews* 4 (2):89-106. doi: 10.1007/s12393-012-9048-x.

Figiel, Adam. 2010. "Drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum-microwave methods." *Journal of Food Engineering* 98 (4):461-470. doi: 10.1016/j.jfoodeng.2010.01.029.

Fu, Yi-Chung, Li Dai, and Binghuei B. Yang. 2005. "Microwave finish drying of (tapioca) starch pearls." *International Journal of Food Science & Technology* 40 (2):119-132. doi: 10.1111/j.1365-2621.2004.00898.x.

Funebo, T., and T. Ohlsson. 1998. "Microwave-assisted Air Dehydration of Apple and Mushroom." *Journal of Food Engineering* 38 (3):353-367. doi: 10.1016/S0260-8774(98)00131-9.

Gerling, J.F. 2000. Waveguide components and configurations for optimal performance in microwave heating system. In *Gerling Applied Engineering Inc.*

Gowen, A. A., N. Abu-Ghannam, J. Frias, and J. Oliveira. 2008. "Modeling dehydration and rehydration of cooked soybeans subjected to combined microwave–hot-air drying." *Innovative Food Science & Emerging Technologies* 9 (1):129-137. doi: 10.1016/j.ifset.2007.06.009.

Gulati, Tushar, Huacheng Zhu, Ashim K. Datta, and Kama Huang. 2015. "Microwave drying of spheres: Coupled electromagnetics-multiphase transport modeling with experimentation. Part II: Model validation and simulation results." *Food and Bioproducts Processing* 96:326-337. doi: http://dx.doi.org/10.1016/j.fbp.2015.08.001.

Gunasekaran, Sundaram. 1999. "Pulsed microwave-vacuum drying of food materials." *Drying Technology* 17 (3):395-412. doi: 10.1080/07373939908917542.

Gunasekaran, Sundaram, and Huai-Wen Yang. 2007a. "Effect of experimental parameters on temperature distribution during continuous and pulsed microwave heating." *Journal of Food Engineering* 78 (4):1452-1456. doi: 10.1016/j.jfoodeng.2006.01.017.

Gunasekaran, Sundaram, and Huai-Wen Yang. 2007b. "Optimization of pulsed microwave heating." *Journal of Food Engineering* 78 (4):1457-1462. doi: 10.1016/j.jfoodeng.2006.01.018.

Hassini, Lamine, Roman Peczalski, and Jean-Louis Gelet. 2013. "Combined Convective and Microwave Drying of Agglomerated Sand: Internal Transfer Modeling with the Gas Pressure Effect." *Drying Technology* 31 (8):898-904. doi: 10.1080/07373937.2012.724489.

Hemis, Mohamed, Ruplal Choudhary, and Dennis G. Watson. 2012. "A coupled mathematical model for simultaneous microwave and convective drying of wheat seeds." *Biosystems Engineering* 112 (3):202-209. doi: 10.1016/j.biosystemseng.2012.04.002.

Ho, J. C., S. K. Chou, K. J. Chua, A. S. Mujumdar, and M. N. A. Hawlader. 2002. "Analytical study of cyclic temperature drying: effect on drying kinetics and product quality." *Journal of Food Engineering* 51 (1):65-75. doi: 10.1016/s0260-8774(01)00038-3.

Holtz, Emma, Lilia Ahrné, Therese Häll Karlsson, Michael Rittenauer, and Anders Rasmuson. 2009. "The Role of Processing Parameters on Energy Efficiency during Microwave Convective Drying of Porous Materials." *Drying Technology* 27 (2):173-185. doi: 10.1080/07373930802603334.

Holtz, Emma, Lilia Ahrné, Michael Rittenauer, and Anders Rasmuson. 2010. "Influence of dielectric and sorption properties on drying behaviour and energy efficiency during microwave convective drying of selected food and non-food inorganic materials." *Journal of Food Engineering* 97 (2):144-153. doi: 10.1016/j.jfoodeng.2009.10.003.

Ikediala, JN, J Tang, SR Drake, and LG Neven. 2000. "Dielectric properties of apple cultivars and codling moth larvae." *Transactions of the ASAE-American Society of Agricultural Engineers* 43 (5):1175-1184.

Ilknur, Alibas. 2007. "Microwave, air and combined microwave–air-drying parameters of pumpkin slices." *LWT – Food Science and Technology* 40 (8):1445-1451. doi: 10.1016/j.lwt.2006.09.002.

Izli, Nazmi, and Esref Isik. 2014. "Color and Microstructure Properties of Tomatoes Dried by Microwave, Convective, and Microwave-Convective Methods." *International Journal of Food Properties* 18 (2):241-249. doi: 10.1080/10942912.2013.829492.

Jindarat, W., P. Rattanadecho, and S. Vongpradubchai. 2011. "Analysis of energy consumption in microwave and convective drying process of multi-layered porous material inside a rectangular wave guide." *Experimental Thermal and Fluid Science* 35 (4):728-737. doi: 10.1016/j.expthermflusci.2010.11.008.

Jindarat, W., P. Rattanadecho, S. Vongpradubchai, and Y. Pianroj. 2011. "Analysis of Energy Consumption in Drying Process of Non-Hygroscopic Porous Packed Bed Using a Combined Multi-Feed Microwave-Convective Air and Continuous Belt System (CMCB)." *Drying Technology* 29 (8):926-938. doi: 10.1080/07373937.2011.560318.

Khraisheh, M. A. M., T. J. R. Cooper, and T. R. A. Magee. 1997. "Microwave and air drying I. Fundamental considerations and assumptions for the simplified thermal calculations of volumetric power absorption." *Journal of Food Engineering* 33 (1–2):207-219. doi: 10.1016/s0260-8774(97)00050-2.

Kouchakzadeh, Ahmad, and Sahameh Shafeei. 2010. "Modeling of microwave-convective drying of pistachios." *Energy Conversion and Management* 51 (10):2012-2015. doi: 10.1016/j.enconman.2010.02.034.

Kowalski, Stefan J., Grzegorz Musielak, and Jacek Banaszak. 2010. "Heat and mass transfer during microwave-convective drying." *AIChE Journal* 56 (1):24-35. doi: 10.1002/aic.11948.

Kumar, C. 2015. "Modeling intermittent microwave convective drying (IMCD) of food materials." PhD, Chemistry Physics and Mechanical Engineering, Queenland University of Technology.

Kumar, C., M. U. H. Joardder, T. W. Farrell, G. J. Millar, and M. A. Karim. 2015. "A Mathematical Model for Intermittent Microwave Convective (IMCD) Drying of Food Materials." *Drying Technology* 34 (8):962-973. doi: 10.1080/07373937.2015.1087408.

