Review of dielectric drying of foods and agricultural products

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Abstract: Dielectric drying methods with microwave (MW) and radio frequency (RF) energy as emerging drying technologies have drawn much attention from both research community and industry over the past decades. When properly applied, MW and RF drying can be energy efficient and of great potential to be used for a wide range of materials. However there are few reviews that cover both MW and RF drying technologies. Such a review is timely considering the ever increasing interest of the food industry in adapting energy efficient new drying technologies. This paper attends to provide a comprehensive review on uses of MW and RF energy in drying of foods and agricultural products. It provides a brief discussion on the fundamental theory of MW and RF heating and gives a general overview of the works of the most active research groups on modeling of drying kinetic, energy control strategy and the influence of MW and RF drying conditions on quality and structural changes of the final products. Finally, it proposes possible solutions to main challenges facing the industrial adaptation of the technologies and makes suggestions on further research directions to improve the dielectric drying.

Keywords: dielectric drying, foods, agricultural products, microwave, RF energy
DOI: 10.3965/j.ijabe.2011.04.01.001-019

Citation: Wang Yunyang, Li Yuanrui, Wang Shaojin, Zhang Li, Gao Mengxiang, Tang Juming. Review of dielectric drying of foods and agricultural products. Int J Agric & Biol Eng, 2011; 4(1): 1－19.

1 Introduction

Drying refers to a process in which water is removed from a moist material by using heat as the energy input. The mechanism of drying is a complex phenomenon involving combined heat and mass transfers within a biological food material. Drying has been reported to account for anywhere from 12% to 20% of the energy consumption in the industrial sector[1]. It is an

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Received date: 2011-02-10 **Accepted date:** 2011-03-15

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energy-intensive process because the latent heat has to be supplied to the material to evaporate the moisture.

Drying offers a means of preserving foods in a stable and safe condition as it reduces water activity and extends shelf-life much longer than that of fresh foods and agricultural products. A major challenge of drying fresh foods and agricultural products is to reduce the moisture content to a certain low level while maintaining the quality attributes such as color, texture, chemical components and shrinkage[2-6]. In conventional heating, such as hot air and infrared drying, thermal energy is transferred from material surface to interior due to temperature gradients. These drying processes have low drying rates causing long drying times in the falling rate period of drying. The long drying times at relatively high temperatures often lead to undesirable thermal degradation of the finished products[7,8]. Unlike conventional thermal processing in which energy is transferred from a hot medium to a cooler material through convection, conduction and radiation, dielectric heating involves the dissipation of the electromagnetic energy directly in materials through molecular interaction with the electromagnetic field[9,10]. The thermal energy required for moisture evaporation is directly generated within the dried material, thus, making it possible to achieve rapid and uniform drying in relatively thick materials[11].

Dielectric heating consists of radio frequency (RF) and microwave (MW) heating. RF and MW waves are a part of the electromagnetic spectrum (Figure 1). In RF heating, the applied frequency is between 10 to 300 MHz, while in MW heating the frequency is between 300 to 30 000 MHz. The US Federal Communications Commission (FCC), the responsible regulatory agency for the out-of-band emissions from the domestic, industrial, scientific and medical (ISM) applications in the United States, has allocated the following frequencies for industrial applications: 13.56 MHz ± 6.68 kHz, 27.12 MHz ± 160.00 kHz, 40.68 MHz ± 20.00 kHz for RF heating and 915 MHz ± 25 MHz, 2 450 MHz ± 50 MHz, 5 800 MHz ± 75 MHz and 24 125 MHz ± 125 MHz for MW processing.

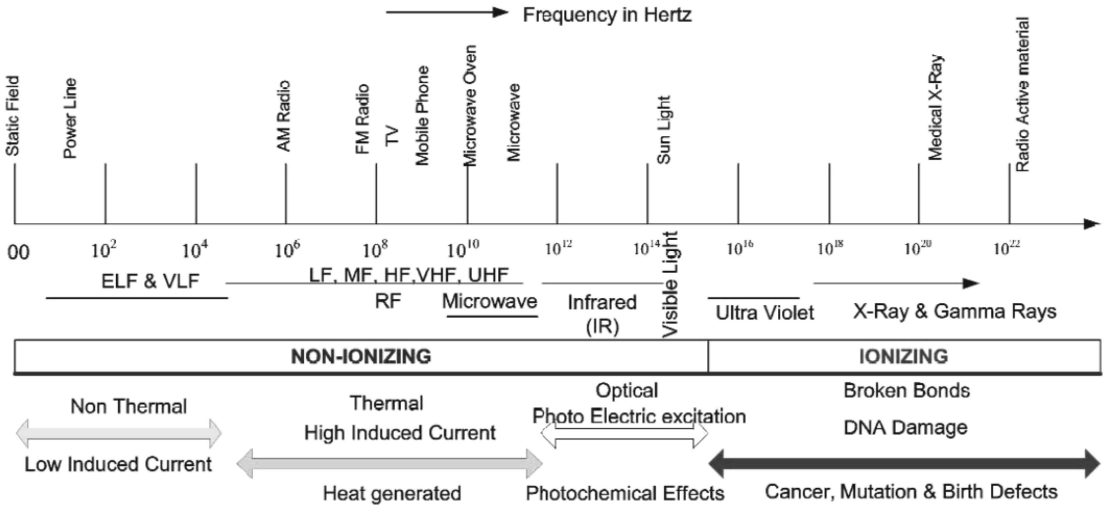


Figure 1 MW and RF allocation in the electromagnetic spectrum[25]

Research on use of MW energy for thermal processing of agricultural commodities started in the 1950's. The broadening of interest to include scientific and industrial applications followed in the early sixties as new markets for MW power sources were established. After overcoming some of the major economic and technical hurdles, only in recent decades, low cost, mass-produced domestic and industrial MW systems have been found for drying applications of food and biological materials[12,13].

Research on RF heating applications in the food industry started in the 1940s[14,15]. The first attempts were to use RF energy to cook processed meat, to heat bread and dehydrate vegetables[16,17]. Thawing of frozen products was the next step on the application of RF energy in 1960s[15,18]. Demeczky showed that juices (peach, quince and orange) in bottles moving on a conveyer belt through a RF applicator had better bacteriological and organoleptic qualities than juices treated by conventional thermal methods[19]. The primary application in the late 1980 s was the post-baking (final drying) of cookies and crackers[20-22].

