

Leaching of Soluble Solids during Blanching of Vegetables by Ohmic Heating

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(Received 20 April 1995; accepted 2 January 1996)

ABSTRACT

Ohmic heating may provide an effective method for blanching, especially of whole large vegetables where the process may be accomplished in a relatively short time regardless of the shape and the size of the product. Such a process eliminates any need for dicing of these large vegetables as commonly done prior to water blanching. The extent of solute leaching during blanching by both ohmic heating and by hot water follows the same pattern. It is proportional to the surface to volume ratio of the product and to the square root of the process time. Therefore, by eliminating the need for dicing, blanching by ohmic heating may considerably reduce the extent of solute leaching, as compared to a hot water process, by a favorable combination of a low surface to volume ratio and a short blanching time. For example, in the case of whole beets, the extent of soluble pigment loss during blanching by ohmic heating was about one order of magnitude lower than that of 1 cm cubes of the same product during the equivalent process in hot water. Copyright © 1996 Elsevier Science Limited.

NOTATION

A	Total surface area (m^2)
a	Cube dimension (m)
C	Solute concentration (kg m^{-3})
C_{po}	Initial solute concentration (kg m^{-3})
C_{pf}	Equilibrium solute concentration (kg m^{-3})
c_p	Specific heat ($\text{J kg}^{-1} \text{ }^\circ\text{C}^{-1}$)
D	Mass diffusivity ($\text{m}^2 \text{ s}^{-1}$)
d	Diameter (m)
G, S, K	Constants

h	Surface heat transfer coefficient ($\text{W m}^{-2} \text{ }^\circ\text{C}^{-1}$)
k	Thermal conductivity ($\text{W m}^{-1} \text{ }^\circ\text{C}^{-1}$)
k_m	Surface mass transfer coefficient (m s^{-1})
L	Characteristic dimension (m)
M_t	Extent of solute loss (kg)
M_{∞}	Total solute loss at infinite time (kg)
n	Number of layers
r	Volume ratio (product/medium)
SVR	Surface to volume ratio
T	Temperature ($^\circ\text{C}$)
t	Time (s)
V_m	Volume of liquid medium (m^3)
V_p	Volume of product (m^3)
δ	Layer thickness (m)
ρ	Density (kg m^3)
η	Viscosity (cp)

Subscripts

c	Cube
s	Sphere
i	Layer number (counting from surface)

Superscript

t	Time (s)
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INTRODUCTION

Loss of soluble solids during water blanching of vegetables has, in many cases, adverse effects on the quality and the yield of the product. Moreover, these solutes may create an environmental problem by considerably increasing the biological oxygen demand (BOD) of the plant waste water. The solute losses may range from 9 to 40% of the initial content (Gooding *et al.*, 1955, 1960; Gooding & Biol, 1956; Lee, 1958; Bomben *et al.*, 1975; Bomben & Hudson, 1977). Mathematical models have been developed to deal with leaching of different solutes during blanching of various products, such as potatoes (Kozempel *et al.*, 1981; Califano & Calvelo, 1983; Luna *et al.*, 1992), peas (Hough & Alzamora, 1984; Alzamora *et al.*, 1985) and carrots (Kincal & Kaymak, 1987). The subject of solute diffusivity in leaching processes was extensively reviewed by Schwartzberg & Chao (1982).

Paradoxically, the relatively high solute losses are sometimes the direct result of an attempt to minimize other adverse effects of blanching, such as undesired product softening. Therefore in large vegetables, dicing precedes water blanching, thereby considerably increasing the surface area of the product that is exposed to the hot water. The need for size reduction is obviated by ohmic heating (Mizrahi *et al.*, 1975). By passing electric current, heat is generated within the product. This method is capable of heating the product very quickly at a rate that is independent of the product size or shape, thus enabling a considerable shortening of the blanching time of whole large vegetables with no need for size reduction. The goal

of this study is to evaluate the potential benefits of ohmic heating in reducing soluble solids losses during blanching.

