Transport Phenomena in Food Processing

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9 Effect of Pretreatment on the Drying Kinetics of Cherry Tomato (*Lycopersicon esculentum* var. *cerasiforme*)

P.M. Azoubel and F.E.X. Murr

CONTENTS

9.1 INTRODUCTION

The cherry tomato (*L. esculentum* var. *cerasiforme*) is considered the ancestral form of tomato (Folquer, 1976). This tomato type is an excellent source of vitamins A and C (Gould, 1974) and is used in salads and has been used as a supplement in astronauts' diet during long periods of residence in space, due to its fast *in vitro* production (Kaur-Sawhney et al., 1996).

The tomato is a very perishable fruit, necessitating the removal of water for its preservation. The drying of solids is a common form of preservation, allowing the foodstuff to be kept for a longer period than would otherwise have been possible (Hawlader et al., 1991). In addition, dried food can be stored and transported at a relatively low cost. However, water removal leads to a serious decrease in food nutritive and organoleptic values, such as lignified texture, slow or incomplete rehydration, and loss of juiciness characteristics of fresh fruit and vegetables. Moreover, color and smell are affected in a negative way. It is generally known that dried food of the best quality is obtained by means of freeze-drying, but this is one of the most expensive methods. For these reasons, efforts are being made to perfect the convection drying process. The preliminary treatment of the raw material is of crucial importance. The utilization of an osmotic prestep can have important advantages in terms of product quality and cost (Lenart, 1996).

The present study was carried out to determine the influence of osmotic pretreatment on the drying kinetics of cherry tomato, using a fixed bed dryer.

9.2 BASIC CONCEPTS

9.2.1 Osmotic Dehydration

Osmotic dehydration of foods has recently gained attention as a processing method to obtain better quality fruit products. It is based on the immersion of foods, whole or in pieces, in hypertonic solution (sugars, sodium chloride, glycerol, sorbitol), originating two simultaneous counter-current flows: an exit of water from the product to the solution and a migration of solutes from the solution to the solid. A third flow consists of the loss of some natural components, such as sugars, organic acids, and mineral salts; although these may be quantitatively of no significant meaning in the mass exchange, they can be important to the final nutritive value and organoleptic properties of the food (Raoult-Wack et al., 1989).

The quantity and rate of water removal depend on several variables and processing parameters. In general, the weight loss in osmosed fruit is increased by increasing solute concentration of the osmotic solution, immersion time, temperature, solution/ fruit ratio, and specific surface area of the food and by using a low pressure system (Lerici et al., 1985).

Osmotic dehydration has generally been applied to fruit, vegetables, meat, and fish (Raoult-Wack et al., 1994). This process will not yield a moisture low enough to make the product shelf stable, but it is considered a prestep to air, freeze, and vacuum drying (Lenart, 1996; Uddin et al., 1990).

Since the osmotic process generally results in some solute uptake, changes in the composition of the food material that can influence the subsequent drying step must be considered. One important property of a material relative to drying is its water sorption isotherm, since this will determine the degree of drying required to obtain a stable product (Islam and Flink, 1982).

9.2.2 Sorption Isotherms

Moisture sorption isotherms can be used to predict changes in food stability and to select appropriate package materials and ingredients (Zhang et al., 1996).

The isotherm curve can be obtained in one of two directions. An adsorption isotherm is made by placing a completely dry material into various atmospheres of increasing relative humidity and measuring the weight gain due to water. The desorption isotherm is found by placing the initially wet material under the same relative humidities, but in this case measuring the loss in weight (Iglesias and Chirife, 1982).

There are several experimental means to determine sorption isotherms (Gal, 1972). The principal methods are:

- *Gravimetric*—The sample weight change in equilibrium with different water vapor pressures is determined.
- *Manometric*—The vapor pressure of water in equilibrium with a food at a given moisture content is measured by a sensitive manometric device.
- *Hygrometric*—The equilibrium relative humidity of a small amount of air in contact with a food at a given moisture content is measured by a hygrometric device.