MW and RF drying methods provide opportunities to shorten drying times and improve the final quality of the dried products. MW ovens are now common domestic appliances worldwide. But use of MW and RF energy in industrial drying applications is little known to the public and even within general research communities. Jones reviewed the heating principles, generators and applications of dielectric drying of PVC welding, preheating of moulding polymers and drying of a range of non-metal products. He also reported new developments of dielectric (MW and RF) drying systems[23]. Orsat et al. gave a brief review on MW assisted drying of biomaterials[6]. Marra et al. reviewed the history, basic principle and recent RF heating applications to food[24]. Zhang et al. provided an general review of recent developing in combined microwave drying with other conventional methods[8].

This paper will provide a comprehensive review on uses of MW and RF energy in drying of foods and agricultural products. It will start with a brief discussion on the fundamental theory of MW and RF heating, and give a general overview on the works of the most active research groups in the world on modeling of drying kinetics, energy control strategy and the influence of MW and RF drying conditions on quality and structural changes of the final products, propose possible solutions to main challenges facing the industrial adaptation of the technologies, and finally make suggestions on further research directions to improve the dielectric drying.

2 Principles of MW and RF heating

Many factors affect the dielectric heating performance of foods. Among the most significant are electromagnetic field distribution and temperature dependent dielectric properties of the food, which describe how materials interact with electromagnetic waves. MW and RF energy generates heat volumetrically within wet materials by the combined polarization mechanisms of dipole rotation and ionic conduction effects, which speed up the drying process[10,26].

2.1 Polarization

An electric dipole is composed of two opposite charges separated by a distance. The dipole constitutes a vector called dipole moment. Molecules with permanent electric dipole moments are called polar molecules. When an electric field is presented, nonpolar molecules may acquire a dipole moment as a result of the distortion of their electronic distributions and nuclear positions.

Water has a permanent dipole and is often a major component in biological materials. In a MW or RF field, the dipoles of water molecules attempt to follow the rapidly changing electric field. These rapid rotating molecules may cause frictions with other molecules adjacent to them, leading to a temperature rise. This is called orientation or dipole polarization, and it is strongly temperature dependent. The inertia causes orientation polarizability to fall off at the higher end of MW frequency spectrum (>1 000 GHz) (1 GHz = 1 000 MHz). Another important mechanism contributing to MW and RF heating is ionic conductance. Salt dissolved in biological materials may be separated into two opposite (+ and –) charged particles or ions. Charged particles move back and forth in an alternating electric field. The collision among the moving charges results in dielectric heating[27, 28].

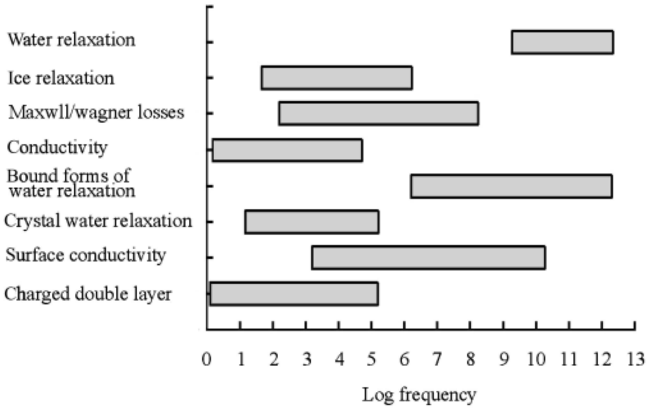


Figure 2 Origin of different types of losses in heterogeneous mixtures containing water [29]

Orientation polarization is perhaps the most significant in MW heating at frequencies above 1 GHz whereas ionic polarization typically predominates at frequencies below 1 GHz[27]. The above two discussed mechanisms, along with several other less important contributors to dielectric heating in MW and RF frequencies applicable to industrial heating, are summarized in Figure 2[29]. With rising temperatures, all the water relaxation phenomena are found at higher frequencies.

2.2 Dielectric properties

Most foods and agricultural products behave as lossy dielectrics. They can store electrical energy in response to an imposed electromagnetic field in the same form as capacitors, and while in the meantime dissipate electrical energy as resistors[30]. These abilities are defined by dielectric properties normally described in terms of the complex relative permittivity, ε:

$$\varepsilon = \varepsilon' - j\,\varepsilon'' \tag{1}$$

Where, $j = \sqrt{-1}$. The real part of the relative complex permittivity, ε', known as the relative dielectric constant, describes the ability of a material to store energy in response to an applied electric field (for vacuum $\varepsilon' = 1$). The imaginary part of the relative complex permittivity, ε'', known as the relative electric loss factor, describes the ability of a material to dissipate energy in response to an applied electric field, which typically results in heat generation.

Dielectric constant and loss factor of biological materials are depended on frequency, temperature and chemical composition, such as moisture and salt content[27,31-35]. At the RF and MW frequencies used in drying applications, ionic conduction and dipole rotation are dominant loss mechanisms[29,36]:

$$\varepsilon'' = \varepsilon''_d + \varepsilon''_\sigma = \varepsilon''_d + \frac{\sigma}{2\pi f \varepsilon_0} \tag{2}$$

Where, subscripts d and σ stand for contributions due to dipole rotation and ionic conduction (S/m), respectively; f is the frequency of electromagnetic waves in Hz (s^{-1}); ε_0 is the permittivity of free space or vacuum (8.854×10^{-12} F m^{-1}).

The properties of materials to describe their interaction with an applied magnetic field are expressed in terms of the complex relative permeability μ:

$$\mu = \mu' - j\,\mu'' \tag{3}$$

The above parameters are relative values respect to free space (vacuum) in which permeability $\mu_0 = 4\pi\times10^{-7}$ H/m[37]. Most natural biological materials do not interact with the magnetic portion of the electromagnetic field. All of the conversion of electromagnetic energy to thermal energy in a food or agricultural material is the result of their interaction with the electric field[10,29,38].

Dielectric loss factor ε'' can be expressed as:

$$\varepsilon'' = \varepsilon' \tan(\delta) \tag{4}$$

Where, δ is referred to the loss angle. It represents the phase shift between the orientation of the molecules and the changing electrical field.

2.3 Power dissipation

Electromagnetic energy is transmitted in space by mutually supportive alternating electric and magnetic fields in form of an electromagnetic wave characterized by the wavelength λ, frequency f, magnetic field strength H, and electric field strength E. When a biological material is exposed to such a wave, part of the electromagnetic energy is absorbed and converted into heat (Figure 3).

