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PULSED MICROWAVE-VACUUM DRYING OF FOOD MATERIALS

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Key words and Phrases: drying efficiency; energy utilization factor; moisture and temperature equilization; pulsing ratio

ABSTRACT

Microwave drying of food materials has been investigated over several years as a potential means for reducing the total drying time. However, some quality loss almost always accompanied when foods were dried completely using microwaves due to non-uniform temperature and moisture distribution. Some strategies used to improve dried product quality include combination of microwave and conventional hot air drying, pulsed or intermittent drying, and microwave-vacuum drying. Combination of pulsing and vacuum drying is a useful technique to maximize energy use efficiency and product quality especially for temperature sensitive products such as fruits. Some results of pulsed, microwave-vacuum drying of cranberries are presented. Pulsed drying is more energy efficient than continuous drying. In pulsed drying, the longer the pulsing ratio (i.e. longer power-off time in relation to power-on time) was more energy efficient. The quality of pulse-dried product was also generally better than that of continuous-dried product. The cycle power-on time and pulsing ratio should be carefully selected to obtain maximize the benefits of pulsed, microwave vacuum drying.

INTRODUCTION

Drying or dehydration is one of the most effective methods of preserving food materials. Depending on the type of product, the moisture content of dried products may range from 1-15% wet basis. The low moisture content makes the foods less susceptible to microbial spoilage and undesirable quality deteriorative reactions. Four major concerns in drying of foods are:

1. Speed of operation – since high moisture foods are perishable, it is essential to lower the moisture content quickly before any significant spoilage can occur.
2. Energy efficiency – drying of foods is a highly energy intensive operation. This is mainly due to high moisture content of most foods and large latent heat of vaporization of water. Water physically and chemically held in the food matrix requires more energy for its removal compared to liquid water at the same temperature and pressure conditions. For food grains, for example, energy required often exceeds the energy used for producing the crop from seedbed preparation through harvesting (Gunasekaran, 1986).
3. Cost of operation – due to low profit margins experienced by most food industries, the total cost of drying per unit mass of dried material (capital plus operating costs) becomes a major consideration (Gempesaw and Gunasekaran, 1988). This constraint often is a major hurdle for innovations in drying technology – new drying methods and/or equipment. Thus, drying should not only be energy efficient but also economically acceptable.
4. Quality of dried foods – assuring high quality of dried foods is perhaps the most important requirement for any drying operation. The quality of dried foods should go beyond they being microbially safe. Dried foods should be acceptable in terms of consumer preferences such as texture, flavor, and color as well as certain functional requirements such as size reduction, rehydration etc.

The most commonly employed method of drying foods is by using atmospheric forced hot-air dryers. The major concern in hot air drying is the tremendous energy consumption and low drying efficiency. Conventional hot air drying methods also diminish the quality of dried products. As drying progresses, the rate of water evaporation is faster than the rate of water diffusion to the product's surface. The outer skin becomes dry and acts as water barrier, causing a wet interior. This quality defect, called casehardening, is common in many foods subjected to rapid drying. Furthermore, loss of volatile compounds inevitably occurs during drying. Since the products are exposed to a high temperature for a long period, these volatile compounds are vaporized and lost with water vapor. This causes a significant loss of characteristic flavor in dried products. High temperature and long drying time also degrades the product's original color. Therefore, it is obvious that the nature of conventional drying methods does not result in best quality and least cost.

Applying microwave energy to dry food materials seems to be an applicable approach for coping with certain drawbacks of conventional drying. When microwave energy is applied to foods, heat is generated within the product. Therefore, the temperature of the product increases rapidly. Consequently, the rate of water removal is faster than with conventional drying. Thus, the major advantages of microwave drying include saving time and energy. In fact, the first food industry application of microwave energy was finish drying of potato chips (Decareau, 1985). In some cases, microwave heating can be very efficient to remove bound water from a material. With conventional heating, it is necessary to bring the entire material to high temperature in order to break the bonds that keep the water absorbed in the material. With microwave heating, on the other hand, the microwaves can excite the bound water molecules directly. An extensive bibliography on dielectric and microwave drying can be found in Kudra et al. (1990).