A number of mathematical models have been proposed for correlation, analysis, and prediction of sorption data, including Guggenheim–Anderson–de Boer (GAB) (van den Berg and Bruin, 1981), Brunauer–Emmett–Teller (BET) (Brunauer et al., 1938), and the models of Halsey (1948) and Oswin (1946), as respectively described in the following equations:

$$X = \frac{X_m\, C_{GAB}\, K_{GAB}\, a_w}{[(1 - K_{GAB}\, a_w)\,(1 - K_{GAB}\, a_w + C_{GAB}\, K_{GAB}\, a_w)]} \tag{9.1}$$

$$X = \frac{X_m\, C_{BET}\, a_w}{(1 - a_w)\ [1 - (C_{BET} - 1)\ a_w]} \tag{9.2}$$

$$a_w = \exp\left[\frac{-A}{X^B}\right] \tag{9.3}$$

$$X = A\left(\frac{a_w}{1 - a_w}\right)^B \tag{9.4}$$

where X is the moisture content (kg/kg, dry basis); X_m is the monolayer moisture content (kg/kg, dry basis); C_{GAB} and K_{GAB} are GAB constants; a_w is the water activity; C_{BET} is BET constant; A and B are Halsey and Oswin constants.

9.2.3 Drying

Dehydration or drying operations are important steps in the chemical and food processing industries. The basic objective in drying food products is the removal of water from the solids to a level at which microbial spoilage is minimized (Vagenas et al., 1990).

Drying is a process of simultaneous heat and mass transfer. Heat transfer occurs during evaporation of the moisture removed from the drying solid object, while mass transfer takes place during the removal of moisture from the object's surface by an external drying fluid, which is usually air (Dincer and Dost, 1995).

The drying curve includes a constant drying rate region and a falling rate region. The constant rate period indicates that a film of water is freely available at the drying surface for evaporation into the drying medium, while the falling rate period indicates an increased resistance to both heat and mass transfer and occurs when the surface water no longer exists, and water to be evaporated comes from within the structure and must be transported to the surface. However, for some material, only the falling rate regions are observed (Hawlader et al., 1991).

A wide variety of dehydrated foods (snacks, dry mixes and soups, dried fruits, etc.) are available today (Vagenas et al., 1990). In the tropics, fresh tomatoes are available throughout the year, while in temperate regions tomatoes are a seasonal crop, and hence, a surplus exists in one season and a shortage in another. Currently, tomatoes are preserved in the forms of ketchup, paste, and juice (Hawlader et al., 1991).

9.3 MATHEMATICAL MODELS

The prediction of the kinetics of osmotic dehydration of cherry tomato was based on a two-parameter equation from mass balance, using data obtained during a relatively short period of time, as developed by Azuara et al. (1992) and adapted to spherical geometry:

$$D_t = \frac{\pi t}{36}\left[\left(\frac{S_1 r}{1+S_1 t}\right)\cdot\left(\frac{WL_\infty^{mod}}{WL_\infty^{exp}}\right)\right]^2 \tag{9.5}$$

where D_t is the apparent diffusion coefficient (m^2/sec) at time t; WL_∞^{mod} and WL_∞^{exp} are the amounts of water (g water/100 g of sample) leaving the solid after infinite time, predicted by the model and experimental data, respectively; r is the radius of the sample; and S_1 is a constant related to the water loss, calculated from the following linear regression that associates the water lost (WL) with time (t) (Azuara et al., 1992):

$$\frac{t}{WL} = \frac{1}{S_1(WL_\infty)} + \frac{t}{WL_\infty} \tag{9.6}$$

The value at equilibrium, WL_{∞}, is fixed for the established conditions of temperature, time, and fruit to solution rate. When WL_{∞}^{exp} is unknown, by assuming that it equals WL_{∞}^{mod}, Equation (9.5) may be used to obtain a good estimation for D_t, as long as the kinetics data are adequately fitted by Equation (9.6). The value of WL is a function of the rate of water loss and time. WL increases as these variables increase, and can be calculated as:

$$WL = \frac{ww_o - (tw - ws)}{ws_o + ww_o} \times 100 \tag{9.7}$$

where ww_o and ws_o are the initial water and solid contents (g), respectively, and tw is the total wet weight.

