

# Sucrose–salt combined effects on mass transfer kinetics and product acceptability. Study on apple osmotic treatments

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Received 1 June 2000; accepted 1 December 2000

## Abstract

Apple samples were osmotically treated in different hypertonic sucrose solutions (with or without NaCl) at low-temperatures (18–30°C). Sodium chloride was employed to assess the possibility to increase the process rate without affecting the sensory acceptability of treated fruit. Mass transfer kinetics were modelled according to Peleg equation (1988); kinetic parameters were calculated and modelled, as functions of solutes concentration and processing temperature, using response surface methodology. Salt concentration improved water loss at equilibrium but showed a negative interaction effect with sucrose concentration. Salt and sucrose concentrations had a synergetic effect on soluble solid impregnation, on the other side sugar concentration showed to reduce salt gain. A variation (as function of the considered variables) of a mass transfer parameter at the equilibrium condition, is not always reflected by a similar variation of the mass transfer parameter's initial rate. This fact could be explained by the existence of instantaneous interactions at the food-solution interface. The addition of a level (0.5%) of NaCl determined a reduction of the product acceptability very close to that determined by the addition of a sucrose level (5%). Salt gain was not sufficient to balance the sweetness of the product, but an addition of NaCl may help to attenuate the excessive sweetness of product processed with high sucrose concentration. © 2001 Elsevier Science Ltd. All rights reserved.

*Keywords:* Osmotic dehydration; Apple; Mass transfer kinetics; Solute effects

## 1. Introduction

Osmotic treatments could be applied with the aim of modifying the composition of food by partial water removal and impregnation without affecting its integrity. Both the concentration of solution and the nature of the solutes influence the extent and the rate of water removal and the impregnation (Ponting, Waters, Forrey, Jackson, & Stanley, 1966; Bolin, Huxsoll, Jackson, & Ng, 1983; Lerici, Pinnavaia, Dalla Rosa, & Bartolucci, 1985; Beristain, Azuara, Cortes, & Garcia, 1990; Palou, Lopez-Malo, Argaiz, & Welti, 1994). Multi-components salt–sugar aqueous solutions have been studied either to increase the driving force of the process (Lerici et al., 1985; Lenart & Lewicki, 1988) or to optimize salting processes for

animal food stabilization (Collignan & Raoult-Wack, 1992). The solute choice depends on the expected water loss (WL) to solid gain (SG) ratio and the sensory properties of the food products. The prediction and control of WL:SG ratio resulting from a selected solute or solute combination is a basic requirement for process design. Mixture of salt and sucrose in different proportion can be used both for plant and animal treatment to obtain higher WL:SG ratios than that with each of the solute in binary solution and to reduce impregnation.

Purpose of this research work was to study the mass transfer parameters during the osmotic treatment of apple sticks in ternary NaCl-sucrose solutions and to point out the effects (individual or combined) of the two solutes concentration on mass transfer kinetic parameters. Moreover, as the enrichment of the solutes gives the possibilities for product modification – usually termed “direct formulation” – (Torreggiani, 1993), the acceptability of the product was assessed as function of the concentrations of the solutes.

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Nomenclature			
$\Delta M_t^\circ = \text{DMo}, t$	total mass change (or WR) at time $t$ (g/g)	$1/k_2^{\text{SS}}$	soluble solids mass change (or SG) at equilibrium (g/g)
$\Delta M_t^{\text{W}} = \text{DMw}, t$	water mass change (or WL) at time $t$ (g water/g)	$1/k_2^{\text{W}}$	water mass change (or WL) at equilibrium (g/g)
$\Delta M_t^{\text{SS}} = \text{DMss}, t$	soluble solids mass change (or SG) at time $t$ (g soluble solids/g)	$M_0^\circ$	total initial mass (g)
$k_1, k_2$	Peleg constants	$M_t^\circ$	total mass at time $t$ (g)
$k_1^{\text{I}}, k_1^\circ, k_1^{\text{W}}, k_1^{\text{SS}}, k_2^{\text{I}}, k_2^\circ, k_2^{\text{W}}, k_2^{\text{SS}}$	mass transfer constants	$P^{\text{I}}$	mass transfer parameter, either $x^{\text{W}}, x^{\text{SS}}$ , or $M^\circ$
$1/k_1^\circ$	initial rate of total mass change or WR (1/min)	$P_E^{\text{I}}$	mass transfer parameter at equilibrium
$1/k_1^{\text{SS}}$	initial rate of soluble solids mass change or SG (1/min)	$t$	time (min)
$1/k_1^{\text{W}}$	initial rate of water mass change or WL (1/min)	$x_0^{\text{W}}$	water mass fraction at time 0 (g water/g)
$1/k_2^\circ$	total mass change (or WR) at equilibrium (g/g)	$x_t^{\text{W}}$	water mass fraction at time $t$ (g water/g)
		$x_0^{\text{SS}}$	soluble solids mass fraction at time 0 (g soluble solids/g)
		$x_t^{\text{SS}}$	soluble solids mass fraction at time $t$ (g soluble solids/g)

## 2. Materials and methods

### 2.1. Materials

Apples (Fuji variety) from the same orchard were supplied by the same provider in a period between December and January. The fruits having a refractometric index of  $16.5 \pm 0.4^\circ\text{Brix}$  were hand peeled, cored and cut in regular sticks of  $9 \times 9 \times 30 \text{ mm}^3$  (ca. 2 g each) with a mechanical cutting device. Salt and sugar (sucrose) were commercial products provided, respectively, by C.I.S. (Rovigo, Italy) and Eridania (Genova, Italy).

### 2.2. Osmotic treatment

Samples were placed in plastic baskets with a mesh having  $15 \times 15 \text{ mm}^2$  holes. In order to prevent the contact between samples the baskets were divided in six zones by means of an iron thread. Each stick was weighed and marked with a coloured pin before immersion in the osmotic solution. Baskets were piled so to maintain a 50 mm distance between the basket basis and dipped in a beaker containing 5 kg of the osmotic medium. Product/solution ratio was ca. 1:100 w/w so to permit to maintain almost unvaried the initial concentration of the osmotic medium that at the end of the treatment showed a variation of 0.8%.

