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Preserving Melon by Osmotic Dehydration in a Ternary System

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Abstract—In this study, the kinetics of osmotic dehydration of melons (*Tille* variety) in a ternary system followed by air-drying for preserving melons in the summer to be used in the winter were investigated. The effect of different osmotic solution concentrations 30, 40 and 50% (w/w) of sucrose with 10% NaCl salt and fruit to solution ratios 1:4, 1:5 and 1:6 on the mass transfer kinetics during osmotic dehydration of melon in ternary solution namely sucrose-salt-water followed by air-drying were studied. The diffusivity of water during air-drying was enhanced after the fruit samples were immersed in the osmotic solution after 60 min. Samples non-treated and pre-treated during one hour in osmotic solutions with 60% (w/w) of sucrose with 10% NaCl salt and fruit to solution ratio of 1:4 were dried in a hot air-dryer at 60°C (2 m/s) until equilibrium was achieved.

Keywords—Air drying, Effective diffusion coefficient, Mass transfer kinetic, Melon, Osmotic dehydration.

I. INTRODUCTION

MELON is a good source of β-carotene and Vitamin C. Like many other fruits, they are low in saturated fat and cholesterol, high in water content, and relatively low in calories. They may have an anti-clotting influence on the blood. Melons are believed to lower cancer and heart disease risk [1, 2]. Hence, improvement of nutritional and sensory properties of air-dried melons could be achieved by applying a suitable osmotic pretreatment.

The final quality of the products plays a significant role in selecting, designing, and operating of a food dryer. Like many tropical fruits, melons are highly perishable and their freezing is impossible, which results in enormous loss by decomposition after harvesting [3]. So melons can be dried in order to save part of the crops that would not be immediately consumed, providing an extension of shelf-life, lighter weight for transportation and requiring less storage space [4].

The simultaneous heat and mass transfer during the hot air-drying is followed by phase change [5, 6]. Consequently, drying via hot air can be so costly. The osmotic dehydration offers more water loss than the drying processes with hot air and also can be applied to reduce initial moisture and accordingly, total processing time of air-drying [7]. Since immersion of foods, whole or in pieces, in osmotic solution prevents oxidation browning, inhibits enzymatic activity, and decreases structural collapse during air-drying, the quality of the final product is improved when compared to dry melon with no preliminary treatment [8-11]. During osmotic dehydration, water removal is carried out without any phase change due to the lower level of water in the crop, which requires lower energy [12]. Osmotic dehydration of fruits and vegetables is based on their immersion in a hypertonic aqueous solution. In fact, this process involves the simultaneous flow of water and solutes leading to the loss of water through the cell wall membranes of the fruit and a migration of solutes from the solution into the solid [13, 14]. However, water transfer usually takes place more than solutes transfer in this process. It is mainly due to differential permeability of cellular membranes [15].

Numerous studies have been carried out for better understanding of the effects of main process variables such as composition and concentration of the osmotic solution, temperature, immersion time of the foods in the solution, agitation, nature and geometry of the food and fruit to solution ratio on the mass transfer mechanism and quality of final product [16-19].

Azuara et al. (1998), Lombard et al. (2008), Khoyi and Hesari (2007), Panades et al. (2008), and Kowalska and Lenart (2001) studied osmotic dehydration of fruits in a binary system (sugar/water), while Souza et al. (2007), Singh et al. (2007), Rodrigues and Fernandes (2007), Telis et al. (2004), and Sachetti et al. (2001) studied this process in a ternary system (sugar/salt/water). Most studies with binary and ternary systems utilize sucrose as a main agent in the formulation of the osmotic solution although other sugars can be used. Few studies [29-33] have been carried out with other sugars, such as mannitol, fructose, glucose or trehalose. However, in this study sucrose was used to formulate the osmotic solutions.

The objective of present study was to choose the best operating conditions, favoring water loss with a minimal solid uptake to evaluate the osmotic dehydration kinetics of melon cubes in ternary solution namely sucrose-NaCl-water solution followed by air-drying to reduce total drying time (time spent in osmotic dehydration and air-drying) as to reduce operational costs. Thus, a simplified model based on Fick's second Law, was used to obtain the detailed information on

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water loss and solid gain kinetics at beginning of the osmotic treatment.

