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ORIGINAL ARTICLE

Osmotic dehydration of some agro-food tissue pre-treated by pulsed electric field: Impact of impeller's Reynolds number on mass transfer and color

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Abstract Tissues of apple, carrot and banana were pre-treated by pulsed electric field (PEF) and subsequently osmotically dehydrated in an agitated flask at ambient temperature using a 65% sucrose solution as osmotic medium. The effect of stirring intensity was investigated through water loss (WL) and solid gain (SG). Changes in product color were also considered to analyze the impact of the treatment. The impeller's Reynolds number was used to quantify the agitation. The Reynolds number remained inferior to 300 thus displaying laminar flow regime. Water loss (WL) and solid gain (SG) increase with the increase of Reynolds number. Mass transfer in osmotic dehydration of all three test particles has been studied on the basis of a two-exponential kinetic model. Then, mass transfer coefficients were related to the agitation intensity. This paper shows that the proposed empirical model is able to describe mass transfer phenomena in osmotic dehydration of these tissues. It is also shown that a higher agitation intensity improves both the kinetics of water loss and solid gain.

1. Introduction

Recently, the development of intermediate moisture foods for human consumption produced by osmotic dehydration has received much attention due the consumer demand of minimally processed products. The use of osmotic dehydration in the food industry has several advantages such as higher nutritional contents than any other drying methods (Raoult-Wack, 1994). Osmotic dehydration minimizes the thermal damage on color

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and flavor, prevents enzymatic browning, limiting the need to use sulfur dioxide and increases nutrient retention during subsequent air drying (Ponting, 1973; Islam and Flink, 1982; Sapers and Ziokowski, 1987; Khin et al., 2005). As a result, by choosing the appropriate conditions, the final product quality can be controlled (Krokida et al., 2000). The color of food plays an important role in appearance, processing, and acceptability of food materials (Krokida et al., 2001). The color of any product may be represented in terms of tristimulus *L*-, *a*-, and *b*-values, or combination thereof, depending upon the nature of pigment present in the food material (Rocha et al., 1993).

Osmotic dehydration (OD) is often applied as a pre-treatment process. The complex cell wall structure of the food acts as a semi-permeable membrane, which is not completely selective. The consequence is counter-current mass transfer flows: diffusion of water from food to solution and diffusion of solute from solution to food (Kowalska and Lenart, 2001; Panagiotou et al., 1998). The mechanisms of water migration and solid transport are complex in nature and are generally indirectly deduced during studies. For instance, to describe mass transfer, Fick's approximation is traditionally used. Some simplifications are normally assumed namely the use of effective diffusion coefficient which takes into account all transport mechanisms contributing to diffusion (Moreira and Sereno, 2003). Mavroudis et al. (1998) indicate free convection as a possible mechanism concerning solute transport during the first stage in OD of apple tissue, while diffusion dominates at later stages.

OD is usually conducted with agitation of the liquid solution in order to reduce the external resistance and increase the overall mass transfer rate (Moreira and Sereno, 2003). Ponting et al. (1966) and Bongirwar and Sreenivasan (1977) have studied the effect of agitation. They showed that agitated samples exhibited greater weight loss than non-agitated ones. Raoult-Wack (1994) and Garrotte et al. (1992) have studied the effect of agitation on both water loss and solid gain. Mavroudis et al. (1998) attempted to quantify the agitation in engineering terms, that is, in terms of Reynolds number. The mass transfer rate was found to be a function of many variables such as the pre-treatment, temperature, concentration and composition of osmotic solution, the immersion time, the nature and geometry of food and the solution to food ratio (Lerica et al., 1985; McMinn and Magee, 1996; Forni et al., 1997). It was also stated that a Pulsed Electric Field (PEF) pre-treatment may be effective to enhance water and solute transfer operations (Jemai and Vorobiev, 2003; Khezami et al., 2010) and in particular to osmotically remove water from fruits (Rastogi et al., 1999; Ade-Omowaye et al., 2001; Amami et al., 2005). More recently, Grimi et al. (2011) presented an extensive work on the impact of PEF on apple juice expression by studying several PEF + pressing test scenarios.

This study aims at evaluating the applicability of PEF for a subsequent osmotic dehydration of porous fruits such as apple and banana disks and vegetables such as carrot disk. In addition, it is desired to determine the effect of agitation on mass transfer phenomena and color characteristics in the osmotic dehydration. The OD kinetics were studied on the basis of a two-exponential kinetic model developed earlier by Amami et al. (2005) for a better consideration of the initial mass transfer. Measurement data were also analyzed on the basis of the solution of Fick's law for unsteady state mass transfer in infinite slab. Coefficients of transfer of water and solid were thus predicted. Mass transfer coefficient was related to the Reynolds number and the coefficient of diffusion. Experimental method is based on the evaluation of solution concentration, in addition to the weight loss and final moisture of a single sample.

