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# Soaking Process in Ternary Liquids: Experimental Study of Mass Transport Under Natural and Forced Convection

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## ABSTRACT

*Cross mass transport during the soaking process of model food gel (gelatin, carraghenan) in concentrated solutions (salt–sucrose–water) at 10°C was investigated using a rotating gel disc device. The concentration profiles in gel were analyzed. The experimental results confirmed the theory that component concentrations are not functions of the disc radius. Two sets of experiments were carried out to study the influence of the main process variables (solute concentration, processing time) on mass transport under forced and natural convection. The results showed that the presence of sucrose enhanced water loss and hindered salt penetration whatever the hydrodynamic conditions. Rotation speed increased water loss as solute concentration increased but had no effect on salt gain, while it hindered sucrose gain. Photographs also showed the presence of very strong natural convection phenomena.*

## NOMENCLATURE

| | |
|---|---|
| $m_i$ | Aqueous molality of solute $i$ in liquid (mol $\mathrm{kg}_{\mathrm{water}}^{-1}$) |
| $M(t)$ | Gel mass at time $t$ (kg) |

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| | |
|---|---|
| $SiG$ | Solute $i$ gain (kg/100 kg of initial gel) |
| $t$ | Time (s) |
| $WL$ | Water loss (kg/100 kg of initial gel) |

**Greek symbols**

| | |
|---|---|
| $\omega_i$ | Mass fraction of species $i$ in gel disc |
| $\Omega$ | Gel disc rotation speed (rad $s^{-1}$) |

**Subscripts**

| | |
|---|---|
| 1,2,3 | Refer to NaCl, sucrose and water, respectively |

## INTRODUCTION

Many traditional processes involve the soaking of water-rich foods (e.g. fruit, vegetables, meat, fish or cheese) in concentrated solutions (salt, sugar, acid, etc.). Such processes include the salting, pickling and curing of meat, fish and vegetables, the candying and semi-candying of fruit and vegetables, and even immersion chilling and freezing. Simultaneous cross flows are induced: the solutes in the solution penetrate into the product while the water in the product flows into the solution. Such operations have generally been termed ‘osmotic dehydration’ (Ponting *et al.*, 1966). The traditional approahc of considering purely osmotic phenomena has been challenged by a number of authors (Raoult-Wack *et al.*, 1991a; Raoult-Wack *et al.*, 1991b; Raoult-Wack *et al.*, 1991c; Saurel *et al.*, 1994a; Saurel *et al.*, 1994b), and Raoult-Wack *et al.* (1991a) even renamed such processes ‘dewatering impregnation soaking (DIS) processes’. Research on DIS processes has been reviewed by Torregian (1993), Raoult-Wack (1994) and Yao (1994).

Aqueous binary sucrose and NaCl solutions are the liquid phases most widely used in soaking. The advantage of ternary (or even more complex) solutions has been established for the treatment of both vegetable (Jackson & Mohamed, 1971; Hawkes & Flink, 1978; Islam & Flink, 1982; Lenart & Flink, 1984a; Lenart & Flink, 1984b; Jayaraman *et al.*, 1990) and animal products (Collignan & Raoult-Wack, 1994). If ternary sucrose–NaCl solutions are prepared at 20°C, the saturation limits of the solution can be pushed back to a total solute concentration of 75% (w/w), whereas binary water–NaCl solutions are saturated at 26% (w/w). Using two solutes thus makes it possible to control concentration over a wider range. From a technological point of view, sugar–salt mixtures prevent over-salting of the product (Collignan and Raoult-Wack, 1992), which is undesirable from an organoleptic point of view, and at the same time provide high levels of dehydration. Poor understanding of the mechanism involved in the three simultaneous flows (water removal, salt and sugar penetration) inside the foodstuff has hindered the development of industrial applications for soaking in sugar–salt solutions.

The present work used a model food (protein gel) to determine the effects of salt and sugar concentrations on mass transfer. Two different hydrodynamic situations (natural and forced convection) were examined using a specially developed experimental rotating disc arrangement. The system allowed precise control of the hydrodynamic conditions in the liquid close to the disc surface (Gregory & Riddiford, 1956; Levich, 1962).

## MATERIALS AND METHODS

### Liquid and gel preparation

Soaking solutions were prepared by mixing NaCl, sucrose (commercial grade) and demineralized water at room temperature to complete dissolution. The solutions were stored at 10°C. NaCl and sucrose concentrations, denoted $m_1$ and $m_2$ respectively, were expressed in terms of aqueous molality (mol kg$^{-1}$). The gels were prepared by mixing $3{\cdot}96 \times 10^{-3}$ kg iota carraghenan (Sanofi X52 TA) and $9{\cdot}90 \times 10^{-3}$ kg gelatin (Sanofi B250) with $66{\cdot}14 \times 10^{-3}$ kg demineralized water to give 0·08 kg gel. An aluminum mold (height $5 \pm 0{\cdot}05 \times 10^{-3}$ m; internal diameter $114 \pm 0{\cdot}5 \times 10^{-3}$ m; opening diameter $100 \pm 0{\cdot}5 \times 10^{-3}$ m) was totally filled with the mixture (Fig. 1). A Pyrex plate (diameter 0·2 m; thickness $3 \times 10^{-3}$ m) was then laid on the mixture. The plate, mold and mixture were vacuum packed (Multivac) together in a polyethylene bag. The airtight bag was then heated to 75°C in a temperature controlled bath and maintained at this temperature for 30 min, after which it was stored for about 24 h at 10°C. The bag was opened just before processing and the glass plate removed. A gel disc was thus obtained which adhered firmly to the aluminum mold. Additional gel present in the bag was used to determine the initial water content ($84{\cdot}1 \pm 0{\cdot}3\%$). The initial gel mass ($51{\cdot}2 \pm 0{\cdot}5$ g), denoted $M(0)$, was also determined.

