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Mass Transfer During Osmotic Dehydration Using Acoustic Cavitation*

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Abstract An experimental study on intensifying osmotic dehydration was carried out in a state of nature and with acoustic cavitation of different cavitating intensity (0.5A, 0.7A and 0.9A) respectively, in which the material is apple slice of 5 mm thickness. The result showed that acoustic cavitation remarkably enhanced the osmotic dehydration, and the water loss was accelerated with the increase of cavitating intensity. The water diffusivity coefficients ranged from $1.8\times10^{-10}\mathrm{m^2\cdot s^{-1}}$ at 0.5A to $2.6\times10^{-10}\mathrm{m^2\cdot s^{-1}}$ at 0.9A, and solute diffusivity coefficients ranged from $3.5\times10^{-11}\ \mathrm{m^2\cdot s^{-1}}$ at 0.5A to $4.6\times10^{-11}\ \mathrm{m^2\cdot s^{-1}}$ at 0.9A. On the basis of experiments, a mathematical model was established about mass transfer during osmotic dehydration, and the numerical simulation was carried out. The calculated results agree well with experimental data, and represent the rule of mass transfer during osmotic dehydration intensified by acoustic cavitation.

Keywords osmotic dehydration, acoustic cavitation, mass transfer rate, mathematical model

1 INTRODUCTION

Osmotic dehydration is a method partially removing water from fruit and vegetable tissues by immersion in a hypotonic solution of given temperature, producing hypotonic pressure by utilizing different concentrations on opposite side of membrane. Considering the advantages of quality and energy consumption, the International Foodstuff has widely paid attention to osmotic dehydration. The active research in the area of osmotic dehydration as a pretreatment of fruits and vegetables is continuing all over the developed countries. Generally, osmotic dehydration is an inherently slow process, therefore it is particularly important to accelerate osmotic dehydration process.

The technology of power ultrasound has many characteristics. Compared with other technologies, it can often improve the speed and efficiency to a great extent, and improve the quality and implement some treatments. Therefore, it has more and more extensive applications in industry, agriculture, national defense, medical and health, environmental protection, *etc.* Ultrasonic wave can remarkably enhance osmotic dehydration[1–3]. Acoustic cavitation induces macroscopic turbulence and strengthens the mixing of solution, and keeps the solution of high concentration flowing back in time. The presence of acoustic streaming decreases the thickness of the boundary layer between liquid and solid and reduces the external resistance of diffusion. The local pressure fluctuation induced by cavitation accelerated degassing of the tissue of material, increasing the mass transfer surface. All of these accelerated the mass transfer process during osmotic dehydration.

In the past few years, numerous studies have been carried out to better understand the internal mass transfer during osmotic dehydration of fruits and vegetables and to model the process[4–6]. A number of investigators used Fick's unsteady state law of diffusion to estimate the water or solute diffusivity, and simulate the experiments with the boundary conditions to overcome the assumptions involved in Fick's law[7–9]. Lazardies *et al.*[10] assumed constant concentration of external solution and negligible surface resistance compared with the internal diffusion resistance. The assumption of constant solution concentration can be satisfied by maintaining a high ratio of solution to materials in laboratory scale. However, many problems may occur when high volume of concentrated solutions is circulated through the equipment in an industrial application. Lenart and Flink[11] reported that solution/materials ratio of 4—6 is optimum for the best osmotic effect. The assumption of negligible external resistance cannot always be satisfied at high viscosities, low temperature and high solute concentration. Mavroudis *et al.*[12] showed that the external resistance cannot be neglected for osmotic dehydration at different agitation condition.

The solution of Fick's law of diffusion for short contact time was used by Hawkes and Flink[13], and later by Magee *et al.*[14] and Biswal *et al.*[15]. In this

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** To whom correspondence should be addressed. E-mail: hxl@mail.etp.ac.cn model, the overall mass transfer coefficient was used instead of the diffusion coefficient and estimated from the slope of concentration *vs.* square root of time. However, this model is not valid for long contact time.

