Fixed and Incremental Levels of Microwave Power Application on Drying Grapes under Vacuum

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ABSTRACT: Microwave vacuum drying has been investigated as promising potential for high-quality dried fruits. In this study, a batch microwave vacuum dryer was used to understand the effect of levels of microwave power on the drying characteristics and moisture content of grapes. Thompson seedless grapes were treated 1st for 30, 60, and 90 min at fixed levels of 500, 750, 1000, 1250, and 1500 W at a reduced pressure of 2.7 kPa and then treated by 3 staged microwave power levels: a higher level of power during the initial stages of dehydration and 2 subsequently lower levels of power applied as the moisture content decreased. A typical temperature profile was found during the drying process, linearly increasing at the start of drying, followed by a nearly constant value during the drying period while water was evaporating. The total specific energy estimated by the energy balance model was 0.97 to 1.01 W-h/g of fresh grapes and agreed well with the experimental specific energy of 0.85 to 0.90 W-h/g for the fixed power tests. The multiple regression results showed that the specific energy was the most influential parameter on the final moisture content of grapes both in fixed and incremental power levels. Further research is needed to further improve the process with high efficiency and good product quality using product temperature as a control measure.

Keywords: microwave vacuum dehydration, specific energy, fruits, grapes

Introduction

Dehydration offers a means of preserving foods in a stable and safe condition providing a shelf life longer than that of fresh fruits and vegetables. The conventional thermal methods used to obtain acceptable final moisture content using heated air change the character of the dried product (Clary and others 2002), and much of the flavor and nutritional composition is lost to thermal degradation (Mousa and Farid 2002). Freeze drying is an alternative to heated air drying and can minimize losses of flavor in dried products because the low temperature used in this process preserves fresh character. However, the cell structure of fruits and vegetables is compromised resulting in loss of color and nutritional value (Dalgleish 1990). Furthermore, freeze drying is one of the most expensive processes because of the slow rate of dehydration and large capital investments (Flink 1975).

Recently, microwave vacuum dehydration has been studied as a potential method to dry fruits in a way that minimizes changes in character (Drouzas and Schubert 1996; Yongsawatdigul and Gunasekaran 1996; Mousa and Farid 2002; Cui and others 2004). Microwave vacuum drying combines the advantages of both vacuum and microwave drying, resulting in a rapid, uniform, and energy-efficient process (Sunjka and others 2004). Microwave energy penetrates into the flesh of fruits and vegetables and induces vaporization from all parts of the product simultaneously. Microwave energy creates internal vapor pressure based on the level of power used. Rapid vaporization of moisture from fruit tissue may preserve original shape of the product. Feng and others (2001) described the effect of microwave power on internal vapor pressure of diced apples in a spouted bed dryer. Higher microwave power resulted in higher vapor pressure within the diced apples due to heat generation. Product temperature reached 80 °C in this ambient pressure process. Use of microwave energy in low-pressure conditions reduced the process temperature and preserved fresh character including color, flavor, volatile aromas, and nutritional value (Petrucci and Clary 1989).

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Microwave energy has been used in many applications to heat and dehydrate foods. Mui and others (2002) studied fixed microwave application to banana, in which 650 g of fresh banana was heated at a fixed level of 1.5 kW to dry the fruit to 3% (db). Durance and Wang (2002) used 16 kW throughout a drying cycle to dry 13.7 kg of fresh tomatoes to a final moisture content of 18.7% (wb) in 0.81 h. To compensate for the sudden rise in temperature, staged microwave power application was tested using a DRI dryer equipped with 4 1-kW magnetrons (Lin and others 1998). This system used staged microwave application by operating multiple magnetrons collectively to apply full power, followed by an incremental decrease in power application as the product dried. A predetermined step down of power was used to dry 1 kg of carrot to a final moisture content of 10.8% (wb). The incremental power sequence was 3 kW for 19 min, 1.0 kW for 4 min, and 0.5 kW for 10 min at a pressure of 13.3 kPa. On the other hand, Feng and Tang (1998) described a balance of microwave power and heat transfer from apple dices during the plateau phase in a spouted bed microwave dryer. A similar temperature profile was reported by Lu and others (1999) in microwave drying of potato slices at ambient pressure. Kiranoudis and others (1997) studied the drying kinetics of apple, kiwi, and pear in a microwave vacuum drying system to develop a 1-parameter empirical mass transfer model, which was validated by using a Sharp microwave oven and a glass vessel to hold the fruit at a pressure of 3.5 to 11.9 kPa. However, moisture removal from grapes is affected by high sugar content and the presence of an epidermis, which mitigates the benefit of cutting fruit to expose the pericarp tissue. Water bound with sugar is difficult to remove, and the barrier characteristics of the grape skin slow moisture migration. Therefore, it is desirable to determine the final moisture contents of grapes as affected by the specific energy when applied fixed and incremental power levels in microwave vacuum drying.