### Experimental apparatus and procedures

The experimental apparatus is illustrated in Fig. 1. The experiments were performed in a parallelepiped-shaped stainless steel container (length $40 \times 10^{-2}$ m, width and height $25 \times 10^{-2}$ m). Closed circuit circulation of freezant fluid maintained the liquid at a constant $10 \pm 0{\cdot}3$°C. Two opposite sides of the container were made of vertical glass sheets, allowing the rotating disc to be observed and photographed. Water plumes were photographed (Canon EOS 100) against the light. Rotation speed was controlled by a contact tachometer (LT Lutron DT-2236). The container was filled with 19 l of liquid at 10°C. A minimum liquid/gel ratio of 380/1 by weight avoided changes in the bulk liquid concentration. The mold containing the gel disc was screwed onto the rotor axis, with the disc positioned 0·1 m above the container bottom. The rotary unit was then set in motion at time zero. The rotation speed, $\Omega$, could be varied from 0 to 146·6 rad s$^{-1}$. At time $t$ (range 30–300 min), rotation was stopped and the gel disc removed from the liquid. The disc was quickly rinsed with cold demineralized water and the gel surface gently blotted with paper to remove any surface liquid. The disc was then removed from the mold and weighed ($M$), and water loss and solute gains were measured. The disc was replaced in the mold, if necessary, for radial concentration profile measurements.

## Analytical methods

For water loss and solute gain measurements, the whole gel disc was blended completely (Moulinex blender) at time *t*. For radial concentration profiles, core samples were taken perpendicularly to the surface of the disc: one central sample (diameter $40 \times 10^{-3}$ m) and samples (diameter $12 \times 10^{-3}$ m) at $28 \times 10^{-3}$ m and $42 \times 10^{-3}$ m from the disc center respectively. Parts of the blended material or core samples were also used to determine the mass fractions of NaCl, sucrose and water in the gel. Water content was determined after oven desiccation for 24 h at 104°C. The NaCl content was analyzerd by potentiometric titration (Corning 926 chlorometer) of aqueous sample extract (5 g sample in 50 ml of 0·3 N $HNO_3$ for 6 h). The sucrose content was analyzed by HPLC of aqueous sample extract (5 g sample in 150 ml of 80% ethanol for 30 min). A Beckman chromatograph (isocratic pump 110B, Knauer refraction index detector, Gold recorder-integrator) was used, with a

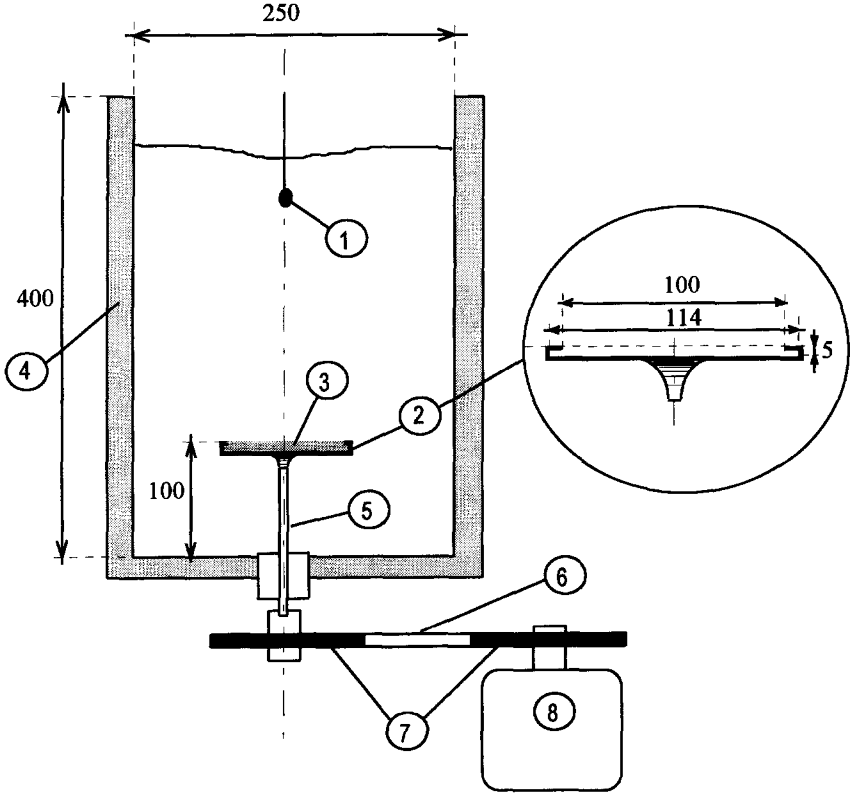

**Fig. 1.** Experimental system: (1) Pt 100 temperature probe; (2) revolving plate; (3) gel disc for processing; (4) freezant fluid; (5) rotation axis; (6) belt; (7) pulley; (8) electric motor.

Lichrospher 10-NH2 column (5 μm, 250 × 4 mm), acetonitrile/water eluent (80/20) and a constant flow rate of 1·2 ml min$^{-1}$.

## Calculation of water loss and solute gains

Water loss, WL, and solute gain of species *i*, SiG, were expressed as a w/w percentage of initial material (% i.m.) according to eqns (1) and (2), respectively:

$$WL = 100\left[\omega_3(0) - \omega_3(t)\left(\frac{M(t)}{M(0)}\right)\right] \quad (1)$$

$$SiG = 100\omega_i(t)\left(\frac{M(t)}{M(0)}\right)(i = 1{,}2) \quad (2)$$

where $\omega_i$ is the mass fraction of species *i* in the gel.

