Brazilian Journal
of Chemical
Engineering

ISSN 0104-6632
Printed in Brazil
www.abeq.org.br/bjche

Vol. 31, No. 02, pp. 403 - 412, April - June, 2014
dx.doi.org/10.1590/0104-6632.20140312s00002668

COMPARISON OF CARROT (*Daucus carota*) DRYING IN MICROWAVE AND IN VACUUM MICROWAVE

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(Submitted: April 24, 2013 ; Revised: June 3, 2013 ; Accepted: July 5, 2013)

Abstract - Drying is a single operation employed to prolong the life of a large quantity of vegetables. Carrot (*Daucus carota*) drying has been the subject of many studies. This plant has been highlighted in the human diet for having high nutritional value, mainly due to the high content of β-carotene. In this work, carrot drying behavior was studied in a regular microwave dryer and a vacuum microwave dryer. A vacuum of 450 mmHg was applied for drying of carrot in different geometrical shapes (cubes, discs and sticks). The samples were dried at power ratings of 1.0 W/g, 1.5 W/g and 2.0 W/g for both methods of drying. The evolution of physical properties such as density, volume and porosity was monitored and related to the moisture content of the sample and to the method of drying and power rating used. The geometric shape of the sample influenced the drying kinetics and it was verified that the cubic form was responsible for a slower drying. The application of vacuum showed no major changes in the drying kinetics in microwave but influenced the physical properties of the material. The influence of power ratings on the content of β-carotene was also evaluated and discussed. The main difference observed was the lower shrinkage of the samples dried in the vacuum microwave compared to those dried only in microwave.

Keywords: Drying; Carrot; Vacuum microwave; β-carotene.

INTRODUCTION

The use of microwaves for drying food is presented as an alternative for conventional drying by hot air. Mujumdar and Menon (1995) listed a number of advantages of the use of microwave energy for heating and drying processes. Among them are uniform heating of the material, the efficiency of energy conversion and improved quality of the final product. Together with these features there are the shortest time and space required and faster and easier process control. However, further studies are necessary on how the drying occurs.

It is known that drying under microwaves is in essence distinct from conventional drying by hot air. While in conventional drying energy transfer is governed by the temperature gradient between the surface and the center, by drying in microwaves the heating occurs throughout the volume of the material mainly by the interaction between the electromagnetic field and the water molecules. Another factor responsible for a faster microwave drying is that the rapid heating of water present in the material to the point of vaporization generates a pressure difference which "pumps" the water in vapor form to the surface. In hot air drying, the moisture transfer is controlled by the concentration gradient between the dry surface and moist center. This process is tightly controlled by diffusion (Schiffmann, 1995).

The study and understanding of changes in the physical structure undergone by the material during the drying is important for obtaining methods which

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*To whom correspondence should be addressed result in products of higher quality. Among these properties, the main ones are: shrinkage, the real and apparent density and porosity. These properties characterize the dry product in relation to its texture and quality, reporting on the characteristics of transport phenomena present in both the dry and intermediate moisture states (Veras *et al*., 2012; Zogzas *et al*., 1994).

Some studies regarding heating by microwaves report that the distribution of microwave heating is related to the geometry of the material (Pereira, 2007; Souraki *et al*., 2009). Cylindrical and spherical shapes when subjected to the action of microwaves show higher absorbed power density, which leads to greater warming in the center and on the surface, while for rectangular shapes, the energy is concentrated in the corners and the center is a cold spot (Yang and Gunasekaran, 2004; Ryynänen *et al*. 2004; Campanone and Zaritzky, 2005).

Li *et al* (2010) studied a microwave drying system. Three drying temperatures were tested (75, 65, 55 °C) and a relationship of the power with respect to drying rates was built for apple drying. The authors achieved a real time power control method to control the microwave power during the drying process to minimize temperature fluctuations, save time and reduce energy consumption. The drying characteristics of carrots in different dryers have already been investigated. The kinetics of microwave drying was compared with those obtained in a lyophilizer and in convective drying by Prakash *et al*. (2004). Zogzas *et al*. (1994) and Madiouli *et al*. (2007) presented different models for the representation of porosity, density and shrinkage of carrots during drying in a convective dryer. Krokida and Maroulis (1997) also suggested equations to determine the same properties of some fruits and vegetables, including carrots, during drying in several dryers, among them microwave dryers and lyophilizers. Krokida and Maroulis (1999) also investigated the microwave drying and microwave-vacuum drying of carrots finalized by convective drying. Figiel (2009) studied the effect of microwave power on the vacuum-microwave method for drying of garlic cloves and slices. The authors also performed a quantitative analysis of the dried material based on shirinkage, compressive strength test, water absorption, color and volatile oils.