Osmotic solution was agitated with an  $8 \times 40 \text{ mm}^2$  magnetic stirrer and the speed of the stirrer was set so to have a Reynolds number of about 300. Reynolds number calculation was performed according to Mavroudis, Gekas, and Sjöholm (1998). Thermoregulation of the osmotic treatment was obtained conducting the osmotic treatment in an ISCO FT260 thermostat. Temperature of the osmotic solution was regulated before the immersion of the beaker in the thermostat.

### 2.3. Analytical determinations

Total solids were determined according to AOAC (1984, method 22.018).

Sodium chloride determination was determined on ashes by titration with 0,1 N silver nitrite using potassium dichromate as indicator (MAF, 1989). Ashes were determined on 2g ca. exactly weighed of sample according to AOAC (1984, method 22.027), washed two times with hot bidistilled water and brought to 50 ml volume.

Soluble solids content was determined by refractometric index (AOAC, 1984, 22.024) using a Shibuya No. 105 Abbe refractometer.

Each determination was carried out on four samples.

### 2.4. Mass transfer parameters

Total mass change at time  $t$  ( $\Delta M_t^\circ$ ), water mass change at time  $t$  ( $\Delta M_t^{\text{W}}$ ) and soluble solids mass change at time  $t$  ( $\Delta M_t^{\text{SS}}$ ) were calculated adopting the following equations:

$$\Delta M_t^\circ = (M_t^\circ - M_0^\circ)/(M_0^\circ), \quad (1)$$

$$\Delta M_t^{\text{W}} = (M_t^\circ \cdot x_t^{\text{W}} - M_0^\circ \cdot x_0^{\text{W}})/(M_0^\circ), \quad (2)$$

$$\Delta M_t^{\text{SS}} = (M_t^\circ \cdot x_t^{\text{SS}} - M_0^\circ \cdot x_0^{\text{SS}})/(M_0^\circ). \quad (3)$$

### 2.5. Kinetic model

In order to study mass transport kinetics, four samples were taken from the osmotic solution after 15, 30, 60, 120 and 240 min of osmotic processing. After each sampling the products were rinsed for 2 s time in distilled water and placed on blotting paper for 4 s (1 s for each main face of the parallelepipedal sample).

Data relative to mass transfer parameters were modelled according to the equation proposed by Peleg (1988) and redefined by Palou et al. (1994) and Barat (1998):

$$x_t^W - x_0^W = -t/(k_1^W + k_2^W \cdot t), \quad (4)$$

$$x_t^{SS} - x_0^{SS} = +t/(k_1^{SS} + k_2^{SS} \cdot t). \quad (5)$$

In this work the same equation rewritten as

$$M_t^o - M_0^o = -t/(k_1^o + k_2^o \cdot t) \quad (6)$$

was also used in order to model total mass change kinetics.

The model is an empirical model that proved to fit well experimental data (Palou et al., 1994) and could be easily transformed to a linear relationship. In its linearized form the equation could be written as

$$\pm t/P_t^J - P_0^J = (k_1^J + k_2^J \cdot t), \quad (7)$$

where  $P^J$  could be respectively:  $M^o$ ;  $x^W$ ;  $x^{SS}$ .

It is easy to demonstrate that at the equilibrium condition ( $t \rightarrow \infty$ ) the value for the considered parameters could be calculated as

$$P_E^J = P_0^J \pm 1/k_2^J. \quad (8)$$

Similarly, the initial rate ( $t=0$ ) of mass transfer parameters will be:  $1/k_1^J$ .

This kinetic model offers the advantage that by calculating the inverse of the two constants ( $k_1$  and  $k_2$ ) it is possible to obtain the initial rate of mass transfer parameters and the mass transfer parameters values at the equilibrium condition.

## 2.6. Experimental design

A second-order central composite design (CCD) with three factors (salt concentration, sucrose concentration and temperature) at five levels each was used in order to take into account the individual and interaction effects of the factors. The central point of the experimental range was defined as: 1% concentration of NaCl, 45% concentration of sucrose and 22°C temperature.

A second degree polynomial model was chosen for the description of the response variables  $Y(1/k_1^W, 1/k_2^W, 1/k_1^{SS}, 1/k_2^{SS}, 1/k_1^o, 1/k_2^o)$  as a function of the factor variables:

$X_1$ : salt concentration (% w/w) [0;2],

$X_2$ : sucrose concentration (% w/w) [45;65],

$X_3$ : temperature (°C) [14;30],

$$Y = \sum a_i X_i + \sum a_{ii} X_i^2 + \sum a_{ij} X_i X_j, \quad (9)$$

where  $a_i$  represents the linear,  $a_{ii}$  the quadratic, and  $a_{ij}$  the interaction effect of the factors. The experimental design included 17 experiments with three replications of the centre point. The actual factor values, chosen from preliminary studies, and the corresponding coded values (-2, -1, 0, 1, 2) are given in Table 1.