MICROWAVE HEATING

The microwave heating of a substance depends on several factors: dielectric permittivity (ε), conductive losses, temperature (T), field intensity, heat capacity (C), and density (ρ). Thermal conductivity can also play an important role when temperature gradients exist. Therefore, successful microwave drying application requires knowledge of both material properties and the microwave equipment. When a substance absorbs microwave energy, its temperature rises. The rate of change of temperature is given by $dT/dt = P/\rho C$. Where, P, the power absorbed per unit volume of material depends directly on the imaginary part of dielectric permittivity, the loss factor (ε''). Since the dielectric properties of most materials change with temperature, even if C and ρ can be assumed constant, the dielectric heating will not be constant.

For most lossy materials, the dielectric properties vary not only with temperature but also with moisture content. The ε'' is directly proportional to moisture content. At low moisture content, the moisture is in the form of thin films, which may or may not be continuos. Moisture in this form is referred to as bound moisture. The ε'' decreases with decreasing moisture content approaching the value of the matrix (Ayappa, 1997). It has been observed that the amount of power absorbed is at a maximum during the initial stages of drying. Therefore, during dielectric heating and drying, the electromagnetic field is highly coupled with heat and mass transfer. Changes in local moisture content and temperature significantly affect the dielectric properties and hence the electromagnetic field distribution. The size of loading, relative to the cavity, also affects the impedance of the cavity and hence the amount of power reflected to the magnetron, which in turn determines the performance of the equipment. Load placement in the microwave cavity has also been shown to affect the heating pattern (Zhang and Datta, 1998).

When a substance absorbs more and more power and therefore heats more and more rapidly it can create a thermal avalanche making the control of the heating process difficult. Thermal avalanche can be particularly harmful in the case of composite materials if the constituents behave differently to microwave energy. If the thermal conductivity of the materials is not sufficient to efficiently dissipate the local heat, there will be hot spots in the composite that could cause quality deterioration. (Goyette et al., 1990). Since most foods are composites, thermal avalanche or runaway heating is a major problem in microwave processing of foods.

Padua (1993) investigated the effect of composition on uneven temperature profile in agar gels containing sucrose. The development of temperature profiles inside samples depended almost exclusively on the ability of the samples to absorb microwave energy. The level of sucrose notably affected heating patterns of cylindrical agar gel samples containing sucrose. Gels prepared of highly concentrated sucrose solutions absorbed microwave energy more efficiently showing surface heating and relatively cold center as opposed to those with no sucrose which absorbed less energy, showed pronounced central heating and relatively cold surface (Fig. 1). Thus, Padua (1993) suggested that it may be possible to manipulate microwave-heating pattern in foods through geometry and formulation.

Foods show temperature sensitive dielectric behavior at low frequencies between 400-900 MHz. Ayappa et al. (1991) presented power distribution and transient temperature profiles for a slab of raw beef exposed to microwaves of equal intensity on both faces. At 450 MHz, dielectric properties are strong functions of temperature. Therefore, penetration depth decreases with increasing temperature. Thus at the onset of heating, the sample appears thinner to the radiation, and the microwaves from opposite faces interfere to produce a peak in the center of the slabs. As heating proceeds, due to the decrease in penetration depth, microwaves decay into the sample without significant penetration. The increasing loss factor, however, causes the face temperature to rise sharply, resulting in a very uneven temperature distribution. At high frequencies (e.g. 2800 MHz) dielectric properties are only weakly dependent on temperature. Thus the power distribution changes only slightly as the sample heats. Nonetheless, a nonuniform temperature distribution exists in samples heated by microwaves at both frequencies (Fig. 2). More importantly, as would be expected, the temperature profile grows more uneven with continued heating.