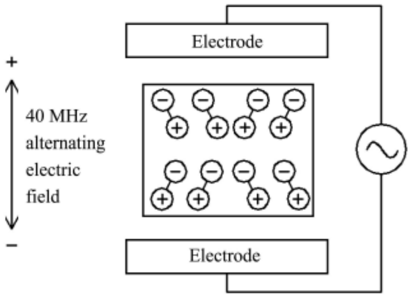


Figure 3 Heat generation in an alternating electric field[39]

The power (P) absorbed in a unit volume of a dielectric material depends on its dielectric properties (the loss factor) and can be calculated from the frequency and the electric field strength of the electromagnetic waves:

$$P = 2\pi f \varepsilon_0 \varepsilon'' E^2 \tag{5}$$

Where, P is the power conversion per unit volume, W/m^3; E is the electrical field strength in the material, V/m.

Equation (5) illustrates that the power absorbed in a dielectric material is linearly proportional to the frequency, the relative dielectric loss factor and the square of the electric field. Experiments have shown that when loss factor is between 2 and 100, it is effective to heat material with dielectric heating technology. Too high of a loss factor would result in small penetration depths in MW drying, which causes only skin heating. On the other hand, too low of a loss factor means that the material is transparent to the electromagnetic wave[10,40]. Dielectric properties are thus essential parameters when assessing the feasibility of MW and RF drying of a material (Table 1). If the loss factor is too low, small amount of salt added in the material can enhance its loss factor notably and render it suitable for MW and RF drying[10].

In dielectric drying, heat is generated within the product through molecular excitation caused by the alternating electromagnetic field. Moisture migrates to material surface driven by internally generated vapor pressure. It is appropriate to combine surface air drying with internal MW and RF heating to speed up the drying processes.

Table 1 Dielectric properties of foods and agricultural products (adapted from Sosa-Morales et al.[41]) at 27.12 MHz (RF) and 915 MHz (MW)

Material	Temperature /℃	Moisture content /% w.b.	Dielectric constant		Loss factor		Penetration depth/cm		Reference
			Frequency/MHz		Frequency/MHz		Frequency/MHz		
			27.12	915	27.12	915	27.12	915	
Apple (Red Delicious)	22	3.8	-	1.7	-	0.1	-	68.0	Feng et al.[42]
	60	3.8	-	3.6	-	0.7	-	14.2	
	22	23.8	-	5.7	-	2.1	-	6.0	
	60	22.4	-	14.4	-	4.5	-	4.4	
	22	69.7	-	33.0	-	6.7	-	4.5	
	60	68.7	-	32.8	-	9.1	-	3.3	
Apple (Golden Delicious)	20	-	72.5	74.3	120.4	8.5	15.1	5.3	Wang et al.[36]
	50	-	68.1	67.8	202.2	8.3	10.3	5.2	
Longan	20	-	75.2	68.2	230.1	13.3	9.6	3.3	Wang et al.[43]
	50	-	69.7	60.8	377.7	15.0	7.0	2.7	
Orange	20	-	84	72.9	223.3	16.5	10.0	2.7	Wang et al.[36]
	50	-	78	66.1	367.7	17.5	7.2	2.4	
White bread	25	34.6	2.35	1.81	2.32	0.47	127.5	15.1	Liu et al. [44]
	25	38.6	2.83	2.08	4.95	0.69	73.4	11.0	
	55	34.6	2.80	1.94	5.09	0.67	71.7	11.0	
	55	38.6	3.15	2.17	8.00	0.83	53.3	9.4	
Walnut	20	-	4.9	2.2	0.6	2.9	650.3	3.1	Wang et al.[36]
	40	-	5.1	3.0	0.4	2.3	994.1	4.2	
	60	-	5.3	3.8	0.4	1.8	1,013.3	5.8	
Sturgeon caviar (salted)	50	-	121.5	22.7	1,501.1	43.3	3.3	0.7	Al-Holy et al.[45]
	80	-	182.0	25.0	2,614.5	73.6	2.5	0.5	
Sturgeon caviar (unsalted)	50	-	46.4	18.3	375.9	14.1	6.8	1.7	
	80	-	59.6	18.9	642.7	22.2	5.1	1.2	
Chickpea flour	20	7.9	2.99	2.51	0.16	0.15	1,902.1	55.1	Guo et al.[46]
	50	7.9	3.44	2.77	0.19	0.21	1,718.1	41.4	
	80	7.9	6.81	4.68	1.38	0.81	334.4	14.0	
	20	20.9	4.50	3.33	0.81	0.54	462.6	17.7	
	50	20.9	11.43	6.64	7.85	1.71	79.7	7.9	
	80	20.9	56.51	216.7	145.88	10.69	12.4	7.2	

2.4 Penetration depth

When electromagnetic waves propagate to a lossy material, part of the waves is reflected. The remaining part will penetrate into the material. But the strength reduces with distance (Figure 4).

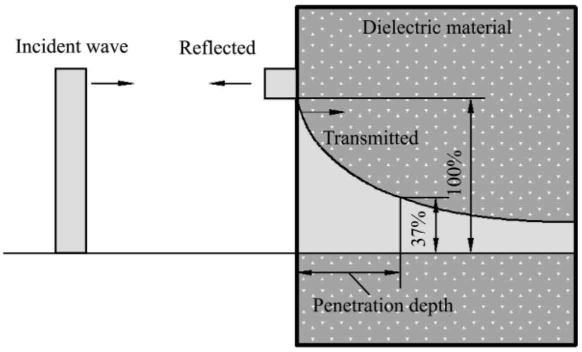


Figure 4 Power flow when an electromagnetic wave strikes a dielectric material with high loss factor[47]

The electric field penetration depth *(d_p)* of a material, is defined as the distance (m) at which an incident electromagnetic wave penetrates perpendicularly beneath the surface of a material before its intensity diminished by a factor of 1/e (e, Naprian base, equal 2.71828) of its amplitude at the surface. The electric field penetration depth is expressed as:

$$d_p = \frac{c}{2\sqrt{2}\pi f\left[\varepsilon'\left(\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right)\right]^{\frac{1}{2}}} \qquad (6)$$

Where, c is speed of light in free space (3×10^8 m/s).

The penetration depth of a material is inversely proportional to the frequency as the dielectric properties are fixed. Based on Equation （6）, one will expect that deeper penetration would be obtained at lower frequencies such as at RF compared to MW. Because of higher frequencies, MW would result in small penetration depths, which mean greater surface heating (Table 1). In general, an electromagnetic field having a short wavelength does not penetrate deeply into most moist food products, whose dielectric constants and loss factors are relatively high[10]. Higher penetration depth will result in small overall variation in the electric field, which can, in turn, improve heating uniformity.