II. MATERIALS AND METHODS

a. Preparation of samples

Ripe and fresh melons (*Tille* variety) were bought from the local market (Mashhad, Iran), and sorted visually for color (light green), size (average 0.2 meter in diameter) and no physical damage. First, the melons were washed with water and then a manually operated vegetable dicer was used to prepare melon cubes of dimensions $0.012\times0.012\times0.012$ m^3. The cubes were washed with fresh running water to remove the melon fines adhered to the surface of the fruit. Finally, the cubes were dried with absorbent paper.

b. Experimental case

Effects of concentration of the solutions, fruit to solution ratio and osmotic dehydration time on water loss and solid gain of the samples were estimated using 2-level factorial design with 2 center points by the software package of Design Expert 7.0 (Stat-Ease Co., Minneapolis, MN, USA). The independent variables were concentrations of the solutions (X_1), the fruit to solution ratio (X_2) and the osmotic dehydration time (X_3). Triplicate experiments were carried out for each treatment, and the mean values were used to fit the parameters. Data were drawn and analyzed by Design Expert 7.0. Table 1 shows the experimental design using both actual and coded levels.

c. Osmotic dehydration

If Sucrose and commercial NaCl salt dissolved in distilled water were used as main elements of osmotic dehydration processes. Three levels of sucrose concentration (30, 40 and 50% (w/w)) and one level of NaCl salt concentration (10%) were considered. Telis et al. (2004) stated stated that addition of salt into the osmotic solution even at low concentration increases considerably the water mass transfer from the fruit to the osmotic solution, leading to significant increase of the water loss from the fruit. In an osmotic dehydration process, the higher the water loss, the better is the dehydration process. However, high solids gain affects the fruit quality and sensory characteristics, which causes salty taste in final product that is very different from the fresh fruit.

Therefore, during this study, osmotic solution with 10% (w/w) salt was considered to be the maximum permissible concentration of salt that can be added to the osmotic solution not to spoil the fruit natural taste.

The melon slices were weighed and placed in separate 5×10^{-6} m^3 glass beakers, containing different concentrations which fitted inside a hot water bath equipped with thermoregulator (WINTOO, BM-5, CHINA) to adjust the temperature of the solution at the controlled temperature (45 ±1 °C). Previous studies of Fernandes et al. (2006) showed that, in order to prevent excessive dilution of osmotic solution, it is necessary to have a solid-to-solution mass ratio of at least 1:4 to maintain the fruit to solution ratio constant, which leads to a good mixing in the osmotic dehydration apparatus.

TABLE I
UNITS FOR MAGNETIC PROPERTIES

Experiment no.	Actual			Coded		
	X_1 (%)	X_2 (dimensionless)	X_3 (h)	X_1 (%)	X_2 (dimensionless)	X_3 (h)
1	30	1:6	1	-1	-1	-1
2	50	1:6	1	1	-1	-1
3	30	1:4	1	-1	1	-1
4	50	1:4	1	1	1	-1
5	30	1:6	3	-1	-1	1
6	50	1:6	3	1	-1	1
7	30	1:4	3	-1	1	1
8	50	1:4	3	1	1	1
9	40	1:5	2	0	0	0
10	40	1:5	2	0	0	0

Agitation is indeed one of the key factors and an adequate level of agitation ensures minimization or elimination of liquid-side mass transfer resistances [7]. Hence, experiments were performed under constant mechanical agitation with 120 rpm to maintain a uniform temperature and concentration throughout the experiment. Agitation was provided by a magnetic stirrer.

At pre-determined time intervals, one group of the samples was taken out from the glass beakers for analysis. Each experimental group consisted of three melon cubes. The treated samples from each group were immediately drained for 60 seconds and then they were spread on absorbent paper to | remove the free water from the outer surface of the fruit and were put in to the pre-weighed petridish for determination of dry matter by oven method. Similarly, 10 ml of osmotic solution was put in pre-weighed petridish for the determination of total solids by oven method. The salt contents of fruit were determined by Mohr method. These methods were selected with regard to works of Singh et al. (2006) on carrot cubs.

Two sets of experiments were done in this work. The first set of experiments was performed in order to determine the equilibrium concentration of water and sucrose. These experiments were performed up to a total time of 72 h, having samples collected at 0, 6, 12, 24, 36, 48, 60 and 72 h. Another set of experiments was carried out in order to obtain more detailed information on mass transfer kinetics of water loss and solid gain. In this set of experiments, melon samples were taken out from the solution at shorter time intervals 0, 0.5, 1, 2, and 3 h.

d. Air drying

After removal of water from the outer surface of the fruit by spreading them on absorbent paper, they were put into the pre-weighed petridish and then transferred into a forced convection air-dryer (SHINSAENG FINE TECH., SFCN-301, CHINA). The drier was operated with air-velocity of 2 m/s. The drier was equipped with an electronic balance with an accuracy of 0.01 g. The weight was continuously registered in a microcomputer using a RS232 interface. The air flowed parallel to the bed that consisted of three wire nets supported by a structure, which substituted the balance plate. The relative humidity was around 15% and was read every 10 min. The relative humidity was monitored digitally by the dryer.