## Experimental design study

Two experimental designs based on Doehlert uniform shell design (Doehlert, 1970) with response surface methodology were used to take factor interactions into account. Both sets of experiments were conducted at $\Omega = 146{\cdot}6\ \mathrm{rad\ s^{-1}}$ (forced convection) and at $\Omega = 0\ \mathrm{rad\ s^{-1}}$ (natural convection). The three independent factors included $m_1$, $m_2$ and processing time (denoted *t*). The center point of experimental area was defined as $m_1 = 3\ \mathrm{mol\ kg^{-1}}$, $m_2 = 2{\cdot}77\ \mathrm{mol\ kg^{-1}}$, and $t = 165$ min. A second order polynomial model was used [eqn (3)] to describe the response variables $Y_i$(*Wl*, *S1G* and *S2G*) as a function of the factor variables $X_i$:

$$Y_i = \beta_o + \Sigma\beta_i X_i + \Sigma\beta_{ii} X_i^2 + \Sigma\beta_{ij} X_i X_j \quad (3)$$

where $X_1$ is NaCl molality, $m_1 \in [0;6]$; $X_2$ is sucrose molality, $m_2 \in [0;5{\cdot}55]$; $X_3$ is time processing, $t \in [30;300]$; $\beta_o$ is the polynomial constant; $\beta_i$, $\beta_{ii}$ and $\beta_{ij\,i \neq j}$ are the linear, quadratic and interaction effects of the factors respectively. Each design was used for 15 experimental runs, including three repetitions at the center point. Factor levels were 3 for $X_1$, 5 for $X_2$ and 7 for $X_3$. The experiments were performed in random order. Multiple linear 4regression coefficients were calculated using Statgraphics software (STSC, Inc., USA, 1991). Regression and coefficient validity were verified by statistical tests ($R^2$ correlation coefficient, variance analysis, Fisher test). Response surfaces were established using only coefficients with a significance level of over 95%. Least significant difference (Tukey test, 95% significance level) was used to compare experimental responses (*WL*, *S1G* and *S2G*) measured under natural and forced convection respectively.

TABLE 1
Radial Profile of Water, NaCl and Sucrose Content, Within the Gel Disc Set into Rotation ($\Omega = 146{\cdot}6$ rad s$^{-1}$) for 2 h 45 min in the Ternary Liquid ($m_1 = 6$ mol kg$^{-1}$, $m_2 = 5{\cdot}55$ mol kg$^{-1}$)

| *Radius ($10^{-3}$ m)* | *Mass fraction % (w/w)* | | |
|---|---|---|---|
| | *Water* | *NaCl* | *Sucrose* |
| 0 | 69·95 ± 0·93 | 3·64 ± 0·05 | 1·32 ± 0·06 |
| 28 | 69·65 ± 1·01 | 3·55 ± 0·05 | 1·67 ± 0·40 |
| 42 | 69·61 ± 0·97 | 3·55 ± 0·03 | 1·96 ± 0·67 |

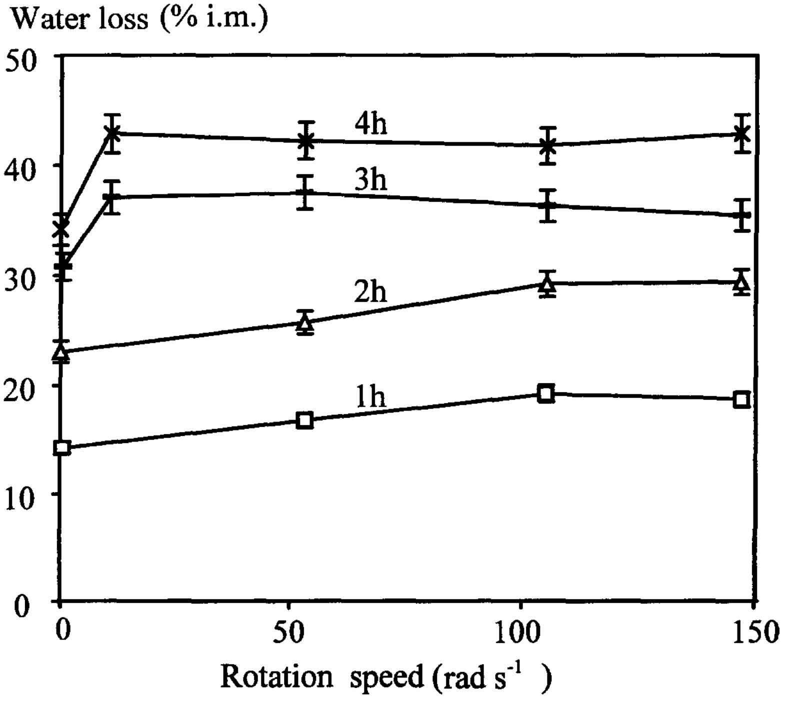

**Fig. 2.** Influence of rotation speed on water loss in standard gel disc after 1 h (□), 2 h (△), 3 h (—), and 4 h ( × ) soaking in ternary liquid ($m_1 = 6$ mol kg$^{-1}$, $m_2 = 5{\cdot}55$ mol kg$^{-1}$).