The objectives of this research were to determine the microwave energy needed to dry grapes using microwave vacuum dehydration at various levels of fixed and incremental microwave power and to explore the effect of the specific energy on the final moisture content of grapes to better understand the heating and drying characteristics of grapes.

Materials and Methods

Microwave vacuum drying system

The microwave vacuum dehydrator (Experimental Prototype, McDonnell Douglas, St. Louis, Mo., U.S.A., a.k.a. Boeing) was used in the experiments for both fixed and incremental levels of microwave power applications. It consisted of a 3-kW, 2450-MHz microwave power supply (GL103A, Gerling Applied Engineering, Modesto, Calif., U.S.A.), wave guide, microwave window, microwave control, a vacuum vessel (90 cm in dia and 120 cm long) equipped with a turntable, vacuum pump (model R5S 100-132, Busch, Inc., Virginia Beach, Va., U.S.A.) and vacuum control (Figure 1). The medium ripple (5%) microwave power supply used an electromagnet surrounding the magnetron. This electromagnet was used to control the level of magnetic field in the magnetron interaction space. If the field was sufficiently high, no electrons crossed the interaction space, resulting in zero output. A reference signal from the magnetron was used to control the magnetic coil. This ensured smooth transition of microwave output without waveform distortion. Therefore, output levels could be maintained continuously at any power level between 0 and 3 kW.

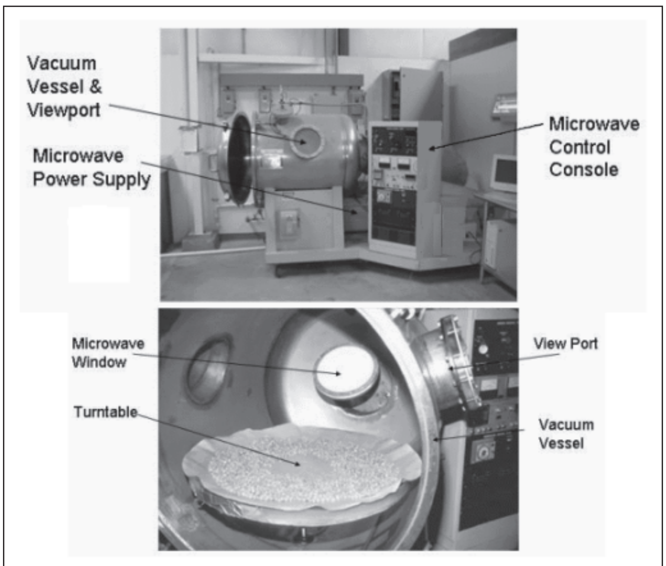

Figure 1—Laboratory microwave vacuum dehydration system

System controls and instrumentation are shown in Figure 2. Microwave power was controlled through the programmable logic controller interface. Grape temperature and vessel pressure were measured by an infrared temperature sensor (model H-L10000, Mikron Infrared, Inc., Oakland, N.J., U.S.A.) and pressure transducer (model P3061-15, Schaevitz/MCI, Fairfield, N.J., U.S.A.), respectively. A fiber-optic system included in the system was not used in this work because of difficulty in keeping the probes embedded in the grapes on a moving turntable.

Grape samples

Before the drying experiments, fresh Thompson Seedless grapes were removed from the cluster and separated into single berries for each test. A subsample of berries was collected randomly for determination of sugar content by refractometer (model 10482, Abbe/Scientific Instruments, Kleene, N.J., U.S.A.), and initial moisture content was determined by vacuum oven (AOAC 1980). The sample of single grapes was weighed and placed on the turntable in the batch unit. The samples consisted of 150 to 200 grapes weighing 907 g in each fixed power level test. The samples consisted of 300 to 400 grapes weighing 1816 g in each incremental power level test. Each test was replicated 3 times.