The average apparent diffusion coefficient is calculated by:

$$D_{avg} = \frac{\sum_{1}^{n} D_t}{n} \tag{9.8}$$

where n is the number of data points used.

For drying kinetics, considering the cherry tomato slice as a flat plate with initially uniform moisture distribution, negligible external resistance to mass transfer, and no shrinkage, the solution for Fick's equation is (Crank, 1975):

$$\frac{w - w_e}{w_o - w_e} = \frac{8}{\pi^2} \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} \exp\left[-(2i+1)^2.\pi^2.D_{eff.}.\frac{t}{L^2}\right] \tag{9.9}$$

where w, w_e and w_0 are the moisture content at t, the equilibrium, and the initial moisture content, respectively (g water/g dry mass); t is drying time (sec); L is length of plane thickness (m); and D_{eff} is effective diffusion coefficient for moisture in solids (m^2/sec). The equilibrium moisture content of a sample being dried depends upon the moisture content of the air and the structure and type of material (Hawlader et al., 1991) and was obtained from water sorption isotherms for cherry tomatoes with and without the osmotic pretreatment.

For conditions where L is small and t is large, the terms in the summation in Equation (9.9) corresponding to n > 1 are small, and the following approximation can be made (Hawlader et al., 1991):

$$\ln\left[\frac{w - w_e}{w_o - w_e}\right] = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff} t}{L^2} \tag{9.10}$$

where D_{eff} can be measured from the slope of the plot of $\ln\frac{w - w_e}{w_o - w_e}$ against t or t/L^2.

The mean relative deviation modulus (E, %) was used as a criterion to evaluate the fit of the tested model, as applied to the experimental data. Values of E were calculated using the following equation:

$$E = \frac{100}{N} \sum \frac{v_0 - v_p}{v_0} \tag{9.11}$$

where v_0 and v_p are the observed and the predicted values, respectively. Values of E less than or equal to 10% are considered to fit the experimental data satisfactorily.

9.4 MATERIALS AND METHODS

Fresh cherry tomatoes harvested between the end of January and the middle of May were purchased from a local market. The fruits were sorted visually for color (completely red), size (approximately 2.8 cm diameter), and lack of physical damage, and the physicochemical characteristics were determined according to Ranganna (1977).

As the cherry tomato waxy skin presents a high resistance to mass transfer, the fruits were washed and perforated with needles (1 mm diameter) (Shi et al., 1997) to pin hole density of 16 holes/cm^2. The perforated cherry tomatoes were immersed in NaCl and NaCl + sucrose (3:2) solutions of different concentrations (10 and 25% w/w) at 25°C (room temperature) and agitation of 70 r/min, maintained in a temperature–agitation controlled shaker (Tecnal, TE-421). In order to avoid any significant dilution effect on the osmotic solution, a 1:10 fruit-to-solution ratio was used. At different processing times, samples were withdrawn from the solution, rinsed with cold water to remove adhering osmotic solution, and gently blotted to remove surface moisture.

The water content of cherry tomato samples was determined gravimetrically by vacuum oven drying at 70°C for 24 h. The salt content was determined by Mohr's titration method (Ranganna, 1977). Three replications were made.

Desorption isotherms of the samples were determined using the static gravimetric method. Saturated salt solutions were prepared to give defined constant water activity (Greenspan, 1977). Three replications of the same experiment were carried out. After equilibrium was reached, the equilibrium moisture content was determined (vacuum oven at 70°C for 24 h). The adequacy of the mathematical models of BET, GAB, Halsey, and Oswin was verified.

For air drying experiments, a cabinet dryer was used, and the tests were conducted at three different temperatures (50, 60, and 70°C) and two air velocities (0.75 and 2.60 m/sec). The tomatoes were cut into quarters along the longitudinal axis and the seeds were removed. The samples (length of 1.8 mm) were spread uniformly on a perforated stainless steel tray in a fixed bed dryer. The processing temperature was controlled using precalibrated cooper-[constantan] thermocouples and the air flow rate was monitored by an anemometer (TSI, 8330-M). The drying curves were determined by periodic weighing of the tray on a semianalytical scale.

9.5 RESULTS AND DISCUSSION

9.5.1 Cherry Tomato Characterization

The physicochemical characteristics of the cherry tomatoes used in the experiments are shown in Table 9.1.