Kumar, C., M. U. H. Joardder, Troy W Farrell, and A. Karim. 2016. "Multiphase porous media model for intermittent microwave convective drying (IMCD) of food." *International Journal of Thermal Science* 104:304-314. doi: http://dx.doi.org/10.1016/j.ijthermalsci.2016.01.018.

Kumar, C., M. U. H. Joardder, Azharul Karim, Graeme J. Millar, and Zakaria Amin. 2014. "Temperature Redistribution Modeling During Intermittent Microwave Convective

Heating." *Procedia Engineering* 90 (2014):544-549. doi: http://dx.doi.org/10.1016/j.proeng.2014.11.770.

Kumar, C., Azharul Karim, M.U.H Joardder, and G.J. Miller. 2012a. "Modeling Heat and Mass Transfer Process during Convection Drying of Fruit." The 4th International Conference on Computational Methods, Gold Coast, Australia, November 25--28.

Kumar, C., Azharul Karim, Suvash C Saha, Mohammad Uzzal Hossain Joardder, Richard J Brown, and Dipankar Biswas. 2012b. "Multiphysics modeling of convective drying of food materials." Proceedings of the Global Engineering, Science and Technology Conference, Dhaka, Bangladesh, December 28--29,.

Kumar, C., M. A. Karim, and Mohammad U. H. Joardder. 2014. "Intermittent drying of food products: A critical review." *Journal of Food Engineering* 121 (0):48-57.

Kumar, C., Graeme J. Millar, and M. A. Karim. 2016. "Effective Diffusivity and Evaporative Cooling in Convective Drying of Food Material." *Drying Technology* 33 (2):227-237. doi: 10.1080/07373937.2014.947512.

Kurniawan, Harvey, Suresh Alapati, and Woo Seong Che. 2015. "Effect of mode stirrers in a multimode microwave-heating applicator with the conveyor belt." *International Journal of Precision Engineering and Manufacturing-Green Technology* 2 (1):31-36. doi: 10.1007/s40684-015-0004-0.

Lehne, M., G. W. Barton, and T. A. G. Langrish. 1999. "Comparison of experimental and modeling studies for the microwave drying of Ironbark timber." *Drying Technology* 17 (10):2219-2235. doi: 10.1080/07373939908917680.

Malafronte, Loredana, Gaetano Lamberti, Anna Angela Barba, Birgitta Raaholt, Emma Holtz, and Lilia Ahrné. 2012. "Combined convective and microwave assisted drying: Experiments and modeling." *Journal of Food Engineering* 112 (4):304-312. doi: 10.1016/j.jfoodeng.2012.05.005.

Marra, Francesco, Maria Valeria De Bonis, and Gianpaolo Ruocco. 2010. "Combined microwaves and convection heating: A conjugate approach." *Journal of Food Engineering* 97 (1):31-39. doi: 10.1016/j.jfoodeng.2009.09.012.

Marzec, Agata, Hanna Kowalska, and Monika ZadroŻNa. 2010. "Analysis of instrumental and sensory texture attributes of microwave–convective dried apples." *Journal of Texture Studies* 41 (4):417-439. doi: 10.1111/j.1745-4603.2010.00234.x.

McMinn, W. A. M., M. A. M. Khraisheh, and T. R. A. Magee. 2003. "Modeling the mass transfer during convective, microwave and combined microwave-convective drying of solid slabs and cylinders." *Food Research International* 36 (9-10):977-983. doi: 10.1016/s0963-9969(03)00118-2.

Metaxas, A.C. 1996a. *Foundation and Electroheat: A Unified Approach*: John Wiley & Sons.

Metaxas, A.C. 1996b. *Foundations of Electroheat*. Chichester, U.K.: John Wiley and Sons.

Mihoubi, D., and A. Bellagi. 2009. "Drying-Induced Stresses during Convective and Combined Microwave and Convective Drying of Saturated Porous Media." *Drying Technology* 27 (7-8):851-856. doi: 10.1080/07373930902988122.

Mujumdar, Arun S. 2004. "Research and Development in Drying: Recent Trends and Future Prospects." *Drying Technology* 22 (1-2):1-26. doi: 10.1081/drt-120028201.

Nair, Gopu Raveendran, Zhenfeng Li, Yvan Gariepy, and Vijaya Raghavan. 2011. "Microwave Drying of Corn (Zea mays L. ssp.) for the Seed Industry." *Drying Technology* 29 (11):1291-1296. doi: 10.1080/07373937.2011.591715.

National Research Council. 1994. *Microwave Processing of Materials*. New York: National Academy Press.

Ni, H., and A. K. Datta. 1999. "Moisture, Oil and Energy Transport During Deep-Fat Frying of Food Materials." *Food and Bioproducts Processing* 77 (3):194-204. doi: http://dx.doi.org/10.1205/096030899532475.

Orsat, V., W. Yang, V. Changrue, and G. S. V. Raghavan. 2007. "Microwave-Assisted Drying of Biomaterials." *Food and Bioproducts Processing* 85 (3):255-263. doi: 10.1205/fbp07019.

Perussello, Camila Augusto, Chandan Kumar, Fernanda de Castilhos, and M. A. Karim. 2014. "Heat and mass transfer modeling of the osmo-convective drying of yacon roots (Smallanthus sonchifolius)." *Applied Thermal Engineering* 63 (1):23-32. doi: http://dx.doi.org/10.1016/j.applthermaleng.2013.10.020.

Pitchai, K., S. L. Birla, J. Subbiah, D. Jones, and H. Thippareddi. 2012. "Coupled electromagnetic and heat transfer model for microwave heating in domestic ovens." *Journal of Food Engineering* 112 (1–2):100-111. doi: 10.1016/j.jfoodeng.2012.03.013.

Prabhanjan, D. G., H. S. Ramaswamy, and G. S. V. Raghavan. 1995. "Microwave-assisted convective air drying of thin layer carrots." *Journal of Food Engineering* 25 (2):283-293. doi: 10.1016/0260-8774(94)00031-4.

Rakesh, V., A. K. Datta, M. H. G. Amin, and L. D. Hall. 2009. "Heating uniformity and rates in a domestic microwave combination oven." *Journal of Food Process Engineering* 32 (3):398-424. doi: 10.1111/j.1745-4530.2007.00224.x.

Rakesh, V., Youngseob Seo, Ashim K. Datta, Kathryn L. McCarthy, and Michael J. McCarthy. 2010. "Heat transfer during microwave combination heating: Computational modeling and MRI experiments." *AIChE Journal* 56 (9):2468-2478. doi: 10.1002/aic.12162.