1.1. Theoretical aspects

Eqs. (1) and (2) show a two-exponential kinetic model, proposed earlier for OD combined with PEF (Amami et al., 2005) and used here to describe the mass transfer. This model involves two simultaneous processes with different kinetic coefficients: (a) convection, with fast solute transfer from the humidified solid surface and from outer broken cells to the solvent; (b) diffusion, with a slower solute transfer from the inside of the solid.

$$\frac{WL_\infty - \overline{WL_t}}{WL_\infty} = C_{ce}e^{-K_{ce}t} + C_{de}e^{-K_{de}t} \quad (1)$$

$$\frac{SG_\infty - \overline{SG_t}}{SG_\infty} = C_{cs}e^{-K_{cs}t} + C_{ds}e^{-K_{ds}t} \quad (2)$$

where $\overline{WL}$ and $\overline{SG}$ (%) represent the standard average of triplicate values of water loss (WL) and solute gain (SG), respectively; The subscripts ∞ and t in Eqs. (1) and (2) represent $\overline{WL}$ and $\overline{SG}$ values at equilibrium and at actual time, respectively. The equilibrium water loss (WL_∞) and equilibrium solid gain (SG_∞) were determined from the plots $\frac{d(\overline{WL})}{dt}$ against $\overline{WL}$ and $\frac{d(\overline{SG})}{dt}$ against $\overline{SG}$. C_{ce} and C_{cs} are respectively the final percentage of water loss and solid gain in the food due to the convection stage alone; C_{de} and C_{ds} are the final percentage of water loss and solid gain in the food due to the diffusion stage alone; K_{ce} and K_{cs} (s^{-1}) are respectively the kinetic coefficients of water and solute transfer during the convection stage of OD; K_{de} and K_{ds} (s^{-1}) are respectively the kinetic coefficients of water and solute transfer during the diffusion stage of OD. At the equilibrium state of OD, the total equilibrium water loss equals the sum of infinite water losses during the convection and diffusion stages:

$$WL_\infty = WL_{c\infty} + WL_{d\infty} \quad (3)$$

$$\text{where} \quad WL_{c\infty} = WL_\infty \cdot C_{ce} \quad \text{and} \quad WL_{d\infty} = WL_\infty \cdot C_{de} \quad (4)$$

Accordingly, the total equilibrium solid gain equals the sum of infinite solid gain during the convection and diffusion stages:

$$SG_\infty = SG_{c\infty} + SG_{d\infty}, \quad (5)$$

$$\text{where} \quad SG_{c\infty} = SG_\infty \cdot C_{ce} \quad \text{and} \quad SG_{d\infty} = SG_\infty \cdot C_{de} \quad (6)$$

Subsequently, the effective diffusion coefficients of water D_{ew} and solid D_{es} were calculated over a range of Re number (0–252) and for 65°Brix concentration of osmotic solution. These coefficients can be defined by the Fick's diffusion equation for an infinite slab of thickness (2*l*), reduced to the first term (Eqs. (7) and (8) ci- dessous). Amami et al. (2005) demonstrated that these coefficients correspond well to the coefficients K_{de} and K_{ds} of the diffusion stage of the two-exponential kinetic model (Eqs. (1) and (2)).

$$\frac{WL_\infty - WL_t}{WL_\infty} = C_1 \cdot e^{-\lambda_{1w} \cdot t} \quad (7)$$

with $\lambda_{lw} = q_1 \cdot D_{ew}/l^2$ (8)

with $$\frac{SG_\infty - SG_t}{SG_\infty} = C_1 \cdot e^{-\lambda_{1s} \cdot t} \quad (9)$$

$$\lambda_{1s} = q_1^2 \cdot D_{es}/l^2 \quad (10)$$

Then D_{ew} and D_{es} are deducted only by determination of the coefficients K_{de} and K_{ds}, where t is the immersion time (s) and l is the half thickness of the infinite slab (m); C_1 is equal to $2\alpha(1+\alpha)/(1+\alpha+\alpha^2 q_1^2)$, where q_1 is the first non-zero positive root of the equation $\tan(q_1) = -\alpha q_1$. Here, α is the ratio of mass of solution to sample (*i.e.* = 3).

Two phenomena occur at the material surface in OD. A boundary layer is formed with a thickness that depends on the agitation of the osmotic solution. At the surface of the material and perpendicular to this surface, there is a large flux of water coming out of the fruit under the osmotic gradient, which is disturbing the boundary layer (Fernandez et al., 2004). The boundary layer without bulk flow is obtained from dimensionless correlations. According to Geankoplis (1983), for a laminar flow past a submerged flat surface, the Sherwood number is given as:

$$Sh = \frac{k_c d_p}{D} = 0.664 Re^{1/2} Sc^{1/3} \quad (11)$$

with $$k_c = \frac{D}{d_p} 0.664 Re^{1/2} Sc^{1/3} \quad (12)$$

and

$$Re = \frac{Lwr\rho}{\mu} \quad \text{and} \quad Sc = \frac{\mu}{\rho D} \quad (13)$$

where L is the length of the piece to dehydrate (assumed to diameter of particle (d_p = 2.8 cm)), the product ($w \times r$) is the superficial velocity equal to $n\pi r/30$, with n is number of rotation per minute, r is the rayon of impeller, and ρ is the density of the fluid. D corresponds to the effective diffusion coefficients of water D_{ew} and solid D_{es}.

In the present study, r was 5×10^{-3}m, and ρ measured by density-meter (M50 ISO 649 and ISO 387) was 1306 kg/m^3. D_{ew} and D_{es} were deducted only by determination of the coefficients K_{de} and K_{ds} as mentioned above and μ is the fluid viscosity, 0.12235 Pa s was measured by a rotation coaxial viscosimeter VT 550 (HAAKE), for the 65% sucrose solution at 20 °C.

2. Materials and methods

Fresh products (apple, banana and carrots) were purchased from a local market. Items having approximately homogenous shapes (same size and ripeness) were chosen and refrigerated at 4 °C at maximum for 7 days until use. The samples were removed from refrigeration and left to equilibrate at the room temperature before experimentations. The apples were then sliced into disks of 2.8 cm diameter and 0.85 cm thickness. In the case of carrots and bananas, medium part was then cut into disks of 2.8 cm diameter and 1 cm thickness. Commercial sugar was used as the osmotic concentration agent. The osmotic solution used had a level of sugar content of 65%, expressed in percentage of weight of sugar per total solution weight (w/w). Nowakunda et al. (2004) reported that an osmotic solution of 65 °Brix seems to be the optimal concentration to obtain a higher water loss. Besides, the duration of osmotic pre-treatment will depend on the maximum sugar uptake considered acceptable from the sensorial point of view.