## 2.7. Sensory analysis

An acceptance test was conducted in order to determine the relative acceptance of the osmotically treated products. A group of 25 male and female (13 and 12, respectively) habitual consumers of apple were enrolled to carry out the sensory evaluation. Evaluations were made by placing a mark on a nine-point like-dislike

Table 1  
Second-order central composite design (CCD)

Experiment no.	Block	Independent variables		
		Salt concentration (% w/w) $X_1$	Sucrose concentration (% w/w) $X_2$	Temperature (°C) $X_3$
1	1	0.5 (-1)	-1 (49.6)	-1 (18)
2	1	1.5 (+1)	-1 (49.6)	-1 (18)
3	1	0.5 (-1)	+1 (59.6)	-1 (18)
4	1	1.5 (+1)	+1 (59.6)	-1 (18)
5	1	0.5 (-1)	-1 (49.6)	+1 (26)
6	1	1.5 (+1)	-1 (49.6)	+1 (26)
7	1	0.5 (-1)	+1 (59.6)	+1 (26)
8	1	1.5 (+1)	+1 (59.6)	+1 (26)
9	1	1 (0)	0 (54.6)	0 (22)
10	1	1 (0)	0 (54.6)	0 (22)
11	2	(0) -2	0 (54.6)	0 (22)
12	2	(2) +2	0 (54.6)	0 (22)
13	2	1 (0)	-2 (44.6)	0 (22)
14	2	1 (0)	+2 (64.6)	0 (22)
15	2	1 (0)	0 (54.6)	-2 (14)
16	2	1 (0)	0 (54.6)	+2 (30)
17	2	1 (0)	0 (54.6)	0 (22)

category scale, with a central neutral category (neither like nor dislike) and with hedonic appeal labelled as: “extremely”, “very”, “moderately”, and “slightly”. Assessor scaling was translated to numerical scores by rating 1 “dislike extremely” and 9 “like extremely”. A score of 7 was considered positive for the calculation of the relative acceptance percentage. Samples were tested paired against a standard (untreated apple sample). Due to the large number of samples each analysis was conducted during two days. A second-order full factorial experimental design (FFD) with two factors (salt and sugar concentration) at five levels each was adopted in order to evaluate the effect of sodium chloride and sucrose on product acceptability. NaCl and sucrose concentration actual factor values were set as reported in Table 1 for  $X_1$  and  $X_2$ , respectively. A second degree polynomial model (Eq. (9)) was chosen for the description of the response variables  $Y$  (acceptance) as a function of the factor variable  $X$ .

### 2.8. Statistical analysis

Data were analysed using the STATISTICA for Windows (StatSoft™, Tulsa, OK) package. In order to estimate the kinetic model constants, non-linear regression was carried out using the quasi-Newton calculus algorithm. The significance associated with the error in the estimation of parameters was determined using a  $t$ -test and the correlation coefficient  $\rho$  of the parameters was calculated in order to test the parameters redundancy (Van Boekel, 1996). The goodness of fit between the experimental and predicted values was determined using a  $\chi^2$  test with the experimental data as the observed and the predicted values as the expected

(Mead, Curnow, & Hasted, 1993). The CCD response variables  $Y$  were calculated by multiple regression and response surface equations were calculated using a definitive model which consider only the influence of factors significant at level  $>95\%$ . Response surface were drawn by plotting  $Y$  as a function of two factor variables, the other factor variable was set to its medium value. The regression validity was checked by estimation of determination coefficient  $R^2$  (Pike, 1986), standard error of estimate (S.E.), Fisher test and the associated  $P$ -values.

## 3. Results and discussion

### 3.1. Kinetic model

The kinetic model was used to fit mass transfer parameter data over processing time. The values of model parameters, together with the determination coefficient are reported in Tables 2–4. The determination coefficients varied from 0.999 to 0.969 for  $\Delta M_t^o$ , from 0.996 to 0.969 for  $\Delta M_t^w$  and from 0.998 to 0.967 for  $\Delta M_t^{ss}$ . In all cases the experimental values and the values predicted by the model were significantly close ( $\chi^2 < \text{critical value } 5\%$ ), to confirm the suitability of the model. The curve described by the equation showed to fit well experimental data whether they referred to osmotic dehydration processes conducted in binary (sugar) or ternary (sugar + salt) solutions. The model also showed to describe mass transfer kinetics at different processing temperatures but it should be considered that the pattern of the curve changes with the variation of the  $k_1$  and  $k_2$  constants. The predictive capability of the model can

Table 2  
Kinetic model of water mass change parameter ( $\Delta M_t^w$ )

Experiment no.	$R^2$	$k_1$	S.E.	$P$	$k_2$	S.E.	$P$
1	0.9800	175.57	35.710	0.0079	3.0500	0.3500	0.0001
2	0.9801	214.19	36.847	0.0044	2.6572	0.3015	0.0009
3	0.9825	201.27	30.778	0.0028	2.2756	0.2490	0.0006
4	0.9853	100.79	15.565	0.0029	2.7950	0.1844	0.0001
5	0.9873	182.20	25.047	0.0019	2.7295	0.2219	0.0003
6	0.9936	169.73	20.071	0.0035	1.9727	0.1558	0.0011
7	0.9955	156.29	12.639	0.0002	2.4086	0.1143	0.0000
8	0.9846	123.76	21.517	0.0045	1.7095	0.1888	0.0008
9	0.9956	176.90	14.457	0.0003	2.2412	0.1201	0.0001
10	0.9902	185.38	22.565	0.0012	2.4251	0.1892	0.0002
11	0.9870	210.01	29.286	0.0020	2.4206	0.2330	0.0005
12	0.9801	169.03	30.371	0.0051	2.2510	0.2567	0.0009
13	0.9800	221.60	38.772	0.0046	2.6254	0.3111	0.0011
14	0.9848	143.63	22.867	0.0033	2.0759	0.2014	0.0005
15	0.9692	176.18	46.537	0.0193	3.0640	0.4560	0.0026
16	0.9830	139.27	23.905	0.0043	2.0076	0.2106	0.0007
17	0.9901	173.16	21.294	0.0012	2.3179	0.1806	0.0007

Table 3  
Kinetic model of soluble solids mass change parameter ( $\Delta M_t^{SS}$ )