Demirel and Turhan (2003) and Karim and Hawlader (2005) proved that the optimum temperature of the air-dryer used for the experiment is 60°C, because sensory characteristics of the product such as color and texture do not change and the diffusion is near maximum in this condition. Hence the operating temperature of the air-dryer used for the experiment was 60°C in this work.

Each Petridish was put in one dryer shelf and every 30 min weight of the samples was read. Osmotically treated and fresh samples were dried until equilibrium moisture was achieved. Solids content was determined in fresh and osmotically treated samples. The concentration of the solution was monitored during the runs determining the osmotic solution soluble solids content (°Brix) using a refractometer (UNICOM-OPTICS, WYA-2S, CHINA).

e. Calculations

i. Mass volume variations

Weight reduction in relation to initial mass of the samples, during osmotic dehydration, was calculated from experimental data following Eq. (1) [14, 37]:

$$WR(\%)=\frac{(m_i-m_f)}{m_i}.100 \tag{1}$$

Souza et al. (2007) and El-Aouar et al. (2006) calculated the water loss (WL) and the solids gain (SG) in relation to initial mass during osmotic dehydration, through the mass balances shown in Eqs. (2) and (3):

$$WL(\%)=\frac{(m_iX_i-m_fX_f)}{m_i}.100 \tag{2}$$

$$SG(\%)=\frac{[m_f(1-X_f)-m_i.(1-X_i)]}{m_i}.100 \tag{3}$$

Weight reduction was also calculated by difference:

$$WR = WL - SG \tag{4}$$

Thus, weight reduction was considered as a dependent response in this work.

ii. Effective diffusion coefficients

1. During osmotic dehydration

The effective diffusion coefficient of water and sucrose (D_k) were determined by Fick's second law applied to a finite slab. The analytical solution in terms of water or sucrose content in the finite slab at osmotic dehydration time "t" has been given by Crank (1975):

$$W_k=\frac{w_k(t)-w_k{}^{eq}}{w_k{}^0-w_k{}^{eq}}=\frac{4}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\cdot\cos[\frac{(2n+1)\pi x}{2\sigma}] \cdot\exp\left\{\frac{-D_k(2n+1)^2\pi^2t}{4\sigma^2}\right\} \quad , \quad k=w,s \tag{5}$$

2. During Air drying

The effective diffusion coefficients of moisture (D_m) were determined by solution of Fick's second Law applied to a finite slab by Crank (1975):

$$X=\frac{X(t)-X^{eq}}{X^0-X^{eq}}=\frac{4}{\pi}\sum_{n=0}^{\infty}\frac{(-1)^n}{2n+1}\cdot\cos[\frac{(2n+1)\pi x}{2\sigma}] \cdot\exp\left\{\frac{-Dm(2n+1)^2\pi^2t}{4\sigma^2}\right\} \tag{6}$$

In drying experiments the equilibrium moisture content was calculated using the equation of Tia et al. (1990):

$$RH=\exp[(\frac{-21065}{R.T}).M_{eq}^{-1.25}] \tag{7}$$

or

$$M_{eq}=[\frac{-21065}{R.T.\ln(RH)}]^{0.8} \tag{8}$$

where RH is the air relative humidity (fraction), T is the air temperature (Kelvin) and R is the gas constant (8.314 J/mol.K).

3. Determination of optimum effective diffusion coefficient

The diffusion coefficients in Eqs. (5) and (6) were determined from the experimental data by minimizing the squares of the deviations between predicted and observed values. The fitting efficiency was expressed by the coefficient of determination (R^2) and Root Mean Square Errors (RMSE); which are according to following equations:

$$R^2=1-\frac{\sum_P(y_{obs}-y_{est})^2}{\sum_P(y_{pred}-\bar{y}_{obs})^2} \tag{9}$$

$$RMSE=\sqrt{\frac{\sum_P(y_{obs}-y_{est})^2}{N}} \tag{10}$$

where y_{obs}, y_{est} are experimental and estimated values, respectively, and N is the number of data. When the RMSE is at its minimum value and R^2 is high, ≥0.8, a model can be judged as very good [40, 41].