Rakesh, Vineet, and Ashim K. Datta. 2013. "Transport in deformable hygroscopic porous media during microwave puffing." *AIChE Journal* 59 (1):33-45. doi: 10.1002/aic.13793.

Ratanadecho, Phadungsak, K. Aoki, and M. Akahori. 2001. "Experimental and numerical study of microwave drying in unsaturated porous material." *International Communications in Heat and Mass Transfer* 28 (5):605-616. doi: http://dx.doi.org/10.1016/S0735-1933(01)00265-2.

Sadeghi, Morteza, Omid Mirzabeigi Kesbi, and Seyed Ahmad Mireei. 2013. "Mass transfer characteristics during convective, microwave and combined microwave–convective drying of lemon slices." *Journal of the Science of Food and Agriculture* 93 (3):471-478. doi: 10.1002/jsfa.5786.

Salagnac, P., P. Glouannec, and D. Lecharpentier. 2004. "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* 47 (19-20):4479-4489. doi: 10.1016/j.ijheatmasstransfer.2004.04.015.

 ACCEPTED MANUSCRIPT

Sanga, E. C. M., A. S. Mujumdar, and G. S. V. Raghavan. 2002. "Simulation of convection-microwave drying for a shrinking material." *Chemical Engineering and Processing: Process Intensification* 41 (6):487-499. doi: 10.1016/s0255-2701(01)00170-2.

Schiffmann, R. F. 1995. *Microwave and dielectric drying*. Edited by A. S. Mujumdar, *Handbook of industrial drying-1*. New York: Marcel Dekker Inc.

Sharma, G. P., Suresh Prasad, and V. K. Chahar. 2009. "Moisture transport in garlic cloves undergoing microwave-convective drying." *Food and Bioproducts Processing* 87 (1):11-16. doi: 10.1016/j.fbp.2008.05.001.

Sosa-Morales, M. E., L. Valerio-Junco, A. López-Malo, and H. S. García. 2010. "Dielectric properties of foods: Reported data in the 21st Century and their potential applications." *LWT – Food Science and Technology* 43 (8):1169-1179. doi: 10.1016/j.lwt.2010.03.017.

Soysal, Y., M. Arslan, and M. Keskin. 2009b. "Intermittent Microwave-convective Air Drying of Oregano." *Food Science and Technology International* 15 (4):397-406. doi: 10.1177/1082013209346588.

Soysal, Y., Z. Ayhan, O. Eştürk, and M. F. Arıkan. 2009a. "Intermittent microwave–convective drying of red pepper: Drying kinetics, physical (colour and texture) and sensory quality." *Biosystems Engineering* 103 (4):455-463. doi: 10.1016/j.biosystemseng.2009.05.010.

Stanish, M. A., G. S. Schajer, and Ferhan Kayihan. 1986. "A mathematical model of drying for hygroscopic porous media." *AIChE Journal* 32 (8):1301-1311. doi: 10.1002/aic.690320808.

Sunjka, P. S., T. J. Rennie, C. Beaudry, and G. S. V. Raghavan. 2004. "Microwave-Convective and Microwave-Vacuum Drying of Cranberries: A Comparative Study." *Drying Technology* 22 (5):1217-1231. doi: 10.1081/drt-120038588.

Suwannapum, Nattawut, and Phadungsak Rattanadecho. 2011. "Analysis of Heat–Mass Transport and Pressure Buildup Induced inside Unsaturated Porous Media Subjected to Microwave Energy Using a Single (TE10) Mode Cavity." *Drying Technology* 29 (9):1010-1024. doi: 10.1080/07373937.2010.548110.

Swain, Sachidananda, D. V. K. Samuel, Lalit M. Bal, and Abhijit Kar. 2013. "Thermal Kinetics of Colour Degradation of Yellow Sweet Pepper (Capsicum Annum L.) Undergoing Microwave Assisted Convective Drying." *International Journal of Food Properties* 17 (9):1946-1964. doi: 10.1080/10942912.2013.775150.

Tulasidas, Tarikere N. 1995. "Combined convective and microwave drying of grapes."

Turner, I. W., and P. C. Jolly. 1991. "Combined microwave and convective drying of a porous material." *Drying Technology* 9 (5):1209-1269. doi: 10.1080/07373939108916749.

Turner, I. W., J. R. Puiggali, and W. Jomaa. 1998. "A Numerical Investigation of Combined Microwave and Convective Drying of a Hygroscopic Porous Material: A Study Based on Pine Wood." *Chemical Engineering Research and Design* 76 (2):193-209. doi: 10.1205/026387698524622.

Turner, Ian W., and Patrick Perré. 2004. "Vacuum drying of wood with radiative heating: II. Comparison between theory and experiment." *AIChE Journal* 50 (1):108-118. doi: 10.1002/aic.10010.

Uprit, S., and H. N. Mishra. 2003. "Microwave Convective Drying and Storage of Soy-Fortified Paneer." *Food and Bioproducts Processing* 81 (2):89-96. doi: 10.1205/096030803322088224.

Vega-Mercado, Humberto, M. Marcela Góngora-Nieto, and Gustavo V. Barbosa-Cánovas. 2001. "Advances in dehydration of foods." *Journal of Food Engineering* 49 (4):271-289. doi: 10.1016/s0260-8774(00)00224-7.

Wang, Jun, Jing Shuang Wang, and Yong Yu. 2007. "Microwave drying characteristics and dried quality of pumpkin." *International Journal of Food Science & Technology* 42 (2):148-156. doi: 10.1111/j.1365-2621.2006.01170.x.

Wentworth, S.M. 2004. *Fundamentals of Electromagnetics with Engineering Applications*: John Wiley.

Wojdyło, Aneta, Adam Figiel, Krzysztof Lech, Paulina Nowicka, and Jan Oszmiański. 2014. "Effect of Convective and Vacuum–Microwave Drying on the Bioactive Compounds, Color, and Antioxidant Capacity of Sour Cherries." *Food and Bioprocess Technology* 7 (3):829-841. doi: 10.1007/s11947-013-1130-8.

Workneh, T. S., and M. O. Oke. 2013. "Thin Layer Modeling of Microwave-Convective Drying of Tomato Slices." *International Journal of Food Engineering* 9 (1):75-89. doi: 10.1515/ijfe-2012-0205.

Yang, H. W., and S. Gunasekaran. 2001. "Temperature Profiles in a Cylindrical Model Food During Pulsed Microwave Heating." *Journal of Food Science* 66 (7):998-1004. doi: 10.1111/j.1365-2621.2001.tb08225.x.