Experiment no.	$R^2$	$k_1$	S.E.	$P$	$k_2$	S.E.	$P$
1	0.9710	243.13	58.914	0.0145	9.1800	0.8300	0.0004
2	0.9771	317.46	91.756	0.0258	8.7425	1.1063	0.0014
3	0.9965	114.05	10.604	0.0004	8.7377	0.2211	0.0000
4	0.9983	268.16	26.987	0.0022	4.8444	0.2374	0.0003
5	0.9911	134.05	20.271	0.0027	9.0037	0.3865	0.0000
6	0.9866	109.46	38.180	0.0642	10.058	0.6266	0.0006
7	0.9876	172.34	26.960	0.0310	5.3100	0.3496	0.0001
8	0.9949	97.764	11.034	0.0009	6.9507	0.2162	0.0000
9	0.9966	200.12	16.178	0.0002	8.3957	0.2476	0.0000
10	0.9677	212.71	53.551	0.0165	7.6161	0.7647	0.0006
11	0.9826	192.62	37.729	0.0070	8.4737	0.5830	0.0001
12	0.9964	132.64	11.245	0.0003	7.0853	0.1939	0.0000
13	0.9876	317.14	46.824	0.0025	10.920	0.6295	0.0000
14	0.9834	85.359	23.129	0.0210	5.6720	0.4570	0.0002
15	0.9796	225.65	45.195	0.0075	9.1422	0.6666	0.0001
16	0.9917	122.88	17.123	0.0020	8.1458	0.3377	0.0000
17	0.9665	225.41	61.481	0.0215	7.9790	0.8500	0.0007

Table 4  
Kinetic model of total solids mass change parameter ( $\Delta M_t^0$ )

Experiment no.	$R^2$	$k_1$	S.E.	$P$	$k_2$	S.E.	$P$
1	0.9650	387.47	93.880	0.0145	4.4000	0.7600	0.0044
2	0.9781	434.59	83.434	0.0065	3.7913	0.6048	0.0033
3	0.9963	728.29	63.526	0.0003	1.7250	0.3136	0.0053
4	0.9934	228.87	23.967	0.0007	5.4881	0.2756	0.0000
5	0.9954	532.05	49.819	0.0004	3.1564	0.3145	0.0005
6	0.9889	379.78	49.291	0.0015	1.9197	0.2999	0.0030
7	0.9986	567.73	28.475	0.0000	3.2382	0.1774	0.0000
8	0.9952	324.96	26.945	0.0003	1.7312	0.1659	0.0005
9	0.9957	416.97	39.470	0.0005	2.5866	0.2526	0.0005
10	0.9702	553.65	146.43	0.0194	2.6009	0.8612	0.0392
11	0.9976	591.69	40.406	0.0001	2.5793	0.2321	0.0004
12	0.9862	678.67	120.30	0.0049	1.6594	0.5980	0.0501
13	0.9924	455.84	55.731	0.0012	2.9523	0.3622	0.0012
14	0.9892	598.06	113.89	0.0135	1.9759	0.5925	0.0445
15	0.9784	375.81	76.281	0.0079	5.0499	0.6562	0.0015
16	0.9887	382.19	49.829	0.0016	1.9203	0.3029	0.0032
17	0.9964	378.39	31.868	0.0003	3.0217	0.2234	0.0002

be observed in Fig. 1 were the Eqs. (4)–(6) were used to model the mass transfer parameters. All the parameters showed the characteristic osmotic concentration behaviour with an initial high rate of water removal and solute uptake followed by slower removal (and uptake) in the later stages. Similar curves were reported by several authors (Ponting et al., 1966; Farkas & Lazar, 1969; Hawkes & Flink, 1978; Conway, Castaigne, Picard, & Vovan, 1983; Lerici et al., 1985; Beristain et al., 1990; Azuara, Cortes, Garcia, & Beristain, 1992; Palou et al., 1994).

The equation parameters  $k_1$  and  $k_2$  showed to be always statistically significant at a  $P$  level  $<0.05$  (Tables 2–

4) and the correlation coefficient  $\rho$  estimated from parameters variance-covariance matrix was never higher than critical value 0.96 according to Johnson and Frazier (1985); this implies that the two parameters are not redundant.

### 3.2. Effect of the single factor variables (NaCl, sucrose concentration and temperature)

Figs. 2–4 present the values of response variables ( $1/k_1^W$ ,  $1/k_2^W$ ,  $1/k_1^{SS}$ ,  $1/k_2^{SS}$ ,  $1/k_1^0$ , and  $1/k_2^0$ ) versus factor variable levels. Graphs were drawn by plotting response

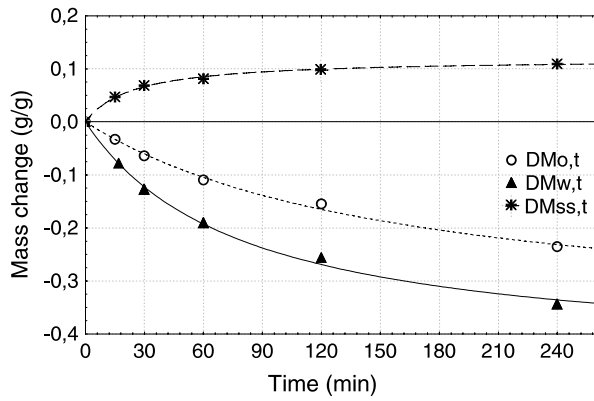
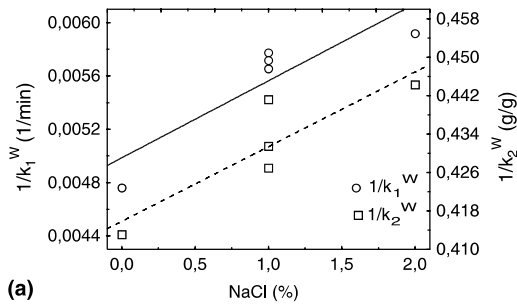
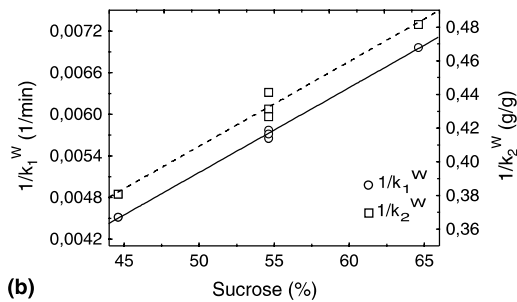


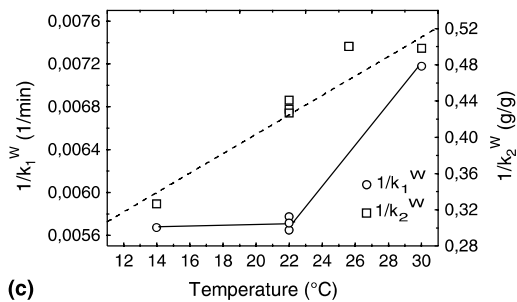
Fig. 1. Application of the Peleg model to mass transfer data: total mass change (DMo,t), water mass change (DMw,t), soluble solids mass change (DMss,t).