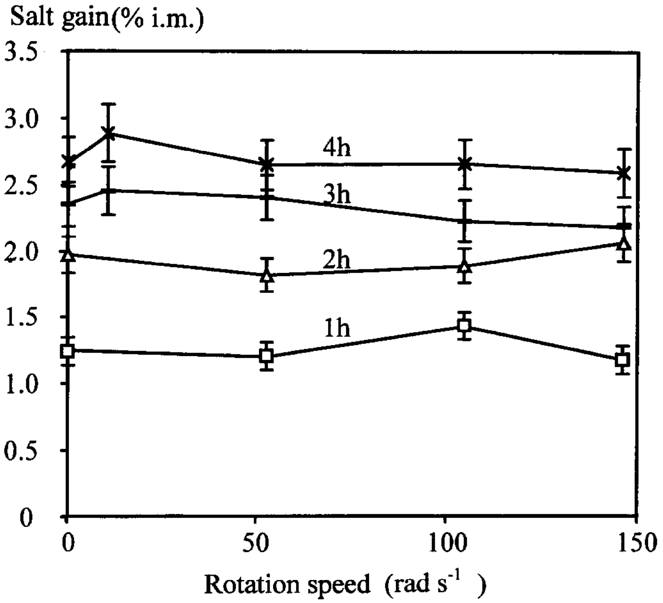

**Fig. 3.** Influence of rotation speed on salt gain in standard gel disc after 1 h (□), 2 h (△), 3 h (—), and 4 h ( × ) soaking in ternary liquid ($m_1$ = 6 mol kg$^{-1}$, $m_2$ = 5·55 mol kg$^{-1}$).

## RESULTS

### Experimental assessment of the rotating gel disc configuration

Table 1 shows changes in component content (water, NaCl and sucrose) within a gel disc, after rotation at 146·6 rad s$^{-1}$ for 2 h 45 min in the ternary liquid, as a function of radius. The experiments were run in triplicate, and mean composition values together with the standard deviation are given. Variance analysis was performed on these data but no significant variations versus radius were observed for any component ($P<1\%$), indicating that the distributions of water, NaCl and sucrose in the gel were not functions of the disc radius.

### Influence of rotation speed on mass transfer

Figures 2– show the different levels of water loss and salt and sucrose gains respectively, as a function of the rotation speed of the gel disc in the ternary liquid over different treatment times. Water loss varied from roughly 15 to 55% i.m. Rotation speed had a positive effect on water loss (Fig. 2). The water loss curves for the four different treatment times had a similar overall pattern: water loss increased with rotation speed, then reached a plateau after a so-called 'limit speed'. The limit speed was significantly lower for longer treatment times: 10·5 rad s$^{-1}$ after 4 h of

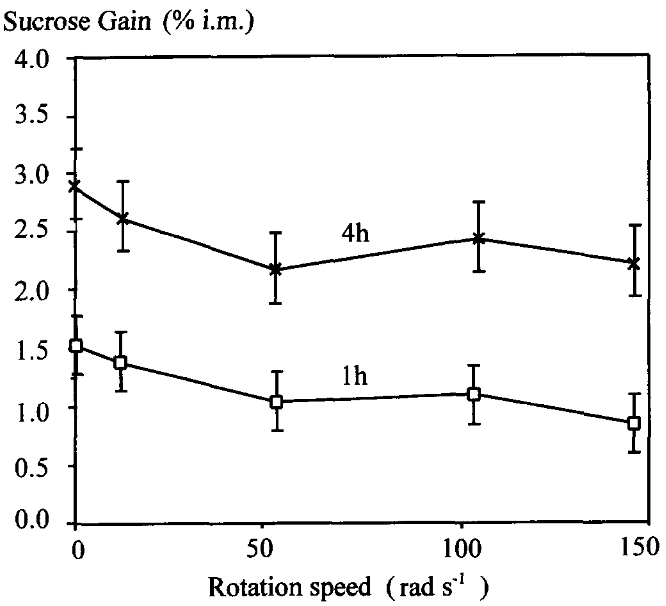

**Fig. 4.** Influence of rotation speed on sucrose gain in standard gel disc after 1 h (□) and 4 h (×) soaking in ternary liquid ($m_1 = 6$ mol kg$^{-1}$, $m_2 = 5{\cdot}55$ mol kg$^{-1}$).

**TABLE 2**
Analysis of the Least Significant Difference Between Natural and Forced Convection Response Variables

| | *Response (g/100 g of initial gel disc)* | | |
|---|---|---|---|
| | *Water loss* | *NaCl gain* | *Sucrose gain* |
| LS mean[a] | | | |
| *NC* | 20·92 | 2·37 | 3·07 |
| *FC* | 24·10 | 2·47 | 2·47 |
| Difference[b] | 3·18 | 0·10 | −0·60 |
| Limit | ±0·95<br>*** | ±0·10<br>* | ±0·33<br>*** |

*NC*, Natural convection ($\Omega = 0$ rad s$^{-1}$).
*FC*, Forced convection ($\Omega = 146{\cdot}6$ rad s$^{-1}$).
[a] Least significant mean.
[b] Difference between LS mean (*FC*) and LS mean (*NC*).
***, **, *Coefficient significant at $P < 0{\cdot}5\%$, $P < 5\%$, $P < 10\%$ respectively.

treatment as against approximately 100 rad s$^{-1}$ after 1 h. The effect of agitation on water loss was more pronounced when treatment time was shorter. The maximum increase in water loss as a result of forced, as opposed to natural, convection was 38% after 1 h after 4 h. Rotation speed had no marked effect on NaCl gain (Fig. 3), which consequently appeared to be independent of it. Sucrose gain, on the other hand, decreased as rotation speed increased (Fig. 4) until a limit speed was reached. Without rotation it was 2·8% i.m. after 4 h but it fell to 2·2% i.m. when the disc was rotating at 52·3 rad s$^{-1}$. Beyond this speed, sucrose gain was stable. One should be cautious when comparing these absolute values, however, because of the high experimental errors arising from low sugar gain.