Azuara *et al.*[5] proposed a two parameter kinetic model based on the mass balance to estimate mass transfer coefficients and the equilibrium point. This model was able to predict water loss and solid gain under equilibrium condition using the experimental data obtained during a relatively short period of time. Toupin *et al.*[16,17] developed a model incorporating cell membrane characteristics for the simulation of water and solute fluxes in complex cellular tissues. Later, Marcotte *et al.*[4] developed a model based on thermodynamic description of the forces in the osmotic process. However, the model[4] depends on a large number of biophysical properties, such as elastic modulus of the cell wall, cell wall void fraction, cell wall tortuosity and membrane permeability, which are very difficult to measure or obtain from the literature for fruits and vegetables.

In this study, a mathematical model of water and solute transfer is established. The diffusivity coefficients for water and solute during osmotic dehydration are calculated, and the average water content and solute gain are simulated numerically, and compared with experimental data. The influence on mass diffusivity during osmotic dehydration using acoustic cavitation and the influence on water loss and solute gain by cavitating intensity are investigated.

2 EXPERIMENTAL APPARATUS AND PROCEDURE

The osmotic installation used for experiments with acoustic cavitation consisted of a 88-1 ultrasonic generator and transducer, with a frequency of 14—20 kHz and intensity in a range of 50—80 $\mathrm{W \cdot cm^{-2}}$ and power in a range of 0—250 W, and the bottom of ultrasonic probe was kept about 2 cm below the solution surface. An electrical balance of high precision (0.01 mg) and an oven were also used. The experimental system was shown in Fig. 1. The solid sucrose was dissolved in water at room temperature and fully mixed to form a relatively uniform sucrose solution with a concentration of 40% by mass.

Ripe, fresh apples are used as the material in the experiments. The apples were washed, peeled, cored, cut into different thickness slices before osmotic dehydration, divided into three groups with similar mass (about 40 g) and washed with flowing water. The surface water was wiped off with tissue paper gently and weighted. The mass ratio of sample to solution was 1 : 10. The solution in cups was tempered at room temperature of (30±1)℃. Two groups were used in the experiments under natural condition and with acoustic cavitation respectively, and the third group was used as the sample. The material after treatment was taken out quickly, rinsed with flowing water to remove adherent solution, wiped with tissue paper and weighed. Then, the three groups materials were put inside the oven of 85℃ and absolutely dried and weighed. The experimental results were dealt with the computer.

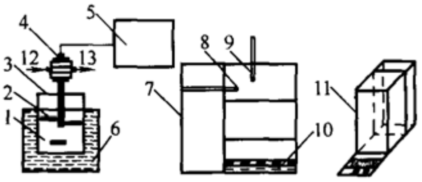

Figure 1 The experimental system of cnhancing osmotic dehydration with acoustic cavitation
1—sucrose solution; 2—materials; 3—glass; 4—ultrasonic generator and transducer; 5—ultrasonic generator; 6—cooling water tank; 7—oven; 8—probe of thermometer; 9—thermometer; 10—heater; 11—electronic balance; 12—entrance of cooling water; 13—exit of cooling water

Water loss rates, solute gain rates and moisture content of materials were calculated from Eqs. (1) to (3) respectively

$$DW = \frac{W_0 - W_\mathrm{t}}{DM_0} \tag{1}$$

$$ID = \frac{DM_\mathrm{t} - DM_0}{DM_0} \tag{2}$$

$$CW = \frac{W_\mathrm{t}}{DM_0} \tag{3}$$

3 MATHEMATICAL MODEL

The diffusion of water from the apple and the diffusion of sugar into the apple occur simultaneously during osmotic dehydration and the counter-current flows are considered. The following assumptions are used in the model:

(1) Apple slices are infinite slabs of width which are $2l$;

(2) The initial moisture content in the apple is uniform, and the initial solute content is negligible;

(3) Apparent diffusion coefficient is constant;

(4) The process is isothermal;

(5) At the apple surface, the concentration is in the equilibrium;

(6) Sample deformation and shrinkage during drying are negligible.