The total solids content, acidity, and soluble solids content were similar to the values obtained by Gould (1974) for tomato, but the NaCl content was higher and the reducing sugars content was lower. Sugars and organic acids were the majority of the total dry matter content of the tomato fruit. Similar results for cherry tomato were obtained by Picha (1987). The pH value was similar to the results of Petro-Turza (1987) for tomato and the density to tomato pulp (Ranganna, 1977).

9.5.2 Osmotic Dehydration

Characterizing the effect of osmotic dehydration on the air drying kinetics of cherry tomatoes was the main objective of this study. The effect of the osmotic agent (NaCl and the NaCl–sucrose mixture) and solution concentration (10 and 25% w/w), at room temperature (25°C), was evaluated by determining moisture and salt contents, as shown in Figure 9.1. The more concentrated the solution, the higher the percentages of water loss and solid uptake, due to an increase in osmotic pressure gradient resulting in increased mass transfer. This finding is in agreement with the results of Rastogi and Raghavarao (1994) for the osmotic dehydration of carrots in sucrose solutions, and of Vijayanand et al. (1995) for cauliflower in salt solutions. The rate of water loss was faster in the first 2 h of the process, decreasing gradually while approaching the end of the experiment, which was not sufficient in length for equilibrium to be reached, except for the 10% solution.

Figure 9.1(b) shows the salt gain during the osmotic dehydration of cherry tomato. It was observed that an increase in the concentration of the osmotic solution gave higher salt gain within 6 h of processing. By fixing the concentration of the

TABLE 9.1
Physicochemical Characteristics of Cherry Tomatoes

Analysis	Mean Value
Moisture content (%)	94.39
Acidity (% citric acid)	0.64
NaCl (%)	0.65
Reducing sugars (%)	1.03
pH	4.04
Brix	5.53
Ascorbic acid (%)	31.39
Density (g/ml)	0.99

TABLE 9.2
Average Water Apparent Diffusion Coefficient (D_{avg}) Obtained from the Osmotic Dehydration Process

Sample	$S_1(10^2)$	D_{avg} (10^{10} m^2/sec)	E (%)
Sodium chloride (10%)	1.76	11.69	8.85
Sodium chloride (25%)	2.28	14.42	0.12
Sodium chloride + sucrose (10%)	0.40	2.17	3.68
Sodium chloride + sucrose (25%)	1.75	11.66	10.01

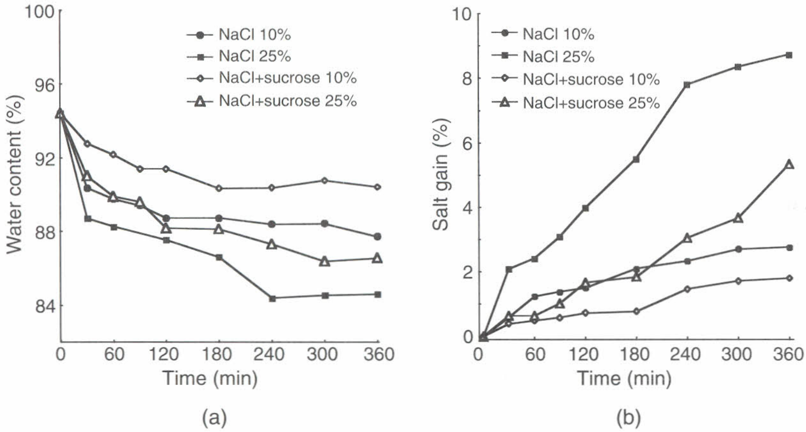

FIGURE 9.1 Moisture (a) and salt gain (b) profiles of osmotically dehydrated cherry tomato.

solution, the effect of the osmotic agent can be evaluated. Our results showed that the salt gain was lower when the mixed NaCl–sucrose solution was used.