2.1. Pulsed electric field pre-treatment

Apple, banana and carrot disks were blotted using a paper tissue and placed at the bottom of a cylindrical device (3 cm diameter) between two electrodes. The electrodes were connected to a PEF generator (1500 V–20 A, Electronic Department of UTC, France) as shown in Fig. 1a. The disks were placed on a fixed electrode and covered by a mobile electrode, of 2.9 cm each in diameter. The mobile electrode was adjusted on the top of the disk surface in order to ensure a good electrical food-electrode contact. The experimental setup consisted in applying for apple disk a field strength intensity of 0.90 kV/cm for a constant time t_{PEF} = 0.75 s (750 rectangular monopolar pulses, each of 100 µs duration), for banana disk and carrot disk 0.30 kV/cm and 0.60 kV/cm respectively for t_{PEF} = 0.05 s (500 rectangular monopolar pulses, each of 100 µs duration).

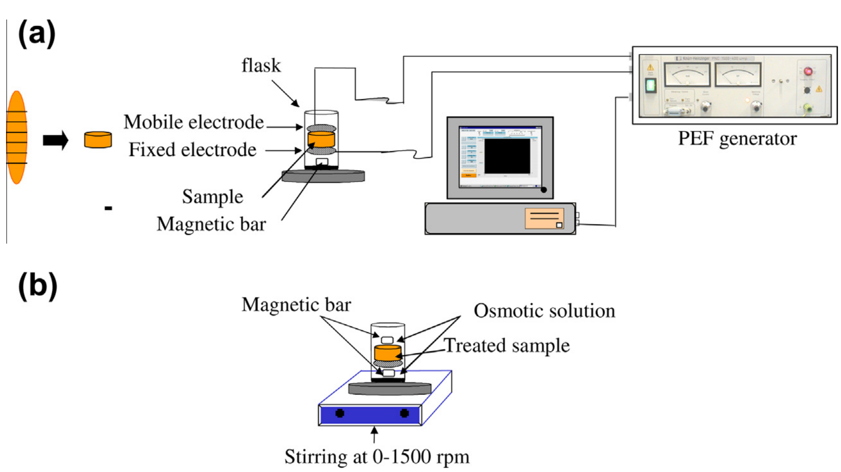

Figure 1 Experimental apparatus: (a) PEF treatment and (b) continuous osmotic dehydration.

Measurements of electrical current amplitudes were ensured by an HPVEE program (HP-VEE, V3.12, Hewlett–Packard Co., USA). The average energy input was in order of 15, 10 and 19 kJ/kg for apple, banana and carrot disks, respectively. It is notable that the temperature increase due to PEF application in apple, banana and carrot disks did not exceed 7 °C in all the experiments.

2.2. Osmotic dehydration

To study the effect of agitation speed, the osmotic process experiments were repeated at fixed sugar concentration (65% w/w), fixed temperature (25 °C), for five different speeds of agitation (0, 250, 500, 1000, 1500 rpm). Apple, carrot and banana disks were treated by PEF and placed in OD flask with the 65% w/w sucrose solution in order to obtain a 3:1 solution to sample ratio (w/w). It has been reported in a review by Tortoe (2010) that a higher solution-to-solid is commonly used to favor solute transfer, but smaller ratios (4:1 or 3:1) were also used for small scale studies. In our case, the experimental setup geometry constraint allowed to use a 3:1 ratio. In the experimental set (Fig. 1(b)), the osmotic medium was agitated continuously with a magnetic stirrer at 0, 250, 500, 1000 and 1500 rpm corresponding to agitation levels of 0, 42, 84, 168 and 252 impeller *Re* number. The OD flask was covered with a plastic plate to reduce moisture loss from syrup during experiments. The °Brix of the solution and the weight of the sample were evaluated after 5, 30, 60, 90, 120 and 240 min of immersion. The measurements of °Brix were provided by a digital refractometer (LEI 25 the leica AR200, AVANTEC, USA). The weights were measured using an electronic balance (Sartorius AG, Goettingen, Germany, $\Delta m = \pm 0.01$ g). The sample was withdrawn from the solution and quickly rinsed with fresh running water to withdraw excess solution. It was subsequently slightly wiped with an absorbent paper and weighed. The °Brix of osmotic solution was measured simultaneously. An additional amount of osmotic solution with the same °Brix was prepared and added to the flask to compensate the loss of solution adhering to the sample surface. The fruit or vegetable disk was then put back into the osmotic solution to continue the OD process. After 4 h of immersion, the sample was washed and blotted with absorbing paper. The sample was used to perform color measurement and the moisture content of the sample was determined by drying in an oven at 105 °C for 24 h. The water loss and solid gain were calculated according to the method proposed by Amami et al. (2005). In this method, the water loss (*WL*) and solid gain (*SG*) are