III. RESULTS AND DISCUSSION

a. Statistical analysis

Different combinations of three factors yielded different range of water loss and solids gain. The p-values of linear, quadratic, and cubic terms of the model for the water loss were <0.0001, 0.682, and 0.0612, respectively, and were 0.0003, 0.567 and 0.0890 for solids gain, which indicated the significance of the linear terms. Thus, the following linear regression equations were obtained to describe the water loss and solids gain:

$$WL = +9.01816 + 1.00853X_1 - 49.87469X_2 + 7.26534X_3 \quad (11)$$

$$SG = +5.70450 + 0.081700X_1 - 25.70570X_2 + 1.57661X_3 \quad (12)$$

where X_1, X_2 and X_3 are the coded values of concentration, fruit to solution ratio, and osmotic treatment time, respectively.

The statistical significance of the first-order model Eq. (11) was evaluated by the analysis of variance (ANOVA).The determination coefficient (R^2) of the model was 0.9844, which indicated 98.44% of the variability in the response could be explained by this model. The R^2 value of 0.9844 was reasonably agreed with the adjusted R^2 value of 0.9766. The model p-value of < 0.0001 (desired <0.05) indicated that the model terms were significant. The coefficient of variation of 3.42% (desired <30%) indicated a good precision and reliability of the experiments carried out. The adequate precision value measures the signal-to-noise ratio. In this case, the value was 33.751 (desired >4), which suggested an adequate signal. Those values indicated a satisfactory fitness of the liner model.

The statistical significance of the first-order model Eq. (12) was also evaluated by ANOVA. R^2 value was 0.9505 which was in reasonable agreement with the adjusted R^2 value of 0.9257. moreover, the model p-value of 0.0003 (desired <0.05) indicated that the model terms were significant. The coefficient of variation of 8.15% (desired <30%) and the adequate precision value was 20.095 (desired >4), which suggested an adequate signal. Those values indicated a satisfactory fitness of the linear model.

b. Mass transfer kinetics of melon cubes during osmotic dehydration

The effects of various process parameters on kinetics of water loss and solids gain during osmotic dehydration of melon cubes were investigated. To study the effect of composition and concentration of osmotic solution as described earlier, osmotic dehydration was carried out in different solutions with 10% (w/w) of NaCl salt and 30, 40, and 50% of sucrose. The obtained results for water loss and solids (solutes) gain are shown in Fig 1. In this figure solution temperature was maintained at 45°C and fruit to solution ratio was 1:4.

After equal processing time, the higher the osmotic concentration, the higher were the solids and sugar contents measured in the samples. The increase in water loss and solids gain might be due to simultaneous presence of sucrose and salt to ascent high osmotic potential, which was in close agreement with the results of Sacchetti et al. (2000) when they studied on apple osmotic treatments.

In this study, increased water loss and solids gain in melon cubes were observed with increase in immersion time for all the process conditions. Figure 1 indicates that the rate of water loss and the rate of Solids gain were higher in the beginning of the dehydration than the later period. As expressed in previous works for carrot and pumpkin [27, 42], this might be because of decreasing osmotic driving potentials for moisture and solute transfer due to the moving of moisture from the sample to solution and solute from solution to sample. Also, the rapid loss of water and uptake of solutes near the surface in the initial phase of osmosis might have resulted in structural changes leading to contraction of surface layers and increased mass transfer resistance for water and solids. Similar results were also reported by Derossi et al. (2008) for osmotic dehydration of apples.

Similarly, to study the effect of fruit to solution ratio, as described earlier, osmotic dehydration was carried out in different fruit to solution ratios (1:4, 1:5 and 1:6). The obtained results for water loss and solids (solutes) gain are shown in Fig 2. In these figure, the solution temperature was maintained at 45°C and solution concentration as 40% sucrose +10% NaCl salt (w/w).