The influence of the thickness of the sample used and the initial mass during drying in a microwave dryer has been studied by Cui *et al*. (2004) and Wang and Xi (2005).The latter also studied the use of microwaves in two stages with different power ratings. Lin *et al*. (1998) made a comparison between the nutritional properties of carrots dried by a vacuum microwave, sunlight and a lyophilizer. Prakash *et al*. (2004) compared the retention of β-carotene in carrots dried in a fluidized bed, a microwave and the sun.

Carrots *(Daucus carota)* play an important role in human diet because they have one of the highest levels of β-carotene, besides being rich in B vitamins, fiber and minerals (Prakash *et al*., 2004). In regard to β-carotene, Bao and Chang (1994) and Bureau and Bushway (1986) cite the carrot as the food with the highest level of this nutrient. By presenting dielectric characteristics due to its high moisture content, it makes microwave drying possible. The drying of carrot (*Daucus carota*) in microwaves has been studied under different aspects (Li *et al*., 2010; Cui *et al*., 2004; Wang and Shi, 2005). The use of microwave and vacuum microwave drying for carrots is an alternative for improving the conservation of the nutritional and physical properties thereof. This work, therefore, has the overall objective of contributing to the studies of the use of microwaves and vacuum microwaves in food drying. Specifically, the influence of the geometric shape of the sample and the evolution of physical properties in relation to the decrease of the moisture content during drying both in microwave and in vacuum microwave dryers will be analyzed. The final characteristics of the material in relation to the retention of β-carotene and its relationship with the method and drying conditions were also evaluated.

MATERIALS AND METHODS

Raw Material

To conduct the study, carrots bought locally were used. The material was carefully purchased in the same establishment to reduce its variability. The average initial moisture content, dry basis (db), was equal to 11.67 ± 1.62 (g water / g dry solid).

Drying Equipment

The equipment used for the drying tests was a laboratory microwave oven of the brand Sairem S.A., with a 600 W power rating and frequency of 2450 Hz This same microwave was adapted for vacuum microwave drying. This adaptation was made by placing a desiccant inside the oven and connecting it by a hose to a vacuum pump. Figure 1 shows a picture of the experimental unit used.

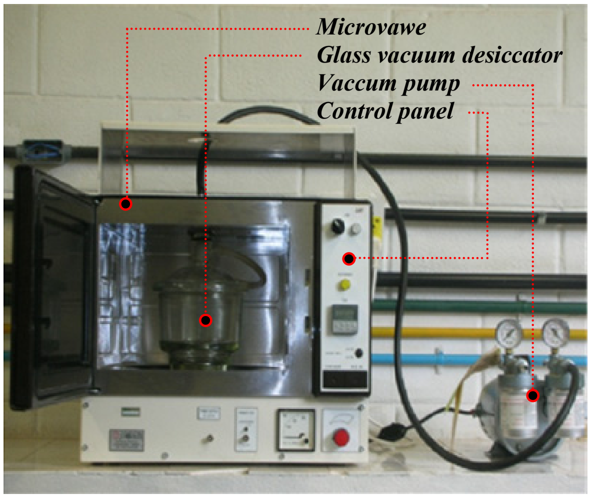


Figure 1: Experimental Unit.

The calibration of the energy supplied by the microwave oven was carried out by calorimetry. The rated power was related to the energy supplied by measuring the temperature variation of a known mass of water during the application of microwaves for a certain time. It was assumed that all the power absorbed by the water mass was transformed into heat, and then applied to Equation (1).

$$Q_{abs} = \frac{m.C_p.\Delta T}{t} \tag{1}$$

For each power rating, it was made six measurements of water temperature variation were made and thus, Q_{abs} was calculated in cal.min^{-1}. Then, this value was converted to J.s^{-1} (W). Through this procedure that there was reproducibility of the energy supplied by the equipment in relation to the small variation of power absorbed by water for each nominal power applied. The average standard deviation of this absorbed power for each value of applied power was 4%, varying from 1.3% to 4.2%. So, it was assured that the experimental conditions were kept constant for equally programmed powers.