Since the dielectric properties also vary with frequency, penetration depth does not vary exactly as $1/f$. During dielectric drying, temperature and moisture content of the material change constantly with time, which in return lead to the change of dielectric properties. Thus, dielectric drying is a very complex process.

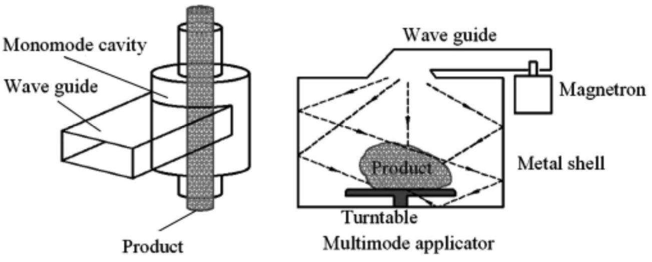
3 Dielectric dryer

The main difference between MW and RF dryers lies in the generator and transportation of electromagnetic waves. In general, dielectric dryer consists of a dielectric wave generator, an adaptor or matching device between the generator and the load, the applicator and the ancillary control and handling devices. Dielectric drying applicator can be built in different structures, depending on the specific characteristics of the products, the combination with other methods (hot air, vacuum, infrared or freeze drying) and on whether the production process is continuous or discontinuous.

3.1 MW drying applicators

The most common MW sources for applications in the food industry are the magnetrons. MW energy is transmitted from the sources to the applicator through waveguides, which are made of sheets of highly conductive metals such as copper or aluminum. The inside surface of waveguides are made smooth and clean to reduce energy losses.

MW applicators are metallic enclosures that contain the material to be heated, and their designs depend on the processing requirements. There are two basic designs of microwave applicators are used in industrial applications (Figure 5).



a. Monomode applicator b. Multimode applicator

Figure 5 Schematic buildup of MW applicators [49]

1) Single Mode Applicators: Single-Mode cavities are small size cavities (with reference to the wavelength of the electromagnetic waves) that can support only a single predictable microwave field pattern. It is used for processing small quantities of material (e.g. filaments), particularly those with low effective loss factors. Full descriptions are given in Metaxas and Meredith[10].

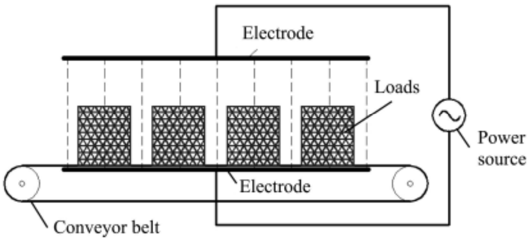
2) Multimode applicators: The most common

applicators are the multimode cavities, which are relatively large metal cavities with at least one dimension larger than the free space wavelength of the microwave (e.g., greater than 122 mm at 2 450 MHz). MW radiation entering a multimode cavity undergoes multiple reflections to form complex three dimensional standing wave patterns. The type and numbers of the patterns in a specific cavity are determined by cavity dimensions, the energy spectrum generated by the magnetron, and the nature of the load. Those patterns are highly unpredictable when dielectric properties and positions of foods change with heating. But multimode cavities are very flexible and suited for heating a wide range of sizes and shapes of products, and thus are most popular in industrial applications.

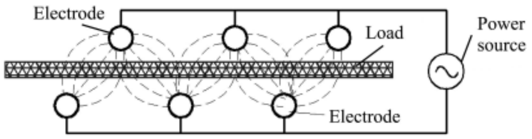
Major problems associated with multi-mode microwave applicators are caused by unpredictable and highly non-uniform electric field patterns. Several measures are taken to overcome those problems to make the average effect of dielectric heating more uniform over a certain period of heating time[48]. One of such a measure is the use of mode stirrers. Mode stirrers can be shaped as rotating vaned metallic fans. The stirs typically rotate at 1–10 r/s[10]. In addition, a load can be heated on moving conveyors or turntables. Other measures include: using multiple inputs for the MW energy into an applicator; using multiple MW sources with slight differences in frequency that cause different mode patterns; and choosing the cavity dimensions to support the maximum number of modes. A domestic MW oven is an example of a multimode cavity. It is often used for initial laboratory investigations.

3.2 RF drying applicators

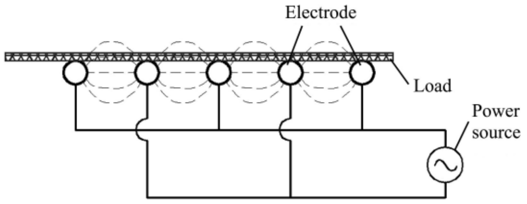
Two general types of RF heating systems are used in the industry: conventional and 50Ω[50]. In conventional RF heating systems, RF power is generated by a standard oscillator circuit using triode tubes. The applicator consists of an electrode system in which the processed material (load) is heated. The electrodes and load constitutes a tuned circuit coupled inductively to the generator's output circuit[51]. Several designs are used for RF applicators. The basic type can be divided into three categories. They are illustrated in Figure (6).



a. Flat electrodes



b. Staggered electrodes



c. Stray field electrodes

Figure 6 Schematic buildup of RF applicators[52]

3.2.1 Conventional RF heating applicators

1) Plate electrodes: The product to be heated is placed between two parallel flat plates. The amount of power coupled in the loads is adjusted by changing the distance between the two electrodes. The material can also be placed in a layer on a moving conveyor belt between the plate electrodes. This type of applicator is used for heating or drying relatively thick layer of materials.

2) Staggered electrodes: In this configuration, two rows of rod or tube electrodes are staggered on either side of a thin layer of material on a moving belt. The relatively higher electric conductivity of material layer compared to the ambient air allows the alignment and concentration of electric field in the layer parallel to the direction of the belt movement. Thus, much higher electric field strengths can be obtained within the thin layer when using staggered electrodes, as compared to that between two plate electrodes. The electric field can also be adjusted by changing the distances between upper rows and lower rows of electrodes. It is possible to transfer high power with the order between 30 and 100 kW/m^2 to a thin-layer material. This configuration

usually offers a more homogeneous field comparing with Stray field electrodes.

3) Stray field electrodes: A series of rod or tube electrodes are configured in a same plane, parallel to the layer of material to be heated. Adjacent electrodes have alternatively connected to opposite polarity. The material to be dried is placed above the banks of the electrodes so that electric field can be parallel aligned in the material layer to allow a high concentration of electric field strength in very thin products. These kinds of applicators are mostly used for thin products up to 10 mm[52-54].

