Accelerated Mass Transfer During Osmotic Dehydration of High Intensity Electrical Field Pulse Pretreated Carrots

N.K. Rastogi, M.N. Eshtiaghi, and D. Knorr

ABSTRACT

High intensity electrical field pulse (0.22 to 1.60 kV/cm) pretreatment was tested to accelerate the osmotic dehydration of carrot. Applied energy in the range of 0.04 to 2.25 kJ/kg, increased cell disintegration index in the range of 0.09 to 0.84 with < 1 °C rise in the product temperature. The effective diffusion coefficients of water and solute, determined using a Fickian diffusion model, increased exponentially with electric field strength according to D = A exp(-B/E). The rise in effective diffusion coefficient may be attributed to an increase in cell wall permeability, facilitating transport of water and solute. Such increase was evidenced by cell disintegration index and softening of product.

Key Words: electric field, pulse treatment, osmotic dehydration, mass transfer, carrot

INTRODUCTION

Osmotic dehydration partially removes water from fruits or vegetables immersed in a hypertonic solution. A driving force for water diffusion is the higher osmotic pressure (or chemical potential) of the osmotic solution. Water loss is accompanied by simultaneous diffusion of solute into the food. Since the membrane involved in the osmotic transport is not selective, other solutes in the solids are also leached into the osmotic solution (Dixon and Jen, 1977; Lerici et al., 1985; Giangiacomo et al., 1987). Mass transfer rate during osmotic dehydration depends upon many factors, such as temperature and concentration of osmotic solution, the size and geometry of the solid, solution to solid mass ratio and agitation of the solution. Much has been published on the influence of such variables on mass transfer rates during osmotic dehydration (Roult-Wack et al., 1992; Torreggiani, 1993; Fito, 1994; Roult-Wack, 1994; Rastogi and Raghavarao, 1994; 1995; 1996; Rastogi et al., 1997). Osmotic dehydration is relatively slow. Therefore, acceleration of mass transfer would be advantageous. Application of vacuum during osmotic dehydration (Fito, 1994; Rastogi and Raghavarao, 1996) and ultra high hydrostatic pressures (Rastogi and Niranjan, 1998) could increase mass transfer rates during osmotic dehydration. High intensity electrical field pulse (HELP) treatment has been reported to increase the permeability of plant cells (Knorr et al., 1994; Geulen et al., 1997; Knorr and Angersbach, 1998). Angersbach and Knorr (1997) showed an increase in permeability of potato tissue by HELP treatment, which resulted in improved mass transfer during fluidized bed drying. Our objective was to study potential acceleration of mass transfer rates during osmotic dehydration, by pretreating the samples with high intensity electric field pulses. The effective diffusion coefficients of water and osmotic solute in HELP treated carrot samples were experimentally determined.

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MATERIALS & METHODS

Materials

Carrots were procured from a local supermarket, cut into discs 2 cm dia × 1 cm. The carrots had an average moisture content of 78 % (wet weight basis), determined by vacuum drying at 70 °C. Sucrose was used as the osmotic agent.

HELP pretreatment

The carrot pieces were subjected to HELP treatment (Table 1). The average electrical conductivities of control and HELP-treated carrot samples were 0.35 and 4.25 mS/cm, respectively. A high voltage generator (Pure Pulse Technologies Inc., San Diego, Calif., U.S.A.) produced a high voltage charge, which supercharged the capacitor. The capacitor was then discharged at 1Hz through the food material in tap water (conductivity 0.8 mS/cm) placed between parallel electrodes. The electrodes were 140 cm^2 each, spaced 3 cm apart. Pulses for the HELP treatment had exponential decay. The pulses were monitored on line with an oscilloscope, and voltage and pulse duration were recorded during treatment. The temperature increase due to HELP treatment at 18 °C was < 1 °C for all experiments.