Yang, H. W., and S. Gunasekaran. 2004. "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* 64 (4):445-453. doi: 10.1016/j.jfoodeng.2003.08.016.

Zhang, J., and A. K. Datta. 2004. "Some Considerations in Modeling of Moisture Transport in Heating of Hygroscopic Materials." *Drying Technology* 22 (8):1983-2008. doi: 10.1081/drt-200032740.

Zhang, J., A. K. Datta, and S. Mukherjee. 2005. "Transport processes and large deformation during baking of bread." *AIChE Journal* 51 (9):2569-2580. doi: 10.1002/aic.10518.

Zhang, M., Hao Jiang, and Rui-Xin Lim. 2010. "Recent Developments in Microwave-Assisted Drying of Vegetables, Fruits, and Aquatic Products—Drying Kinetics and Quality Considerations." *Drying Technology* 28 (11):1307-1316. doi: 10.1080/07373937.2010.524591.

Zhang, M., J. Tang, A. S. Mujumdar, and S. Wang. 2006. "Trends in microwave-related drying of fruits and vegetables." *Trends in Food Science andTechnology* 17 (10):524-534. doi: 10.1016/j.tifs.2006.04.011.

Zhao, Dandan, Kejing An, Shenghua Ding, Lijun Liu, Zhiqiang Xu, and Zhengfu Wang. 2014. "Two-Stage Intermittent Microwave Coupled with Hot-Air Drying of Carrot Slices: Drying Kinetics and Physical Quality." *Food and Bioprocess Technology* 7 (8):2308-2318. doi: 10.1007/s11947-014-1274-1.

Zhao, Huawei. 1997. "Computational models and numerical techniques for solving maxwell's equations: A study of the heating of lossy dielectric material inside arbitary shaped cavities." PhD, Centre for statistical science and industrial mathematics, Queensland University of Technology.

Zhou, L., V. M. Puri, R. C. Anantheswaran, and G. Yeh. 1995. "Finite element modeling of heat and mass transfer in food materials during microwave heating — Model development and validation." *Journal of Food Engineering* 25 (4):509-529. doi: 10.1016/0260-8774(94)00032-5.

Zhu, Huacheng, Tushar Gulati, Ashim K. Datta, and Kama Huang. 2015. "Microwave drying of spheres: Coupled electromagnetics-multiphase transport modeling with experimentation. Part I: Model development and experimental methodology." *Food and Bioproducts Processing* 96:314-325. doi: http://dx.doi.org/10.1016/j.fbp.2015.08.003.

Table 1: Summery of microwave assisted convective heating and drying of food material

Material	Drying time saving (Maximum)	Modeling of power distribution	Reference
Apple	N/A	N/A	(Marzec, Kowalska, and ZadroŻNa 2010)
Apple cylinders	N/A	N/A	(Andrés, Bilbao, and Fito 2004)
Apple cube	50%	N/A	(Chong et al. 2014)
Apple and Mushroom	N/A	N/A	(Funebo and Ohlsson 1998)
Beetroot	75%	N/A	(Figiel 2010)
Carrot	N/A	Lamberts law	(Sanga, Mujumdar, and Raghavan 2002)
Carrot cubes	82%	N/A	(Prabhanjan, Ramaswamy, and Raghavan 1995)
Chinese jujube	61%	N/A	(Fang et al. 2011)
Clipfish	90%	N/A	(Bantle, Käfer, and Eikevik 2013)
Cooked soybeans	62.5%	N/A	(Gowen et al. 2008)
Corn	N/A	N/A	(Nair et al. 2011)
Cranberries	N/A	N/A	(Sunjka et al. 2004)
Garlic	N/A	Lambert's law	(Abbasi Souraki and Mowla 2008)
Garlic cloves	65%	N/A	(Sharma, Prasad, and Chahar 2009)
Gel	N/A	Maxwell*	(Pitchai et al. 2012)
Green peeper	N/A	Empirical	(Darvishi et al. 2013a)
Green pepper	N/A	Empirical	(Darvishi et al. 2013b)
Lemon slice	97%	Empirical	(Sadeghi, Mirzabeigi Kesbi, and Mireei 2013)
Mashed potato	N/A	Maxwell*	(Chen et al. 2014)
Minced beef	N/A	Lambert's Law*	(Campañone and Zaritzky 2005)
Moringa oleifera pods (Drumsticks)	79%	N/A	(Dev et al. 2011)
Mushrooms	N/A	N/A	(Argyropoulos, Heindl, and Müller 2011)
Oyster mushroom	80%	Empirical	(Bhattacharya, Srivastav, and Mishra 2013)
Pineapple	N/A	N/A	(Botha, Oliveira, and Ahrné 2011)

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Material	Drying time saving (Maximum)	Modeling of power distribution	Reference
Pistachios	N/A	Empirical	(Kouchakzadeh and Shafeei 2010)
Potato	N/A	Maxwell's Equation	(Malafronte et al. 2012)
Potato	96%	Lamberts law	(McMinn, Khraisheh, and Magee 2003)
Potato spheres	N/A	Maxwells	(Gulati et al. 2015)
Pumpkin slices	76%	N/A	(Ilknur 2007)
Swede, potato, bread, and concrete	N/A	N/A	(Holtz et al. 2010)
Sour Cherries	N/A	N/A	(Wojdyło et al. 2014)
Tomato	N/A	N/A	(Swain et al. 2013)
Tomato slice	85%	Empirical	(Workneh and Oke 2013)
Two-percent agar gel	N/A	Lambert's and Maxwell's* equations	(Yang and Gunasekaran 2004)
Wheat seeds	N/A	Lambert's Law	(Hemis, Choudhary, and Watson 2012)

*-heating only (no mass transfer); N/A-Not available

Table 2: Summary of intermittent microwave assisted convective heating and drying of food material

Material	**Modeling of power distribution**	**Single phase or multiphase models**	**Reference**
Bananas	N/A	N/A	(Ahrné et al. 2007)
Carrots, mushrooms	N/A	N/A	(Orsat et al. 2007)
Carrot Slices	N/A	N/A	(Zhao et al. 2014)
2% agar gel	Lambert's Law*	Single Phase	(Yang and Gunasekaran 2001)
Dill leaves	Empirical	N/A	(Esturk and Soysal 2010)
2% agar gel	N/A*	N/A*	(Gunasekaran and Yang 2007a)
Mashed potato	Maxwell's*	Single Phase	(Gunasekaran and Yang 2007b)
Oregano	N/A	N/A	(Soysal, Arslan, and Keskin 2009b)
Pineapple	N/A	N/A	(Botha, Oliveira, and Ahrné 2012)
Red pepper	N/A	N/A	(Soysal et al. 2009a)
Sage(Salvia officinalis) Leaves	N/A	N/A	(Esturk 2012, Esturk et al. 2011)
Apple	Labmert's Law	Single Phase	(Kumar et al. 2015)
Apple	Labmert's Law	Multipahse	(Kumar et al. 2016)