During drying process, both loss factor and dielectric constant change with moisture content and temperature as shown in Table 1. According to Equation (5), a reduction in loss factor results in reduced absorbed power. To compensate for this effect, the graduated field configurations or pulsed field systems can be used[55].

3.2.2 50Ω Technology

In a 50Ω system (Figure 7), an automatically tuning device as a part of the applicator circuit continuously adjusts its overall impedance to 50Ω to match the impedance of the generator, thus providing a stable coupling of RF energy to the load during a drying process. The 50Ω systems used to be expensive and are only used in experimental setting. With reduced cost of the systems, they become economically viable for commercial applications. The main advantages of this technology include: 1) Use of quartz driven generators ensuring frequency stability; 2) Higher energy efficiency because of the continuous permanent tuning; 3) Limitation of flask risk; 4) Reduced power consumption as compared to traditional RF systems; and 5) Improved operation (simplified control, reduced adjusting time, complete automation, versatile and remote command of the system, etc.).

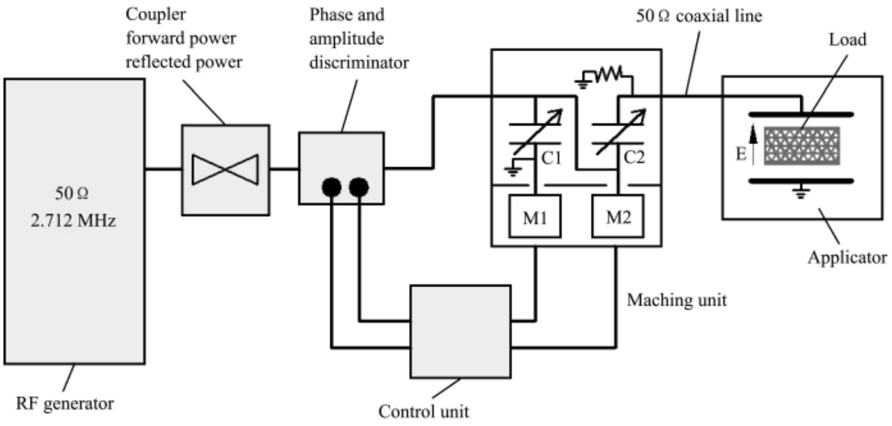


Figure 7 Principle of the “50Ω technology”[56]

4 Use of MW and RF drying of foods and agricultural products

4.1 MW drying of foods and agricultural products

Numerous researches on MW assisted drying were conducted since 1960’s as new markets for MW power sources have been established. Several very active groups worldwide studied on applications of MW energy in drying of foods and agricultural products. The main focuses of those investigations were on drying kinetics, use of different combinations of MW drying with conventional drying methods to improve drying uniformity, and the influences of drying conditions on quality, structural change, and rehydration ratios of the final products.

A research team led by Raghavan at McGill University, Canada conducted extensive research on MW drying different agriculture produces, including corns, grapes, carrots, strawberries, cranberries, soybeans, mushrooms, idlies, okras and apples[1, 6, 57-78]. Specific research topics include drying rates, equilibrium moisture contents, drying modes (continuous or intermittent), osmotic pretreatments, quality attributes and temperature (or power) control strategies. From the studies on MW drying of corns in combination with hot air, they found that drying rates increased with MW power level but decreased with air velocity. The inlet air temperature did not affect the drying behavior. Intermittent MW operation reduced energy loss but using more time to reach the same final moisture content than comparable drying in the continuous mode[57-59, 79]. Surface drying coefficient was used when modeling the drying kinetics of maize in a MW system. The resulting empirical model better described the observed drying kinetics. The model also provides fits to data of convective drying of rough rice, MW drying of wheat and combined MW-fluidized bed drying of wheat[61]. Overall, microwave drying resulted in a significant reduction (25%–90%) of drying time when compared to convection or conduction drying of grapes, carrots, strawberries and apples[60,62,63,66,72,73]. Pretreatments of certain agriculture products were found to be necessary to make the microwave drying effective. For example, dipping of seedless grapes in hot alkaline solution of ethyl oleate considerably reduced combined convection and MW drying time and resulting in better quality raisins[64]. A study on MW-vacuum drying of strawberries showed that although osmotic pretreatment did not help in terms of drying time and energy saving, the process resulted in a better quality dried product[72]. Quality parameters viz. sensory, texture, color, water activity and rehydration ratio were used when evaluating different drying methods such as hot air drying, MW-vacuum drying, MW-convection drying, freeze-drying and vacuum drying. Carrots and cranberry dried by MW-assisted convective drying had better quality at lower microwave power levels[62, 67]. Research was done on two drying methods (MW-vacuum and MW-convective) for cranberries. In almost all observed parameters, MW-vacuum drying exhibited enhanced characteristics[70] and more energy-efficient.

But most all the studies in the group were made with small drying devices. For example, the MW drying devices were constructed from a domestic MW oven with a nominal power output of 600 W, which could continuously and automatically adjust the MW power output from 0 to 500 W. Apple samples were placed on a Teflon plate suspended from an electric balance on the top of the oven for weight measurement. Temperature of the samples was recorded online with optical fiber temperature sensors. Four different combinations of temperature and power controls were investigated for drying apples to optimize temperature and power control. The MW power was adjusted based on predefined power profiles in combination with a temperature feedback for the best temperature control to obtain high product quality[76]. In a further research by the same group, a linear and three-step power control method was developed to make the control strategy simple and easy to practice in industry. The energy consumption was reduced significantly than fixed power MW drying[75].