MATERIALS AND METHODS

Leaching experiments

Beets were selected as a model for this study. Water blanching was carried out by placing slices or cubes of beet in boiling water. In all these cases the volume of the liquid was at least ten times larger than that of the product. Small samples of the blanching medium were withdrawn about every 30 s and analysed for their content of leached betanine and betalamic acid according to the method of Saguy *et al.* (1978). This method, which is based on curve fitting of the visible spectrum of these pigments, is free of any error that might result from the possible cleavage of betanine into betalamic acid during the blanching process.

The initial concentration of the pigments was determined by blending a sample of known weight in a known volume of water in a Warring blender and filtering the extract. Analyses of the filtrates were carried out using the above mentioned method.

Blanching by ohmic heating was carried out on the whole, diced or sliced vegetable using the procedure outlined by Mizrahi *et al.* (1975). In this method, the product was immersed in an aqueous medium between two electrodes having no direct contact with the product. These electrodes were connected to an AC voltage source (e.g. 380 V), whereby current was passing through the product via that liquid medium. To obtain as uniform heating as possible, the initial specific electrical conductivity of that medium was adjusted, by adding salt solution, to have the same value as that of the product. Boiling temperature in both the medium and the sample was reached in less than 30 s.

Simulation model

In order to develop a relatively simple qualitative tool to analyse leaching losses during blanching, a simulation model was used to generate data. This model was formulated to allow for changing of medium and product volume, initial solute concentration in the product and in the medium, partition factors, plate and medium temperature, external heat and mass transfer coefficients and plate thickness. The model is based on a process of unidirectional heat and mass transfer in an infinite plate that is divided into n layers of equal size. The momentary changes in temperature and in solute concentration was evaluated by calculating heat and mass transfer as well as energy and mass balance in each layer as follows:

$$C_i^{t+\Delta t} = C_i^t + \frac{D' \Delta t}{\delta^2} (C_{i+1}^t + C_{i-1}^t - 2C_i^t) \quad (1)$$

$$T_i^{t+\Delta t} = T_i^t + \frac{k' \Delta t}{\delta^2 \rho c_p} (T_{i+1}^t + T_{i-1}^t - 2T_i^t) \quad (2)$$

where C is the solute concentration (w/v), T is the temperature, δ is the layer thickness, D is the solute diffusivity, ρ , c_p and k are the density, the specific heat and the thermal conductivity of the plate, respectively. The subscript denotes the layer number (i) starting the count from the surface layer. The superscript denotes the time (t).

At the surface, these two equations eqns (1) and (2) are modified to account for the surface heat (h) and mass (k_m) transfer coefficients as follows:

$$C_i^{t+\Delta t} = C_i^t + \frac{D'\Delta t}{\delta^2} (C_2^t - C_1^t) - \frac{k_m\Delta t}{\delta} (C_1^t - C_0^t) \quad (3)$$

$$T_i^{t+\Delta t} = T_i^t + \frac{h\Delta t}{\delta\rho c_p} (T_0^t + T_1^t) - \frac{k'\Delta t}{\delta^2\rho c_p} (T_1^t - T_2^t) \quad (4)$$

The extent of solute loss (M_t) was calculated by subtracting the momentary solutes content in the plate from the initial one as follows:

$$M_t = A(C_{po}L - \frac{\delta}{2} \sum_{i=1}^n C_i^t) \quad (5)$$

where A is the total surface area, C_{po} is the initial solutes concentration and L is the characteristic dimension (half thickness) of the plate.