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Table 3. Summary of governing equations used in multiphase modeling

Physics and Phases				Governing Equations	Eq. No.
Heat and Mass Transport	Mass Transport	Water	Liquid water	$\frac{\partial}{\partial t}\left(\phi S_w \rho_w\right)+\nabla\cdot\left(-\rho_w \frac{k_w k_{r,w}}{\mu_w}\nabla P+\rho_w \frac{k_w k_{r,w}}{\mu_w}\nabla p_c\right)=-R_{evap}$	(18)
		Gas	Vapor	$\frac{\partial}{\partial t}\left(\phi S_g \rho_g \omega_v\right)+\nabla\cdot\left(-\rho_g \omega_v \frac{k_g k_{r,g}}{\mu_v}\nabla P-\phi S_g \rho_g D_{eff,g}\nabla\omega_v\right)=R_{evap}$	(19)
			Air	$\omega_a = 1-\omega_v$	(20)
			Gas pressure	$\frac{\partial}{\partial t}\left(\rho_g \phi S_g\right)+\nabla\cdot\left(-\rho_g \frac{k_g k_{r,g}}{\mu_g}\nabla P\right)=R_{evap}$	(21)
	Energy		Energy	$\rho_{eff} c_{peff}\frac{\partial T}{\partial t}+\nabla\cdot\left(\vec{n}_g h_g+\vec{n}_w h_w\right)=\nabla.(k_{th,eff}\nabla T)-h_{fg}R_{evap}+Q_m$	(22)
Nomenclature	Symbols		ϕ = porosity, S = saturation, ρ = density, k = permeability, P = gas pressure, μ = viscosity, P = gas pressure, c = concentration, D = Diffusion coefficient, ω = mass fraction, T = Temperature, $\vec{n}$ = flux, k_{th} = thermal conductivity, h = latent heat, E = Electric field, f = microwave frequency, c = speed of light, Q_m = microwave heat generation, R_{evap} = evaporation of liquid water, p = pressure, μ_m = magnetic permeability, ε' = dielectric constant, ε'' = dielectric loss factor, ε_0 = permittivity in free space,			
	Subscript		w = water = vapor, g = gas, eff = effective, m = microwave, r = relative = capillary, evap = evaporation, m = microwave			

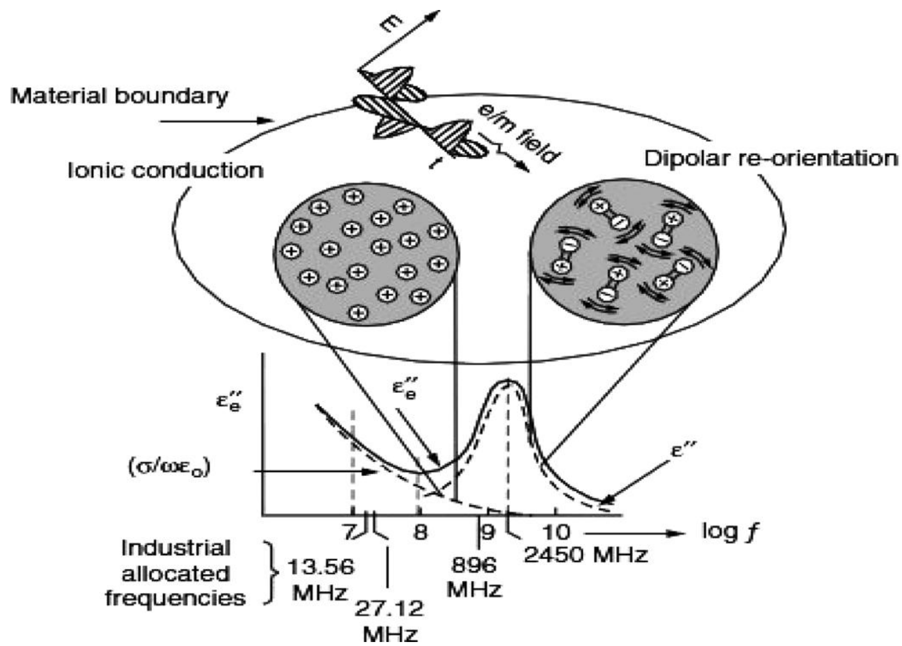

Figure 1: Schematic diagram depicting the dipolar and ionic loss mechanisms and their contributions to the dielectric properties as a function of frequency (Metaxas 1996b).

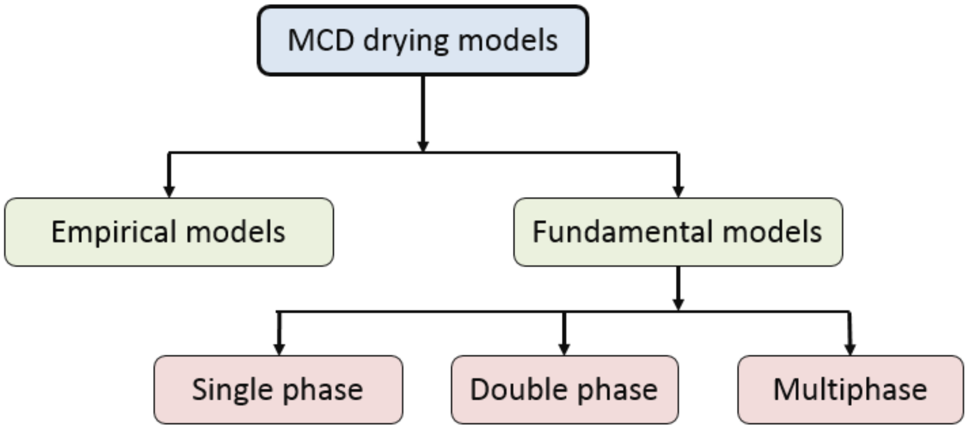

Figure 2. General classification of microwave drying models

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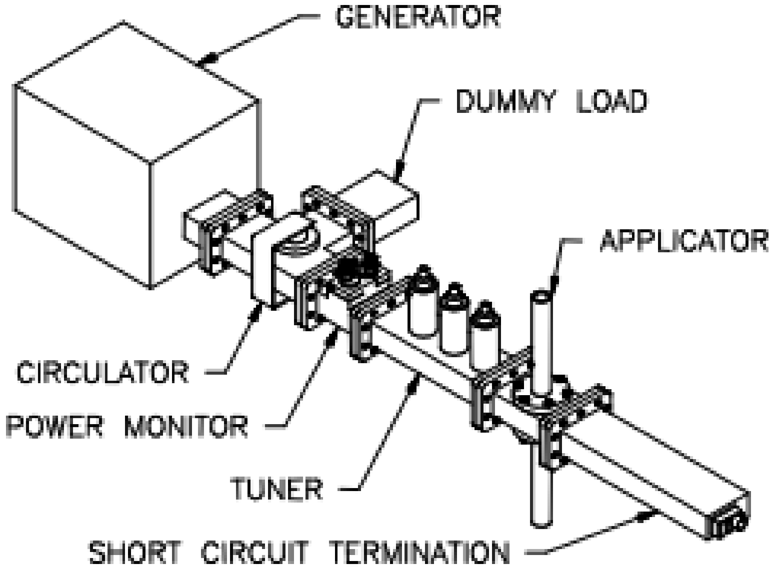