Methods

Sample Preparation

The dried carrots were washed in running water and peeled manually. Shortly thereafter, they were cut manually into the forms of cube with edges equal to 8mm, discs of thickness of 4 and 8 mm and diameter of 25 mm and sticks with dimensions of 4x4x50 mm. Discs were cut longitudinally. The cube and stick forms were cut from transverse plates.

After cutting, the samples were blanched for enzyme inactivation and color preservation in distilled water at 70 °C for 3 min. Shortly after, they were cooled under running distilled water during 1 minute and the excess water removed with absorbent paper.

Drying

The initial mass was set at 80g and the nominal power ratings used were 80 W, 120 W and 160 W for both microwave and vacuum microwave drying. The samples were arranged in single layers on petri plates placed on the turntable of the microwave oven for the drying condition in microwave. As for the mode of vacuum microwave drying, a plate with the sample was placed within the desiccator that was then placed inside the oven. The mass measurement during the drying was determined by taking samples from the drying equipment at time intervals of 5 minutes and measuring their mass on an analytical balance with a precision of 0.002 g. In vacuum drying, the pressure was kept constant at 450 mmHg.

Characterization

The samples were characterized along the drying process for the real and apparent densities, the porosity and volume. The apparent density and volume of the samples were determined by liquid pycnometry with hexane. The real density was determined in a helium pycnometer, model 1000 Ultrapycometer of the brand Quantachrome Instruments. The shrinkage of samples was expressed in terms of the shrinkage coefficient V/V_0, defined by Madiouli *et al.* (2007). Moisture was determined in a chamber at 105 ± 5 °C for 24 hours. The porosity was determined by the ratio between the real and apparent densities, according to equation 2 (Zogzas *et al.*, 1994):

$$\varepsilon = 1 - \frac{\rho_{ap}}{\rho_r} \tag{2}$$

The content of β-carotene was obtained by High Performance Liquid Chromatography (HPLC): a column of the brand Synergi C_{12}, model 4 μ MAX-RP 80A with dimensions of 250 mm x 4.5 mm was used as the stationary phase.