The specific energy input over the pulse duration for exponential decayed pulse was calculated as follows and reported (Table 1):

$$Q = n(E^2_{max}Kt/10\ p) \qquad [J/kg] \qquad (1)$$

where E_{max} is the peak electric field strength (V/m), K is the electrical conductivity (S/m), p is the density of the product (kg/m^3), t is the pulse duration (s), and n is the number of pulses.

Osmotic dehydration

HELP-treated as well as control samples were subjected to osmotic dehydration after adhering water was blotted with tissue paper. The carrot pieces were pre-weighed and suspended in the vessel containing 50 °B sucrose solution at 40 °C. The carrot-to-sucrose solution ratio was 1:25. Samples were withdrawn at 1 h intervals, rinsed with tap water, and wiped gently with tissue paper. The samples were then weighed and dried in a vacuum oven at 70 °C for 18 h. All experiments were done in triplicate.

Determination of effective diffusion coefficients of water and solute

Fick's second law for diffusion from a finite cylinder of dia 2 r and height 2 l was solved by superposition of solution for an infinite cylinder and a semi infinite slab (Crank, 1975):

$$M_r = (m_t - m_\infty)/(m_o - m_\infty) = \sum_{n=1}^{\infty} C_{pn}C_{cn}\exp\left[-D_{ew}t(q_{pn}^2/l^2 + q_{cn}^2/r^2)\right] = \sum_{n=1}^{\infty} C_{pn}C_{cn}\exp\left[-D_{ew}t(q_{cn}^2/A^2)\right] \qquad (2)$$

and

$$S_r = (s_t - s_\infty)/(s_o - s_\infty) = \sum_{n=1}^{\infty} C_{pn}C_{cn} \exp\left[-D_{es}t(q_{pn}^2/l^2 + q_{cn}^2/r^2)\right] = \sum_{n=1}^{\infty} C_{pn}C_{cn} \exp\left[-D_{es}(tq_{cn}^2/A^2)\right] \qquad (3)$$

where M_r and S_r are the moisture and solute ratio; m and s represent the moisture and solid content; the subscripts o, ∞, and t represent the relevant concentrations at t = 0, t = t, and t = ∞, respectively; D_{ew} and D_{es} are the effective diffusion coefficients of water and solute, respectively. The effective diffusion coefficients are independent of water and solute concentrations. C_{pn} is equal to $2\alpha(1 + \alpha)/(1 + \alpha + \alpha^2 q_{pn}^2)$ where, q_{pn} s are the non-zero positive roots of the equation $\tan q_{pn} = -\alpha q_{pn}$. Here α is the ratio of volume of solution to that of each piece. $C_{cn} = 4\alpha(1 + \alpha)/(4 + 4\alpha + \alpha^2 q_{cn}^2)$ where, q_{cn} s are the non-zero positive roots of the equation $\alpha q_{cn} J_o(q_{cn}) + 2\ J_1(q_{cn}) = 0$. The $J_o(q_{cn})$ and $J_1(q_{cn})$ are the roots of Bessel function of zero and first order, respectively. Where A is defined as: $1/A^2 = 1/r^2\left[1 + (r/l)^2(q_{pn}/q_{cn})^2\right]$. For an infinite cylinder $l \gg r$ and A = r.

At Fourier numbers $(D_e t/A^2) > 0.1$, Eq (2) and (3) reduce to the first term (McCabe et al.. 1993):

$$-1n(M_r/C_{p1}C_{c1}) = \left[D_{ew}t(q_{pl}^2/l^2 + q_{cl}^2/r^2)\right] \qquad (4)$$

and

$$-1n(S_r/C_{p1}C_{c1}) = \left[D_{es}t(q_{pl}^2/l^2 + q_{cl}^2/r^2)\right] \qquad (5)$$

Values of D_{ew} and D_{es} can be obtained from the slopes of a plot $-\ln(M_r/C_{p1}C_{c1})$ and $-\ln(S_r/ C_{p1}C_{c1})$, respectively, against t, as per Eq (4) and (5).