Figure 3: Basic single mode applicator setup (Gerling 2000)

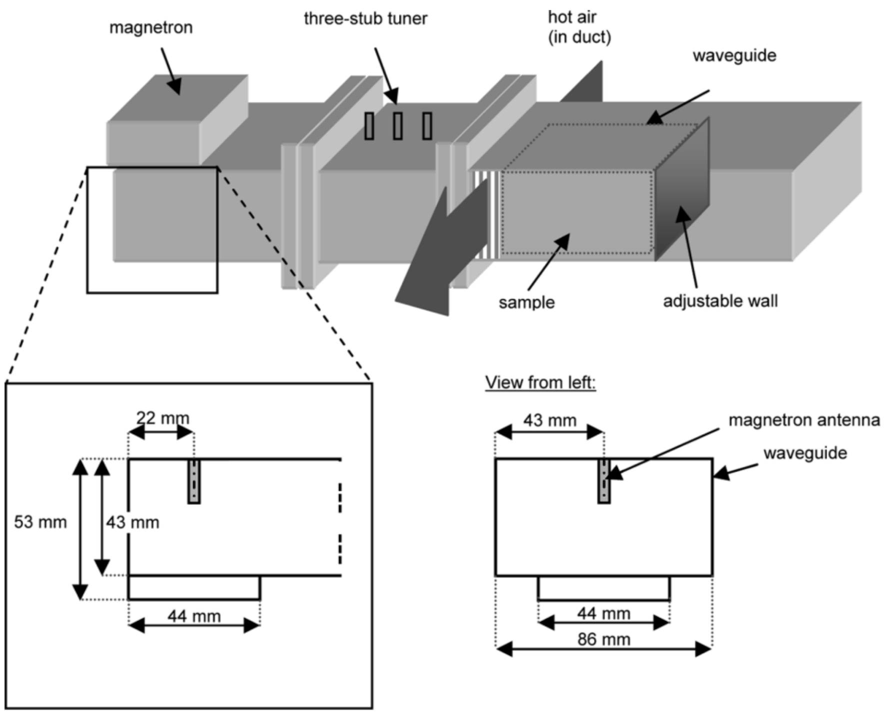

Figure 4. Microwave convective drying equipment. Schematic image and dimensions of the dryer (applicator)(Malafronte et al. 2012)

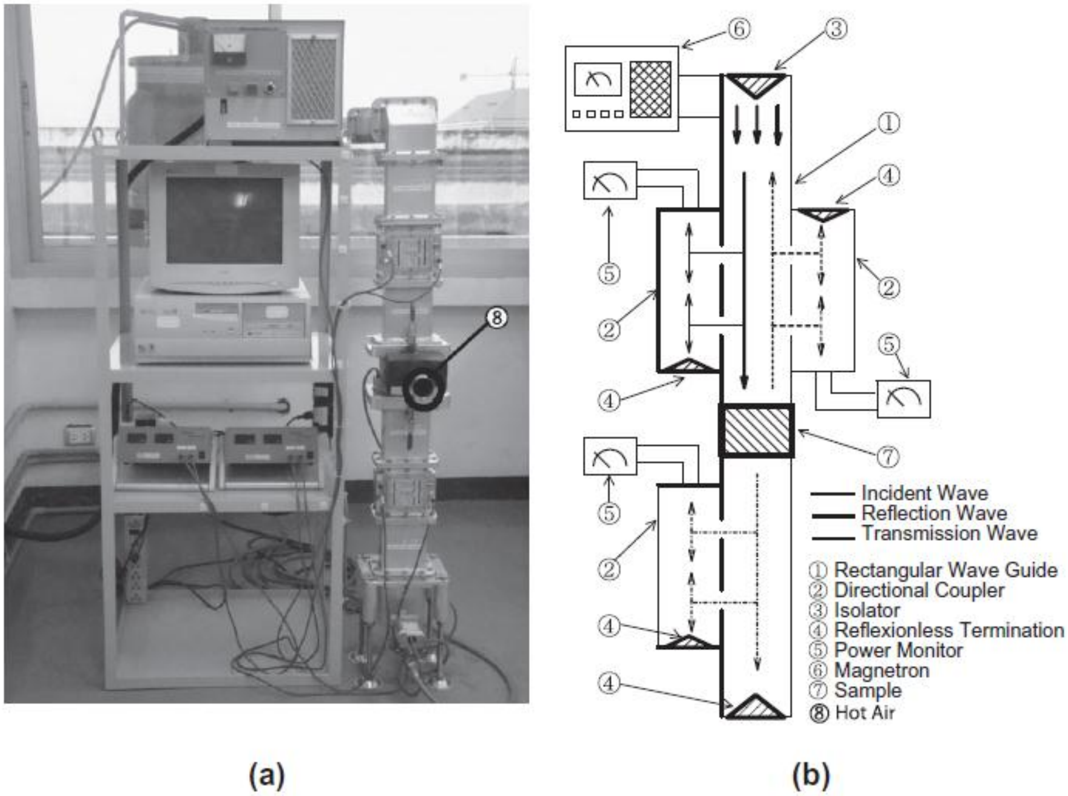

Figure 5. Schematic of experimental facility: (a) equipment setup; (b) microwave measuring system.(Jindarat, Rattanadecho, and Vongpradubchai 2011)