Treatments under fixed and incremental levels of microwave power

The microwave power application levels for the fixed microwave

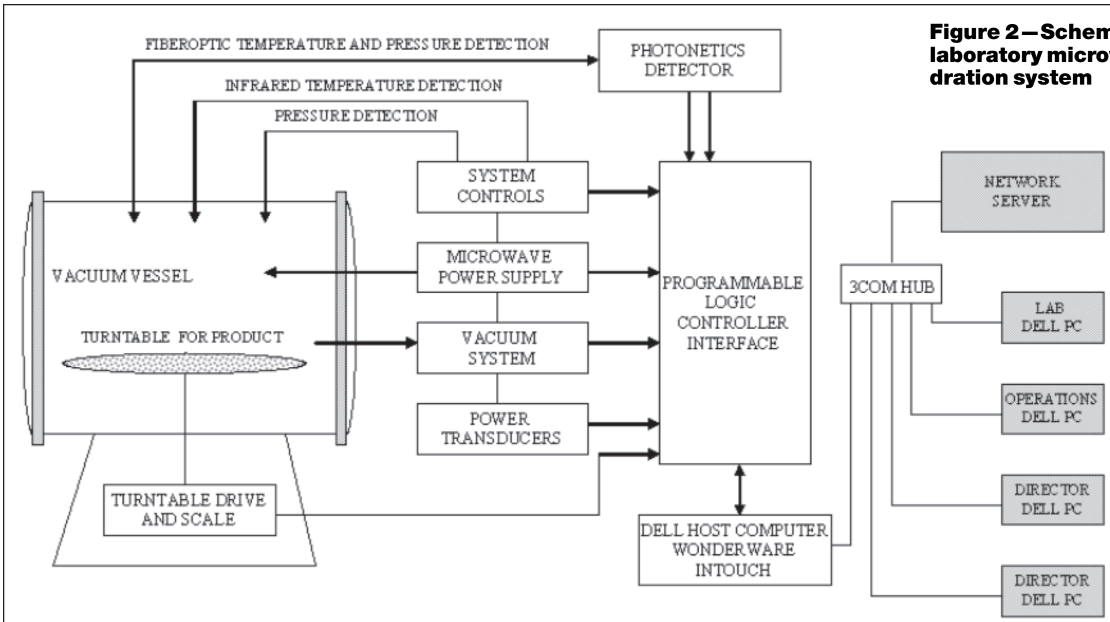

Figure 2—Schematic diagram of the laboratory microwave vacuum dehydration system

tests were 500, 750, 1000, 1250, and 1500 W applied for 30, 60, and 90 min. Each power-time test was replicated 3 times. Incrementally staged microwave energy tests were intended to expose the grapes to higher levels of power during initial stages of dehydration. Two subsequently lower levels of power were applied as the moisture content decreased. The incremental levels of microwave power were 3.0, 1.5, and 0.5 kW applied from 5 to 40 min within each stage (Table 1). Each test was terminated after the treatment time or if there was evidence of burning. The actual time was noted and the grapes were removed from the vessel. If the treatment time was not reached in any stage, the actual time was used for calculation of specific energy.

A vessel pressure of 2.7 kPa was used in all the experiments. This pressure was selected in preliminary tests to minimize product temperature and maintain the stability of the microwave field in the vessel. Lower levels of vessel pressure would increase the potential of glow discharge and arcing in the microwave energy field. At 2.7 kPa, free water boiled at about 20 °C (Goff and Gratch 1951).

The actual specific energy for each power-time test was determined for each test based on the actual duration of the test and the net microwave power from difference between forward and reflected power levels. The power was measured using crystal diodes inserted in the wave guide. Multiple linear regression analysis was used to develop a regression model to predict the effect of the treatment variables on final moisture content. Regression analysis was also used to determine the significance of each treatment variable in predicting final moisture content.

The condition of the grape sample during the tests was monitored visually through an observation window. Time, temperature, pressure, and forward and reflected power levels were recorded throughout each test. After each test, the dried grape sample was removed from the vessel, weighed, and separated into categories of puffed and crispy, soft/chewy, and burned. The final moisture content was determined by vacuum oven (AOAC 1980) for each category and average final moisture content was calculated. Specific energy for each microwave power stage, fresh fruit moisture content, and initial moisture content were analyzed using multiple linear regression analysis (Minitab 14, 2003) to develop a prediction model for determining final moisture content. Similar analysis of the time power was applied in each stage was analyzed to predict final moisture content.