The thermal conductivity, which is changing as a function of the temperature, was assumed to have the same value as water. By curve fitting of data summarized by Geankoplis (1983), the following equation was obtained ($r=0.9973$):

$$k(\text{Wm}^{-1}\text{K}^{-1}) = -0.6 + 0.00653T(\text{K}) - 8.3 \times 10^{-6}T^2 \quad (6)$$

The mass diffusivity is assumed to be equivalent to that of sucrose in water which is $0.56 \times 10^{-9} \text{ (m}^2\text{s}^{-1}\text{)}$ at 25°C (Perry, 1963). The effect of the temperature on the diffusivity was evaluated by the Stokes–Einstein equation, having the following form:

$$\frac{D\eta}{T} = \text{Constant} \quad (7)$$

where η is the viscosity. Assuming water-like properties for the diffusivity in the product, the viscosity of the water can be expressed as:

$$\eta(\text{cp}) = 0.001874 \exp\left(\frac{1849}{T[\text{K}]}\right) \quad (8)$$

This equation is obtained by curve fitting of water viscosity data (Washburn, 1929) with $r=0.9959$. The diffusivity can be therefore evaluated by:

$$D(\text{m}^2\text{s}^{-1}) = 0.93 \times 10^{-9}T/\exp\left(\frac{1849}{T}\right) \quad (9)$$

A range of values, as indicated, were used for the external film mass and heat transfer coefficients. The rest of the equation parameters were taken as those of

water, namely density of $1000 \text{ (kg m}^{-3}\text{)}$ and specific heat of $4186 \text{ (J kg}^{-1} \text{ }^\circ\text{C}^{-1}\text{)}$. Typical number of layers in the simulation was 99 cm^{-1} and time interval 0.001 s . The validity of the simulation data was confirmed by checking some of them against analytical solutions (Crank, 1964).

RESULTS AND DISCUSSION

Effect of temperature gradient on leaching of solutes

As compared to isothermal leaching, solutes loss during water blanching is apparently a more complicated problem due to the fact that both mass and heat transfer are taking place simultaneously. The product mass diffusivity depends on the momentary temperature in each layer of the product. However, the simulation data clearly indicate that the extent of leaching is practically the same for a plate having initial temperature of 20°C or of 100°C (Fig. 1). Even when the heat transfer coefficient is relatively low, such as $300 \text{ (W m}^{-2} \text{ }^\circ\text{C}^{-1}\text{)}$, which is typical of natural convection (Hough *et al.*, 1990), one observes only a small drop in the extent of leaching due to the temperature gradient. Obviously, due to the large ratio between thermal and mass diffusivity in water blanching, the leaching of solutes is practically taking place from layers that have already reached a temperature close to that of the external medium. In contrast, when the plate and the liquid temperature are kept at 20°C , the extent of leaching is markedly reduced (Fig. 1). These results clearly indicate that leaching of soluble solids during water blanching may be

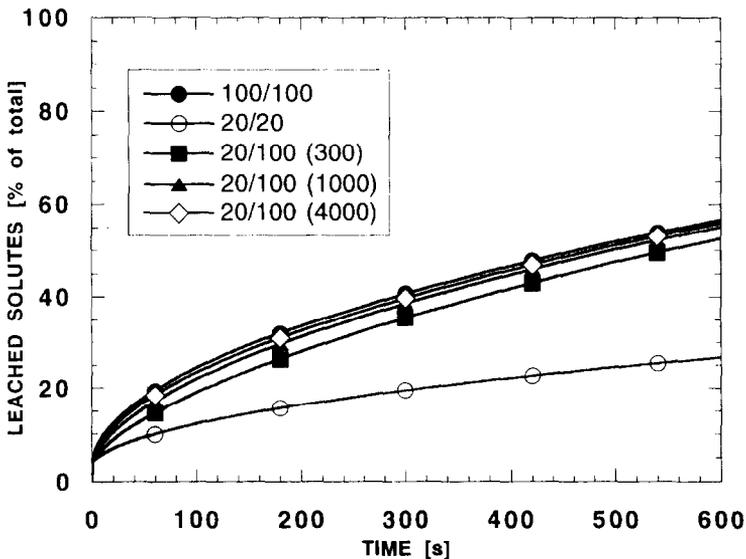


Fig. 1. Extent of solute loss in water blanching at different initial plate temperature and heat transfer coefficients (numbers in legends indicate from left to right: initial plate temperature, water temperature and, in brackets, the heat transfer coefficient [$\text{W m}^{-2} \text{ }^\circ\text{C}^{-1}$]).

practically treated as an isothermal process where the value of the mass diffusivity is that of the product at the temperature of the external hot liquid.