The experimental water loss results were used to estimate the apparent water diffusion coefficients. The time used for prediction by the proposed model was 180 min. Table 9.2 presents the obtained average water apparent diffusivities (D_{avg}) and S_1 values. Increasing the osmotic solution concentration (10 to 25% w/w) caused an increase in D_{avg}. Changing the osmotic medium from salt to a mixed salt–sucrose solution, at the same temperature, resulted in a decrease of the diffusion coefficient. This is due to sodium chloride ionization in solution, and as the molecular weight of sodium chloride is lower than that of sucrose, its rate of penetration into vegetable tissues is higher. Higher values for S_1 indicate a higher diffusion of water per unit of time. The model was able to predict the entire osmotic dehydration process up to equilibrium, using data obtained over a short period of time, with satisfactory mean relative modulus.

Consumer demand for fresh, convenient, and safe vegetables has promoted interest in processed products with fresh-like qualities (Shi et al., 1997). The osmotic dehydration process was carried out within a short period of time in order to achieve

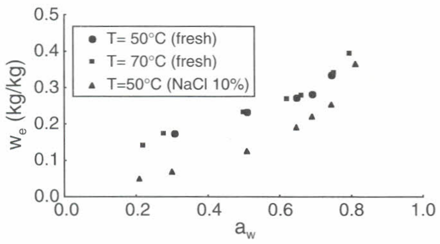

FIGURE 9.2 Sorption isotherms for fresh and osmoticly dehydrated cherry tomato.

a high degree of dewatering with relatively small solids gain. Pretreatment with sodium chloride, 10% w/w for 2 h, was chosen for the air drying experiments, and desorption isotherms of these samples were determined.

9.5.3 Sorption Isotherms

The results of the experimental measurements of the equilibrium moisture content (w_e) of cherry tomato with and without pretreatment, at relative humidity ranging from 10.75 to 81.20%, are shown in Figure 9.2. The pretreated sample obtained lower values of water activity than the fresh fruit. Sloan and Labuza (1976) noted that components such as glycerol or salt are particularly effective in reducing the water activity. No temperature dependence of the experimental data of the fresh fruit can be seen. Similar behavior was observed by Bolin (1980) for prunes. The results for 50°C were considered for all samples, and temperature independence was assumed for the osmotically pretreated samples. It can be seen that the desorption isotherms do not intersect. For products with high sugar content, the intersection of sorption isotherms can be observed (Saravacos et al., 1986). For products with low sugar, high protein, or high starch, there is no intersection point with increased temperature (Benado and Rizvi, 1985).

The results of direct nonlinear regression analysis of fitting the GAB, BET, Halsey, and Oswin models to the experimental points (Tables 9.3, 9.4, and 9.5) showed that the GAB equation was satisfactory in predicting the equilibrium moisture content of fresh cherry tomato, and that the Halsey model presented the best fit for samples pretreated in 10% NaCl osmotic solution for 2 h (Figure 9.3).

9.5.4 Air Drying

The effect of air temperature (50, 60, and 70°C) at air velocities of 0.75 and 2.60 m/sec on the drying kinetics of cherry tomato is illustrated in Figure 9.4. Increasing the temperature of the drying medium increased the drying potential and the moisture removal rates. When the flow rate was increased at constant temperature, similar behavior was observed. The effect of osmotic pretreatment was clearly verified at a temperature of 50°C and air velocity of 2.60 m/sec. In this condition, the drying time was reduced, with higher drying rates and effective diffusion coefficients (Table 9.6).

For the other conditions studied (60 and 70°C at both air velocities), the drying time of pretreated samples with 10% NaCl solution was not faster when compared

TABLE 9.3
Estimated Parameters for Fresh Cherry Tomato at 50°C

Model	Parameters			R^2	E (%)
BET	Xm	C	n		
	0.133	20.087	S	0.979	3.221
GAB	Xm	C	K		
	0.138	95.615	0.781	0.990	2.278
Halsey	A	B			
	0.026	2.205	—	0.995	2.341
Oswin	A	B			
	0.227	0.335	—	0.990	2.171

TABLE 9.4
Estimated Parameters for Fresh Cherry Tomato at 70°C

Model	Parameters			R^2	E (%)
BET	Xm	C	n		
	0.145	11.154	S	0.97	8.022
GAB	Xm	C	K		
	0.135	51.868	0.822	0.99	3.747
Halsey	A	B			
	0.036	1.988	—	0.99	6.617
Oswin	A	B			
	0.231	0.370	—	0.99	3.353