Specific energy calculation

The microwave power applied in these tests was quantified as specific energy (E_s) and defined as W-h/g of fresh grapes. To determine a method of predicting the specific energy required to dry grapes based on the properties of the fruit, the following heat loads were calculated.

Sensible heat of water in product (Q_p, kJ) and dry matter (Q_d, kJ):

$$Q_p = M_w \cdot C_w \cdot \Delta T = M \cdot MC_i \cdot C_w \left(T_f - T_i\right) \tag{1}$$

$$Q_d = M_d \cdot C_d \cdot \Delta T = M \cdot \left(1 - MC_i\right) \cdot C_d \cdot \left(T_f - T_i\right) \tag{2}$$

where C_d and C_w are specific heat of product and water (kJ/kg°C); M, M_d, and M_w are mass of product, dry matter, and water in product, respectively (kg); MC_i is initial moisture content (% wb); T_f and T_i are average final and initial temperatures (°C).

Latent heat of water removed (E_w, kJ) from a product (W_r, kg) can be calculated as follows:

$$E_w = W_r \cdot L \tag{3}$$

$$W_r = M\left[1 - \frac{1 - MC_i}{1 - MC_f}\right] \tag{4}$$

Table 1 — Treatment levels for staged microwave applications used to develop a prediction model for final moisture content

Test nr	Stage 1 time (min) at 3000 W	Stage 2 time (min) at 1500 W	Stage 3 time (min) at 500 W	Specific energy (W-h/g)
1	5	20	80	0.78
2	5	30	80	0.92
3	5	40	60	0.96
4	10	20	80	0.92
5	10	30	30	0.83
6	15	25	25	0.87
7	15	30	30	0.96
8	20	10	5	0.71

where L is latent heat of water evaporation (2437 kJ/kg). Therefore, the total microwave power required (P, kW) was calculated based on the sum of the sensible heat of the dry matter and water in the grape sample:

$$P = \frac{Q_p + Q_d + E_w}{60 \cdot \lambda \cdot t} \tag{5}$$

where t is the treatment time (min) and λ is the microwave coupling efficiency. The specific energy E_s (W-h/g fresh product) was derived for a product based on estimated microwave power and total processing time t (min) per unit mass of grape at the fixed power level:

$$E_s = \frac{P \cdot t}{60M} \tag{6}$$

As the values of the related parameters were inputted, the estimated specific energy can be obtained from Eq. 1 through 6. According to the literature and test conditions, C_d and C_w are 3.7 and 4.2 kJ/kg°C for grapes and water (Rahman 1995), the grape mass in the fixed power level was 0.907 kg each run, the average initial temperature was about 21 °C, the microwave coupling efficiency was about 60% according to the preliminary tests, and the average final temperature and the initial and final moisture contents were measured. The infrared temperature sensor would provide an acceptable estimation of average grape temperature because microwave heats throughout the grape berry in which the volume heating induces vaporization from all regions of the berry simultaneously. This estimated specific energy could be used to compare with the experimental value directly obtained from the microwave power and treatment time.

For the incremental power level tests listed in Table 1, the total specific energy was determined from the sum of that for each stage base on the net power and treatment time using Eq. 7:

$$E_s = \frac{1}{60M} \sum P_i t_i \tag{7}$$

where i is an incremental stage. The experimental specific energy was used for further analyses.

Results and Discussion

Temperature of grapes

When a fixed level of microwave power was used as a treatment, the temperature profile for each treatment of power and time consisted of 3 phases: (1) a temperature increase from ambient to a temperature plateau, (2) a plateau temperature representing a balance of heating and drying (heat of moisture loss), and (3) a temperature increase when balance of heating and drying ended. An example of temperature-time history is shown in Figure 3 during the microwave heating for 60 min. During the 1st 5 to 10 min of microwave power application, the temperature of the grape sample increased from about 20 °C to a temperature plateau of about 55 °C. Once the grape sample reached a temperature sufficient to induce vaporization, the temperature of the sample stabilized during the balanced heating and drying period. When most of the free water was removed, the temperature rose sharply due to the sensible heating of the dried matter. A similar temperature profile was reported by Lu and others (1999) in microwave drying of potato slices at ambient pressure. Feng and Tang (1998) described a balance of microwave power and heat transfer from apple dices during the plateau phase using a spouted bed microwave dryer. The plateau phase was described as constant temperature period. Most of the moisture loss took place during this period. The plateau temperature in our study was about 55 °C at 2.7 kPa, which was lower than the 80 °C observed by Lu and others (1999) because of the lower pressure used. Mousa and Farid (2002) noted that the temperature of banana slices increased at the start of drying, followed a constant drying period during which temperature stabilized while water was evaporating.