RESULTS AND DISCUSSION

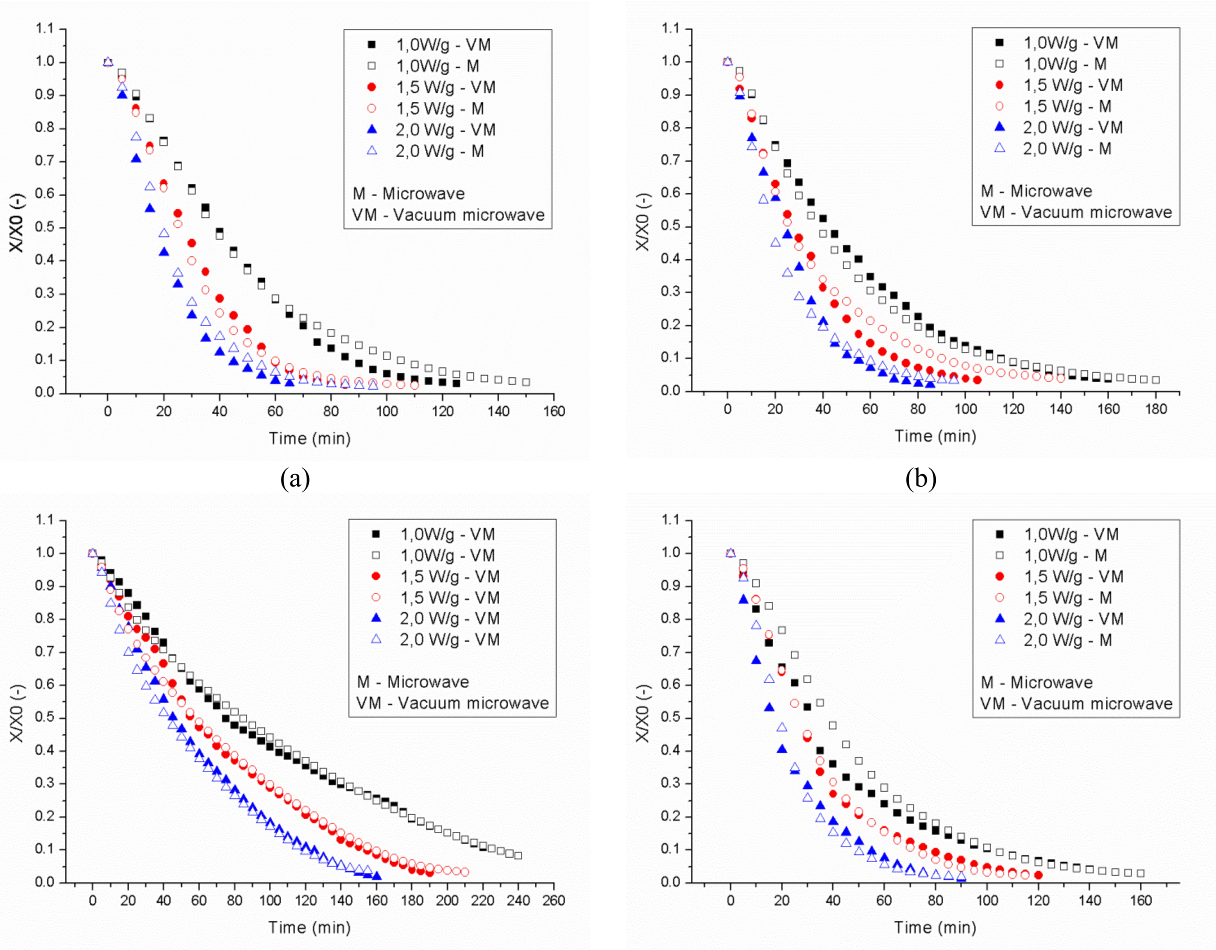
After performing drying tests (in triplicate for each power) with samples of the different geometric shapes evaluated in this study at various power ratings for drying in the microwave and in the vacuum microwave ovens (1.0, 1.5 and 2.0 W/g), it was observed that the final moisture content obtained (db) was in a range between 0.3 and 0.4 g water / g dry solid. The drying time ranged from 90 to 240 min. The drying in cube form was considerably slower. Several features associated with drying in the microwave and in the vacuum microwave are discussed below.

Drying Mode Effect

Figure 2 illustrates the drying kinetics for the different configurations of sample geometry and applied power that were evaluated in this study, both for the traditional drying in microwave and in vacuum microwave.

It was not possible to observe a significant reduction of the drying time using the combination of vacuum with microwave drying for any sample geometric shape and any power rating used. It was found that the kinetics of both drying modes were very similar, so the use of vacuum did not contribute to a faster drying. These results indicate that the main mechanism of drying occurs due to the incidence of microwaves. Cui *et al*. (2004) observed that microwave power and vacuum pressure affect the drying rate. However, the drying rate was strongly affected by microwave power output and slightly affected by vacuum pressure. Therefore, compared with the microwave, it is possible to conclude that vaccum applied on the samples did not present a relevant effect on drying under the operating conditions evaluated for this study.

Drying of carrots in both microwave and vacuum



(a) (b)

(c) (d)

Figure 2: Dimensionless moisture during drying with microwave (M) and with vacuum microwave (VM): (a) 4 mm discs, (b) 8 mm discs, (c) cubes (d) sticks.

microwave occurred mainly during the decreasing rate period where a period of constant rate could not be observed in any of the drying conditions employed. The evaporation of water from the surface during drying - a characteristic of the constant rate period of drying - was not observed. This indicates a drying process controlled by diffusion, behavior previously observed by Wang and Xi (2005) for carrot microwave drying and Prakash *et al*. (2004) for carrot drying in microwaves, in fluidized bed and by the Sun.

Analyzing the effect of power rating on the drying behavior (Figure 2), it is possible to observe that increasing the applied power results in an increased drying rate and, consequently, less time required to reach the final moisture content in all experimental conditions evaluated. This result was expected since the higher the power applied, the higher the amount of energy transformed into heat inside the sample and the faster the water vaporization.

To evaluate the effect of the microwaves and vacuum on the behavior of carrot drying kinetic parameters, equations commonly used in the literature were statistically adjusted. Table 1 lists the parameters estimated for the different conditions evaluated for drying carrot in the shape of discs 4 mm thick. The other conditions studied in this work are not shown in this table, but they indicated an overall similar behavior when comparing the different conditions in which the drying was performed.