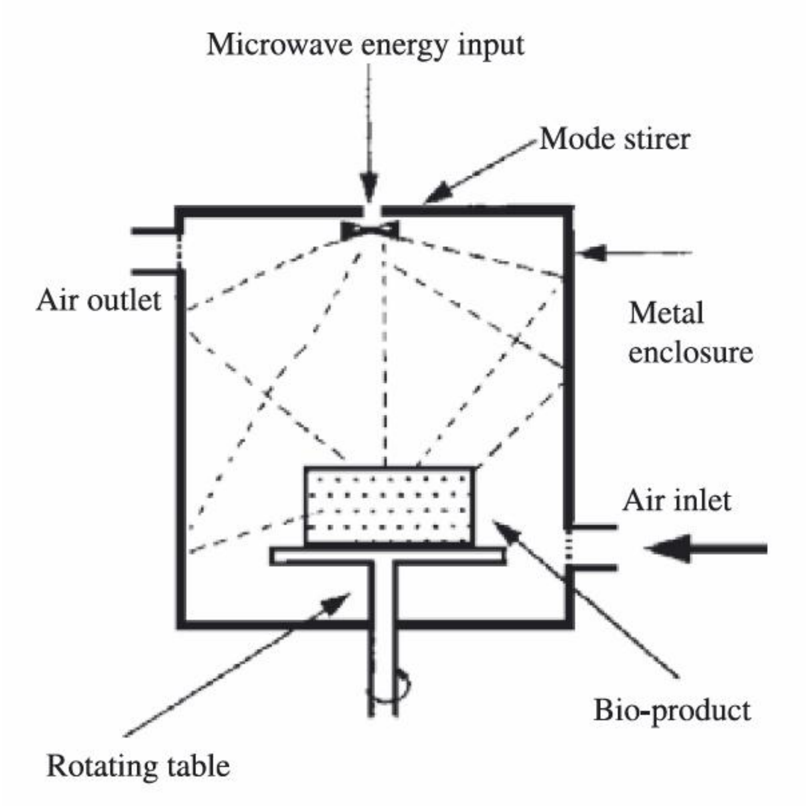

Figure 6: Multimode applicator with mode stirrer and turntable (Wang, Wang, and Yu 2007).

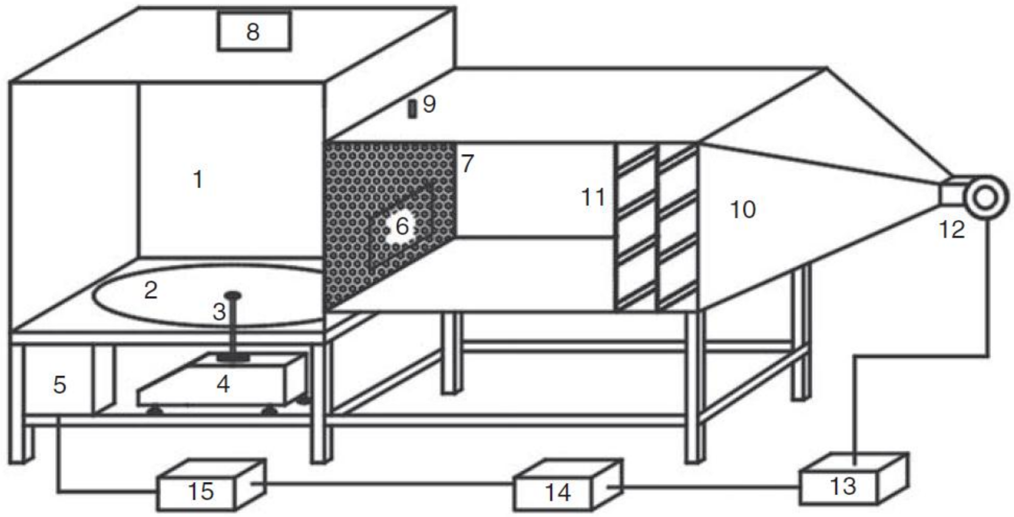

Figure 7: Experimental microwave–convective drying system: 1. microwave drying chamber; 2. rotating glass tray; 3. tray rotating rod; 4. digital balance; 5. PID control unit and solid-state relay; 6. air entrance; 7. wire mesh; 8. moist air exit opening; 9. temperature sensor; 10. air duct; 11. electric heaters; 12. fan; 13. fan speed adjuster; 14. digital wattmeter; 15. PLC control unit (Soysal, Arslan, and Keskin 2009b, Soysal et al. 2009a).

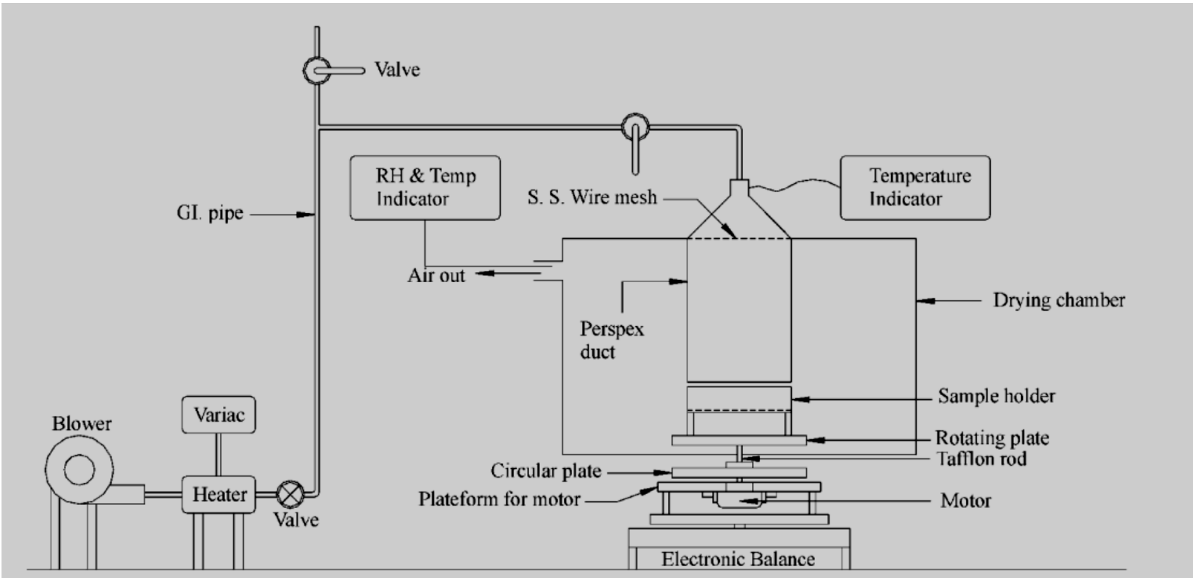

Figure 8. Schematic of microwave convective dryer (Uprit and Mishra 2003)