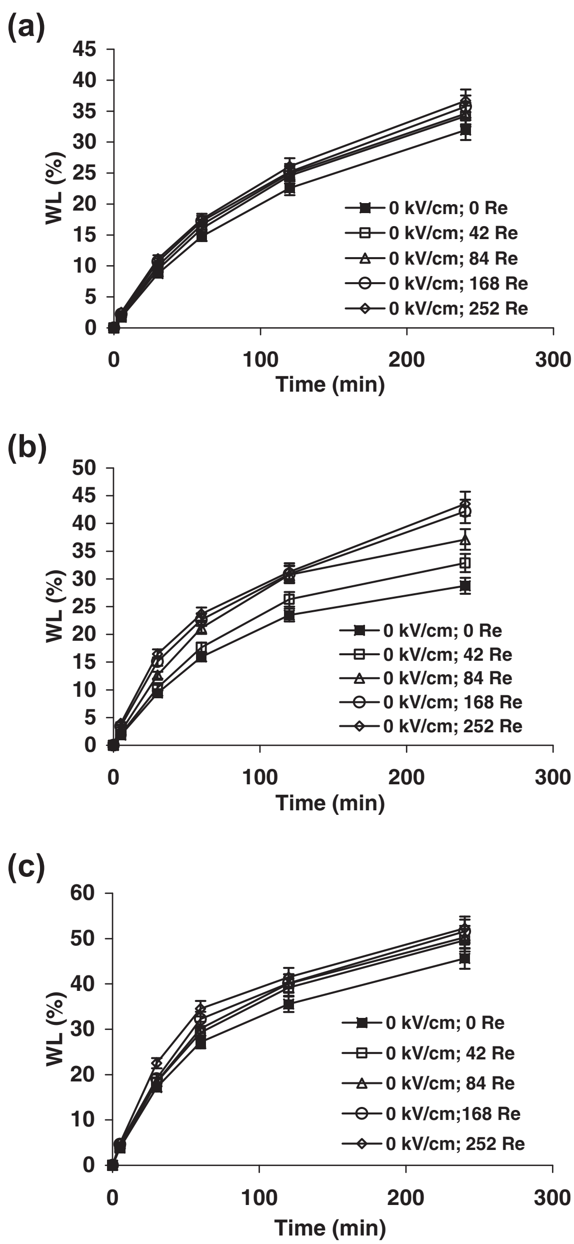

Figure 2 Effect of *Re* number on water loss with osmotic dehydration time: (a) apple; (b) banana and (c) carrot.

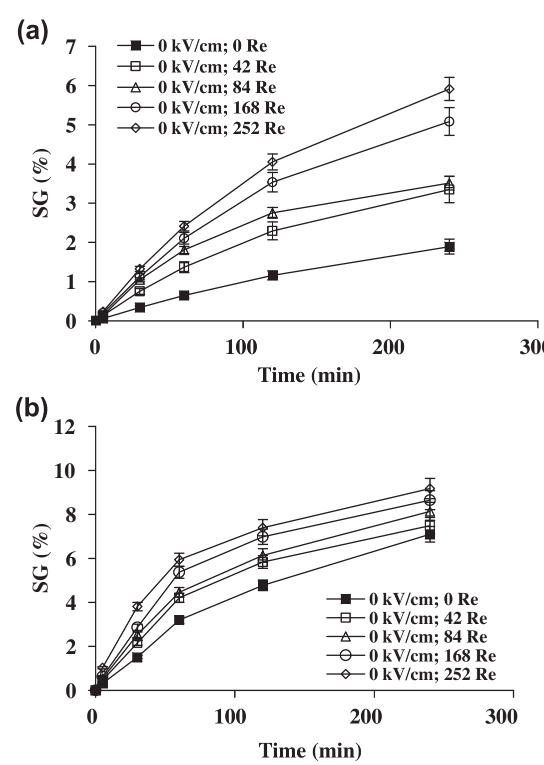

Figure 3 Effect of *Re* number on solid gain with osmotic dehydration time: (a) apple and (b) carrot.

calculated from the weight of osmotic solution. The *WL* and *SG* were expressed in (%) of the initial weight of sample in order to account for initial weight differences between samples. The OD experiments at different conditions were done in triplicate. Mean values were indicated in this document with the corresponding standard deviations.

2.3. Color measurement

For the representation of color in the three-dimensional space, the CIE 1976 $L^* a^* b^*$ system was adopted. Color difference values L^*, a^*, and b^* were calculated as:

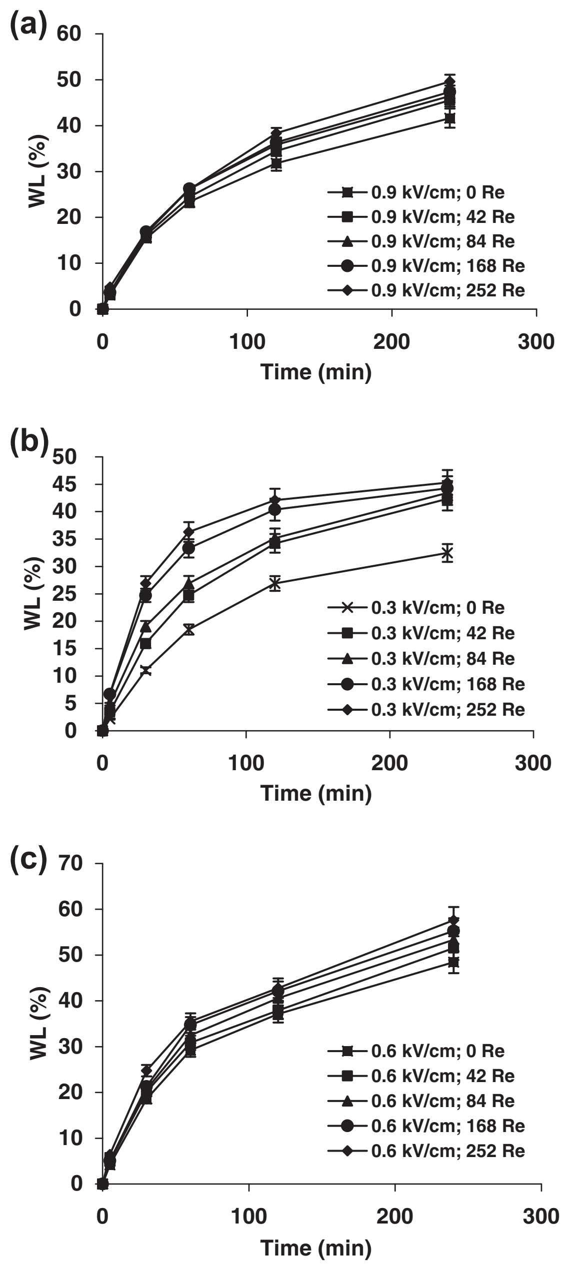

Figure 4 Effect of PEF pre-treatment and *Re* number on water loss with osmotic dehydration time: (a) apple; (b) banana and (c) carrot.

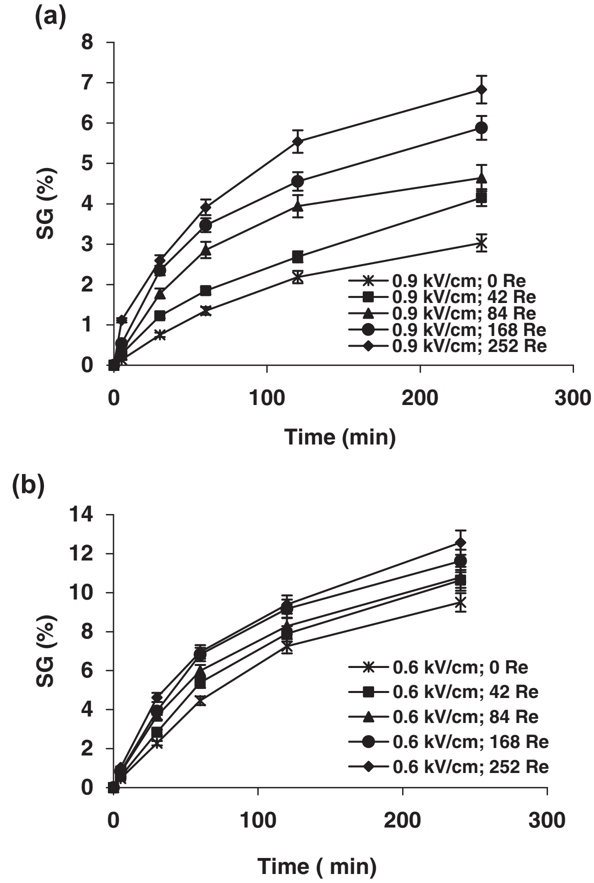

Figure 5 Effect of PEF pre-treatment and *Re* number on solid gain with osmotic dehydration time: (a) apple and (b) carrot.

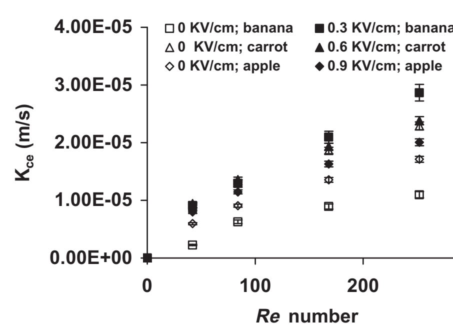

Figure 6 Effect of PEF pre-treatment and *Re* number on mass transfer coefficient (for water loss) with osmotic dehydration time.

$$L^* = L - L_{t0} \quad (14)$$

$$a^* = a - a_{t0} \quad (15)$$

$$b^* = b - b_{t0} \quad (16)$$

where t_0 represents the color taken as reference; *L*-value indicates the lightness ranging from zero (black) to 100 (white) in the international color system; a-value indicates the redness ranging from +60 (red) to −60 (green) in the international color system; b-value indicates the yellowness ranging from +60 (yellow) to −60 (blue) in the international color system. This allows evaluating the total difference of color defined by the equation:

$$E^*_{ab} = \sqrt{a^{*2} + b^{*2} + L^{*2}} \quad (17)$$

The values of lightness (L), redness (a) and yellowness (b) of fresh and osmotically-dehydrated apple, carrot and banana were determined by direct reading with a Minolta Chroma meter, CR321 (Minolta, Japan). The instrument was calibrated each time with a white ceramic plate (calibrated with a standard white (L = 91.65; a = −0.05; b = 2.08). Each samples were scanned at 3 different locations to determine the average L, a, and b values over three measurements. From these values, chroma (C^*) was calculated according to the equation:

$$C^*_{ab} = \sqrt{a^{*2} + b^{*2}} \quad (18)$$

A greater chroma value represents a more pure and intense color (Rodrigues et al., 2003).

3. Results and discussion

The evolution of water loss (WL) is shown in Fig. 2a–c as function of time and Re numbers for apple, banana and carrots, respectively. The agitation has affected the water removal. Both apple and banana samples showed higher WL kinetics at higher agitation levels (Re = 168 and 252). The corresponding values for banana and apple fruits are 43.5% (Fig. 2b) and 36.7% (Fig. 2a), respectively. As shown in Fig. 2c, the carrot WL can reach up to 52% of the initial carrot mass, at the highest Re number. The dehydration is larger for carrot due probably to a higher initial water content than fresh banana and apple. The large difference in water content between the sample and the osmotic solution leads to a high difference in osmotic pressure, which results in a higher water

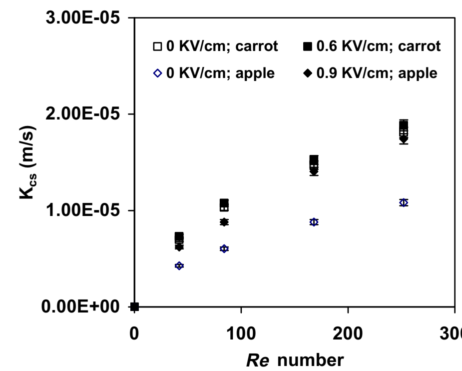

Figure 7 Effect of PEF pre-treatment and Re number on mass transfer coefficient (for solid gain) with osmotic dehydration time.