By evaluating the correlation coefficients, it is possible to verify that the adjustments of all the equations presented to the experimental results are adequate. By evaluating the adjusted constants, it is possible to verify that the qualitative behavior with vacuum and in the absence of vacuum is similar. Comparing individually each equation tested, in all cases, larger k values were found for a greater incidence of microwave radiation during drying, regardless of the use or not of vacuum during drying.

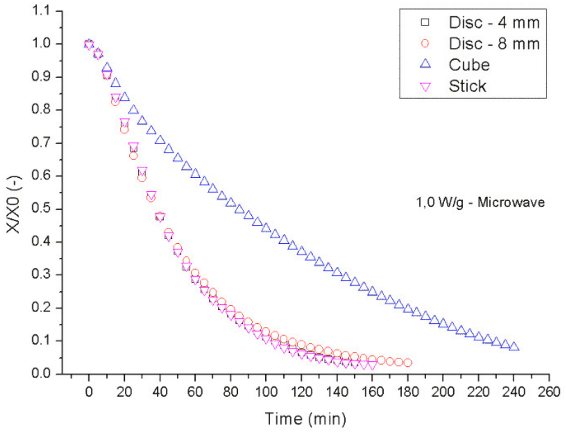
Table 1: Statistically adjusted parameters for 4 mm discs.

Model	**System**	**Power (W / g)**	**k**	**n**	**SE (*standart error*)**	**R^2**
Lewis (1921) $MR = e^{(-k.t)}$	vacuum	1.0	0.0205		k = 0.0008	0.9815
		1.5	0.0298		k = 0.0016	0.9792
		2.0	0.0449		k = 0.0019	0.9907
	without vacuum	1.0	0.0196		k = 0.0005	0.9915
		1.5	0.0318		k = 0.0014	0.9849
		2.0	0.0396		k = 0.0015	0.9906
Page (1949) $MR = e^{(-k.t^n)}$	vacuum	1.0	0.0034	1.4454	k = 0.0001 n = 0.0130	0.9997
		1.5	0.0049	1.4945	k = 0.0002 n = 0.0151	0.9997
		2.0	0.0169	1.3008	k = 0.0014 n = 0.0255	0.9994
	without vacuum	1.0	0.0068	1.2590	k = 0.0004 n = 0.0173	0.9992
		1.5	0.0066	1.4350	k = 0.0008 n = 0.0339	0.9987
		2.0	0.0141	1.3053	k = 0.0017 n = 0.0366	0.9984
Henderson and Pabis (1961) $MR = n.e^{(-k.t)}$	vacuum	1.0	0.0228	1.1149	k = 0.0009 n = 0.0303	0.9888
		1.5	0.0331	1.1168	k = 0.0018 n = 0.0394	0.9870
		2.0	0.0481	1.0745	k = 0.0021 n = 0.0296	0.9940
	without vacuum	1.0	0.0214	1.0943	k = 0.0004 n = 0.0162	0.9962
		1.5	0.0351	1.1145	k = 0.0316 n = 0.0015	0.9910
		2.0	0.0428	1.0877	k = 0.0016 n = 0.0262	0.9943

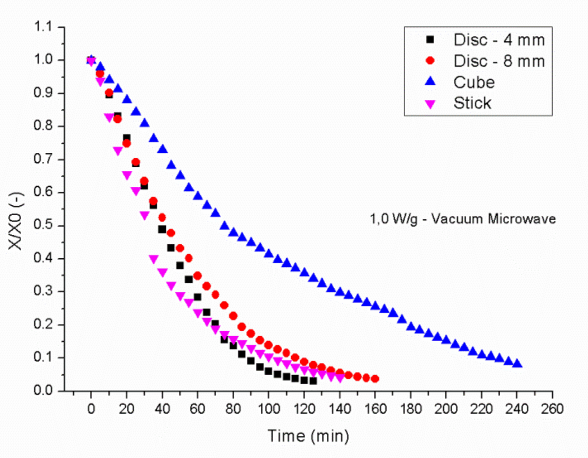
The order of magnitude of the drying equation parameters corroborates the observations made previously about the drying kinetic behavior. In general, it can be seen that vacuum did not significantly alter the parameters of the drying equations, showing the small influence that vacuum had on the material drying kinetics.