In tests with grapes, the cooling effect of vaporization remained in balance with the microwave heating for a period of 20 to 50 min depending on the level of microwave power used in the 60 min tests. This was followed by a sudden rise in temperature. For example, after 30 min of microwave power applied at 1250 W, the temperature of the grape sample increased suddenly. The final moisture content of the sample was 16% (wb). Similar results were observed after about 45 min at 1000 W microwave power and about 50 min at 750 W. Application of microwave power at 500 W for 60 min dehydrated the grape sample to a final moisture content of 58%.

Specific energy comparisons

The estimated specific energy was plotted against the experimental value in Figure 4. The linear regression results showed that the estimated specific energy from Eq. 1 through 6 agreed well with the experimental value obtained directly from the power and time combinations (r^2 value of 0.86). Among the energy contributions, the water vaporization was dominant in the microwave vacuum drying process. The specific energy required to dry the fruit from about 78% to 10% moisture content (wb) was 0.97 to 1.01 W-h/g of fresh grapes. Mui and others (2002) used 2.31 W-h/g fixed power to dry banana to 3% (dry basis), and Durance and Wang (2002) applied 1.17 W-h/g to dry tomato to 18.7% (wb). Lin and others (1998) used 1.10 W-h/g in staged power application to dry carrot slices to 10.8% (wb). Yousif and others (1999) applied 1.30 W-h/g to dry sweet basil to 7.1% (wb).

Multiple regression for final moisture contents

Multiple regression analysis showed a correlation between final moisture content (FMC) and the treatment variables including specific energy, fruit sugar content, initial moisture content, and process temperature ($r^2 = 0.957$) at fixed levels of microwave power (Table 2). Decomposition of the regression sum of squares indicated that of the treatment variables analyzed, specific energy accounted for 98.8% of the variation due to treatment. The contribution of fruit sugar content, initial moisture content, and process temperature to the final moisture content was negligible. The linear regression analysis of specific energy and final moisture content resulted in an r^2 value of 0.946 (Figure 5). Specific energy levels below 0.5 W-h/g fresh grapes resulted in limited dehydration yielding product with a final moisture content of 55% to 78%. At specific energy levels between 0.5 and 1.0 W-h/g fresh grapes, some dehydration occurred resulting in a final moisture content of 30% to 55%. At a specific energy above 1.0 W-h/g, burning occurred before the grape sample dried to an acceptable final moisture content of 5% or less. The lowest final moisture content obtain in these experiments was 10.9% (wb) at 750 W applied for 70 min. At that time, the temperature of the grape sample increased abruptly and the test was terminated. The specific energy was 0.96 W-h/g.

All of the fixed microwave energy treatments caused grapes to overheat and burn before a final moisture content of <5% (wb) was reached. The temperature of the grapes increased abruptly, and the sample overheated when the moisture content of the grape sample decreased during drying to the extent that latent heat of vaporization was no longer balanced with microwave energy input. Lu and others (1999) noted that in ambient microwave drying, sample temper-

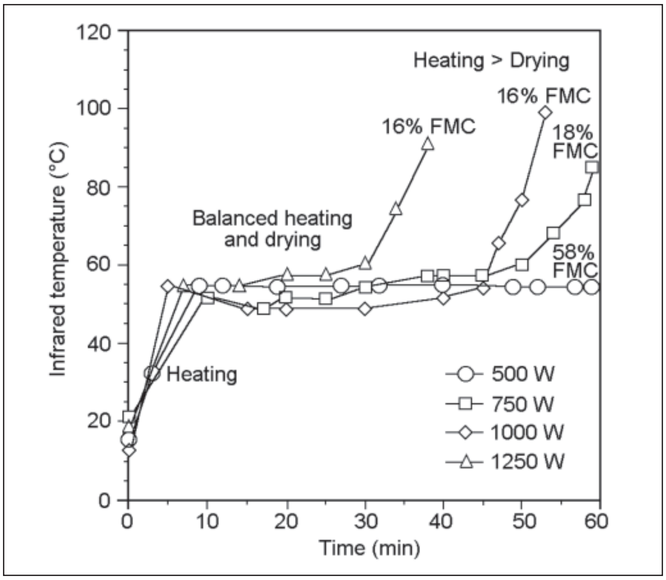

Figure 3—Typical temperature increases of grapes treated at 4 fixed levels of microwave power under the final moisture content (FMC)