## Experimental design study

Table 2 gives the results of the least significant difference analysis of the experimental responses (*WL*, *S1G* and *S2G*) measured under natural and forced convection, respectively. The difference between the results was significant for water

**TABLE 3**

Regression Coefficients and Analysis of Variance of the Second Order Polynomial Equation

| *Coefficient*[a] | *Water loss (WL)* | | *NaCl gain (S1G)* | | *Sucrose gain (S2G)* | |
|---|---|---|---|---|---|---|
| | *FC* | *NC* | *FC* | *NC* | *FC* | *NC* |
| $\beta_0$ | 25·853 | 24·310 | 2·250 | 2·163 | 2·838 | 3·787 |
| Linear | | | | | | |
| $\beta_1$ | 6·681** | 6·214*** | 2·181*** | 2·228*** | −0·550** | −0·748* |
| $\beta_2$ | 9·790** | 8·992*** | −1·959*** | −1·700*** | −0·021 | 0·881* |
| $\beta_3$ | 14·860*** | 12·568*** | 1·236*** | 1·246*** | 1·907*** | 1·777** |
| Quadratic | | | | | | |
| $\beta_{11}$ | 2·481 | 0·214 | −0·166 | 0·006 | 0·740* | 0·110 |
| $\beta_{22}$ | −8·768* | −9·539*** | 0·955** | 0·788** | −1·963** | −2·370** |
| $\beta_{33}$ | 0·995 | −2·024* | −0·132 | −0·095 | 0·110 | −0·148 |
| Interaction | | | | | | |
| $\beta_{12}$ | −4·127 | −5·156** | −1·513** | −1·390** | 1·059* | −0·116 |
| $\beta_{13}$ | 3·295 | 4·752** | 1·126** | 1·263** | 0·141 | 0·468 |
| $\beta_{23}$ | 4·786* | 4·398** | −1·039** | −0·836** | −0·567 | −0·502 |
| $R^2$ | 0·988 | 0·991 | 0·998 | 0·998 | 0·861 | 0·942 |

[a] Indices 1, 2 and 3 referred to NaCl concentration, sucrose concentration and time processing respectively.
*NC*, Natural convection ($\Omega = 0$ rad s$^{-1}$).
*FC*, Forced convection ($\Omega = 146{\cdot}6$ rad s$^{-1}$).
***, **, *Coefficient significant at $P<0{\cdot}1\%$, $P<1\%$, $P<5\%$, respectively.

loss and sucrose gain, but not for salt gain. The least significant water loss mean was 15·2 ± 4·5% higher for forced convection than for natural convection. Conversely, the least significant sucrose gain mean was 24·3 ± 13·3% lower for forced convection than for natural convection. Regression coefficients (coefficient values and significance levels) for the polynomial equation are given in Table 3. The second order polynomial model satisfactorily described experimental results for water loss and salt gain (all $R^2 > 0{\cdot}98$) but only indicated trends in the case of sucrose gain ($R^2 = 0{\cdot}86$ under natural convection).

*Effect on water loss*

All linear effects were positive and significant. The time effect was twice as great as the salt concentration effect and 1·4 times greater than the sucrose effect. The linear time and concentration effects observed with forced convection were slightly greater than those observed with natural convection. The linear sucrose concentration effect was enhanced by a negative quadratic effect, suggesting a maximum for water loss.

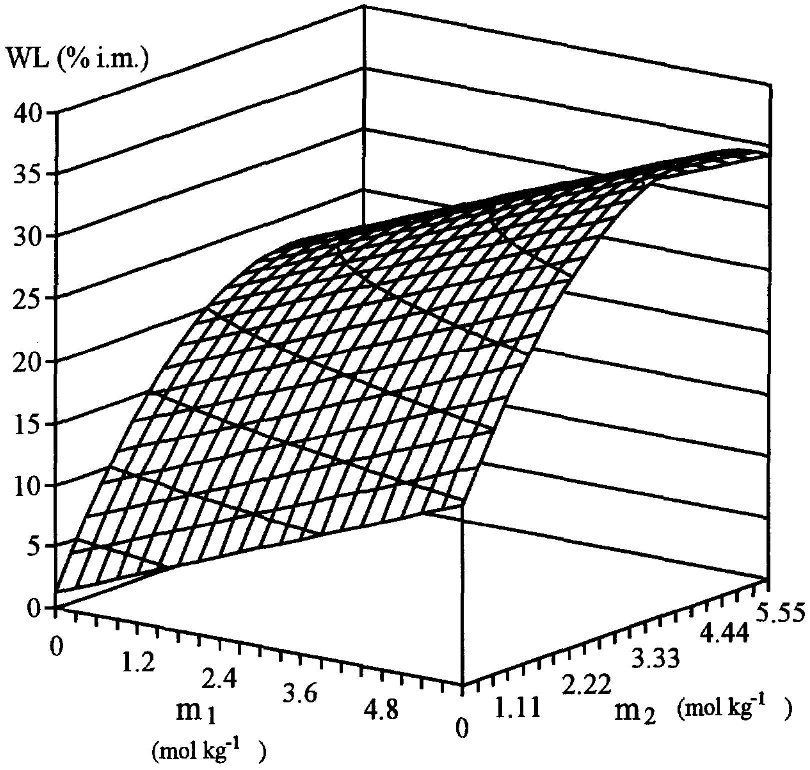

**Fig. 5.** Response surface $WL = f(m_1, m_2)$ at 2 h 45 min under forced convection ($\Omega = 146{\cdot}6$ rad $s^{-1}$) ($WL$ = water loss; $m_1$ = salt molality; $m_2$ = sucrose molality).