On the basis of above assumptions, the mathematical description about mass transfer of one dimensional unsteady state diffusion during osmotic dehydration are as follows

Water transfer

$$\begin{cases} \dfrac{\partial W}{\partial t} = D_{\mathrm{w}} \dfrac{\partial^2 W}{\partial x^2} \\ W = W_0 \quad t = 0 \quad -l \leqslant x \leqslant +l \\ W = W_{\mathrm{e}} \quad t > 0 \quad x = l \\ \dfrac{\partial W}{\partial x} = 0 \quad t > 0 \quad x = 0 \end{cases} \tag{4}$$

Solute transfer

$$\begin{cases} \dfrac{\partial c}{\partial t} = D_{\mathrm{s}} \dfrac{\partial^2 c}{\partial x^2} \\ c = 0 \quad t = 0 \quad -l \leqslant x \leqslant +l \\ c = c_{\mathrm{e}} \quad t > 0 \quad x = l \\ \dfrac{\partial c}{\partial x} = 0 \quad t > 0 \quad x = 0 \end{cases} \tag{5}$$

Equations (4) and (5) can be solved analytically by separation of variables and the solution expresses the moisture and solute concentrations in the solid, in a dimensionless way

$$\Psi(t) = \frac{W_{\mathrm{t}} - W_{\mathrm{e}}}{W_0 - W_{\mathrm{e}}} \tag{6}$$

$$c^*(t) = \frac{c_{\mathrm{t}} - c_{\mathrm{e}}}{c_0 - c_{\mathrm{e}}} \tag{7}$$

The infinite slab solutions for water and solute transport are shown in Eqs. (8) and (9).

$$\Psi(t) = \frac{8}{\pi^2} \sum_{\nu=0}^{\infty} \frac{1}{(2\nu+1)^2} \exp\left[-(2\nu+1)^2 \frac{3\pi^2 D_{\mathrm{w}} t}{4l^2}\right] \tag{8}$$

$$c^*(t) = \frac{8}{\pi^2} \sum_{\nu=0}^{\infty} \frac{1}{(2\nu+1)^2} \exp\left[-(2\nu+1)^2 \frac{3\pi^2 D_{\mathrm{s}} t}{4l^2}\right] \tag{9}$$

The solution of Fick's second law, when t is small, reduces to

$$\psi(t) = 1 - 4\left(\frac{D_{\mathrm{w}} t}{\pi l^2}\right)^{1/2} \tag{10}$$

$$c^*(t) = 1 - 4\left(\frac{D_{\mathrm{s}} t}{\pi l^2}\right)^{1/2} \tag{11}$$

and values of D_{w} can be inferred from the slopes of the plots of $\Psi(t)$ *versus* $t^{1/2}$ Azuara *et al.*[5], Rastogi & Raghavarao[8] have found that this situation is valid over a reasonably long period of osmotic dehydration.

The accuracy can be checked by the average relative error between the calculated and experimental data

$$E = \frac{1}{N} \sum_{i=1}^{N} \left| \frac{W_{\mathrm{E}} - W_{\mathrm{C}}}{W_{\mathrm{E}}} \right| \times 100\% \tag{12}$$

4 RESULTS AND DISCUSSION

The acoustic frequency was 18.8 kHz in all experiments with acoustic cavitation, the acoustic intensity was in the range of 50—80 $\mathrm{W \cdot cm^{-2}}$ and the electrical power input was 0—250 W. The acoustic parameter during osmotic dehydration was expressed by cavitating intensity, which refers to the input current intensity of ultrasonic transducer, and indicates the violent degree of acoustic cavitation. The greater the cavitating intensity, the more violent the acoustic cavitation. The acoustic intensity used in experiments was 0.5A, 0.7A and 0.9A respectively.

Water loss and solute gain of materials were measured at different time during the osmotic process. Results of water content calculated according to Eq. (3) and solute gain from Eq. (1) are shown in Table 1.

Through Table 1 it can be seen that water loss and solute gain were faster for osmotic dehydration with acoustic cavitation than that in a state of nature. Both of them increased with the increase of cavitating intensity. The water loss of material was more extensive, but the solute gain increased in a small range. The increase of water loss ranged from 39% at 0.5A to 71% at 0.9A, and the increase of solute gain ranged from 15% at 0.5A to 21% at 0.9A.