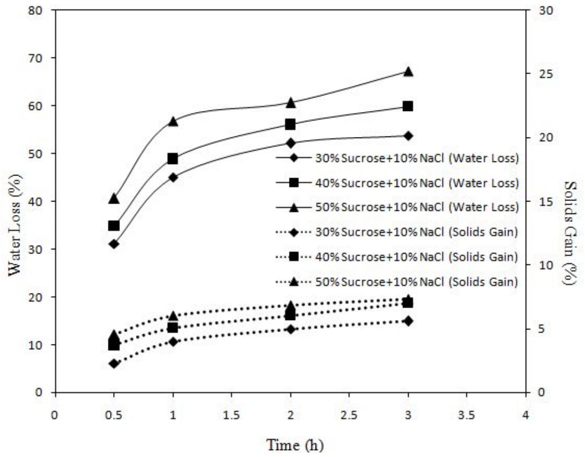

Fig. 1 Effect of osmotic solution concentration and processing time on water loss and solids gain at 45°C and fruit to solution ratio 1:4

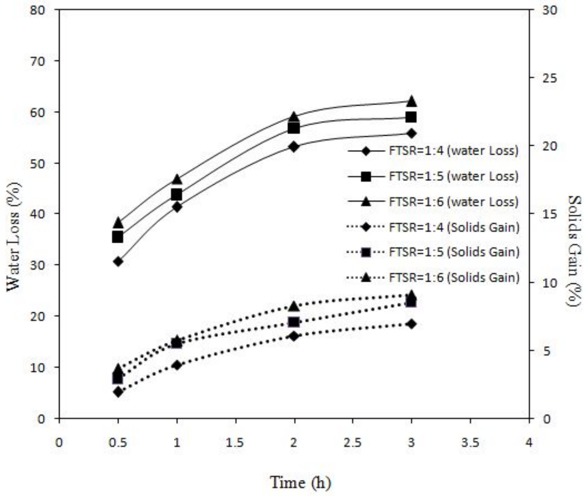

Fig. 2 Effect of fruit to solution ratio (FTSR) on water loss and solids gain at 40% sucrose +10% NaCl salt and solution temperature 45°C

TABLE II
EQUILIBRIUM CONCENTRATIONS AND EFFECTIVE DIFFUSION COEFFICIENTS FOR WATER AND SUCROSE DURING OSMOTIC DEHYDRATION OF MELON AT DIFFERENT FRUIT TO SOLUTION RATIOS CONSIDERING SHORT AND LONG TIMES

Osmotic solution (%Suc./%NaCl)	Total time (h)	Water Equilibrium Concentration (g/100 g total mass)	Sucrose Equilibrium concentration (g/100 g total mass)	Dwater (10^{-10} m^2/s)	RMSE	R^2	Dsuc. (10^{-10} m^2/s)	RMSE	R^2
1:4	3	-	-	3.25	1.23	0.945	2.49	17.99	0.94
	72	71.02	26.78	2.75	1.58	0.972	2.0	15.31	0.954
1:5	3	-	-	1.99	2.48	0.963	1.45	19.89	0.963
	72	55.73	38.57	1.93	2.71	0.991	1.44	16.23	0.997
1:6	3	-	-	2.11	2.84	0.968	1.64	20.64	0.944
	72	49.97	47.83	2	3.65	0.975	1.5	17.26	0.971

TABLE IV
WATER CONTENT (W/W) OF FRESH, OSMOTICALLY DEHYDRATED AND DRIED MELON (60°C); WEIGHT REDUCTION (WR), WATER LOSS (WL), AND SUGAR GAIN (SG) IN RELATION TO THE INITIAL MASS, DURING OSMOTIC TREATMENT (60% SUCROSE SOLUTION, FTSR 1:4, 1 HR)

Drying temperature	Fresh W_W (gr/100gr)	Osmotically dehydrated W_W (gr/100gr)	Mass variations during osmotic treatment			Dried
			WR (gr/100gr)	WL (gr/100gr)	SG (gr/100gr)	
60 °C –non-treated	92.38	-	-	-	-	6.57
60 °C –pre-treated (50%, 1:4, 1 hr)	92.63	74.85	48.73	55.32	6.59	9.2

TABLE III
EQUILIBRIUM CONCENTRATIONS AND EFFECTIVE DIFFUSION COEFFICIENTS FOR WATER AND SUCROSE DURING OSMOTIC DEHYDRATION OF MELON AT DIFFERENT CONCENTRATIONS OF OSMOTIC SOLUTION CONSIDERING SHORT AND LONG TIMES

Osmotic solution (%Suc./%NaCl)	Total time (h)	Water Equilibrium Concentration (g/100 g total mass)	Sucrose Equilibrium concentration (g/100 g total mass)	Dwater (10^{-10} m^2/s)	RMSE	R^2	Dsuc. (10^{-10} m^2/s)	RMSE	R^2
30 / 10	3	-	-	3.64	0.37	0.958	3.35	17.2	0.948
	72	67.13	28.47	2.86	0.91	0.975	3	15.15	0.981
40 / 10	3	-	-	2.33	0.82	0.948	2.49	12.93	0.950
	72	51.14	42.46	2.27	1.54	0.961	2	13.58	0.961
50 / 10	3	-	-	3.11	1.48	0.948	3.64	13.33	0.970
	72	43.37	53.43	2.37	2.37	0.988	2.02	12.59	0.987