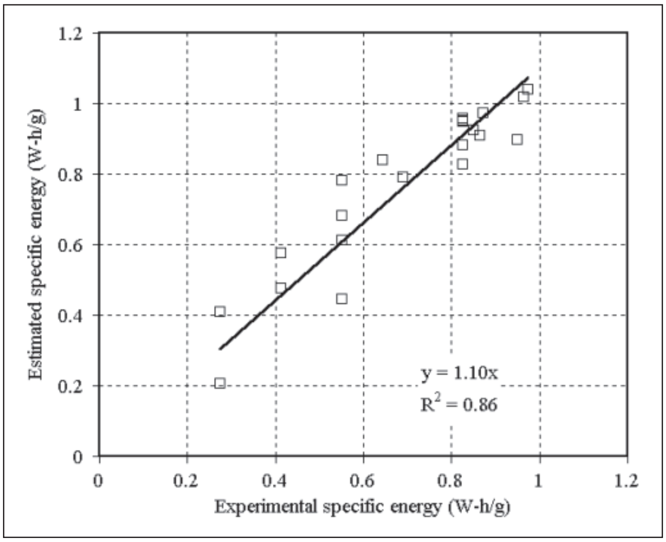

Figure 4—Correlation between estimated and experimental specific energy at fixed levels of microwave power application

Table 2—Multiple regression analysis of the effect of specific energy, fresh fruit sugar content, moisture content, and process temperature on final moisture content of grapes at fixed levels of microwave power application [$Y_{(FMC)} = b_0 + b_1(x_1) + b_2(x_2) + b_3(x_3) + b_4(x_4)$]

Variable	Mean response coefficient	Decomposition[a] (SSE_{Xi}/SSR)
Constant	$b_0 = 42.41$	—
x_1 = Specific energy (W-h/g)	$b_1 = -98.50$	0.988
x_2 = Fruit sugar content (°Brix)	$b_2 = 1.95$	0.01
x_3 = Initial moisture content (%)	$b_3 = 0.39$	<0.001
x_4 = Grape temperature (°C)	$b_4 = 0.03$	0.002
Coefficient of determination	$r^2 = 0.957$	

[a]Decomposition of the sum or squared errors (SSE_{Xi}) indicates the amount x_i contributes to the prediction of Y. SSR = sum of squared regression.

Table 3—Multiple regression analysis of the effect of specific energy, fresh fruit sugar, and initial moisture content on final moisture content at incremental levels of microwave power application [$Y_{(FMC)} = b_0 + b_1(x_1) + b_2(x_2) + b_3(x_3) + b_4(x_4) + b_5(x_5)$]

Variable	Mean response coefficient	Decom-position[a] [SSE_{Xi}/SSR]
Constant	$b_0 = 222.85$	—
x_1 = Specific energy at stage I (W-h/g)	$b_1 = -107.11$	0.365
x_2 = Specific energy at stage II (W-h/g)	$b_2 = -133.61$	0.369
x_3 = Specific energy at stage III (W-h/g)	$b_3 = -118.81$	0.228
x_4 = Fresh fruit sugar content (%)	b_4 = - 2.12	0.025
x_5 = Initial moisture content (%)	b_5 = - 0.83	0.012
Coefficient of determination	$r^2 = 0.875$	

[a]Decomposition of the sum or squared errors (SSE_{Xi}) indicates the amount x_i contributes to the prediction of Y. SSR = sum or squared regression.

ature started to increase beyond the plateau when moisture content dropped, and it was recommended to reduce the microwave power level in this drying phase.