The reasons for experimental error may be as follows: (1) The thickness of material in a group of experiments was slightly different because the material was cut by hand; (2) There was some water or adherent solution on the surface of material before weighed; (3) The initial moisture content of material was different, it is about $(7.62 \pm 0.6)\,\mathrm{g_{water} \cdot g_{initial\ dry\ matter}^{-1}}$.

Table 1 Experimental moisture and solute content *vs* time with acoustic cavitation and under natural condition

Time, min	Acoustic cavitation							
	Natural condition		0.5A		0.7A		0.9A	
	moisture content	solute content	moisture content	solute content	moisture content	solute content	moisture content	solute contentr content
0	7.62	0	7.62	0	7.62	0	7.62	0
10	7.01	0.13	6.68	0.21	6.63	0.23	6.40	0.27
20	6.42	0.17	6.42	0.30	6.20	0.32	6.02	0.35
30	6.38	0.23	6.05	0.33	5.85	0.39	5.75	0.42
40	6.28	0.32	5.91	0.41	5.67	0.42	5.45	0.48
50	5.70	0.35	5.55	0.46	5.42	0.48	5.21	0.54
60	5.53	0.38	5.42	0.50	5.11	0.51	4.92	0.56

The diffusivity coefficients of water and solute were calculated from experimental results and the mathematical model [Eqs. (10) and (11)]. The equilibrium moisture content and solute content were experimentally determined by maintaining apple samples in a 40% sucrose solution for 36 h. These values were $1.56\,\mathrm{g_{water}}\cdot\mathrm{g_{initial\ dry\ matter}^{-1}}$ and $2.98\,\mathrm{g_{dry\ matter}}\cdot\mathrm{g_{initial\ dry\ matter}^{-1}}$ respectively.

By means of the proposed mathematical model, the diffusivity coefficients of water and solute were $1.3\times10^{-10}\,\mathrm{m^2\cdot s^{-1}}$ and $1.8\times10^{-11}\,\mathrm{m^2\cdot s^{-1}}$ respectively for experiments under natural condition. The diffusivity coefficients of water ranged from $1.8\times10^{-10}\,\mathrm{m^2\cdot s^{-1}}$ at 0.5A to $2.6\times10^{-10}\,\mathrm{m^2\cdot s^{-1}}$at 0.9A for experiments using acoustic cavitation, while the diffusivity coefficients of solute ranged from $3.5\times10^{-11}\,\mathrm{m^2\cdot s^{-1}}$ at 0.5A to $4.6\times10^{-11}\,\mathrm{m^2\cdot s^{-1}}$ at 0.9A. The diffusivity coefficients of water and solute using acoustic cavitation were apparently higher than that obtained under natural condition. These values were similar to the apparent diffusivities proposed by different authors for similar system. Hough *et al.*[7] reported water and glucose diffusivities in apple slices osmosed under agitation at 45℃ in a 55% glucose solution to be $2.0\times10^{-10}\,\mathrm{m^2\cdot s^{-1}}$ and $1.6\times10^{-10}\,\mathrm{m^2\cdot s^{-1}}$, respectively. Salvatori *et al.*[18] reported water and sucrose diffusivity figures of $8.4\times10^{-11}\,\mathrm{m^2\cdot s^{-1}}$ and $7.3\times10^{-11}\,\mathrm{m^2\cdot s^{-1}}$, respectively, for apple slice of 2 cm of thickness osmosed under agitation at 40℃ in a 65% solution. Simal *et al.*[1] reported water diffusivity coefficients ranged from $2.6\times10^{-10}\,\mathrm{m^2\cdot s^{-1}}$ at 40℃ to $6.8\times10^{-10}\,\mathrm{m^2\cdot s^{-1}}$ at 70℃ for apple cube of $(5\times5\times5)\,\mathrm{cm^3}$ osmosed using ultrasound in a 70° Brix, whereas solute diffusivity coefficients at all temperature had an average value of $7.9\times10^{-11}\,\mathrm{m^2\cdot s^{-1}}$.

Utilizing the calculated diffusivity coefficients of water and solute in the mathematical model, the average content of water and solute at different time was calculated. The results are shown in Fig. 2 which agree well with the experimental data. The proposed model can describe the water and solute transfer in an osmotic dehydration process at different cavitating intensity.