(a)



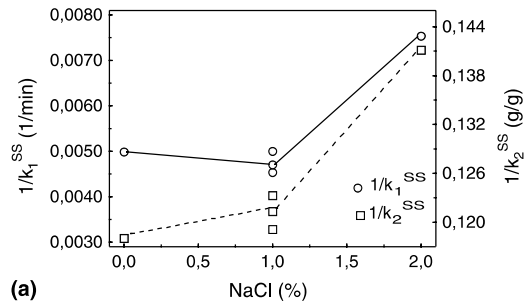
(b)



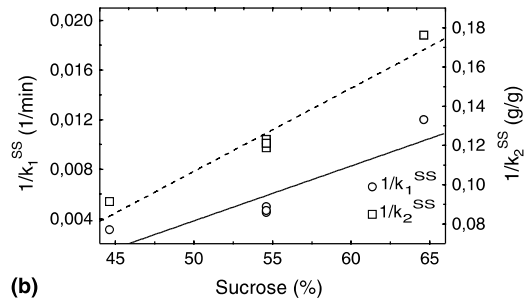
(c)

Fig. 2. Individual effect of the variables on water mass change kinetic parameters ( $1/k_1^w$ ,  $1/k_2^w$ ). (a) NaCl concentration (% w/w); (b) sucrose concentration (% w/w); (c) temperature (°C).

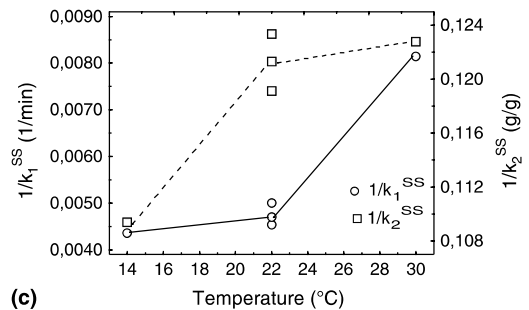
variables as a function one factor variables (at -2, 0 and +2 coded levels) and setting the other two variables to their medium value (0 coded level).



(a)



(b)



(c)

Fig. 3. Individual effect of the variables on soluble solids mass change kinetic parameters ( $1/k_1^{SS}$ ,  $1/k_2^{SS}$ ). (a) NaCl concentration (% w/w); (b) sucrose concentration (% w/w); (c) temperature (°C).

The linear regression lines were shown only when the correlation coefficient between dependent and independent variables resulted significant at a  $P < 0.05$  level.

The  $1/k_2^w$  parameter (water mass change at equilibrium) showed a positive linear correlation with the three factor variables, the  $1/k_1^w$  parameter (water mass change initial rate) showed a positive linear correlation only with NaCl and sucrose concentration whilst it seemed to be affected by temperature only over 22°C.

Both  $1/k_2^{SS}$  parameter (soluble solids mass change at equilibrium) and  $1/k_1^{SS}$  parameter (soluble solids mass change initial rate) showed a positive linear correlation with sucrose concentration; on the other side they showed to be affected significantly by NaCl concentration only at values higher than 1%. Processing temperature influenced positively  $1/k_2^{SS}$  and  $1/k_1^{SS}$  parameters.  $1/k_2^{SS}$  rapidly increased as temperature increased to 22°C and then it seemed to be stabilized, while  $1/k_1^{SS}$  showed to be affected by temperature only over 22°C.

Total mass change at equilibrium ( $1/k_2^o$ ) was positively influenced by the three factor variables; while it

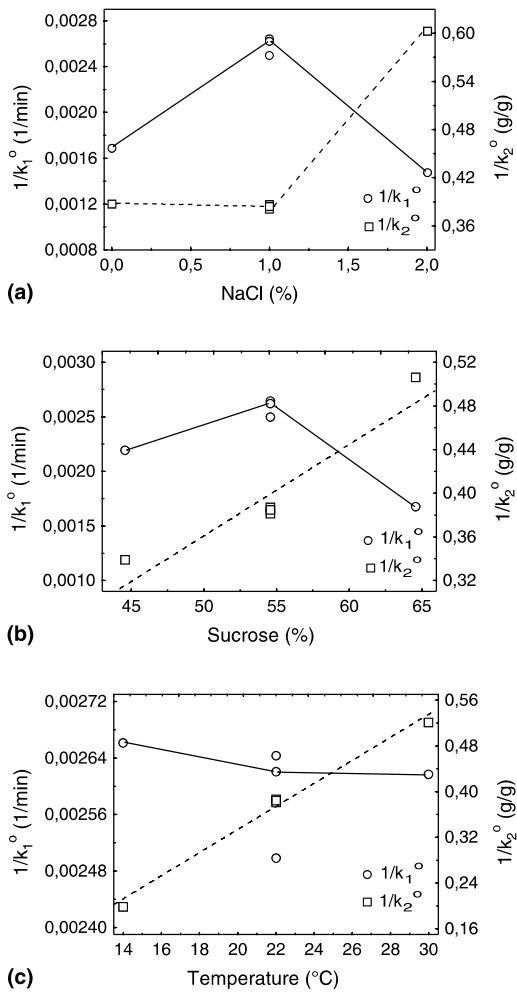


Fig. 4. Individual effect of the variables on total mass change kinetic parameters ( $1/k_1$ ,  $1/k_2$ ). (a) NaCl concentration (% w/w); (b) sucrose concentration (% w/w); (c) temperature (°C).