Shape Effect

Figure 3 illustrates the drying curves for the different shapes used in this work. The condition shown in Figure 3 corresponds to the power rating of 1.0 W/g, since it was the condition in which the most pronounced differences were observed when compared to higher powers ratings. As can be seen in the results, the 4 and 8 mm thick disc shapes and the stick shape had very similar drying kinetics to each other. In contrast, the cubes showed a considerably slower kinetics for both situations.



(a)



(b)

Figure 3: Dimensionless moisture during drying for different shapes and 1.0 W / g power rating: (a) microwave, (b) vacuum microwave.

The lowest drying rate for the cube may be explained by the fact that the volumetric power density absorbed by rectangular shapes is smaller than those of spherical and cylindrical shapes. For the stick form, the larger area of exposure to microwave incidence, 632 mm^2, compared to the area for the cube, 320 mm^2, may have offset the smaller volumetric power absorption tendency, since the larger area of exposure causes a larger amount of microwaves to be absorbed. It is noted that the area in contact with the petri dish was not considered as an exposure area for the incidence of microwaves.

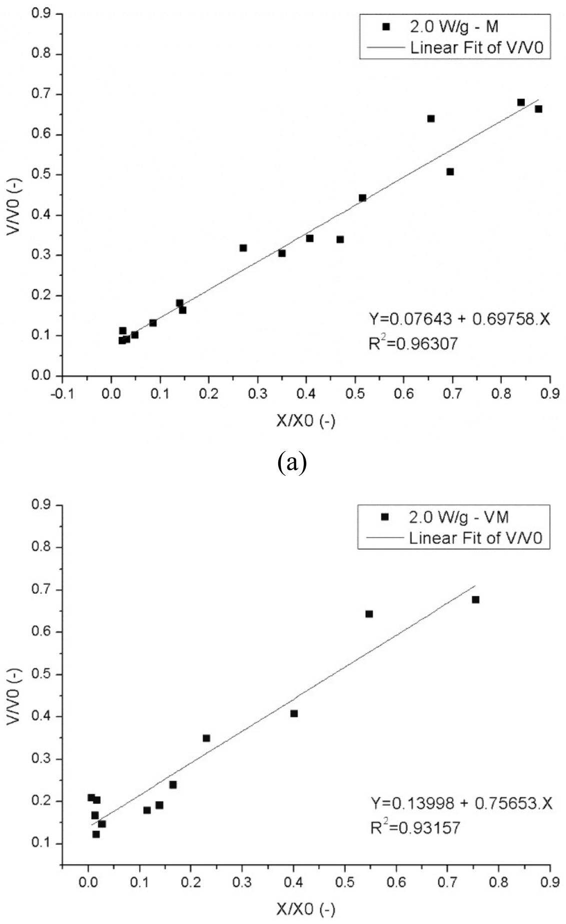
The variation in thickness of the sample did not significantly influence the drying kinetics, since the drying curves for the 4 and 8 mm thick discs were almost superimposed. This result is related to internal heat generation and moisture vaporization inside the material, which generates a pressure difference which pumps water vapor to the surface. Thus, the moisture transfer has little influence from diffusion and it occurs primarily by the pressure difference. Also, due to internal heat generation, heat transfer does not occur by conduction in microwave drying. Therefore, the thickness increase does not represent an obstacle for heating the interior of the sample, provided that the thickness is smaller than the penetration depth of microwaves. The different thicknesses used in this work were smaller than the penetration depth of microwaves for carrots, which range between 16.35 mm and 14.11 mm depending on the humidity.

The comparison among the conditions shown in Figure 3 makes the small influence that vacuum had on material drying kinetics even more evident. It should also be noted that the condition shown in Figure 3 (output of 1.0 W / g) was the one in which the application of vacuum provided the greatest differences between the drying kinetics of the samples.

Physical Properties

The evolution of the shrinkage coefficient, the porosity and the real and apparent densities were monitored during drying.

Figure 4 is a representation of the shrinkage coefficient during drying. In Figure 4(a), the values predicted by linear regression and the experimental points obtained are shown for microwave drying. The average deviation was 0.012, ranging from 0.000 and 0.056. The values predicted by linear regression and the experimental points for the evolution of the shrinkage coefficient during vacuum microwave drying are shown in Figure 4(b).The average deviation was 0.020, ranging from 0.003 and 0.063.