TABLE 9.5
Estimated Parameters for Osmosed Cherry Tomato at 50°C

Model	Parameters			R^2	E (%)
BET	Xm	C	n		
	0.575	0.11	S	0.98	6.060
GAB	Xm	C	K		
	0.074	5.973	0.991	0.99	2.573
Halsey	A	B			
	0.069	1.099	—	0.99	2.211
Oswin	A	B			
	0.120	0.751	—	0.99	3.353

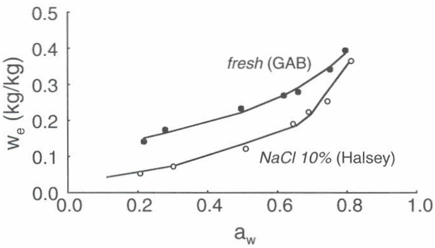

FIGURE 9.3 Equilibrium moisture content at 50°C and the predictions of the GAB and Halsey models for fresh and preteated cherry tomato, respectively.

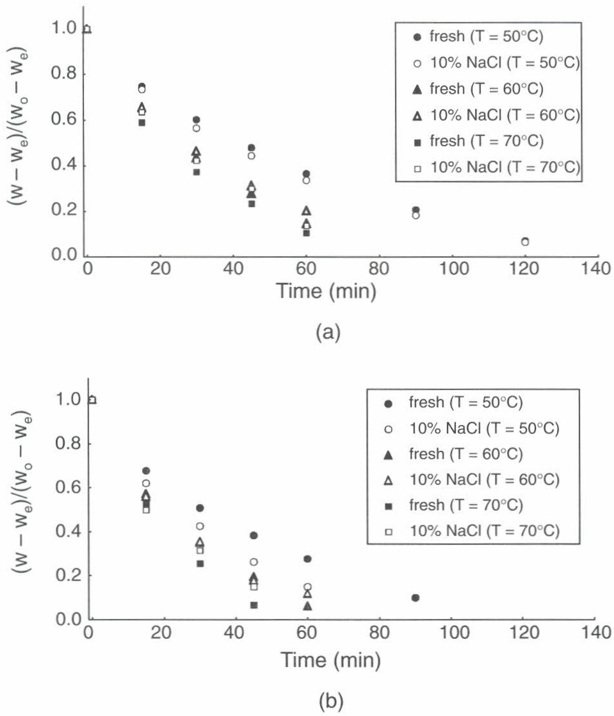

FIGURE 9.4 Effect of temperature on water removal for fresh and osmotically dehydrated cherry tomato at constant air velocities of 0.75 m/sec (a) and 2.60 m/sec (b).

to the untreated samples at the same air temperature and velocity, The effective diffusion coefficients were lower, indicating a less favored diffusional process. The differences in the effective diffusion coefficients can be attributed to the compositional changes that occur following osmosis. The uptake of salt and the loss of water that occur in osmosis give increased internal resistance to moisture movement. However, the dried cherry tomato in 10% NaCl solution presented a flexible structure, smaller shrinkage, and a more natural coloration when compared with the dried

TABLE 9.6
Effective Diffusion Coefficients of Air Dried Cherry Tomatoes

		D_{eff} (10^{11}m²/sec)	
T (°C)	v (m/sec)	Fresh	10% NaCl
50	0.75	12.02	12.02
	2.60	13.66	17.49
60	0.75	17.49	14.21
	2.60	26.78	19.67
70	0.75	20.77	18.03
	2.60	37.70	21.86

TABLE 9.7
Activation Energy for Diffusion in Cherry Tomatoes

Sample	v (m/sec)	E_a (kJ/mol)	R
Fresh	0.75	25.39	0.99
	2.60	46.61	0.99
10% NaCl	0.75	18.31	0.99
	2.60	10.56	0.99

fruit with no preliminary treatment. The same behavior was found by Lenart (1996) for osmodehydrated dried apples.