Solute concentration profile during water blanching

Solute leaching during the relatively short blanching time results in a concentration profile having a plateau at the center and a very steep gradient over a relatively thin surface layer (Fig. 2). The same pattern was shown also by Califano & Calvelo (1983) and by Luna *et al.* (1992) for potatoes during water blanching. That concentration profile indicates that for a blanching time of e.g. 300 s and 600 s, the leaching is taking place mainly from 2 and 4 mm of the surface layer, respectively. Therefore, in practical cases of blanching, the extent of leaching should be independent of the product thickness. The only geometrical parameter of importance is, therefore, the product surface area.

Master curves of solute leaching during water blanching

As long as the surface solute concentration of the plate is in equilibrium with that of the medium, analytical solutions are available (Crank, 1964). However it is more convenient to express the extent of leaching by a master curve (Fig. 3) that produces two simple empirical expressions. The first one is the quantitative form of the master curve, namely:

$$\frac{M_t}{A(C_{po} - C_{pf})} = S(\sqrt{Dt} + G) \quad (10)$$

where G and S are constants and C_{pf} the equilibrium concentration of solutes in the product.

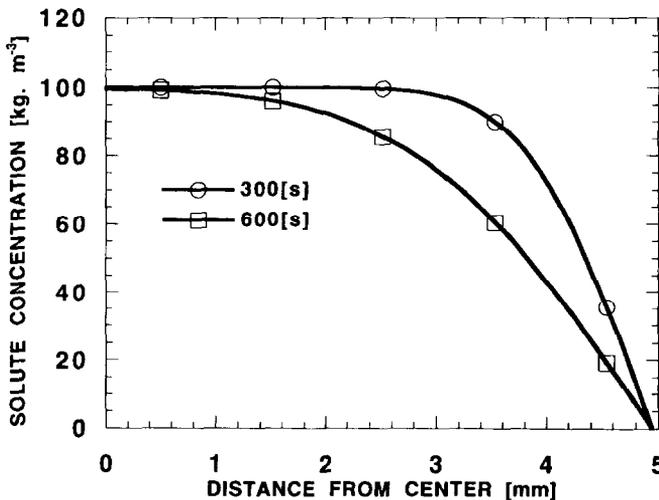


Fig. 2. Concentration profile in an infinite plate after 300 and 600 s of water blanching.

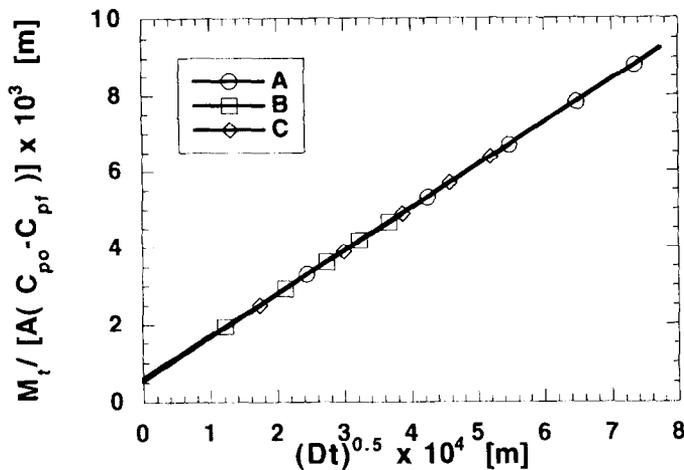


Fig. 3. Master curve of solute leaching in water blanching (A=0.01, 100, 0; B=0.02, 200, 50; and C=0.05, 50, 10; numbers represent plate thickness, initial solute concentration in plate and in medium, respectively).