Negative interaction was observed between salt concentration and sucrose concentration only in the case of natural convection, as was positive interaction between salt concentration and time. Figures 5 and 6 show the influence of salt and sucrose concentrations on water loss at $t = 2$ h 45 min for both convection situations. When the disc was rotating (forced convection), the effect of salt concentration on water loss was constant, whatever the sucrose concentration. When the disc was static (natural convection), on the other hand, the salt effect depended heavily on the sucrose level: at low sucrose concentrations ($<3$ mol kg$^{-1}$) the presence of salt increased water loss, whereas at high sucrose concentrations water loss was independent of salt content. In the case of natural convection, maximum water loss was observed with solutions containing 3·3 moles of sucrose per kg water, whereas with forced convection water loss continued to increase beyond this concentration level. For high concentrations of salt ($> 3$ mol kg$^{-1}$) and sucrose ($> 3{\cdot}3$ mol kg$^{-1}$), water loss was 20% higher with forced convection than with natural convection.

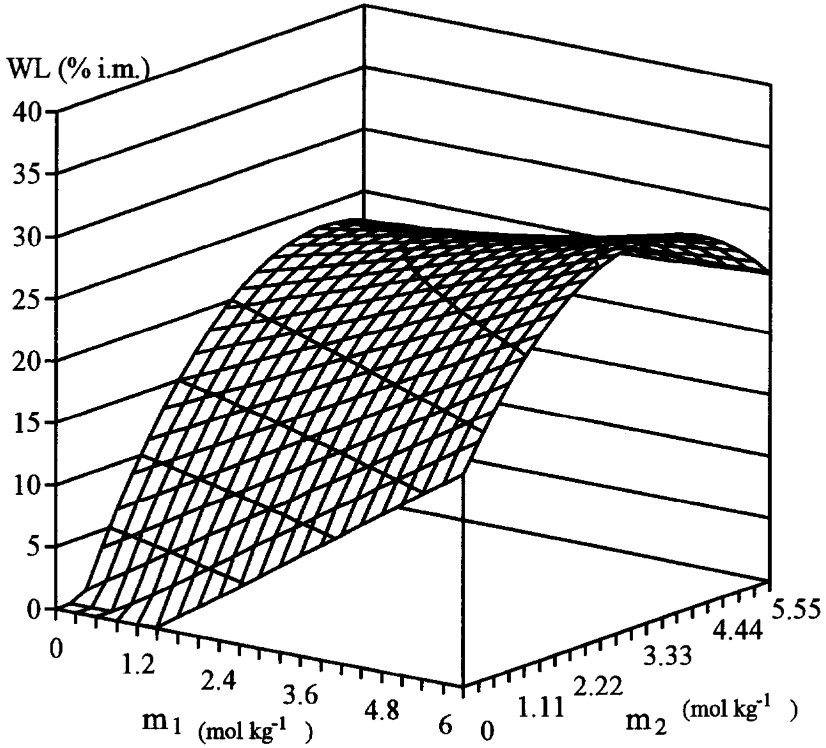

**Fig. 6.** Response surface $WL = f(m_1, m_2)$ at 2 h 45 min under natural convection ($\Omega = 0$ rad s$^{-1}$) ($WL$ = water loss; $m_1$ = salt molality; $m_2$ = sucrose molality).

### *Effect on NaCl gain*

Linear, quadratic, and interaction effects were similar for both experimental designs. The linear sucrose concentration effect was negative, and reinforced by a positive quadratic term which suggested a minimum for salt gain. The negative interaction between sucrose concentration and salt concentration was high. Fig. 7 shows the influence of salt and sucrose concentrations on salt gain at $t = 2$ h 45 min when the disc was rotating. At low sucrose concentrations ($<3$ mol kg$^{-1}$), salt gain increased markedly with salt concentration. At high sucrose concentrations, salt gain was far less dependent on salt concentration and remained low. $S1G$ was 9% i.m., for instance, for $m_1 = 6$ mol kg$^{-1}$ and $m_2 = 0$ mol kg$^{-1}$, whereas it was only 2·15% i.m. when solute concentrations were close to the saturation point.

### *Effect on sucrose gain*

We have already noted that the multilinear regression analysis of the experimental data, and the associated polynomial equation, indicated trends, but did not provide a sufficient level of correlation to analyze the influence of the factor accurately in

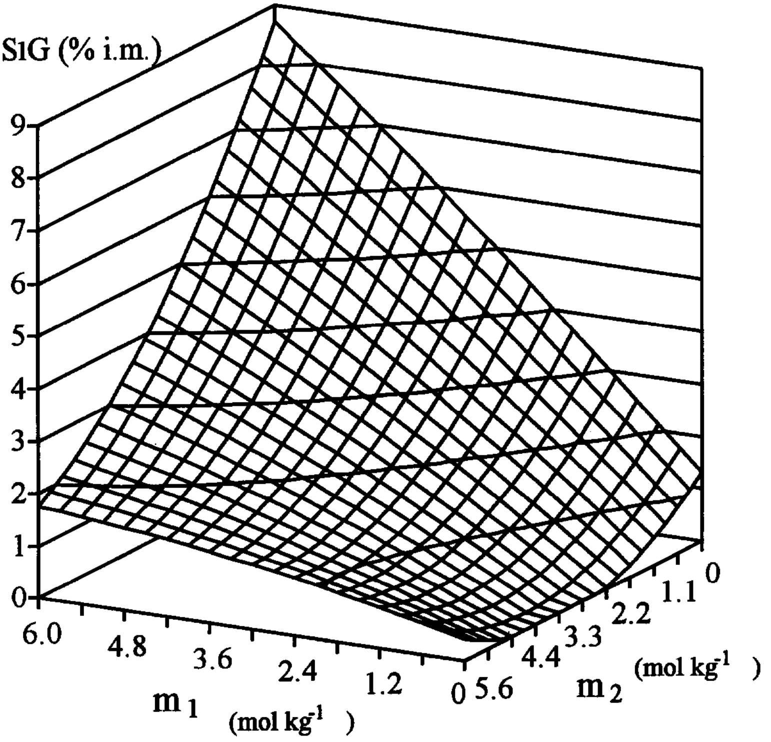

**Fig. 7.** Response surface $S1G = f(m_1, m_2)$ at 2 h 45 min under forced convection ($\Omega = 146{\cdot}6$ rad s$^{-1}$) ($S1G$ = salt gain; $m_1$ = salt molality; $m_2$ = sucrose molality).