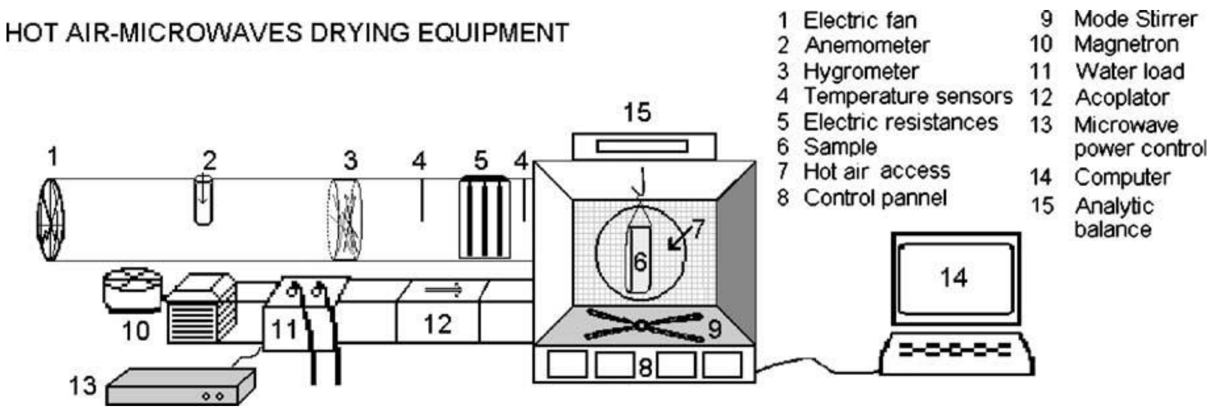

Figure 9. Schematic illustration of the combined hot air–microwave drying equipment (Andrés, Bilbao, and Fito 2004).

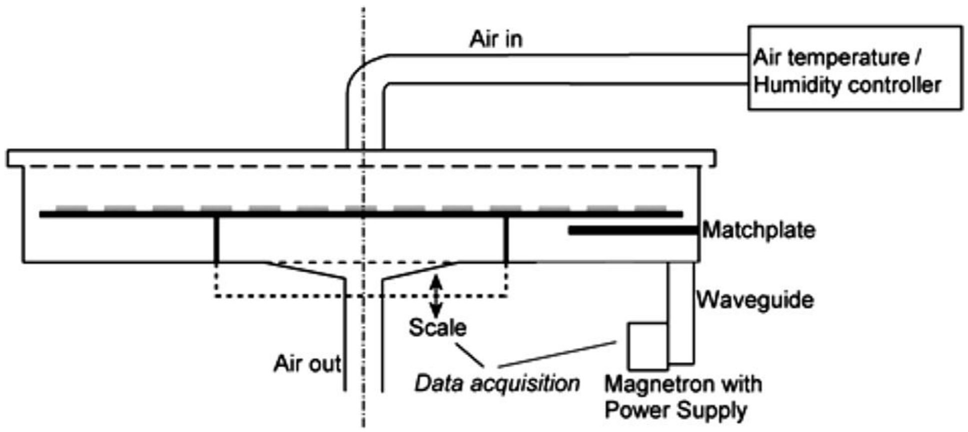

Figure 10. Schematic representation of the microwave convective dryer.(Ahrné et al. 2007)

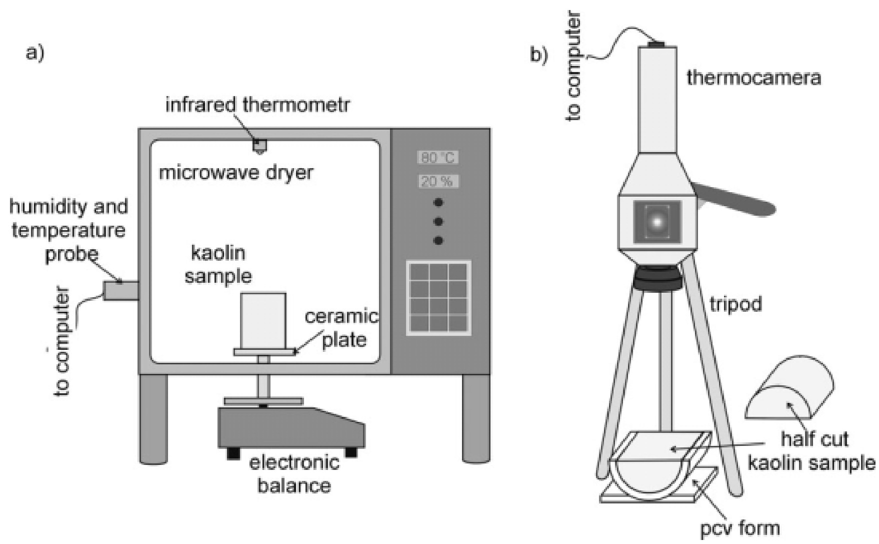

Figure 11. The experimental set-up: (a) microwave-convective dryer and (b) determination of the temperature distribution

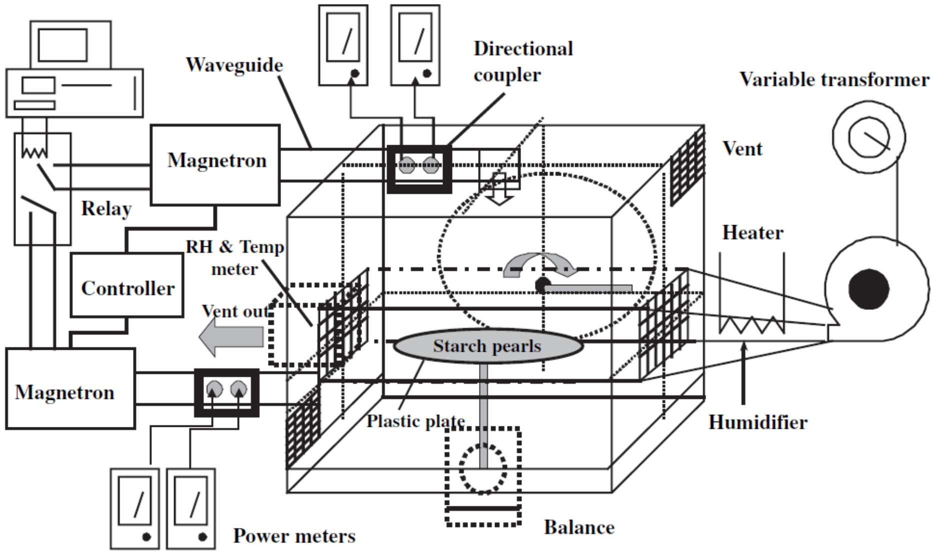

Figure 12. Apparatus for convective and microwave finish drying (Fu, Dai, and Yang 2005)