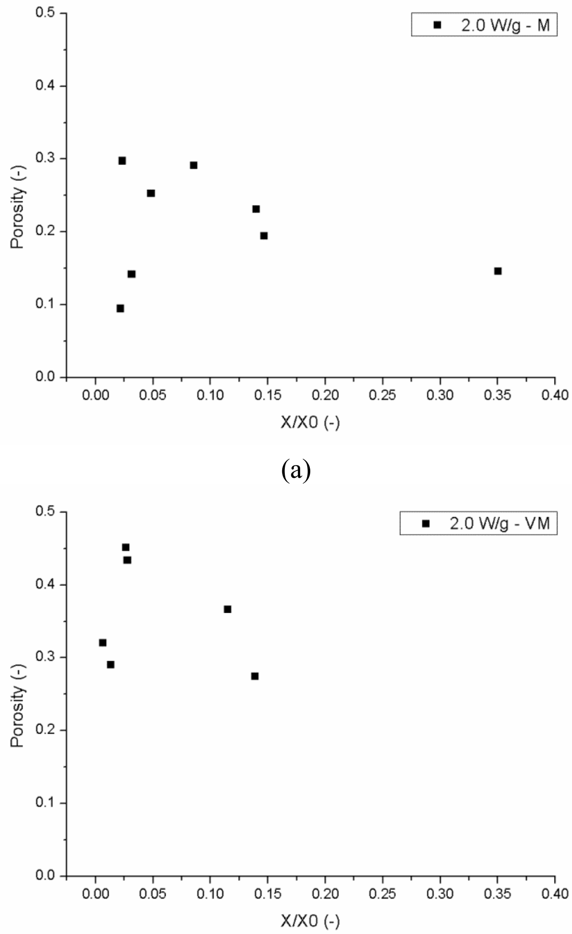
(a)

(b)

Figure 4: V/V$_0$ as a function of dimensionless humidity for microwave drying at 2.0 W / g: (a) microwave, (b) vacuum microwave.

Note that the carrots dried in microwave showed linear shrinkage, a behavior considered ideal. That is, the volume reduction was proportional to the amount of water removed. In this case, the porosity of the material remains constant over the drying course. The porosity development with moisture content can be observed in Figure 5. It is possible to note that the porosity for microwave drying showed no tendency to increase or decrease, and it corroborates the earlier comment about the ideal carrot shrinkage when subjected to this drying method. The same behavior was observed for a lower power rating of 1.0 W / g.

Figure 5(b) illustrates a tendency of an increase in porosity at the end of the drying. Through the joint analysis of Figure 4(b) and Figure 5(b), it is noted that, during drying in vacuum microwave, a small deviation in linearity occurred. This fact is in accordance with the statement of Krokida and Maroulis (1997) that, when shrinkage is smaller than the evaporated water volume and therefore not ideal, the process leads to an increased material porosity. In general, vacuum microwave drying resulted in a less shrunk and more porous final product, when compared with that obtained by microwave drying. These features can be advantageous because the product with higher porosity can be rehydrated more easily.



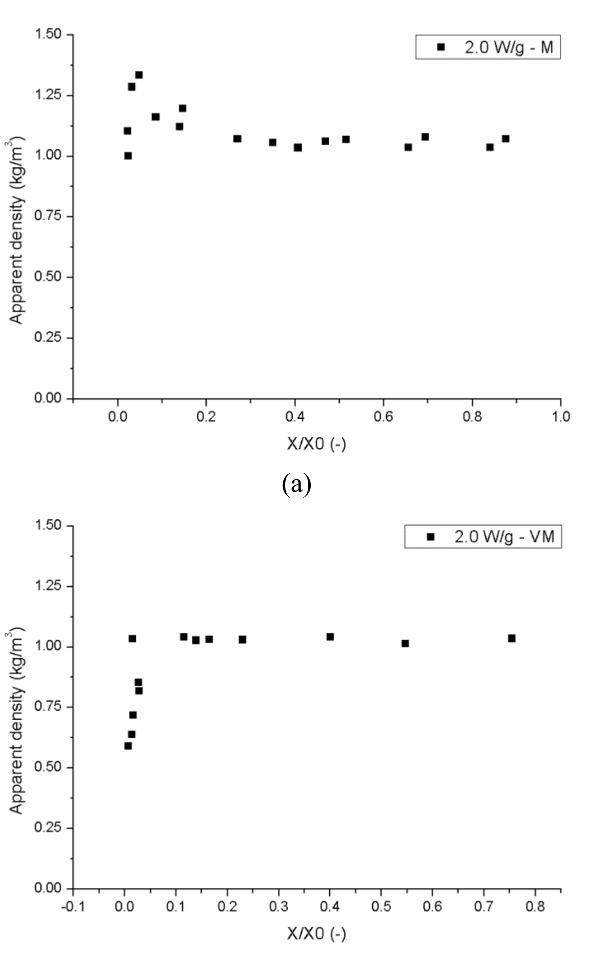
(a)