Water loss and solids gain were favored by increasing solution to fruit ratio (Fig 2). This behavior could be explained by the fact that water loss and solid gain took longer time to obtain equilibrium during osmotic dehydration in sucrose-salt solution. Singh et al. (2007) also reported the increased rate of water loss and solute gain with the increase of solution to fruit ratio during osmotic dehydration of carrot.

c. Effective diffusion coefficients of water and sucrose during osmotic dehydration operation

Tables 2 and 3 show equilibrium concentrations and effective diffusion coefficients of water and sucrose determined from Eq. (5) at each condition of osmotic dehydration.

Two different effective (apparent) diffusion coefficients were calculated for water and sucrose at each condition of osmotic treatment (Tables 2 and 3). The first one corresponds to short time experiments, where samples were kept up to 3 h in the osmotic solutions. The second diffusion coefficient was calculated by joining the results of short and long time experiments (up to 72 h).

Effective diffusion coefficients of sucrose were lower than water in all treatments. It might be due to several reasons, such as high sucrose concentration, which causes damage to the melon tissue [44].

d. Mass transfer kinetics of melon cubes during convective air-drying

The mass transfer efficiency of osmotic dehydration treatment is usually estimated as the ratio water loss/solid gain [42]. The most efficient treatments were with 50% sucrose with 10% NaCl salt and fruit to solution ratio of 1:4 for 1 h. So, on taking into account efficiency, short process time and low water content, a 50% sucrose solution with fruit to solution ratio of 1:4 during 1 h treatment was selected to be employed in convective air-dryer.

TABLE V
EFFECTIVE MOISTURE DIFFUSION COEFFICIENTS ACCORDING TO EQ. (6)

Samples	D_m ($10^{-10}m^2/s$)	RMSE	R^2
Non-treated	1.83	12.5	0.991
Pretreated	2.69	17	0.983

Both non-treated and osmotically treated samples treated in this condition were dried at an air-drier with previously mentioned conditions. Water content measured in fresh and osmotically treated samples, and that obtained in dried samples by mass balance, as well as the weight reduction (WR), the water content (WL) and the solids gain (SG), are shown in Table 4.

The D_m values determined from Eq. (6) can be observed in Table 5. The results reveal the fact that the use of osmotic dehydration followed by air-drying brings on some advantages. The total processing time for only the air-drying process operating at 60°C was compared to the total processing time for osmotic dehydration process followed by air-drying operating at 60°C for all operating conditions used in the osmotic dehydration experiments. It shows that using an osmotic solution accelerate the process, reducing the drying time from 12.5 to 5.7 h (3.2 h in osmotic concentration and 2.5 h in dehydration), which can reduce operational costs and increase the overall productivity.

IV. CONCLUSIONS

Mixtures of NaCl/sucrose showed to be adequate for the osmotic pre-treatment of melon cubes. Regarding the influence of independent variables over the water and sucrose diffusion coefficients, it was verified that: immersion time exerted significant influence over the diffusion coefficients for water and sucrose, and the osmotic solution concentration influenced the diffusion coefficient for sucrose. Maximum moisture loss occurred when osmotic treatment was conducted in a more concentrated solution. The obtained effective diffusion coefficients for water and sucrose were calculated from Crank (1975) equation and were 1.93×10^{-10} to 3.64×10^{-10} and 1.5×10^{-10} to 3.35×10^{-10} m/s^2, respectively.

Drying kinetics was determined for pre-treated (60%, 1:4, 1 h) and non-treated melon, at 60 °C. Pre-treatments enhanced the water transfer during drying. The moisture diffusion coefficients resulted to be higher than those for the non-treated ones. This unusual behavior was related to the fast surface drying of the fresh samples, forming areas of hardness on the surface and reducing drying rates.

The total processing time for only the air-drying process operating at 60°C was compared to the total processing time for osmotic dehydration process followed by air-drying operating at 60°C for all operating conditions used in the osmotic dehydration experiments. It shows that using an osmotic solution accelerate the process, reducing the drying time, which can reduce operational costs and increase the overall productivity.

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