The rate of change of moisture as well as solids content (from Fig. 2a and 2b) were plotted against average solids and moisture content, respectively, (plot not shown) and the equilibrium moisture (m_∞) and solids contents (s_∞) were inferred from slopes of such plots and reported (Table 2).

Determination of texture of the HELP-treated samples

Texture was measured using a Texture Analyzer (Model TA-XT2, Stable Micro System, Surrey, United Kingdom) with a 25-kg load cell. The maximum compressive strength required to rupture the sample (disc 2 cm dia × 1 cm) up to 3 mm depth on a nonlubricated flat platform using a cylindrical probe (dia 11 mm) was recorded by the texture analyzer and used as a measure of hardness. The cross-head speed was 1 mm/s.

Determination of cell disintegration index (Z_p)

The conductivity–frequency spectra (Fig.1) of HELP-treated and control samples of carrots were determined (Angersbach et al., 1997; Knorr and Angersbach, 1998). The cell integration index (Z_p) was defined as:

$$Z_p = 1 - b\left[(K_h' - K_l')/(K_h - K_l)\right]; \quad 0 \le Zp \le 1 \qquad (6)$$

where $b = K_h/K_h'$; K_l and K_l' are the electrical conductivity of control and treated samples at low frequency field (1 to 5 kHz), and K_h and K_h' are the electrical conductivities of control and treated samples in a high frequency field (3 to 50 MHz). The cell disintegration index characterizes the proportion of cells with highly permeable cell walls. Z_p is between 0 and 1, corresponding to 100% intact cells and total cell disintegration, respectively. The conductivity for control and treated samples was determined with impedance measurement equipment (Electronic Manufacture Company, Mahlsdorf, Germany) between parallel disc electrodes (9.7 mm diameter) spaced 10 mm apart. The phase voltages were each of equal amplitude (typically between 1 to 5 V peak to peak), and the frequency changed in the range from 3 kHz to 50 MHz.

Statistical determinations

Statistical analyses were carried out using SAS (SAS Institute Inc., 1985) software package. Analyses of variance was performed by ANOVA procedures. Significant differences between means were determined by Duncan's multiple range tests. Significance of differences was defined at $P < 0.05$.

Table 1—Treatment schedule for HELP pretreatment conditions

Treatment no.	Pulse no.	Electrical field strength (kV/cm)	Pulse duration (μs)	Total specific energy input (kJ/kg)	Cell disintegration index, Z_p[a]
1	5	0.22	378	0.04	0.09
2	5	0.64	322	0.28	0.38
3	5	1.09	336	0.86	0.70
4	5	1.60	405	2.25	0.84

[a]Average of 5 determinations

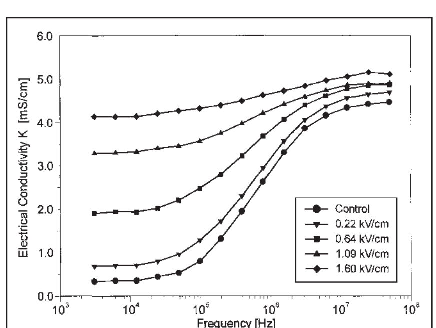

Fig. 1—Frequency dependent electrical conductivity spectra of control and HELP-treated carrot samples.

RESULTS & DISCUSSION

Effect of HELP treatment on cell disintegration

Moisture (Fig. 2a) and solid contents (Fig. 2b) of control and HELP-treated samples were compared. Moisture and solute diffusion increased as applied electrical field strength increased. As expected, sol-

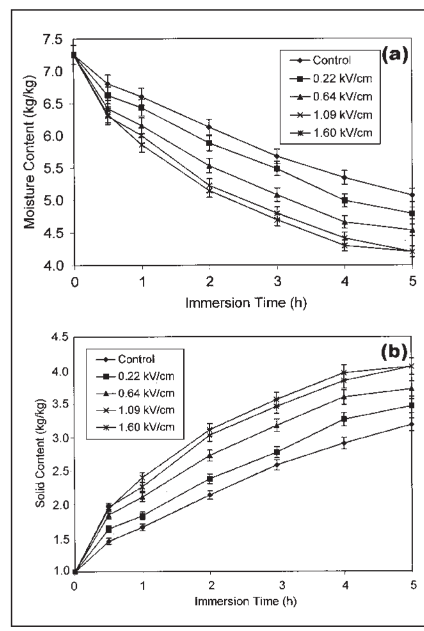

Fig. 2—Variation of (a) moisture content and (b) solid content with time during osmotic dehydration at 40 °C.