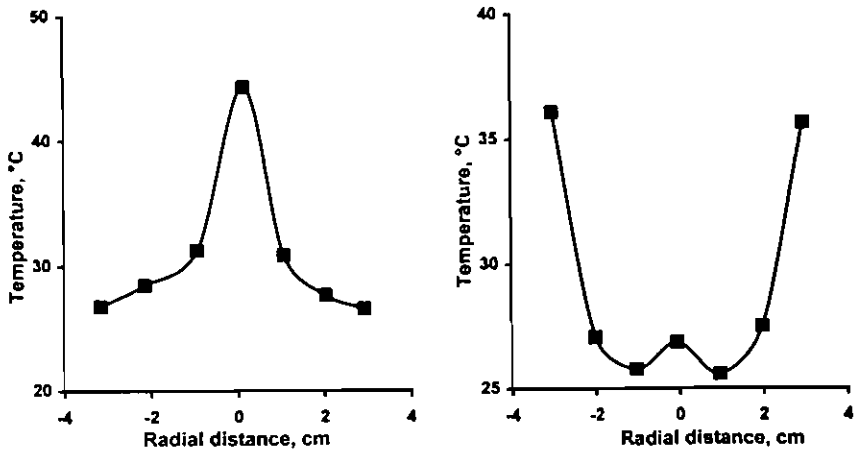

Fig. 1. Temperature profile of 2% sucrose agar gel (top) and 60% sucrose agar gel (bottom). Gels were heated 15 s in a 1500-W microwave oven at 2450 MHz. (Data from, Padua, 1993).

In addition, at 2450 MHz, one of the two common microwave frequencies, as the product temperature increases more energy is absorbed near the product surface (Mudgett, 1986). Because of this, upon continuous supply of microwave energy, product temperature tends to increase rapidly. This skin effect is responsible to scorching of the product surface (Gunasekaran, 1990). To avoid such overheating of the product and to use the applied energy more efficiently, both heat and mass transfer should be carefully balanced.

PULSED DRYING

Success of microwave heating of foods often depends on the expected uniformity of heating (Zhang and Datta, 1998). However, some common problems in microwave processing stem from the above mentioned uneven and excessive heating (Gunasekaran, 1990; Ramaswamy et al., 1991). Physical damage to product such as scorching, off-color, case hardening are often reported (Datta, 1990; Gunasekaran, 1990; Tulasidas et al., 1993). Furthermore, energy utilization is not as efficient as it should be. These problems are due to poorly controlled heat and mass transfer during microwave drying. Several strategies have been proposed in order to effectively apply microwaves for drying: 1. Combination of microwave and conventional drying ; 2) microwave drying

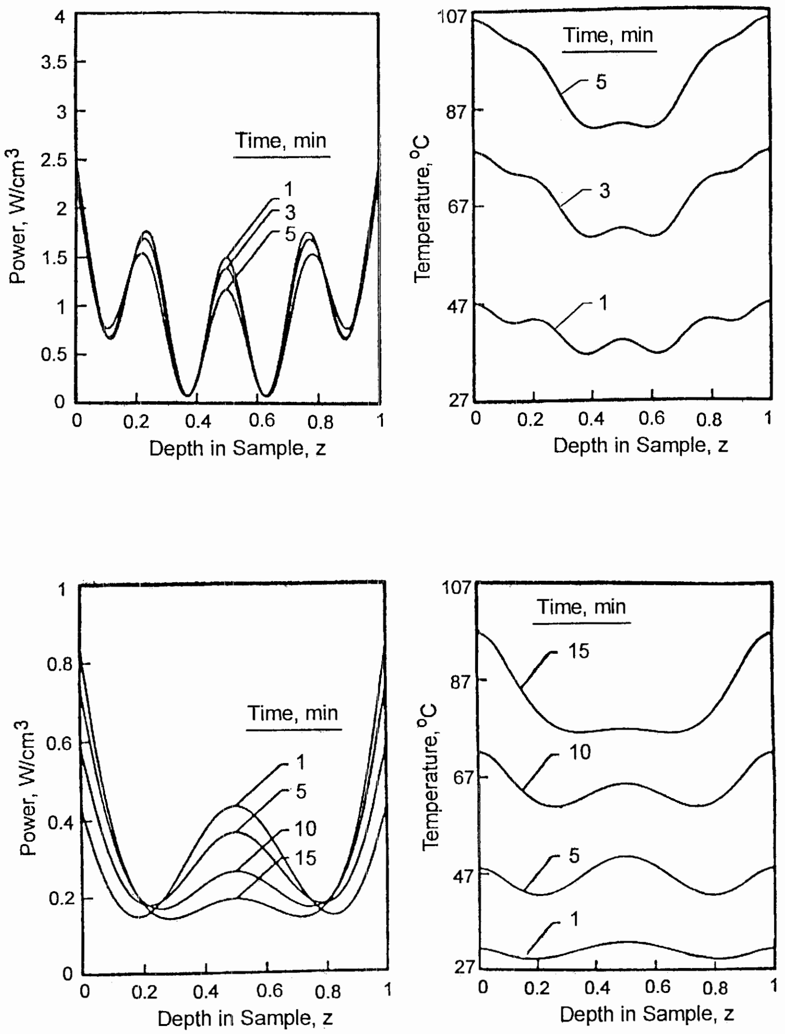

Fig. 2. Power and temperature distributions for a raw beef sample exposed to microwaves at 450 MHz (top) and 2800 MHz (bottom). (Data from Ayappa et al., 1991).