showed a linear correlation with sucrose concentration and temperature and it was affected by NaCl only at concentration higher than 1%. The initial rate of total mass change ( $1/k_1$ ) showed a maximum value for intermediate levels of NaCl and sucrose concentration. This behaviour could be due to a cellular response to the osmotic pressure increment: over the concentration of 1% for NaCl and 54.6% for sucrose the functionality of the cellular membrane was reduced and the membrane lost its selectivity allowing the solutes to enter in the cell. Thus determined an increase of solid gain and a reduction of the total mass change initial rate (Fig. 4(a) and (b)). The total mass change initial rate seemed to be not affected by processing temperature (Fig. 4(c)).

### 3.3. Experimental design study

Linear, quadratic and interaction effects of the polynomial model used (coefficient value and significance level) are reported in Table 5 together with the model

significance ( $P$  associated to  $F$ ) and goodness of fit ( $R^2$  and S.E.). The definite models were computed using the only significant effects at  $P < 0.05$  level. All the models were considered satisfactory at  $P < 0.01$  level except for the total mass change initial rate model that showed no significance ( $P < 0.089$ ).

### 3.4. Salt-sugar combined effects

The simultaneous increase of sucrose and NaCl determined an increment of water mass change at equilibrium (Fig. 5), on the other side the negative interaction between the two independent variables (data reported in Table 5) permit to assess that there is an antagonistic effect of the two solutes on water mass change at equilibrium. These results are in agreement with those obtained by Lenart and Flink (1984a,b) and Collignan and Raoult-Wack (1994). The salt-sucrose antagonistic effect on water mass change is of particular interest if we consider that the chemical potential of the ternary solution increases when the concentration of both solutes increases. These results could be explained by a reduction of plasmatic membrane permeability that takes place during plasmolysis process, as suggested by other authors (Tonzig & Marré, 1971). Furthermore, it would be considered that, due to the different molecular dimensions, sucrose remains mainly in the extracellular space whilst sodium chloride can penetrate into the cell, thus leading to a reduction of the osmotic pressure gradient.

The water mass change initial rate showed a completely different behaviour (Fig. 6). At low concentration of both sucrose and NaCl the initial transfer rates are hindered by the increasing of a single solute. On the other side the positive interaction effect on water mass change initial rate of the two solutes showed to be synergetic. The increasing of salt concentration at low sugar levels, in the process conditions, appeared to determine a slight but statistically significant reduction of water mass change initial rate that could be related to a fast NaCl diffusion into the cells thus reducing the dewatering driving force.

On the other hand, in absence of NaCl, the water transfer initial rate seemed to be not significantly influenced by the increasing of sugar concentration and this could be explained considering the enhancement of the solution viscosity (from  $8.27 \times 10^{-3}$  Pa s at 45°Brix to  $128.3 \times 10^{-3}$  Pa s at 65°Brix) that can affect dehydration process.

Taking into account the soluble solids mass change at equilibrium (Fig. 7), it showed to be positively influenced by sucrose concentration and the two solute concentrations showed to have a synergetic effect. Soluble solids mass change initial rate was positively influenced by the two considered factor variables (Fig. 8) but there was not observed any interaction effect.

Table 5  
Polynomial models of kinetic parameters, as calculated from Peleg's equation constants, as function of the factor variables<sup>a</sup>

Coefficient	$1/k_1^W$	$1/k_1^{SS}$	$1/k_1^c$	$1/k_2^W$	$1/k_2^{SS}$	$1/k_2^c$
$b_0$	0.0099**	0.0022	0.0072*	0.5168**	-0.0194	-0.0901
<i>Linear</i>						
$b_1$	-0.0188**	-0.0075**	-0.0102*	n.s.	n.s.	n.s.
$b_2$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$b_3$	n.s.	n.s.	n.s.	-0.0344**	n.s.	n.s.
<i>Quadratic</i>						
$b_{11}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$b_{22}$	1.3 E-5*	0.3 E-5**	0.2 E-5*	n.s.	n.s.	0.0004**
$b_{33}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
<i>Interaction</i>						
$b_{12}$	0.0004**	n.s.	2 E-4**	-0.0064**	0.0027**	-0.0232**
$b_{13}$	n.s.	3.6 E-4**	n.s.	0.1795**	-0.0061**	0.0506**
$b_{23}$	0.9 E-5*	n.s.	n.s.	0.0005**	0.0001**	-0.0006*
$R^2$	0.7799	0.6521	0.3828	0.8967	0.7929	0.8289
S.E.	7.3 E-4	0.0017	6.3 E-4	0.0251	0.0245	0.0684
$F$	10.628	8.124	2.687	26.03	16.59	10.665
$P <$	0.0007	0.0027	0.089	0.0000	0.0001	0.0006

<sup>a</sup> 1: NaCl (% w/w); 2: sucrose (% w/w); 3: temperature (°C).

\* Effect significant at  $P < 0.05$  confidence level.

\*\* Effect significant at  $P < 0.01$  confidence level.

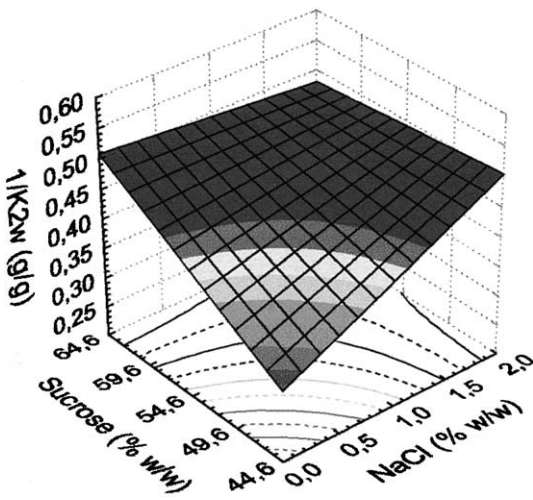


Fig. 5. Water mass change at equilibrium ( $1/k_2^W$ ) as function of the NaCl and sucrose concentration of the solution.