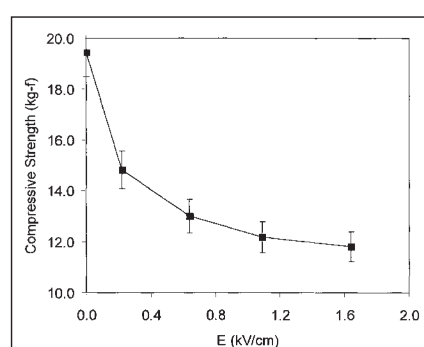

Fig. 3—Variation of compressive strength required to rupture the carrot sample as a function of field strength.

Table 2—Water and solute effective diffusion coefficients (D_{ew}, D_{es}) and equilibrium moisture and solid content (m_∞, s_∞) during osmotic dehydration at different electric field strengths

Conditions	$D_{ew} \times 10^9$ (m^2/s)	$D_{es} \times 10^9$ (m^2/s)	m_∞(kg/kg)	s_∞(kg/kg)
Control	0.98	1.05	4.60	3.50
0.22 kV/cm	1.13	1.09	4.50	3.60
0.64 kV/cm	1.39	1.31	4.40	3.95
1.09 kV/cm	1.51	1.36	4.20	4.20
1.60 kV/cm	1.55	1.44	4.10	4.25

ute infusion increased with increasing applied electric field strength at all times.

The compressive strength (Fig. 3) showed that softening of tissue resulted from cell damage induced by the HELP treatment and the loss of turgor pressure reduced compressive strength. Above 1.09 kV/cm, further softening was very limited with increasing field strength. The cell disintegration index (Fig. 4) increased rapidly with the increase in total energy up to 0.857 kJ/kg and beyond that value it did not lead to much further increase in cell membrane disintegration (Table 1). HELP application affected the cell wall structures leaving the cells more permeable for moisture and solute transfer. The hardness (compressive strength) of the carrot tissue correlated with the cell disintegration index ($R^2 = 0.952$). As cell disintegration index increased, the compressive strength was reduced indicating tissue softening (Fig. 5).

Effect of HELP treatment on effective diffusion coefficients

The effective diffusion coefficients of water (D_{ew}) as well as of the solute (D_{es}) (Table 2) showed an increasing trend with an increase in electrical field strength. Increase in effective diffusion coefficients was not very prominent after 1.09 kV/cm electrical field strength was applied. HELP treatment may have caused increased solute and water diffusion coefficients, giving shorter osmotic dehydration times.

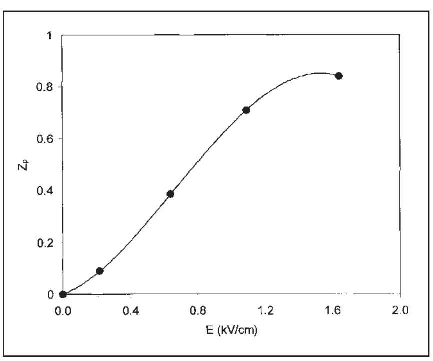

Fig 4—Variation of cell disintegration index (Z_p) of carrot sample with electrical field strength applied.