The calculated and experimental moisture and solute content *vs.* time by using acoustic cavitation at 0.9A and in a state of nature were shown in Fig. 3. The moisture content during osmotic dehydration using acoustic cavitation was lower than that under natural condition, whereas solute gain was higher. The average relative error between predicted values and experimental data of moisture and solute content in a state of nature was 10.67% and 15.98% respectively, whereas the relative errors using acoustic cavitation were less than 10%.

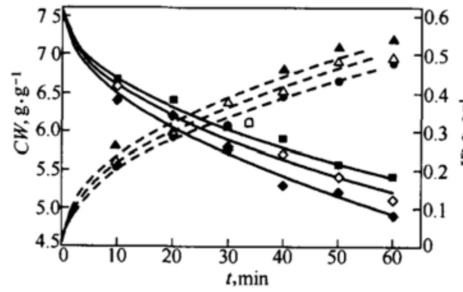

Figure 2 Estimated and experimental moisture and solute content *vs.* time with acoustic cavitation

■ moisture content at $I = 0.5$A;
◇ moisture content at $I = 0.7$A;
◆ moisture content at $I = 0.9$A;
● solute content at $I = 0.5$A;
△ solute content at $I = 0.7$A;
▲ solute content at $I = 0.9$A;
—— calculated moisture content;
- - - - calculated solute content

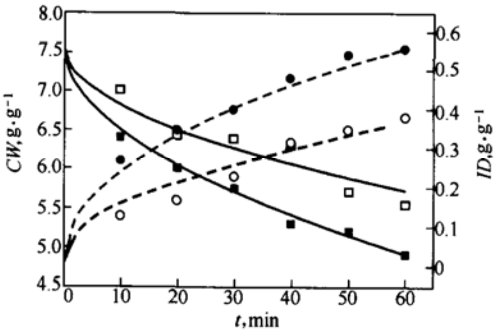

Figure 3 Calculated and experimental moisture and solute content *vs.* time with and without acoustic cavitation

□ moisture content in nature;
■ moisture content at $I = 0.9$A in acoustic cavitation;
○ solute content in nature;
● solute content at $I = 0.9$A in acoustic cavitation;
—— calculated moisture content;
- - - - calculated solute content

5 CONCLUSIONS

A mathematical model of water and solute transfer was established. The diffusivity coefficients for water and solute during osmotic dehydration were calculated. The average water content and solute gain *versus* time were numerically simulated, and compared with experimental data. The main conclusions are as follows:

(1) Acoustic cavitation remarkably enhanced osmotic dehydration. The mass diffusivity, water loss and solute gain of materials were all increased.

(2) The water loss and solute gain all increased with the increase of cavitating intensity. The water loss of materials increased more rapidly, but the solute gain only increased a little.

(3) The average content of water and solute in the material at different time simulated by proposed mathematical model agreed well with the experimental data. The proposed mathematical model can de-

scribe the mass transfer during osmotic dehydration intensified by acoustic cavitation.

(4) The diffusivity coefficients for water and solute calculated are similar to the apparent diffusivities proposed by different authors for similar systems.

NOMENCLATURE

CW	moisture content after treatment, $g_{\text{water}}^{-1} \cdot g_{\text{initial dry matter}}$
c	sucrose concentration, $g_{\text{sucrose}} \cdot g_{\text{initial dry matter}}^{-1}$
D	the diffusivity coefficients, $m^2 \cdot s^{-1}$
DM	dry matter content, g
DW	water loss rates of material, $g_{\text{water}} \cdot g_{\text{initial dry matter}}^{-1}$
E	average relative error of calculated and experimental result, %
ID	solute gain rates, $g_{\text{dry matter gain}} \cdot g_{\text{initial dry matter}}^{-1}$
l	half thickness of material slice, m
N	the experimental number
t	time, s
W	moisture content of material, g
x	x-axis distance, m
$\psi(t)$, $c^*(t)$	dimensionless moisture content and dimensionless solute concentration respectively

Subscripts

C	calculated value
E	experimental value
e	equilibrium value
o	initial value
s	solute
t	value after treatment
w	water

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