Figure 9.5 shows the variation in the drying rate for all samples as a function of moisture content with air velocity and temperature. For the given experimental conditions, the samples did not show a constant rate of drying. Higher temperature, higher air velocity and the pretreatment for the lower temperature increased the potential for the transport of moisture, thus increasing the drying rate. For temperatures of 60 and 70°C, the untreated samples showed higher drying rates in the beginning, due to a higher free water content.

The activation energy was estimated by an Arrhenius type equation, using the value of effective diffusivity for each temperature from Table 9.6:

$$D_{eff} = A \exp\left(\frac{-E_a}{RT}\right) \tag{9.12}$$

where E_a is activation energy (kJ/mol), R is the universal gas constant (8.314 J/mol K), A is the integration constant, and T is temperature (K).

The values of activation energy and the correlation coefficient are presented in Table 9.7. The pretreated samples' activation energy was much lower than that of the fresh samples, indicating that temperature has less influence on drying rate for

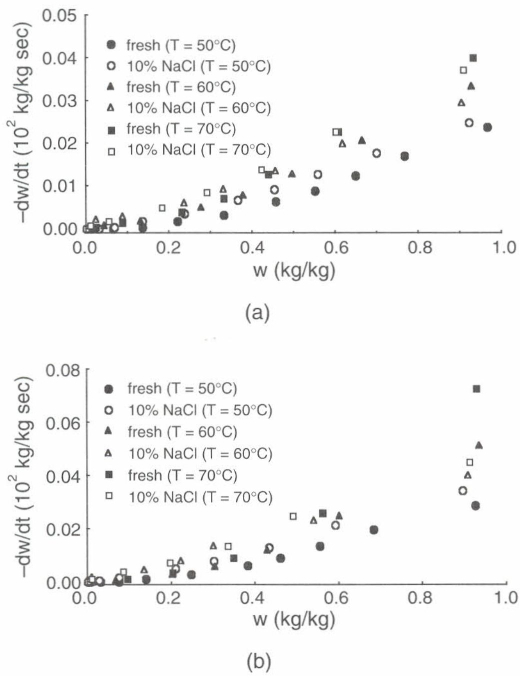

FIGURE 9.5 Drying rate vs. moisture content at constant air velocities of 0.75 m/sec (a) and 2.60 m/sec (b).

salt osmosed fruits. These results are similar to those of Islam and Flink (1982) for osmotically dehydrated potatoes in NaCl solution.

9.6 CONCLUSIONS

The rate of moisture removal and solids gain in the osmotic dehydration of cherry tomato was directly related to the concentration of the solution, the osmotic agent and the immersion time. In order to obtain a processed product with fresh-like qualities, pretreatment with 10% NaCl solution for 2 h was the condition used prior to drying.

The water apparent diffusivity for osmotic dehydration ranged from 2.17×10^{-10} to 14.42×10^{-10} m^2/sec and the calculated effective diffusivity ranged from 12.02×10^{-11} to 37.70×10^{-11} m^2/sec for fresh fruit and from 12.02×10^{-11} to 21.86×10^{-11} m^2/sec for cherry tomatoes pretreated in 10% NaCl solution for 2 h. For the given experimental conditions, the samples did not show a constant rate of drying.

Osmotic dehydration of cherry tomato in 10% NaCl solution for 2 h before air drying was efficient in increasing the water removal rate and the effective diffusion coefficient, and in decreasing the drying time at 50°C with air velocity of 2.60 m/sec.

For all conditions studied, the osmodehydrated dried samples presented a flexible structure, smaller shrinkage, and a more natural coloration when compared to dried cherry tomato with no preliminary treatment.

The activation energy for effective diffusivity was lower for osmosed samples, indicating less influence of temperature on drying rate.

NOMENCLATURE

D_{avg}	Moisture apparent diffusion coefficient, m^2/sec
D_{eff}	Moisture effective diffusion coefficient, m^2/sec
E_a	Activation energy, kJ/mole
L	Thickness, m
R	Universal gas constant, J/mol K
R	Radius, m
t	Time, sec
w	Moisture content, kg/kg
w_e	Equilibrium moisture content, kg/kg
w_0	Initial moisture content, kg/kg
WL	Water loss, g water/100 g sample
WL_∞	Amount of water leaving the solid at equilibrium, g water/100 g sample
T	Temperature, K

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