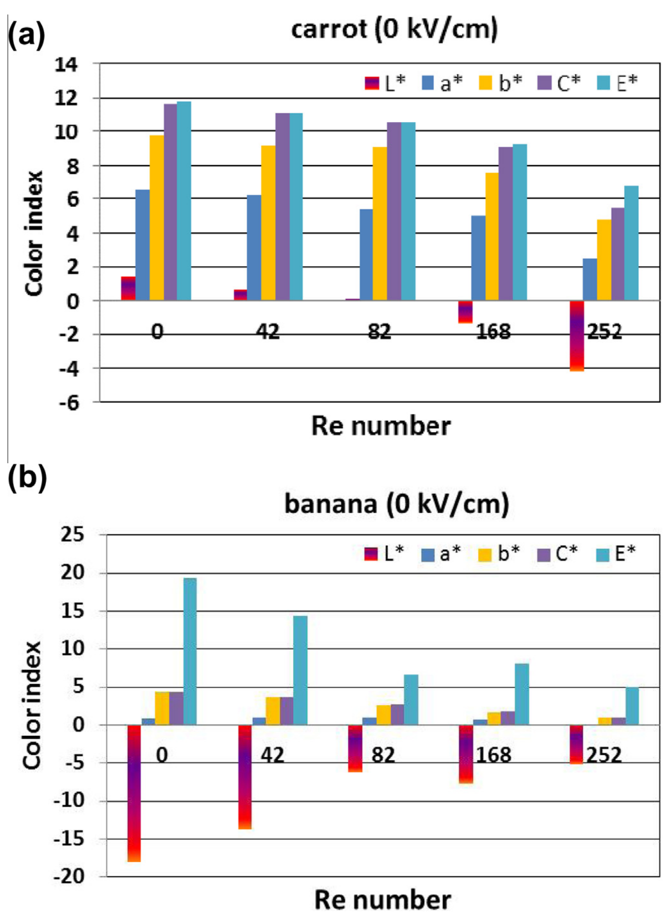

Figure 8 Effect of Re number on color measurement parameters after osmotic dehydration treatment (for 0 kV/cm PEF): (a) carrot; (b) banana. (where L^*, a^*, b^*, C^*, and E^* are relative color differences as described in Section 2.3).

transport from the interior of fruit to the external solution. Similar to water removal, solid gain *SG* was significantly affected by the agitation level, as shown in Fig. 3a and b, where *SG* kinetics are presented for various Reynolds numbers for the apple and carrot. It suggests that the internal and external mass transfer rates control the process. Such results are confirmed by Panagiotou et al. (1999) who have worked at a higher temperature and in turbulent regime. They showed the solid acquisition in the material was a function of speed of agitation.

Osmotic dehydration rates increase with the agitation speed during process due to the reduction of the external resistance against the water removal. It can be confirmed that a higher *Re* number improves the water loss and the solid gain in the sample, in reason of a higher gradient of water activity. For $Re = 252$, the equilibrium may be obtained after approximately 2 h of immersion time. This duration is smaller in a faster agitation speed, as shown in Fig. 2a and b.

The effect of PEF pre-treatment on *WL* and *SG* from osmotically dehydrated apple, banana and carrot is shown in Figs. 4 and 5 for different agitation speeds. Under atmospheric pressure, samples treated by PEF dehydrated in five agitation speeds displayed a higher water loss (4–35%) than untreated samples. These observations of PEF impact on water loss agrees with the literature (Rastogi et al., 1999; Taiwo et al., 2001; Amami et al., 2005). At the end of OD (4 h), PEF treated samples had 15–60% greater solid gain than the untreated samples. This improvement of solid gain with the PEF pre-treatment was also put in evidence by Lazarides et al. (1995) and Taiwo et al. (2001). Indeed, they showed that when membranes lose their functionality under PEF, external solutes diffuse freely to all parts of the tissue, not only to the open intercellular spaces. Through Figs. 4 and 5, it can be observed that water loss and solute gain rates were faster with PEF pre-treatment.

For banana fruit, water loss increased with treatment time. About 45% of the water loss occurred after 240 min for the highest speed of agitation of PEF conditions. An extended treatment in a high concentration of sucrose (65 °Brix) resulted in a very soft product, which is difficult to handle and is unsuitable for further drying. The difference in behavior of *WL* and *SG* with agitation may reflect different mechanisms. The observed mass transport phenomenon can be modeled (empirically or fundamentally) to relate these mechanisms. An empirical model developed by Amami et al. (2005) was used to predict the diffusion coefficient of water and solid during osmotic dehydration of apple, banana and carrot.