the case of sucrose gain. The surface shown on Fig. 8 was obtained by smoothing 15 data points ($R^2 = 0{\cdot}89$) to facilitate analysis. At low sucrose concentrations ($<2{\cdot}5$ mol kg$^{-1}$), sucrose gain increased markedly with sucrose concentration (quasi-logarithmic growth), whatever the NaCl concentration. At high sucrose concentrations, sucrose gain was independent of sucrose concentration. At low sucrose concentrations ($<2{\cdot}5$ mol kg$^{-1}$), sucrose gain was independent of NaCl concentration.

## Visual observation of flow patterns

Photographs were taken of the gel/liquid interface of gel discs immersed in ternary liquids ($m_1 = 6$ mol kg$^{-1}$ and $m_2 = 5{\cdot}55$ mol kg$^{-1}$) in a static situation. Fig. 9 shows upward water plumes photographed after 30 s, 1 min and 6 min of treatment. After 30 s the plumes were approximately 0·3 mm in diameter and 4·6 mm in height and arranged at regular 4 mm intervals. They rose spontaneously from the surface of the disc under the effect of density differences, which were themselves caused by concentration differences. The mean upward velocity at 30 s [Fig. 9(a)] was estimated at 0·1 mm s$^{-1}$ by visually following the changing positions of the peaks. Other water

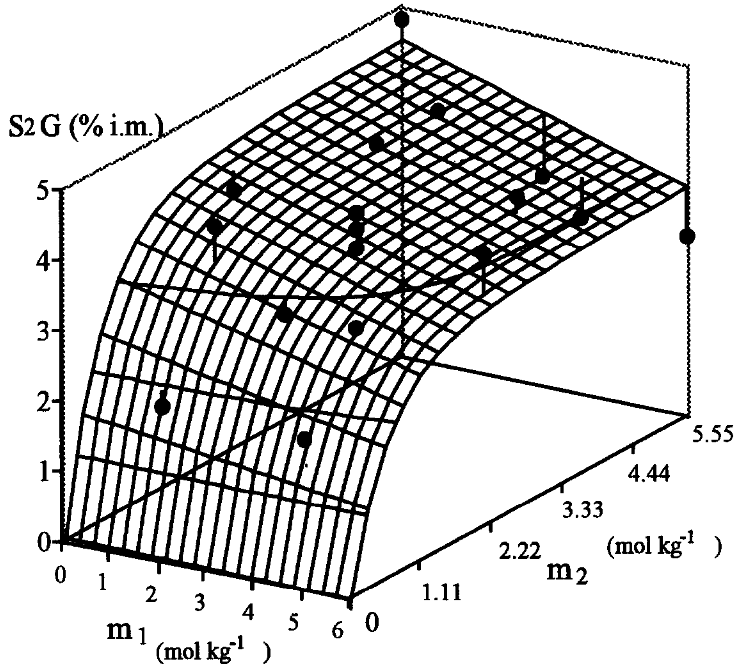

**Fig. 8.** Influence of salt molality ($m_1$) and sucrose molality ($m_2$) on sucrose gain ($S2G$) at 2 h 45 min under natural convection ($\Omega = 0$ rad s$^{-1}$); (●) experimental data.

**Fig. 9.** Visual observation of progressive implementation of natural convection on the water plumes at horizontal up facing gel disc. Time after contacting gel disc and ternary liquid ($m_1 = 6$ mol kg$^{-1}$, $m_2 = 5{\cdot}55$ mol kg$^{-1}$): (a) 30 s, (b) 60 s and (c) 6 min.

**Fig. 9.** *Continued*

plumes formed subsequently. At 60 s [Fig. 9(b)], the number of water plumes had significantly increased, covering the whole surface of the disc. During their upward motion the plumes partially coalesced and at 6 min [Fig. 9(c)] the plumes were concentrated in the central region as they left the disc surface. These coalescence phenomena can be explained both by the drag effects which locally lower the pressure of the system and by the presence of a concentration gradient between the plumes and the surrounding solution. Mass transfer at the liquid/liquid interface would alter the surface tension and generate its own convection effects (Berg & Morig, 1969). Natural convection seemed to be in the form of a turbulent flow. These observations suggest that water outflow at the gel/liquid interface led to a significant local dilution in solute concentration. The phenomena can actually be seen with the naked eye when the gel disc is soaking in a concentrated sucrose–water solution ($m_2 > 2$ mol kg$^{-1}$), but not in a NaCl–water solution.

## DISCUSSION

The uniformity of the treatment conditions in the neighborhood of the gel/liquid interface over the whole disc surface was verified, as this would mean that they were independent of the disc radius. The result was consistent with those obtained with very dilute systems (Gregory and Riddiford, 1956) and corroborated the conclusions of Levich (1962), who demonstrated that the thickness of the mass boundary layer is constant over the whole area of the disc surface. This confirmed the existence of one-dimensional mass transfer, characteristic of spinning discs, as had been anticipated.