A research group led by Zhang et al. from the Key Laboratory of Food Science and Safety, Ministry of Education, Southern Yangtze University, China also conducted extensive research on MW energy associated drying of fruits, vegetables and sea products[8,80-91]. Studies were done on combination of MW with hot air, vacuum or freeze drying in order to reduce the drying time and energy consumption. They found that combining hot air and MW vacuum drying reduced drying time to half needed by hot air drying of wild cabbage[92]. MW freeze drying can greatly reduce the drying time compared with ordinary freeze drying[82]. Henderson Pabis model gave better simulation of the drying curves when potato slice was vacuum MW dried[90]. Potato chips predried by vacuum MW drying absorbed less oil and contained less moisture contents when they were vacuum-fried. However vacuum MW pre-drying had negative effects on the color of potato chips[85]. Apple slices freeze dried for 8.28 h followed by MW vacuum drying had the best appearance. This procedure reduced energy consumption by 39%. Apple slices freeze dried for 6 h followed by MW vacuum drying reduced the use of energy by 54% with acceptable appearance[89]. Four drying methods such as vacuum MW drying, freeze drying, hot air drying, and combined hot air-vacuum MW drying were compared using edamames as raw material. The drying rate was fast initially and then falled slowly when drying bighead carp muscles with MW and combined air with MW. Drying curve of air MW was steeper than that of MW alone during the initial period of 0–120 s. The equation $MR =$

a exp(-*kt*) fitted the data better than other models[93]. Experiments of vacuum MW drying on edamame in a deep bed showed that the deeper the bed, the higher of moisture content of the products[84]. When researching on the quality changes of granular edamame during drying, retention of vitamin C, chlorophyll contents, shrinkage, rehydration capacity, color, texture, and microstructure changes were evaluated as quality indexes. The results showed that the quality of freeze dried products was the best, followed by MW vacuum drying, and combined hot air-MW vacuum drying. The products from hot air drying had the lowest quality. Optimum drying process was obtained by hot air and MW vacuum drying combination that could greatly increase drying rate and enhance product quality[80].

The same group conducted studies in which microwave vacuum drying was used to produce dried fish and seafood products. They found that proper initial moisture content of bighead carp slices and appropriate MW power had positive effects on puffing and crispness. Under fixed moisture content and MW power, higher vacuum enhanced higher puffing ratio of fish muscles[86]. In another study, sea cucumber was coated with novel nanoscale silver in order to investigate its effect on microbial reductions. The result showed that MW freeze drying combined with nanoscale silver coating treatment leaded to a much lower microorganism number with little effect on drying efficiency and sensory quality[87]. Ultrasonically enhanced osmotic pretreatment of sea cucumber can reduce by about 2 h of the time needed for MW freeze drying[88].

A research group led by Durance in the Faculty of Land and Food Systems, University of British Columbia, Vancouver, British Columbia, Canada studied the influence of microwave drying on sensory, nutrition and texture change of food and gel product. Carrots, apples, bananas, potato chips, sweet basils, and Echinacea purpurea were dried by air, freeze or vacuum MW. Color, density, nutritional value, texture properties or flavor volatiles were evaluated. MW vacuum dried products had lighter color, and higher texture value, retention of nutritional constituents and flavor volatiles than those of air drying. MW vacuum dried sweet basils had a high rehydration rate. Freeze dried berries had the highest amount of anthocyanin and antioxidant activities, followed by vacuum MW dried ones. Electrospray mass spectrometry analysis showed a total of 12 compounds detected in freeze dried ginseng compared with 10 compounds in vacuum MW dried products[94-111].

Özbek et al. in the Department of Chemical Engineering, Yıldız Technical University, Istanbul, Turkey conducted researches on MW drying of okras, spinaches, mint leaves, leeks and basils[79, 112-122]. MW output power ranging from 180 to 900 W and sample weights from 25 to 100 g were used in the experiments, and the effective moisture diffusivities and drying kinetics were studied. They found that drying time decreased with increase of power and smaller weight of samples. Page’s model gave a better fit for all drying conditions of okras and spinaches[114,115,117]. But the semi-empirical models developed by Midilli et al.[123] worked well for mint leaves and leek[79,122]. Among the several studied models, the semi-empirical logarithmic model gave a better fit for all drying conditions of basils[121]. The dependence of drying rate constant on effective moisture diffusivity gave a linear relationship for spinaches, mint leaves, leeks and basils[79,117,121,122]. The mathematical modeling study of color change kinetics of okras and basils showed that L, b, chroma and browning index (BI) followed a overall first-order kinetic reaction, whereas, total color change (Delta E) and hue angle followed a zero-order reaction. On the other hand, the data of the total color change (Delta E), chroma, hue angle, and browning index depending on the ratio of the MW output power to sample amount fitted well to a quadratic model[113,120].

Prasad et al. at the Indian Institute of Technology, Kharagpur, India studied MW hot air combined or MW vacuum drying of garlic cloves, button mushrooms and carrot slices[124-134]. It was found that MW hot air combined drying could greatly reduce the drying time as compared to hot air drying alone. Hot air drying used 5 to 10 times of specific energy per kg of removed water than that of MW combined convective drying of garlic cloves. The effective moisture diffusivity increased with increases in the applied MW power. The effective moisture diffusivity within the dried materials decreased with the increase of air velocity during MW convective drying. The activation energy for moisture diffusivities in the MW convective drying was much lower than that of convective drying[130,132]. When using MW vacuum drying for mushrooms, the drying rate constant was affected mainly by the MW power level followed by sample thickness while the system pressure had a little effect on the drying rate[125]. Color, hardness, rehydration ratio, and sensory attributes of mushrooms were significantly affected by the system pressure. A lower pressure resulted in better quality products. Freeze dried mushrooms had the best quality followed by MW vacuum drying, and then hot air drying[127].

In addition to the above mentioned laboratories, Wang et al. studied on mathematical modeling on thin layer MW drying of apple pomace with and without hot air pre-drying. The results showed that the Page model was most adequate in predicting moisture transfer for fresh and pre-dried apple pomace[135].

Böhm et al. studied the MW vacuum drying of strawberries with the objective of maximizing their nutritional quality. They found that the control of process temperature was critical to maintain the stability of ascorbic acid and the total content of phenolic compounds in dried strawberries[136]. Figiel researched on drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum MW methods. The drying kinetics of beetroot cubes was described with an exponential function[137].