The value of the slope S is dependent (Fig. 4) on the ratio r between the volume of the product (V_p) and that of the medium (V_m). At least for the practical range of $r=0$ to $r=1$, the slope S can be expressed (Fig. 5) by:

$$S = 1.12 + 0.65r \quad (11)$$

It is interesting to note that data obtained from the graphical presentation in Crank (1964) for the same conditions fit exactly the line shown in Fig. 5.

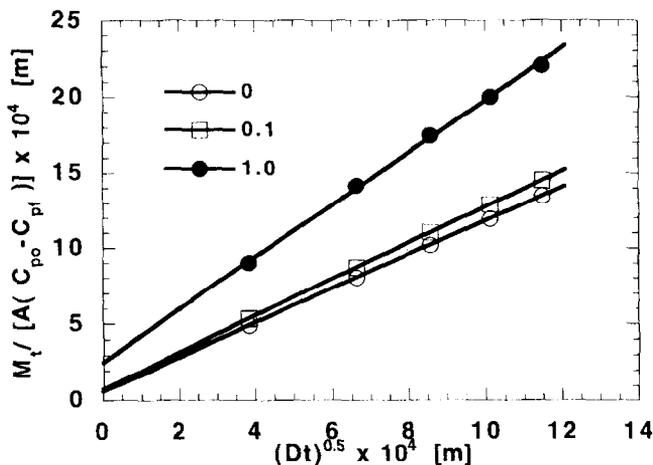


Fig. 4. Effect of the product to medium volume ratio on the master curve parameters (numbers in legend are values of the volume ratio).

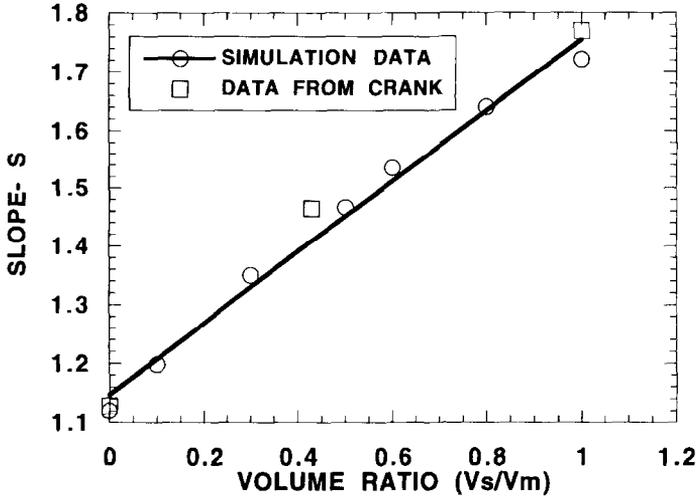


Fig. 5. Effect of the product to medium volume ratio on the master curve slope.

The second empirical expression is applicable to those cases where it is more convenient to express the extent of leaching by a non dimensional form of M_t/M_∞ , where M_∞ is the total amount of solutes leached at infinite time, namely at equilibrium between the product and the medium. The value of M_∞ can be calculated from:

$$M_\infty = V_p(C_{po} - C_{pf}) \quad (12)$$

Therefore:

$$(C_{po} - C_{pf}) = \frac{M_\infty}{V_p} \quad (13)$$

Inserting this value into eqn (10), one gets:

$$\frac{M_t}{M_\infty} = \frac{A}{V_p} S(\sqrt{Dt} + G) = SVR \times S(\sqrt{Dt} + G) = K(\sqrt{Dt} + G) \quad (14)$$