Similar multiple regression analysis was conducted for a correlation between the final moisture content and specific energy levels used in each stage, fresh fruit sugar, and initial moisture content at incremental levels of microwave power application (Table 3). Total response coefficient indicated an r^2 value of 0.875. Decomposition of the regression sum of squares of specific energy at each stage accounted for 96.2% of the variation in final moisture content showing that the specific energy at three stage dominated the prediction model. The effect of initial moisture content and initial sugar content was minor.

Analysis of total specific energy as a single factor indicated that this variable accounted for 78.7% of the variation in final moisture content ($r^2 = 0.787$). The best fit of total specific energy and final moisture content was shown in Figure 6. After applying the staged microwave power treatments, the final moisture content of the grapes was 3.5% to 36.5% (wb) depending on treatment. The range of specific energy was 0.71 to 0.91 W-h/g of fresh grapes. Drying times were 35 to 107 min.

A regression surface plot showed the effect of specific energy and the time on final moisture content at different puffed characters (Figure 7). We observed that application of 3 kW for 5 min followed by 1.5 kW for an additional 10 min increased the portion of finished product that exhibited a dried, puffed texture from 6% to 63%. A further increase in the duration of the 1.5 kW stage to 40 min resulted in 70% of the dried grapes having a puffed, dried character. Generally, optimum treatments were observed in a specific energy of 0.92 W-h/g of fresh grapes and a total time of 95 min (Figure 7). This was lower than the specific energy determined by Lin and others (1998) and Yousif and others (1999) for other food products. The dried grape sample had a final moisture content of 3.5% and 70% of the dried sample exhibited a puffed, crispy character. Outside this treatment range, higher final moisture content was evident as well as a decrease in puffed character.

Although analysis of total specific energy offered some insight in optimizing the characteristics of the dried grapes, a similar regression surface plot of final moisture content with puffed character was obtained to define the separate effects of specific energy at stage I and II of microwave power application (Figure 8). Analysis of the effect of the specific energy at the 1st and 2nd stages on final moisture content indicated optimum results using 0.1 W-h/g in stage I combined with 0.575 W-h/g in stage II (0.245 W-h/g in stage III). The specific energy used in these stages resulted in 70% of the dried grape sample exhibiting a puffed character at a final moisture content of 3.5% (wb).

Unlike cut fruit, the grape skin inhibits transfer of moisture during drying. Using incremental levels of microwave power improved the character of dried grapes compared with use of a single fixed level of power because the power was reduced in stages to prevent overheating as the grapes dried. However, the final moisture content and puffed character were still not as uniform as expected. Future work will focus on further optimizing the process to produce a more uniform dried grape product using product temperature as a means of controlling the microwave power.

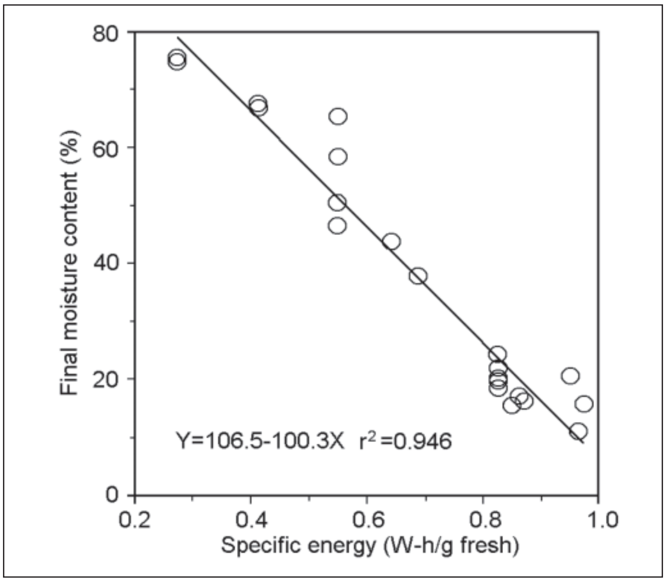

Figure 5—Linear correlation between final moisture content and specific energy at fixed levels of microwave power application

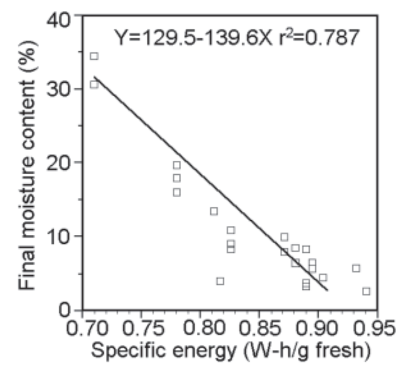

Figure 6—Linear correlation between final moisture content and specific energy at incremental levels of microwave power application