(b)

Figure 5: Porosity during drying for a power rating of 2.0 W / g: (a) microwave, (b) vacuum microwave.

Figures 6(a) and 6(b) illustrate the densities of carrots during drying in microwave and in vacuum microwave, respectively. These figures confirm what was previously mentioned. Samples that were dried in vacuum microwave had lower final density when compared to those dried in microwaves.

Besides the ease of rehydration, this fact may indicate that, in association with vacuum, the carrots dried in microwave may have a less rubbery consistency, a common problem for products obtained by this method of drying.



(a)

(b)

Figure 6: Apparent density during drying for a power rating of 2.0 W / g: (a) microwave, (b) vacuum microwave.

β-Carotene Content

The content of β-carotene was determined in samples of natural carrot and after several drying experiments for the 4 mm disc geometry. The objective of this analysis was to evaluate the effects of increasing power rating and method of drying on the deterioration of this important nutritional component of carrots.

By observing the values shown in Table 2 for the different methods of drying, it is noted that the final content of β-carotene was dependent on the power rating and on the drying method used. The deterioration of β-carotene increased when the power rating was increased in a same drying method. As an example, for a microwave drying at a power rating of 1.0 W / g, the deterioration was 6.6% and at a 2.0 W / g power rating, the deterioration was equal to 41.9%. The increased β-carotene deterioration upon increasing the power rating can be attributed to a greater oxidation of the unsaturated β-carotene structure with an increase in temperature (Prakash *et al.*, 2004).

When comparing the drying method, microwave drying provided a final product richer in β-carotene. During drying in a microwave at 1.0 W / g power rating, the loss of β-carotene was 6.6% whereas for the same power rating in a vacuum microwave, this nutrient loss was 20%. The increase in porosity achieved with the vacuum microwave drying allows a greater permeability for the vapor formed, thus causing more intense β-carotene degradation. The same behavior was observed for the power rating of 2.0 W / g.

Table 2: β-carotene content on a dry basis after drying of 4 mm discs.

Method of Drying		β-Carotene Content (mg / g dry solid)
Microwave	1.0 W / g	2.375
	2.0 W / g	1.478
Vacuum microwave	1.0 W / g	2.032
	2.0 W / g	0.905
Natural carrot	–	2.543

CONCLUSIONS

From the studies carried out, it was concluded that the shape of the cut sample has an influence on the microwave drying. The cubic form, due to its lower absorbed power density should be avoided since it requires a longer drying time compared to the other forms used. Furthermore, based on the drying kinetics for the stick shape, it is concluded that this microwave absorption deficiency presented by rectangular shapes can be counterbalanced by increasing the exposure area for incidence of microwaves.

Although it did not accelerate the drying kinetics of carrots, the combination of vacuum drying with microwaves influenced the physical properties of the final product. The lower shrinkage and higher porosity found in vacuum microwave drying may indicate a lower breakdown of the physical structure and a better rehydration capacity, but with a higher loss of β-carotene.

NOMENCLATURE

C_p	water specific heat	cal / g°C
k	parameter associated with the drying model	
m	mass	G

MR	moisture ratio	(-)
n	parameter associated with the drying model	
Q	energy	cal / min
R	correlation coefficient	(-)
SE	standard error	(-)
T	temperature	°C
t	time	Min
V	volume	cm^3
X	moisture on a dry basis, db	g water / g dry solid

Greek Symbols

ε	Porosity	(-)
δ*p*	wave penetration depth	mm
ρ	density	(-)

Subscript

0	initial
abs	absorbed
ap	apparent
r	real

Abbreviations

M	microwave	
VM	vacuum microwave	
wb	moisture on a wet basis	g water / g wet solid

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