under a vacuum to lower the drying temperature; and 3) applying microwave energy in a pulsed manner to maximize drying efficiency since continuous heating does not accelerate the rate of water removal when critical moisture content is reached. An excellent example of microwave drying in conjunction with hot air drying is drying of pasta which now has become an industry standard (Giese, 1992). In general, microwave-assisted convective hot air drying reduces drying time compared to convective drying and improves product quality compared to microwave drying (Tulasidas et al., 1993).

The idea of pulsed (or intermittent) drying is not new. First investigation of the intermittent drying in 1933 has been credited to Edholm (Harnoy and Radajewski, 1982). In this technique, the energy for drying is intermittently turned on and off. Intermittent drying improves energy efficiency and product quality (Farkas and Rendik, 1997). While these are desirable features, for microwave drying, most important benefit of pulsed drying is in temperature and moisture equalization – redistribution of temperature and moisture profiles within foods during off times due to thermal diffusion. Pollak and Foin (1960) measured temperature of roast beef immediately after microwave cooking and 30 min later. The temperature redistribution they observed is presented in Fig. 3. This is a good illustration of temperature redistribution within foods during power-off times.

It has been suggested that intermittent supply of energy can improve thermal energy utilization as well as quality of dried product which are heat sensitive when internal heat and mass transfer rates control overall drying rate (Carabin, 1990). Gunasekaran (1990) used continuous and pulsed microwave energy to evaluate drying rates of corn. Typical drying curves exhibited an initial period of relatively slow moisture removal followed by a rapid drying period. Apparently, during the initial few seconds the microwave energy was used in raising the grain temperature and very little moisture was evaporated. Once the moisture in the corn reached the saturation temperature it is rapidly evaporated upon subsequent microwave energy input. The power-off times provided the rest times necessary for moisture redistribution within the kernels leveling the moisture profile throughout the grain mass. Therefore, during the subsequent power-on times, the drying was more efficient. Drying rates for microwave drying was the highest for continuous power application (70×10^{-3} to 85×10^{-3} kg of H_2O/h). However, the pulsed application was still much faster (35×10^{-3} to 60×10^{-3} kg of H_2O/h) than conventional hot air drying. Gunasekaran and Paulsen (1985) reported conventional hot air drying rate of 75×10^{-6} to 150×10^{-6} kg of H_2O/h for drying corn from 25% to 15% moisture. Reporting similar results, Shivhare et al. (1992) discussed the trade off between energy use and total drying time. Thus, the optimal drying operation should be set based on relative cost of time and energy.

VACUUM DRYING

During vacuum drying, as high-energy water molecules rapidly diffuse to the surface they desorb into reduced pressure (vacuum) atmosphere. The reduced pressure

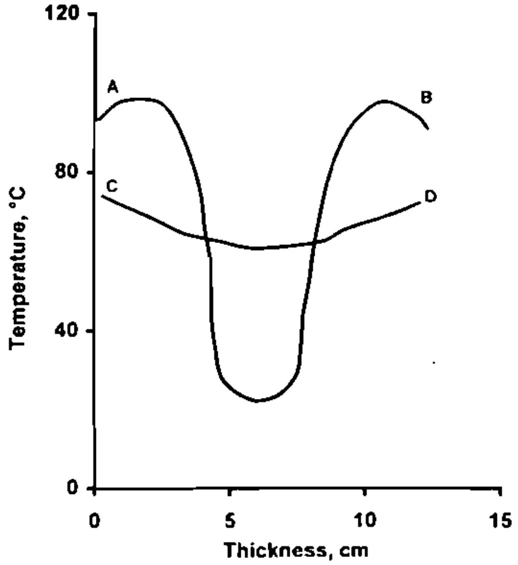

Fig. 3. Temperature equalization in roast beef sample just after microwave application (AB) and after a 30-min rest time (CD). (Data from Pollak and Foin, 1960).