By means of the proposed model (Eqs. (1) and (2)), effective water and sucrose diffusivity coefficients (D_{ew} and D_{es}) were identified for the experiments carried out at 65°Brix under different agitation speeds. The osmotic pressure gradient, which is the driving force for osmotic mass transfer, depends on the viscosity of the osmotic solution. Under otherwise similar conditions, an increase in agitation speed results in a higher osmotic pressure gradient, thus a higher mass transfer and thereby higher values of effective diffusion coefficients. Identified D_{ew} ranged from 7.89, 0.59 and 14.50×10^{-10} m^2/s at $Re = 0$ to 10, 5.14 and 15.50×10^{-10} m^2/s at $Re = 252$ for banana, apple and carrot, respectively. And the D_{es} ranged from 3.11 and 9.65×10^{-10} m^2/s at $Re = 0$ to 5.04 and 10.90×10^{-10} m^2/s at $Re = 252$ for apple and carrot, respectively. Previous experiments without PEF were compared to PEF ones. Diffusivity coefficients were higher after PEF. For instance, water and sucrose diffusivity coefficients were $D_{ew} = 1.27$ and 16.1×10^{-10} m^2/s and $D_{es} = 10.3$ and 11.6×10^{-10} m^2/s for apple and carrot disks, respectively, osmosed under $Re = 252$.

Table 1 shows the equilibrium water loss from PEF pretreated apple, carrot and banana at infinite process time. The agitation speed has a positive effect on this parameter for apple and carrot. Table 2 shows for the same experiments the equilibrium solid gain. The agitation speed has a moderate effect on this parameter for apple and carrot. Tables 1 and 2 show that values of kinetic coefficients K_{ce} and K_{cs} are increased for a higher *Re* number, as well as the equilibrium coefficients

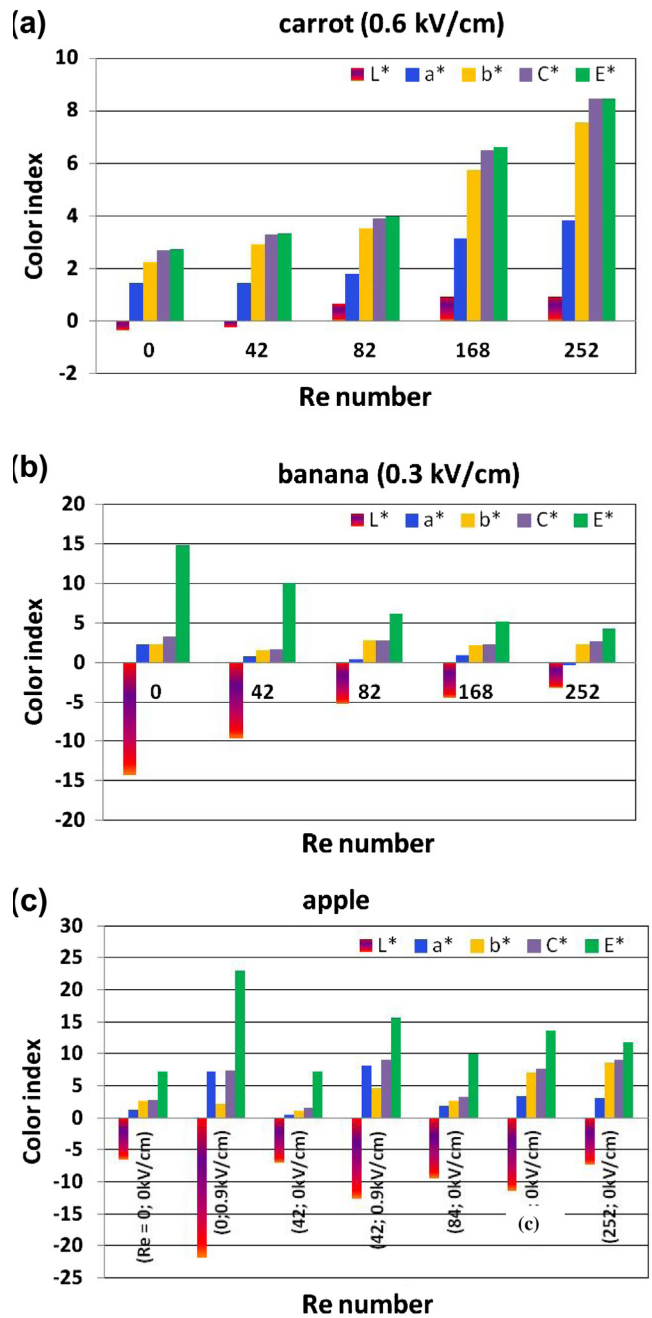

Figure 9 Effect of PEF pre-treatment and *Re* number on color measurement parameters after osmotic dehydration treatment: (a) carrot; (b) banana; (c) apple. (where L^*, a^*, b^*, C^*, and E^* are relative color differences as described in Section 2.3).

Table 1 Effect of the *Re* number on the coefficients of the convection stage of OD kinetics model (Eq. (1)) as well as the equilibrium water loss for the PEF pretreated apple, banana and carrot.

Parameters	Samples	0 *Re*	39 *Re*	78 *Re*	156 *Re*	235 *Re*
WL_∞ (%)	Apple	43.82	49.43	50.04	51.14	53.07
	Banana	36.14	44.94	45.2	45.47	45.76
	Carrot	50.55	53.43	55.84	57.82	58.50
C_{ce}	Apple	0.20	0.23	0.24	0.25	0.26
	Banana	0.09	0.15	0.23	0.43	0.52
	Carrot	0.19	0.23	0.24	0.25	0.26
K_{ce} (10^3 s^{-1})	Apple	2.28	3.38	3.39	3.45	3.79
	Banana	0.22	0.88	0.90	0.96	0.97
	Carrot	4.00	7.67	7.78	7.88	7.89
$1/K_{ce}$ (s)	Apple	438.6	295.8	294.9	289.8	263.8
	Banana	4545.4	1136.3	1111.1	1041.6	1030.9
	Carrot	250.0	130.3	128.5	126.9	126.7

Table 2 Effect of the *Re* number on the coefficients of the convection stage of OD kinetics model (Eq. (2)) as well as the equilibrium water loss for the PEF pretreated apple and carrot.