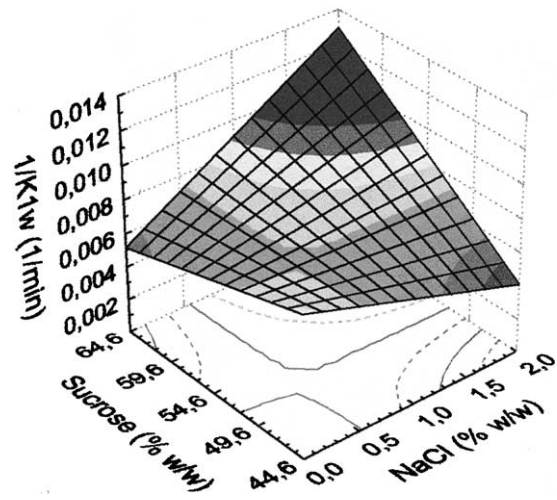


Fig. 6. Water mass change initial rate ( $1/k_1^W$ ) as function of the NaCl and sucrose concentration of the solution.

Total mass change at equilibrium (Fig. 9) resulted to be mainly influenced by water mass change but the positive salt-sucrose interaction effect on soluble solids mass change determined a decrease of the total mass changes when NaCl and sucrose were at maximum concentrations.

### 3.5. Sodium chloride gain

Salt gain showed to be limited by high sucrose concentrations (Fig. 10). This phenomenon, observed

on model gels (Raoult-Wack, Guilbert, LeMaguer, & Rios, 1991) and vegetable products (Lenart & Flink, 1984a,b; Collignan & Raoult-Wack, 1994), was related to the formation of a concentrated superficial sucrose layer. In this study it was possible to observe that soluble solids gain ( $\Delta M^{SS}$ ) is positively affected by the two solute concentrations; so, in our advice, the hypothesis of a permeability reduction of the cell membrane during plasmolysis should be taken in consideration. While salt gain was negatively affected by the increase of sucrose concentration, the soluble solids uptake showed to increase together with the



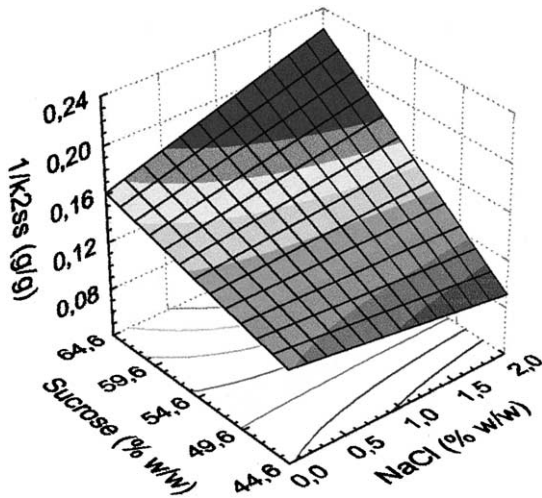


Fig. 7. Soluble solids mass change at equilibrium ( $1/k_2^{SS}$ ) as function of the NaCl and sucrose concentration of the solution.

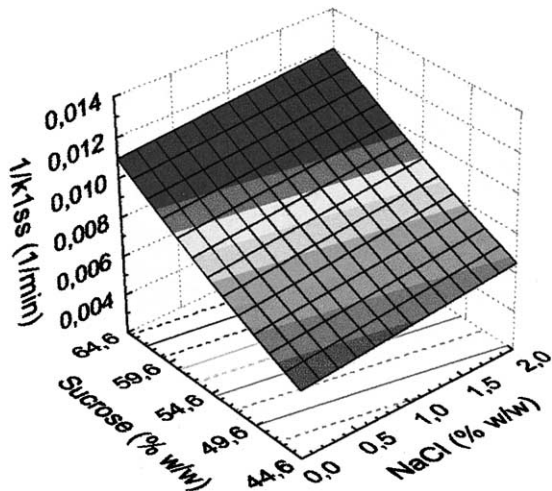


Fig. 8. Soluble solids mass change initial rate ( $1/k_1^{SS}$ ) as function of the NaCl and sucrose concentration of the solution.

sugar content of the solution. This behaviour is probably due to an increase of osmotic pressure gradient that could determine a loss of functionality of the cell plasmatic membrane that allows the solutes to enter by loosing its selectivity.

### 3.6. Effect of temperature

Processing temperature, considered in the range 14–30°C, showed to influence positively the water and solid transfer when NaCl was set at fixed level (zero coded factor level) except for  $1/k_2^{SS}$  which was affected positive by temperature only at highest sucrose concentration. On the other side, at fixed level of sucrose, dehydration ability of NaCl showed to be strongly dependent on temperature.

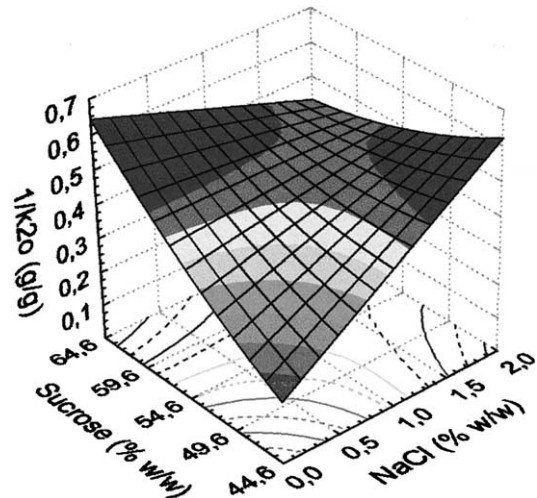


Fig. 9. Total mass change at equilibrium ( $1/k_2^t$ ) as function of the NaCl and sucrose concentration of the solution.