lowers the concentration of water in the air surrounding the product thereby increasing the rate at which the water molecules desorb from surface of the kernel. Thus, for a given rate of drying, reduced pressure enables the products to be dried at a lower product temperature than would be required at atmospheric pressure. Moreover, the absence of air during dehydration diminishes oxidation reactions. Because of these advantages, the color, texture and flavor of dried products are improved. Vacuum drying is especially suitable for products that are prone to heat damage such as fruits. However, a disadvantage is that vacuum drying has high installation and operating costs (Woodroof and Luh, 1986).

The microwave-vacuum drying technique has been successfully applied to numerous food materials – fruits, vegetables, and grains (Delwiche et al., 1986; Gunasekaran, 1990; Kiranoudis at al., 1997; Wadsworth et al., 1990; Yongsawatdigul and Gunasekaran, 1996). Microwave vacuum drying of cottonseeds was reported to improve free fatty acid content of the cottonseed (Anthony, 1983). It is a significant advantage as most of the cottonseed produced in the US is marketed for their oil properties.

The temperature of the product during microwave drying can be regulated by the rate of input of microwave energy and by the vacuum maintained in the chamber. Examining drying curves for parboiled rice dried with 53.2 and 6.7 kPa, dryer operating pressures, and two microwave power levels (0.6 and 1.8 kW), some expected trends of faster drying at higher power levels and at lower pressure levels can be noticed (Fig. 4). This indicates that drying rate was not limited by liquid water diffusion rate and that the rate of adsorption/desorption of water on the surface of rice was a significant factor in overall drying rate. In addition, Wadsworth et al. (1990) made two other claims with respect to lower operating pressure: 1. The rate of increase in drying rate (slope of lines in Fig. 4) with increasing power level was greater at lower operating pressure. This indicates that adsorption/desorption rate was a more important factor in determining overall drying rate at lower power levels. 2. For a given power input, power absorbed by the product is considerably higher at lower operating pressure. Despite these advantages, some quality losses have been observed with microwave heating (Wadsworth et al., 1990; Drouzas and Schubert, 1996). Therefore, an optimal material temperature should be maintained during microwave-vacuum drying.

PULSED, MICROWAVE-VACUUM DRYING

Combining the advantages of pulsed drying and vacuum drying, thus, appear to be a valid method to optimize energy use and product quality. Accordingly, we investigated pulsed microwave-vacuum drying of cranberries (100-g samples) using a laboratory-scale microwave-vacuum oven (Zwag, Model Labotron 500) (Yongsawatdigul and Gunasekaran, 1996a). The factors studied were: microwave incident power (250 W), pressure/vacuum (5.33, 10.67 kPa), initial moisture (62 and 76), and pulsing ratio (1, 2, 2.5, 3 , 3.5, 4 and 6). The pulsing ratio, PR was defined as:

$$PR = \frac{\textit{Cycle Power on Time} + \textit{Cycle Power off Time}}{\textit{Cycle Power on Time}}$$

These PRs can be grouped as: continuous drying, CD: PR=1; pulsed drying, PD Set A: PR=2, 2.5, and 3.5 (those with power-on times of 60 s and off times of 60, 90, and 150 s, respectively) and Set B: PR=3, 4, and 6 (those with power-on times of 30 s and off times of 60, 90, and 150 s, respectively). At each set of experimental conditions, three replicates were performed.

Product Temperature

The temperature of the product was measured outside of microwave cavity using a digital thermocouple readout at the beginning and end of each power-on time. The thermocouple was inserted into one cranberry at the center of the sample. The

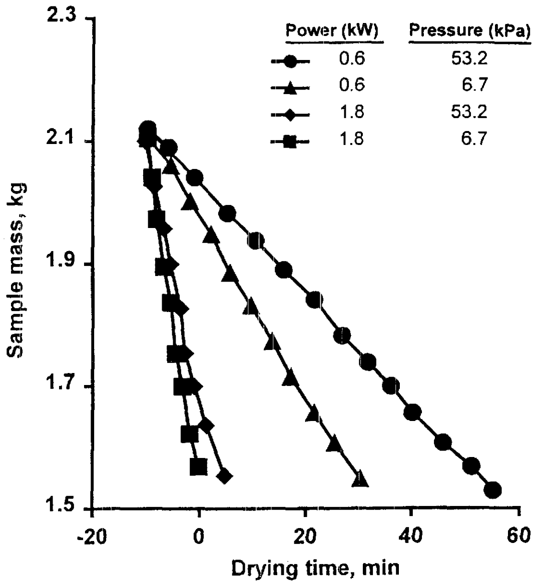

Fig. 4. Microwave-vacuum drying curves for parboiled rice at two dryer operating pressures and power levels. (Data from, Wadsworth et al. 1990).