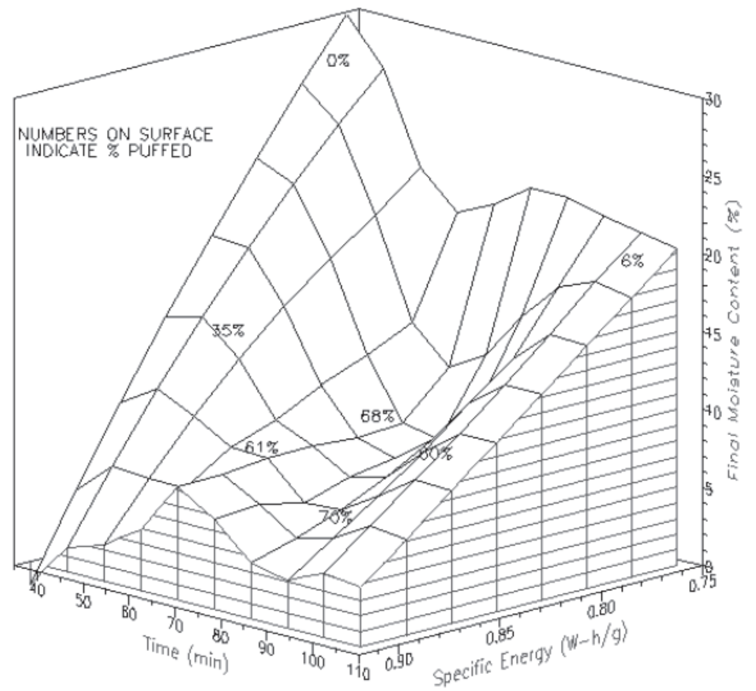

Figure 7—Regression surface plot of the effect of time and total specific energy on final moisture content

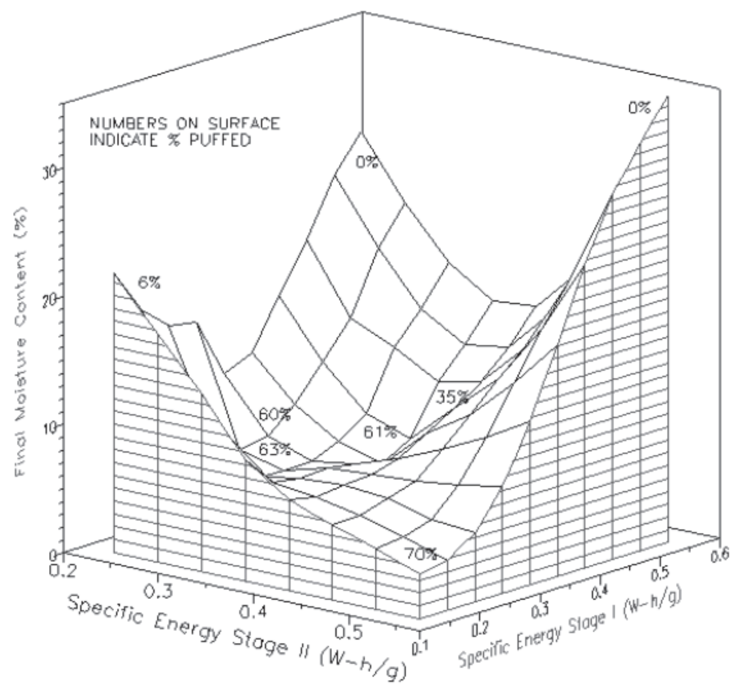

Figure 8—Regression surface plot of the effect of specific energy applied in stages I and II on final moisture content

Conclusions

The optimum specific energy needed to dry grapes using microwave vacuum dehydration was 0.97 to 1.01 W-h/g fresh grapes in fixed levels of microwave application. However, the power level applied overheated the grapes before low final moisture content could be attained. When the microwave power application was decreased in incremental stages as the grapes dried, the optimum total specific energy was 0.92 W-h/g of fresh grapes to dry grapes to a moisture content of 3.5%. Specific energy calculated from a prediction model correlated well with the experimental results and was the dominant predictor of final moisture content and puffed character of the dried grapes. A process temperature measure may offer better control of microwave power and improve drying performance.

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