In particular, several groups conducted fundamental research on how to address this challenge in MW drying for industrial applications. Lu et al.[138, 139] reported that a complete microwave drying process generally consists of three drying periods: 1) heating-up period in which microwave energy is converted into thermal energy within the moist materials and rapidly raises product temperature; 2) the constant temperature and rapid drying period during which the thermal energy converted from microwave energy is mostly used to vaporize moisture and product temperature stays at a relatively constant level; 3) rising temperature and/or falling drying rate period during which the conversion of electromagnetic energy into thermal energy exceeds the rate of thermal energy removal by evaporation (Figure 8). Without special means to remove the thermal energy, localized product temperature may rises to cause severe browning and even charring of the product[10,138,139]. Because of the inevitable uneven microwave field in a drying cavity described above, pieces of the materials in different locations of the cavity may enter those periods at different times, causing severe quality problems. Feng and Tang at Washington State University, Pullman, WA, USA used a spouted bed in microwave cavity to overcome the above challenge, and used diced apples and blueberries as the products for drying. Their laboratory scale system comprised a 2 450 MHz MW power source, a metal cavity, a hot air source, and a spouted bed[140-142]. In the study on microwave spouted bed (MWSB) finish drying from 24% moisture content to about 5% of the diced apples, the drying time was reduced by more than 80% as compared to that with a stationary bed. Experimental evidence indicated that the end product temperature was effectively controlled by the air temperature of the spouted bed. As a result of uniform product temperature and short process times, products experienced less discoloration and shrinkage compared with hot air drying[140]. Feng et al.[141] developed a heat- and mass-transfer model and used experimentally validated model to study influence of various process parameters on MW SB drying kinetics for diced apples. The study clearly demonstrated the spouted bed air controlled final product temperature (Figure 9). Nindo et al.[143] used the same system developed by Feng et al., to evaluate the influence of different drying methods on retention of physical quality and antioxidants in sliced asparagus. They reported good rehydration, color characteristics, and good retention of total antioxidant activity of asparagus under suitable power level (2 W/g) and heated air temperature (60℃) in the spouted bed. Yan, W. Zhang’s group at JiangNang University in China collaborated with Tang at Washington State University and successfully scaled up the process to a 5 kW system[144]. They produced high quality diced potato cubes on the scaled up system.

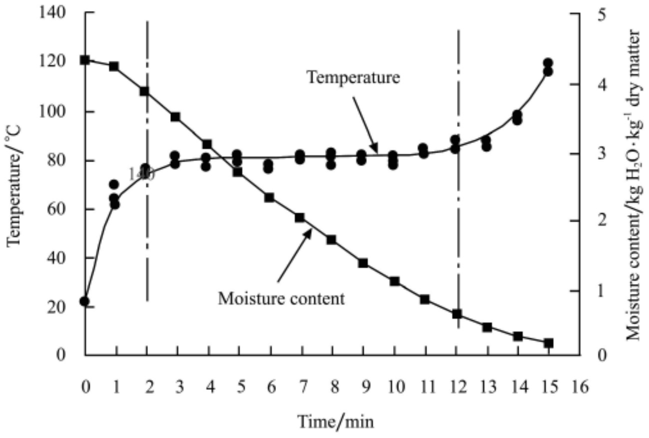


Figure 8 A typical drying curve for changes in sample temperature and moisture content in sliced potatoes[139]

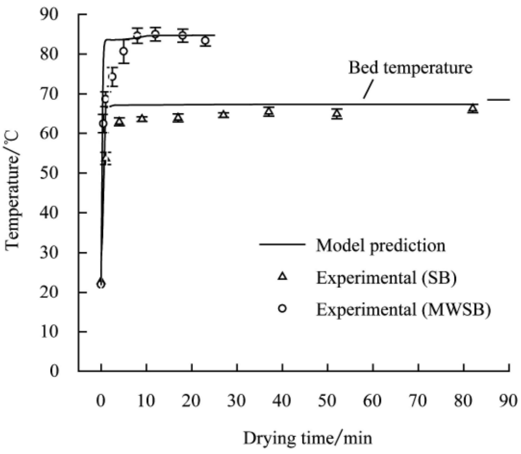


Figure 9 Diced apple temperature in microwave spouted bed drying as compared to hot air spouted bed drying[141]

4.2 RF drying of foods and agricultural products

From 1940 s, RF drying has been used in drying of food materials. The early effort was drying vegetables. RF energy has been used for the post baking of cookies and snack foods since late 1980 s[20-22]. RF heating is also currently used in nonfood industries such as: the drying of various wood, paper, textiles, glass fibers and spools, water-based glues, pharmaceutical products, plastics, board and many other applications[145-148]. In general, RF heating enables the water content inside the product to be reduced very rapidly thus sharply shortens drying times and reduces energy consumption.

From 1990s, most of researches were conducted on the RF assisted vacuum drying of wood. Extensive research has been also conducted on use of RF for heating agricultural products and industrial scaling up for commercial applications[144,149-151]. But there appeared to be few literature reports on RF assisted drying of foods and agricultural products, some of which are reviewed here.

Murphy et al. studied drying of alfalfa using a combination of RF power at 27 MHz with heated forced air. The method increased the overall drying rate, but did not increase the evenness of drying. Applying RF power to partially-dried alfalfa was not effective in leveling the moisture contents of the stems and leaves[152]. Jumah[153] presented a theoretical analysis of simultaneous heat and mass transfer in the RF assisted fluidized bed drying of particulates. Corn was chosen as a test material. Continuous and intermittent heating modes were tested. Effects of relevant parameters such as electric field strength, frequency, inlet air temperature and intermittency were evaluated and discussed. A diffusion-based model was developed for simulation of RF-assisted fluidized bed drying of corns under continuous as well as intermittent RF heating. The numerical results were in a good agreement with the experimental data (Figure 10). With proper control of drying parameters, significant energy and quality advantages could be made from intermittent drying of heat-sensitive materials. The model was an effective tool for computer-aided optimization of RF-enhanced fluidized bed drying processes. The figure showed the drying and temperature curves for different levels of electric field strength under the selected conditions (Figure 11). In RF-assisted convective drying, electromagnetic energy was absorbed selectively in the wet core. The loss factor decreased as moisture evaporating, and followed a reduction in the absorbed power. The rate of evaporation decreased. The temperature change characterized as follows. First, a warming-up period where the temperatures rose quickly and RF heating was very efficient due to higher loss factor of moist material. Then the temperature dropped noticeably and remained almost constant for $E \leq 150\ 000$ V/m. throughout the drying. This temperature-maintaining phenomenon was caused by the fact that the absorbed energy was balanced by the energy losses associated with moisture evaporation and surface convective cooling. However, at higher electric field strength, the particle temperature increased again due to unbalanced energy transferring. During intermittent RF heating, the average moisture content reached a peak value at the end of an ‘off’ period and then falls down at the beginning of the following RF heating. The other feature of the drying curves is that periodic RF heating requires longer drying time as compared to the continuous case. Ptasznik et al. developed a simulation model on RF assisted convective drying for seed quality of broad bean. Based on the experimental data and analysis of the heat and mass transfer mechanism, a semi-empirical model for RF assisted convective drying of shrinkable and hygroscopic materials with internal resistance to mass flow had been derived and used to simulate RF drying of the seed quality of broad bean[154].