measurements were made within a very short time (~ 5 s). The product temperature varied up and down as microwave power was turned on and off, respectively. For both PD and CD the temperature profiles at both pressures overlapped toward the end of drying (Yongsawatdigul and Gunasekaran, 1996a). This is because, when only a limited amount of water is available in the product, operating pressure no longer controls the product temperature. Under such conditions, the sensible heat becomes a dominant factor influencing product temperature. Besides the pressure level, power-on and -off times also influenced product temperature. As expected, the temperature of the product dried at higher pressure (10.67 kPa) was higher than the temperature obtained from lower pressure (5.33 kPa). The boiling point of water at 5.33 kPa (34°C) is lower than at 10.67 kPa (47.2°C). Therefore, operating at lower pressure allows water to evaporate at a lower temperature. However, the product temperature was relatively higher than the corresponding boiling point, indicating some sensible heating of samples as drying progressed. As would be expected, longer on-time increased, and longer off-time decreased, the final product temperature. This is represented in terms of PR in Fig. 5. The smaller the PR, the larger the final product temperature. For PR>1, the product temperature is significantly lower. The difference in product temperature at PR of 2 and

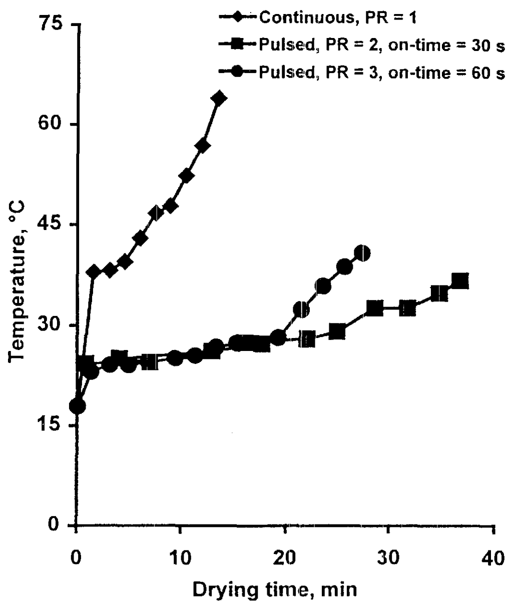

Fig. 5. Product temperature during continuous and pulsed, microwave-vacuum drying at different pulsing ratios (PR). The vacuum level was 5.33 kPa. (for pulsed drying teperatures plotted were average of measured values at the beginning and at the end of each on-time).

3 becomes more acute as drying progresses. The decrease in temperature with greater off-time (PR=3) is due to evaporative cooling and convective heat losses from the cranberries.

Drying Time and Drying Rate

In pulsed drying, the drying time can be considered in two ways: power-on time and total time. The power-on time is the duration over which energy was supplied for complete drying. The total time is the total duration required for complete drying i.e. power-on plus power–off times. These considerations have different implications. The power-on time directly relates to total energy input and thus the cost of energy for the drying operation. The total time, on the other hand, relates to dryer capacity as well as product quality. This can be referred to as cost of time. An ideal drying system should result in low cost of energy and cost of time.

For PD, drying was faster when a longer power-on time setting was used. This is because a greater temperature gradient is normally established in products exposed to longer power-on time. However, total power-on time of the runs operating at a longer cycle power-on schedule was greater than those operating at shorter cycle power-on schedule. These imply that PD utilizes energy more efficiently than CD, and a shorter power-on time setting provides more favorable energy utilization. In general, for a given set of operating conditions (magnetron power setting, pressure level, and initial sample moisture content), it was observed that any attempts to lower the power-on time invariably results in prolonging the total time (Table 1). Total time as well as power-on time was lower when the microwave was operated at lower pressure. It can be explained that a pressure gradient established inside the product played a vital role in moisture removal. Wei et al. (1985) stated that vibration of water molecules generated positive pressure inside the product being dried during microwave heating. Hence, a lower operating pressure created a larger pressure gradient accelerating moisture removal.