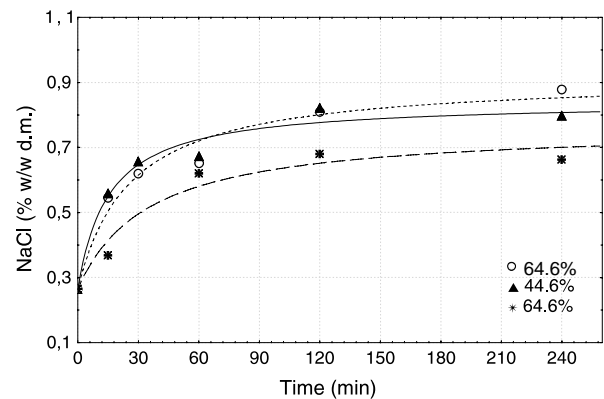


Fig. 10. Effect of the sucrose concentration (44.6%: ( $\blacktriangle$ ) S.D.  $\pm 0.1$ ; 54.6%: ( $\circ$ ) S.D.  $\pm 0.1$ ; 64.6%: ( $*$ ) S.D.  $\pm 0.1$ ) on sodium chloride uptake during fruit osmodehydration.

### 3.7. Sensory quality

Sucrose and NaCl concentration showed a negative correlation with acceptability judgement of the osmotically processed product (Fig. 11), at increasing concentrations of the two molecules the product sweetness and saltiness were enhanced, respectively. The increment of a level of sucrose showed a negative effect on product acceptability similar to that of one level increment of sodium chloride. This fact was determined, as reported by the panelists, by an excessive sweetness of the product which in turn was probably dependent on the high sugar content of the raw material; in fact the fruits presented a mean refractometric value of 16.5°Brix. Other authors (Lerici et al., 1985) reported that an addition of 1% NaCl might help to attenuate the sweetness, caused by the sugar uptake of the solution, of osmodehydrated apple. In this study a positive interaction of sugar and salt concentration on product acceptability was evidenced

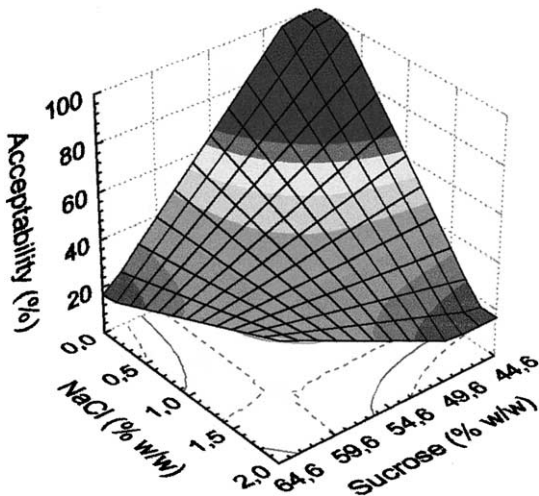


Fig. 11. Product acceptability as function of the NaCl and sucrose concentration of the solution.

Table 6  
Polynomial model of acceptability as function of the factor variables<sup>a</sup>

Effect	Coefficient	S.E.	<i>P</i> <
<i>b</i> <sub>0</sub>	385.333	61.246	0.0001
<i>b</i> <sub>1</sub>	−6.000	1.109	0.0002
<i>b</i> <sub>2</sub>	−258.085	50.007	0.0003
<i>b</i> <sub>12</sub>	4.330	0.906	0.0006
<i>Model significance</i>			
<i>R</i> <sup>2</sup>	0.7765	<i>F</i>	12.744
S.E.	20.2550	<i>P</i> <	0.0007

<sup>a</sup> 1: NaCl (% w/w); 2: sucrose (% w/w).

(Table 6) but the interaction coefficient was quite low and product acceptability was not improved effectively at high sucrose and salt levels. This behaviour could be related both to the presence of high levels of sugar that could decrease the saltiness threshold, so to hide salt presence, and to the sodium chloride increasing effect on sucrose sweetness (Amerine, Pangborg, & Roessler, 1965). Moreover it is to consider that high sugar concentrations showed to hinder salt entrance (Fig. 10) so the factor variable NaCl% of the solution is not strictly related to actual salt content of the final product. The osmodehydrated apple pieces were evaluated as “as is products” but since the interest in the utilization of such products as functional ingredients to include in complex food as dairy products, ice-creams or bakery foods is increasing, it would be helpful to evaluate these ingredients once included in the final products.

#### 4. Conclusions

Peleg’s equation showed to be suitable to model the water removal (water mass change), solute uptake (sol-

uble solids mass change), and weight reduction (total mass change), during osmotic concentration of apple whether it is conducted in binary or ternary solutions or at different processing temperatures.

All the considered factor variables (sucrose concentration, salt concentration and temperature) showed to influence the mass transfer kinetics and the relative parameters ( $1/k_1^W$ ,  $1/k_2^W$ ,  $1/k_1^{SS}$ ,  $1/k_2^{SS}$ ,  $1/k_1^o$ , and  $1/k_2^o$ ).

The kinetic parameters showed different trends with the variation of the factor variables. This fact could be explained by a biological response of plant membranes that undergo plasmolysis under the influence of the osmotic stress.

The antagonistic effect between the two solutes on product dehydration and salt gain, that was observed in studies conducted on different foodstuffs, was confirmed and it was observed a synergistic action of the two solutes on soluble solids gain.

With respect to the sensory analysis of apple samples dehydrated in ternary solutions, it is possible to assert that salt gain was not sufficient to balance the excessive sweetness of product processed at high sucrose concentrations. Small additions of NaCl (up to 1%) did not determine the complete decay of product acceptability if coupled with limited sucrose concentrations (<54.6%).

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