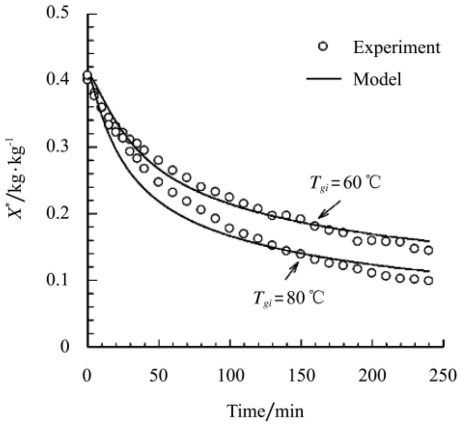
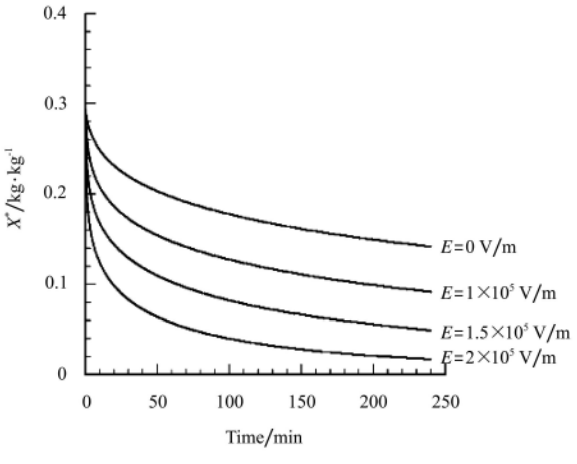
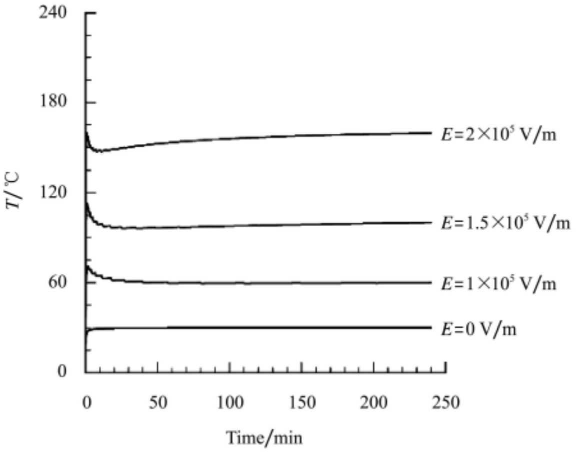


Figure 10 Test of the model for pure convective (E= 0V/m) drying of corn[153]



a. Drying



b. Temperature

Figure 11 Drying and temperature curves as functions of electric field strength (f =13.56 MHz, T_{gi} =30℃)[153]

According to Orfeuil, a commercial cracker production line in which final drying was needed to remove 80 kg/h of water, using a 5 m, 27.12 MHz RF heating system at 80 kW replaced a 30 m conventional oven. The system had a specific energy consumption ranging between 1.2 and 1.4 kWh/kg of evaporated water, and the energy saving was approximately 30% compared to a conventional fossil fuel oven[148]. Anon reported that using RF energy to dry baked products avoided discoloration and loss of flavor while achieving a reduction in energy cost of up to 30% and reduction in floor-space requirements. As much as 60% of baking time can be reduced by using an RF baking containers developed by Electricity Council Research Center at Capenhurst, UK[21]. In addition, using a 27 MHz RF oven manufactured by Proctor Strayfield (Wokingham, UK) efficiently and uniformly removed excess moisture from the crackers. The process was repeatable in mass production with a moisture-level accuracy of ±0.2%[22]. Mermelstein reported developments in RF drying of snack crackers and cookies in deep-bed configuration, with 10 to 15 cm deep. By eliminating the drying burden from the conventional oven, conveyor band speeds increased by up to 60%[155].

Variations in product moisture uniformity in conventional ovens had been the main problems in bakery industry. RF Post baking processes holds solution to this problem. It was possible to add a RF drying unit immediately after conventional baking oven to achieve a significant increase in production and savings in floor space. RF drying leads to more uniform moisture content in final products to reduce chances of mould growth thus significant enhancing shelf life[156].

5 Problems and future prospect

Dielectric drying has many advantages over conventional methods, but is still not used widely for commercial purposes because of technical and economical reasons. Although numerous research reports show that the quality of dielectric dried products is better or equal to that of conventional drying. Most of those studies are conducted on laboratory scale devices, which may not be scalable for commercial operations. Major challenges include non-uniform heat and higher equipment costs compared to conventional drying methods. To make dielectric drying practical and acceptable by the industry, more significant scientific and technological advancements need to take place:

1) Modern food companies are in favor of continuous processing lines and on-line process control. There will be a need for design of reliable and economically viable continuous industrial systems for commercial operations of dielectric drying. It is now possible to develop sophisticated applicators using computer-assisted design to provide even power distributions and with improved process control. Examples of such efforts can be seen in recent work at Washington State University for RF heating of packaged dry powders[150, 151].

2) Rapid increase in computing power of lap-top computers and commercial numerical software (e.g., COMSOL, FEMLAB, and QW3D) can be readily used to study electromagnetic field distributions in complicated MW cavities or RF applicators. Further development of mathematical models and computer simulation models based on commercial software for specific applications will be valuable tools in studying the influence of process conditions, cavity configuration and product shape, sizes and dielectric and thermal properties on electric field distribution and heating patterns. More efforts will be needed in development of computer aided design of industrial scale systems and engineering of processes.

3) Dielectric heating alone is expensive and has several inherit limitations. For effective use of the technology, it needs to be combined with other conventional drying methods (e.g., hot air, infrared, vacuum) to make it economically viable with maximum energy and operational efficiencies. Further studies are needed to investigate appropriate process conditions for the combined dielectric and conventional methods that are scalable to industrial operations.

4) Dielectric properties of food materials govern efficiency and uniformity of dielectric heating. Reliable data as influenced by moisture content and temperature at appropriate frequencies are necessary in computer simulation to provide useful insight into the drying processes and aid the design of industrial systems and process operations. There has been a general lack of those dielectric property data for most food products as influenced by temperature and moisture contents.

5) Extensive research has been conducted in the area of microwave heating, but most results have been generated from small laboratory devices that may not be applicable to industrial operations. Systematic scale-up studies are necessary in evaluation economic viability of the industrial process and to truly understand the influence of the process on the product quality. The key issue here is to ensure desired heating uniformity and the ability to couple large enough energy so as to achieve needed drying rates for continuous processes. Overall, more research is needed for RF drying to take the advantage of more uniform field distribution and deep penetrations in foods, as compared to microwave energy.

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