The effect of PR should be considered carefully. In general, longer the PR, the lower the total power-on time. Since it is possible to obtain a given PR with different combinations of power on- and off-times going simply by the PR values can be misleading. For example, PR of 3.5 required a power-on time of 10.5 s whereas the PR of 3 required lower power-on time, 10.3 s. The difference is that PR of 3 was obtained with a cycle power-on time of 30 s. The PR of 3.5 was obtained with a cycle on-time of 60 s. Therefore, the cycle power-on time and the PR should be considered together. Of course, for a given cycle on-time, the larger the PR the lower the total power-on time. Among the test conditions the lowest total power-on time was required for pressure setting of 5.33 kPa at a PR of 6.

Drying rate (DR) is defined as amount of water removed per unit and time per unit dry matter (kg H_2O removed/h-kg dry matter). Thus, for given initial and final product moisture content, DR is inversely proportional total drying time. Accordingly, opposite of observations relating to total time discussed above applies to DR.

Energy Utilization and Drying Efficiency

Energy considerations in microwave drying should be based on both energy input and energy absorbed. Energy input is just the total energy supplied for complete drying.

$$EUF = \frac{Total\ Energy\ Absorbed}{Total\ Energy\ Input}$$

This is the product of magnetron power setting (250 W in this study) and the total power-on time for complete drying. On the other hand, energy absorbed is a strong function of dielectric properties of the product, which continuously change during drying due to varying product temperature and moisture content. As mentioned previously, energy

TABLE 1. EFFECT OF OPERATING PRESSURE AND PULSING RATIO ON POWER ON-TIME (ON-T, min) AND TOTAL DRYING TIME (TT, min)

Moisture Content (% w.b.)	Pressure (kPa)	CD	PD Set A Pulsing Ratio*						PD Set B Pulsing Ratio**					
			3		4		6		2		2.5		3.5	
			On-T	TT	On-T	TT	On-T	TT	On-T	TT	On-T	TT	On-T	TT
62	5.33	15.5	10.3	30.8	9.8	39.0	8.5	51.0	12.0	24.0	12.0	30.0	10.5	36.8
	10.67	17.5	11.5	34.5	10.5	42.0	9.0	54.0	14.5	29.0	14.0	35.0	13.0	45.5
76	5.33	18.0	12.5	37.5	12.0	48.0	9.5	57.0	14.5	29.0	13.5	33.8	12.0	42.0
	10.67	20.0	14.5	43.5	13.3	53.0	10.5	63.0	17.0	34.0	16.5	41.3	13.0	45.5

* - PD Set A – cycle power-on time was 60 s.

** - PD Set B – cycle power-on time was 30 s.

absorbed is also a function of microwave characteristics – cavity size, loading, load placement etc. An estimate of energy absorbed can be obtained by accounting for the sensible (temperature change) and latent (moisture lost) heat (Yongsawatdigul and Gunasekaran, 1996). An energy utilization factor (EUF) was defined to consider the energy efficiency of the drying operation at different settings.

Drying efficiency (DE) is defined as the amount of moisture evaporated (kg H_2O) per unit of energy input (MJ). Since, microwave (field distribution) and product characteristics (size, shape etc.) can be altered to improve the energy absorbed, a modified drying efficiency (MDE) was defined based on the total energy absorbed as: MDE = DE/EUF. These three efficiency measures are listed in Table 2.

It is seen that EUF for CD are less than for PD (i.e. larger the PR, the larger the EUF). Also, the lower the operating pressure, the better the EUF. Wadsworth et al. (1990) stated that the reflection of microwave power was less at lower pressure and higher microwave power level. Thus, at lower pressure, more microwave energy was available to be absorbed. As in all drying systems, the energy is utilized more efficiently when drying higher moisture product when compared to its lower moisture counterparts. All these observations are as expected

Besides the above factors, cycle power-on time (PD Set A vs. PD Set B) inversely affected EUF. As described earlier, temperature gradient is a predominant driving force for water removal when a longer cycle power-on time is applied. Thus, energy is used for increasing product temperature and removing water. On the other hand, a shorter cycle power-on time gradually increases product temperature and allows water to redistribute within the product. Therefore, energy input is mainly utilized for removing water rather than increasing product temperature. Consequently, EUF of PD Set B (shorter cycle power-on time of 30 s) is higher than that of PD Set A.