Where SVR is the surface to volume ratio of the product and K is:

$$K = SVR \times S = SVR(1.12 + 0.65r) \quad (15)$$

Since the characteristic dimension (L) is half the thickness for a plate and is the radius for a cylinder and a sphere, the surface to volume ratio (SVR) is $1/L$, $2/L$ and $3/L$ for these bodies, respectively. For plate, cylinder and sphere the value of K in eqn (15) may be expressed by:

$$K_{\text{plate}} = \frac{1.12 + 0.65r}{L} \quad (16)$$

$$K_{\text{cylinder}} = 2 \times \frac{1.12 + 0.65r}{L} \quad (17)$$

$$K_{\text{sphere}} = 3 \times \frac{1.12 + 0.65r}{L} \quad (18)$$

Effect of mass transfer coefficient on the master curve parameters

So far eqn (10) to eqn (18) are based on a leaching process where the solute concentration at the surface is in equilibrium with that of the medium, namely the external mass transfer coefficient is practically infinite. However, if this coefficient is low enough, the slope is lower than that shown in eqn (11) (Fig. 6). Nevertheless, in these cases it is convenient to keep using eqn (11) as it is and compensating for that shift in the slope S by an equivalent change in the value of the diffusivity. In that case the diffusivity will assume an apparent value rather than the real one.

Low mass transfer coefficients cause also a shift in the constant G from a positive to a negative value. Negative G appears as a lag period on the graph. The value of the lag time depends on the magnitudes of the mass transfer coefficient and the diffusivity (Fig. 7). In such case G is simply the square root of the lag time. The main reason for that lag period is the come up time required for the surface to reach, in this case, its steady state concentration.

The maximum lag period (Fig. 7) is about 18 s, but one expects such a value only in the extreme case of a very low mass transfer coefficient. In most practical cases, the expected lag period is small and therefore only a relatively small error will be introduced by eliminating G from the above equations.

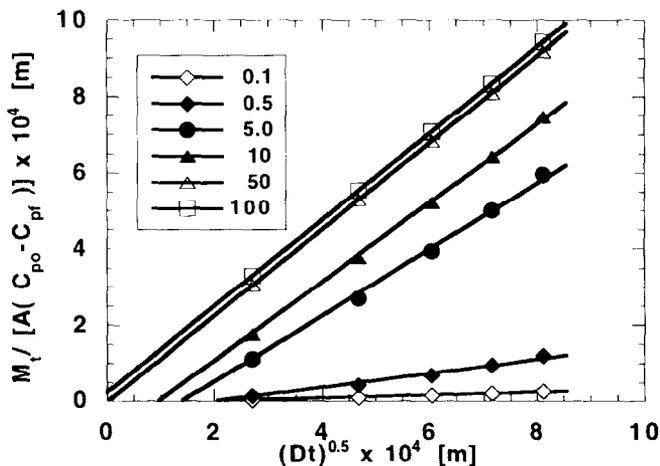


Fig. 6. Effect of the mass transfer coefficient on the rate of solute losses (numbers in legend are mass transfer coefficients $\times 10^9$ [ms^{-1}]).

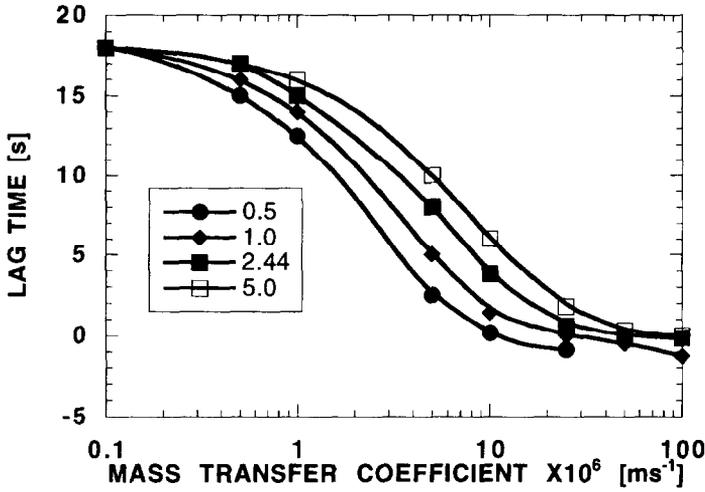


Fig. 7. Effect of the mass transfer coefficient and the diffusivity on the lag time (numbers in legends indicate mass diffusivities $\times 10^9$ [m²s⁻¹]).