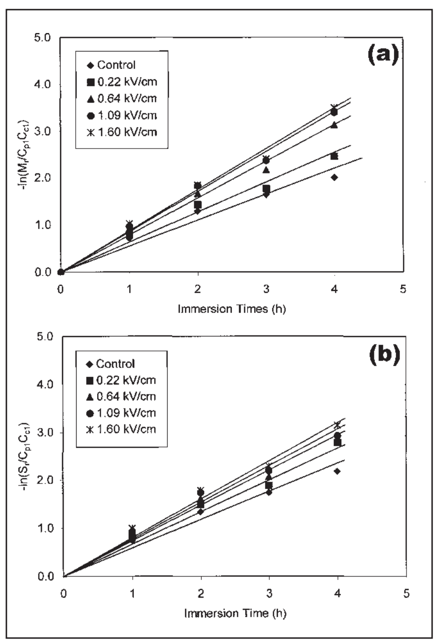

Fig 6—Plot of (a) $-\ln(M_r/C_{p1}C_{c1})$ and (b) $-\ln(S_r/C_{p1}C_{c1})$ vs time showing the agreement between the experimental data and the assumed model.

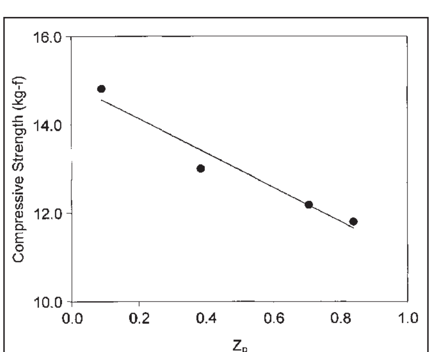

Fig. 5—Correlation between compressive strength required to rupture the carrot sample and disintegration index (Z_p).

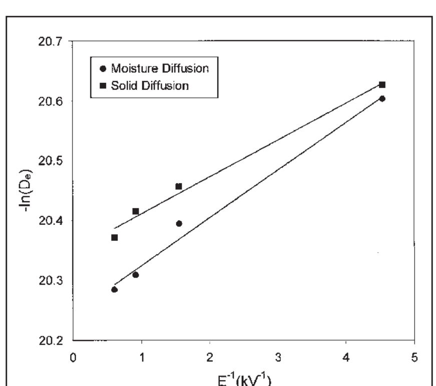

Fig. 7—Plot of $-\ln(D_e)$ with E^{-1}, representing the exponential increase of diffusion coefficients with electrical field strength.

Plots of $-\ln(M_r/C_{p1}C_{c1})$ and $-\ln(S_r/C_{p1}C_{c1})$ vs t (Figs. 6a and 6b) showed the fit of the assumed model (Eqn. 4 and 5) to experimental data. The curves indicated that the increase in diffusion coefficients was an exponential function of the electrical field strength (Fig. 7). This supported the hypothesis that HELP treatment, which increased the cell disintegration index (Z_p), increased cell permeability facilitating diffusion of water and solute. Under our experimental conditions, cell disintegration index did not exceed 0.84 (Knorr and Angersbach, 1998). The effective diffusion coefficient leveled after 1.09 kV/cm. To explain the exponential nature of effective diffusion coefficients with the electrical field strength, the following expressions were fitted to the data:

$$D_{ew} = A_w \exp(-B_w/E) \quad (R^2 = 0.989) \qquad (7)$$

$$D_{es} = A_s \exp(-B_s/E) \quad (R^2 = 0.995) \qquad (8)$$

The values of A_w, A_s B_w, and, B_s were 1.61×10^{-9} m^2/s, 1.45×10^{-9} m^2/s, 0.80 kV/cm, and 0.06 kV/cm, respectively.

CONCLUSION

HELP RESULTED IN INCREASED PERMEability index (Z_p) of carrots up to 0.84, which resulted in increased mass transfer rates during osmotic dehydration. The effective diffusion coefficients of water as well as sucrose increased after the HELP treatment. The diffusion coefficients increased exponentially with the electric field strength applied. Cell disintegration index increased, and compressive strength of samples was reduced by the treatment. Moisture and solid contents could be predicted accurately at any time by the diffusion model.

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