Parameters	Samples	0 *Re*	42 *Re*	84 *Re*	168 *Re*	252 *Re*
SG_∞ (%)	Apple	3.98	5.26	5.46	6.28	7.34
	Carrot	11.43	11.78	11.98	12.79	13.40
C_{cs}	Apple	0.20	0.24	0.42	0.43	0.46
	Carrot	0.14	0.18	0.19	0.20	0.21
K_{cs} (10^3 s^{-1})	Apple	0.25	0.3	0.45	0.49	0.5
	Carrot	1.07	1.81	1.83	1.84	1.85
$1/K_{cs}$ (s)	Apple	4000.0	3333.3	2222.2	2040.8	2000.0
	Carrot	934.5	552.48	546.4	543.5	540.5

C_{ce} and C_{cs}. It displays first that the kinetics of convective mass transfer were accelerated. It means also that the electropermeabilization of cell membranes and a higher *Re* number increase the quantities of water and solute rapidly transferred by convection.

The values of $1/K_{cs}$ represent the time needed for the solid gain SG_t to reach 63.2% of $SG_{c\infty}$ (Table 2). This time did not change much for all sets of experimental conditions. Meanwhile the time corresponding to water loss ($1/K_{ce}$) varied significantly and remained small for high agitation speeds (Table 1). For example, with banana samples, the duration to reach 63.2% of $WL_{c\infty}$ at $Re = 252$ is only 18.60% of that needed in static conditions.

Figs. 6 and 7 show the effects on apples and carrots of the PEF pre-treatment and the agitation speed on K_{WL} (rate constant for water loss) and K_{SG} (rate constant for solid gain), respectively. Both parameters K_{WL} and K_{SG} increase when PEF was applied and with subsequent agitation during osmotic dehydration.

Results of color measurement on osmotically dehydrated carrot and banana are shown in Fig. 8a and b. Fresh samples were taken as reference. It is observed that as far as the agitation speed progresses, the carrot became darker. It involved lower L^* values at a higher *Re* number. Generally, it is well known as browning increases, *L* values decrease, therefore L^* is negative and (*a*) values increase therefore a^* is positive. The color changes in fruit tissues (darkening) due to enzymatic browning (Mastrocola and Lerici, 1991). Compared to fresh sample, the increase in redness ($a^* > 0$) and yellowness ($b^* > 0$) is clear for osmotic dehydrated carrot. E^* of carrot decreases with the agitation speed.

As shown in Fig. 8b, although the *L* parameter of the osmotically treated banana samples was less than that of fresh tissues ($L^* < 0$), it showed an increase over the whole speed of agitation. This occurred to the solute uptake, which resulted in lower O_2 being transferred to the surface. This resulted in less discoloration of the osmosed samples by enzymatic browning (Kim, 1990). The chroma parameter (b^*) behaved similar to the redness parameter during the OD process. Osmotically banana samples showed the smallest increments of yellowness.

The L^*, a^* and b^* values for carrot, banana and apple obtained after PEF pre-treatment and osmotic dehydration are presented in Fig. 9a–c. PEF increased brightness of carrot samples (as reflected by positive L^* values with a higher *Re* number Fig. 9a) while the color of static sample darkened (as reflected by negative L^* values). This agrees with Moreno et al. (2000) who observed that OD increased the illuminance of pre-treated strawberry compared with the fresh fruit. The carrot after PEF treatment and osmotic dehydration had color characteristics close to those of the fresh natural color.

PEF pre-treated banana had the highest L^* values compared to untreated one (which increased with *Re* number), implying greater product brightness which might be the result of greater pigment leaching.

Apple with PEF treatment had a darker color than those untreated with PEF. It is a direct result of browning effects due to the oxidative reaction. Taiwo et al. (2001) indicating that the activation energies for colorless browning intermediate formation increased as glucose concentration and temperature increased, and the higher the activation energy, the higher the degradation of the brown pigments to the colorless compounds. Ade-Omowaye et al. (2001) reported that a prolonged pulse application induced reactions leading to darker products showing lower L values ($L^* < 0$). However, the relative increase in redness displayed by a value for all osmotically PEF pretreated samples was small compared to the significant increase for untreated samples. The yellowness is higher in the PEF pre-treated samples ($b^* > 0$). Eventually, the color characteristics are improved by the PEF treatment.

4. Conclusion

Osmotic treatment of apple, banana and carrot was studied in the present work in sucrose solution under static and non-static conditions. A model for mass transfer (water removal and solid acquisition) in osmotic treatment is presented with satisfactory agreement (R^2 up to 0.996). In all cases, a PEF treatment gives higher water removal and solid acquisition. An agitation in the osmotic treating solution provides a laminar flow regime which is accompanied by an increase of the kinetics of water loss and solid gain.

The effect of the PEF treatment and the agitation speed on color of apple, carrot and banana was investigated in osmotic dehydration. color characteristics were studied measuring the lightness L, redness a and yellowness b at the process end. The results were compared to those obtained for fresh products. The PEF treatment and the speed of agitation affect the three color parameters. PEF treated materials caused extensive browning in the apple fruit. This was manifested by a significant drop of L parameter and an increase of a and b parameters. Osmotically pre-treated carrot did not brown as much as the untreated samples where the lightness L decreased only slightly while a and b increased slightly.

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