Leaching of pigments during blanching of beets

Actual solute losses during blanching, of a large number of samples of slices or cubes of beet, by hot water and by ohmic heating follow the same pattern as shown by the simulation data (e.g. Fig. 8). In that particular figure, the apparent mass diffusivity is 2.9×10^{-9} (m² s⁻¹) and the lag time is 1.6 s. In comparison, the mass diffusivity for glucose in potatoes is as high as 2.5×10^{-9} (m² s⁻¹) at the same

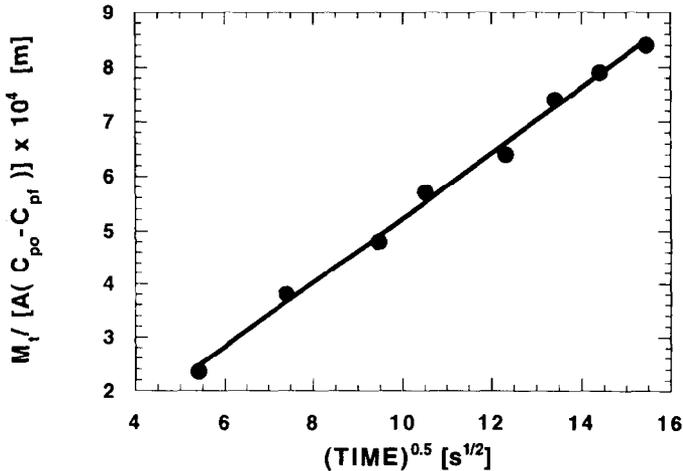


Fig. 8. Leaching of pigments in water blanching of beet slices.

TABLE 1
Leaching of Pigments from Beet Cubes during Water Blanching at 100°C

Sample no.	Mass diffusivity (m^2s^{-1})	Lag time (s)	Average mass diffusivity \pm S.D. (m^2s^{-1})	Average lag time (s)
1	2.9×10^{-9}	0		
2	1.65×10^{-9}	3.8	2.8×10^{-9}	1.8
3	3.1×10^{-9}	4.3	$\pm 1.3 \times 10^{-9}$	
4	1.4×10^{-9}	0.3		
5	4.9×10^{-9}	0.6		

temperature (Tomasula & Kozempel, 1989). It should be noted that the molecular weight of betanine and betalamic acid is 550.22 and 210.17, respectively. Initially, betanine to betalamic acid ratio is about 3:1, but that ratio changes to about 1:1 due to thermal cleavage into betalamic acid. Nevertheless, it seems that the value of the mass diffusivity that was found for the beet pigments is high in comparison with other solutes in different food products (Schwartzberg & Chao, 1982). It is possible that a small flux of concentrated solution is induced by the loss of turgor pressure in the beet during blanching, resulting in a large value of apparent mass diffusivity.

Data in Tables 1 and 2 indicate that these two blanching methods have practically the same pattern of solute loss. The average mass diffusivity in both cases is essentially the same. The lag time in both cases is short enough to allow its elimination while introducing only a small error. In any case, this error is obviously negligible as compared to the relatively wide range of the mass diffusivity values due to natural variations between the beet samples, thus indicating the futility of pursuing the development of accurate mathematical models when the behavior of the real systems vary so much.

Comparison between blanching by hot water and ohmic heating

Data in Table 3, clearly demonstrate the large difference in the extent of solute loss between blanching by ohmic heating as compared to hot water, when the former is carried out on the whole vegetable and the latter on the same vegetable after dicing.