Since the initial and final moisture contents of samples were the same, DE is an inverse function of total power-on time. Therefore, previous discussions relating to the total power-on time also applies to DE. Simply put, PD is more efficient than CD; shorter power-on time followed by longer power-off time results in higher DE (i.e. DEs of PD Set B is better than those of PD Set A; and the larger the PR, the better the DE). The DE values for PD are in the range of 0.3 to 0.4 kg H_2O/MJ. These compare very well with the DE for hot air drying of prunes (product with properties similar to cranberries we used) 0.15 to 0.2 kg H_2O/MJ (Hayes, 1987; Thompson et al., 1981).

The MDE does not offer any clear trend except that drying of higher moisture product results in a lower MDE. The effect of vacuum level and PR are not clear in terms of MDE. A careful study of materials of widely differing absorption characteristics may be necessary to draw any valid conclusions regarding MDE.

TABLE 2. EFFECT OF OPERATING PRESSURE AND PULSING RATIO (PR) ON ENERGY UTILIZATION FACTOR (EUF); DRYING EFFICIENCY (DE); AND MODIFIED DRYING EFFICIENCY (MDE).

Process	Operating Condition		EUF		DE ($kg H_2O/MJ$)		MDE ($kg H_2O/MJ$)	
	Pressure (kPa)	PR	Moisture content (% w.b.)		Moisture content (% w.b.)		Moisture content (% w.b.)	
			62	76	62	76	62	76
PD Set A*	5.33	2	0.68	0.78	0.28	0.29	0.41	0.38
		2.5	0.68	0.82	0.29	0.31	0.42	0.38
		3.5	0.76	0.87	0.31	0.36	0.41	0.41
	10.67	2	0.53	0.68	0.22	0.25	0.42	0.37
		2.5	0.55	0.76	0.25	0.25	0.45	0.33
		3.5	0.61	0.84	0.25	0.33	0.41	0.39
PD Set B**	5.33	3	0.70	0.80	0.32	0.33	0.46	0.42
		4	0.75	0.87	0.34	0.37	0.46	0.41
		6	0.85	0.95	0.36	0.40	0.42	0.42
	10.67	3	0.59	0.70	0.28	0.29	0.48	0.42
		4	0.61	0.76	0.32	0.32	0.52	0.41
		6	0.77	0.95	0.35	0.41	0.45	0.43
CD	5.33	1	0.49	0.56	0.20	0.23	0.41	0.42
	10.67	1	0.43	0.50	0.18	0.21	0.41	0.42

* - PD Set A – cycle power-on time was 60 s.

** - PD Set B – cycle power-on time was 30 s.

It is important to note here that no attempts were made to optimize the EUF or DE. A careful selection of cycle power-on time and PR will be necessary to optimize the pulsed, microwave drying. A comprehensive experimental study in conjunction with modeling of drying kinetics will allow for such an optimization.

Product Quality

Any alternative drying technique should be selected based not only on cost considerations but also based on superior product quality. Poor quality of dried materials can potentially represent a very high drying cost. Therefore, the quality of pulsed, microwave-vacuum dried cranberries was evaluated for their color and texture. In general, our results indicated that the color of the cranberries was affected by the method of drying. Longer total drying time adversely affected the redness of the dried cranberries somewhat but was not statistically significant. The product texture, measured by the force necessary to cut through, was softer for pulsed, microwave-dried cranberries compared to conventional hot-air dried product. The PD resulted in a softer product compared to CD. Details of the product quality test methods and results can be obtained from (Yongsawatdigul and Gunasekaran, 1996b).

CONCLUSIONS

The pulsed, microwave-vacuum drying is very suitable for drying temperature sensitive products such as fruits. This method generally results in lower energy cost and better product quality. In general, lower the cycle power-on time and larger the pulsing ratio, the better the energy utilization and lower the energy cost. In order to maximize the benefits of pulsed, microwave-vacuum drying both cycle power-on time and pulsing ratio should be optimized for a given product and microwave properties.

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