Rotation speed increases water loss, whatever the solution used (binary or ternary). The positive effect of rotation speed on water transfer can be explained by dilution phenomena at the gel/liquid interface. When the disc was not set in motion, very pronounced natural convection phenomena occurred at the interface, as shown in the photographs. Water plumes rose from the disc surface as soon as treatment started. The aqueous phase was thus extremely heterogeneous in this region. The advantage to be gained from agitation might thus be that it reduces dilution phenomena at the interface. Rotation of the gel disc ensured renewal of the concentrated solution in contact with the solid, thereby restoring a concentration difference favoring mass transfer. This is consistent with the observations of Dalla-Rosa *et al.* (1982), Magee *et al.* (1983), Lenart and Flink (1984a,b), Raoult-Wack *et al.* (1989) and Raoult-Wack (1991a).

Agitation had no marked effect on NaCl gain. On the other hand, agitation lowered sucrose gain, especially for long treatment times. This is in agreement with the results reported by Raoult-Wack *et al.* (1989), who observed that long treatment under agitation had a negative effect on sucrose gain. This means that increased water flux reduces sucrose flux but has no effect on NaCl flux. As far as sucrose flux is concerned, the results are consistent with the conclusion of Yao and Le Maguer (1996), who estimated that water flow washed back the sugar penetrating into potato tissue slices by diffusion. Bulk flow velocity therefore has a 'sharpening' effect on sugar transport but affects salt transport only slightly (Turhan & Kaletunc, 1992).

The mechanisms governing the cross mass transport of water and solute within the gel were investigated in the case of internal transport which have a limiting effect ($\Omega = 146{\cdot}6\ \mathrm{rad\,s^{-1}}$). The study, carried out using the widest range of NaCl and sucrose concentrations, showed that major water loss ($\geq 40\%$ i.m.) could be obtained at low temperature (10°C) and with a short treatment time ($\leq 4$ h). NaCl/sucrose interactions were high with ternary solutions, particularly with high concentrations of NaCl and sucrose. In such a situation, NaCl gain was independent of NaCl concentration, and the presence of sucrose significantly limited NaCl impregnation (salt gain could be divided by five). These results confirm previous observations carried out on meat products treated in ternary solutions (Collignan & Raoult-Wack, 1994). Such phenomena might be explained by the mass transport properties of the NaCl–sucrose–water system. Ternary diffusion coefficients for the system have not yet been published in the literature, but are available for the closely related KCl–sucrose–water system (Reinfelds & Gosting, 1964; Henrion, 1964). When sucrose was added to the KCl–water system, the main diffusion coefficient for KCl was divided by 11. Sucrose tends to greatly retard the diffusive transport of NaCl, which may be a consequence of the effect of NaCl–sucrose–water viscosity (Bohuon *et al.*, 1997) on NaCl diffusivity. The ratio between the mutual diffusion coefficient of NaCl–water and that of sucrose–water varied between 3 (infinite-dilution) and 33 (saturation concentration) for the whole concentration range used in experiments (Rard & Miller, 1979; Maurandi, 1989). This means that NaCl and sucrose diffusion behaved differently and sucrose would only diffuse into a peripheral layer of the gel. The existence of a concentrated peripheral layer has been demonstrated experimentally (concentration profiles) with model foods in binary sucrose solutions (Raoult-Wack *et al.*, 1991c), and with vegetable products in mixed salt/sugar solutions (Lenart and Flink, 1984b). Such a high concentration zone would reduce the apparent coefficient of NaCl diffusion in the gel. This concentrated layer effect would be reinforced by product shrinkage when water losses are high.

Sucrose gain as a function of sucrose concentration grew logarithmically up to a limit concentration of 2·5 molality of sucrose. Beyond this point, sucrose gain reached a plateau and became independent of sucrose concentration. NaCl concentration affected sucrose gain only slightly. This is consistent with the behavior of the KCl–sucrose–water system in that the influence of KCl on the main diffusion coefficient for sucrose was weak (Reinfelds and Gosting, 1964; Henrion, 1964). It would thus be possible to consider a pseudo-mutual-diffusion approach for sucrose transport using a pseudo-solvent (NaCl–water).

With average sucrose concentrations, the direct effects of NaCl and sucrose concentrations on water loss were not cumulative. The effect of sucrose concentration decreased, however, with high sugar concentrations, and water loss was constant beyond a 4·4 molality of sucrose. The effect of sucrose could be explained by the fact that its presence within the gel would decrease the water transport coefficient.

## CONCLUSION

The respective contributions of external convective transfer and internal diffusive transport could be identified, thanks to the use of a specially developed experimental device (a rotating gel disc configuration) which allowed the convective resistances developed in the mass boundary layer to be controlled. Such a configuration could also be used to investigate simple one-dimensional mass transfer. Dilution of the boundary layer was shown to be a key point in controlling the soaking process in concentrated sucrose solutions. Agitation played a significant part in accelerating the kinetics of blending the diluted and concentrated phases in the vicinity of the solid–liquid interface, thus maintaining the driving force between the food and the solution. The study of internal water and solute transport mechanisms confirmed the existence of strong interactions between the salt and sugar concentration factors. Such interactions are most likely due to the mass transport properties of the NaCl–sucrose–water system and may therefore be a consequence of the effect of solution viscosity on the ternary diffusion coefficient. Moreover, the bulk flow velocity that was generated appeared to wash back the sucrose penetrating by diffusion. These interactions are a very noteworthy characteristic of DIS in ternary solutions. They not only represent a fundamental advance in our understanding of the process and in its modeling, but are also of technological importance in that they offer new possibilities for the process and open the way to very precise control of water and solute transfer.

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