TABLE 2
Leaching of Pigments from Beet Cubes during Blanching by Ohmic Heating

Sample no.	Mass diffusivity (m^2s^{-1})	Lag time (s)	Average mass diffusivity \pm S.D. (m^2s^{-1})	Average lag time (s)
6	4.3×10^{-9}	8.8		
7	2.7×10^{-9}	4.1	2.9×10^{-9}	4.8
8	3.5×10^{-9}	9	$\pm 1.0 \times 10^{-9}$	
9	1.3×10^{-9}	0.05		
10	2.8×10^{-9}	1.9		

TABLE 3
Comparison of Solute Loss during Water Blanching and Ohmic Heating

Sample mass (g)	Solute loss after 2 min ohmic heating (% of total)	Solute loss after 4 min water blanching (% of total)	Leaching ratio (water/ohmic)	Average leaching ratio \pm S.D.
236	3.6	33.4	9.3	
231	3	29.5	9.8	
242	4.5	40.5	9.0	9.7 \pm 0.6
224	4.3	40.5	9.4	
235	3.8	40.9	10.8	

In order to eliminate errors due to the natural variation between different samples, a consecutive blanching procedure was used where ohmic heating was carried out first on the whole vegetable. Following that, the beet was cooled, diced and blanched by hot water. The ratio of solute losses in these two methods of blanching was therefore calculated for the same beet sample. This method involves a minimal error since the extent of losses during the initial blanching stage is below 5% of the total solutes. In such experimental design, the extent of solute losses during the hot water blanching is about ten times larger than that during the ohmic heating. The reason for that one order of magnitude reduction in solute loss can be explained by assuming that the whole beet is a sphere having a diameter d , the diced cubes a dimension of 'a' and that in both cases the blanching is carried out at the same product to medium volume ratio. The loss of solutes in the cube as compared to the sphere can be calculated from eqn (14), assuming negligible lag time, as follows:

$$\frac{M_{tc}}{M_{ts}} = \frac{SVR_c}{SVR_s} \sqrt{\frac{t_c}{t_s}} \quad (19)$$

where the subscripts c and s denote cube and sphere, respectively. The surface to volume ratio for cube and sphere is $6/a$ and $6/d$, respectively. Therefore, in this case eqn (19) may be changed into:

$$\frac{M_{tc}}{M_{ts}} = \frac{d}{a} \sqrt{\frac{t_c}{t_s}} \quad (20)$$

The diameter of the whole beets in these experiments was about 7.5 cm, the cube dimension was about 1 cm and since the blanching times were $t_c=4$ min and $t_s=2$ min, the expected solute loss ratio should be:

$$\frac{M_{tc}}{M_{ts}} = \frac{7.5}{1} \sqrt{\frac{4}{2}} = 10.6 \quad (21)$$

This value is similar to the empirical one. The larger the vegetable the less solutes will be leached by using ohmic heating. It should be noted that in addition to

reducing the surface to volume ratio and to shortening the blanching time, more solutes may be saved by decreasing the medium volume (increasing the value of r). This can be accomplished to a much larger extent in the case of blanching by ohmic heating than in hot water process.

CONCLUSIONS

Leaching of solutes during blanching follows the same pattern regardless of the heating method, namely hot water or ohmic. In both methods, the extent of solute loss is practically linearly proportional to the surface to volume ratio of the product and to the square root of the process time. Large vegetables, having a relatively small surface to volume ratio, can be blanched in a short time by ohmic heating without any need for dicing it first. The energy, dissipated by the electric current passing through the product, is capable of heating it uniformly and very fast regardless of its shape or size. In contrast, dicing is required in order to maintain a reasonably short water-blanching time. A reduction of one order of magnitude in solutes losses may be achieved when blanching by ohmic heating due to a favorable combination of low surface to volume ratio and short process time.

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