



A description of a flat geometry direct osmotic concentrator to concentrate tomato juice at ambient temperature and low pressure

Konstantinos B. Petrotos *, Alexandra V. Tsiadi, Eleftherios Poirazis, Dimitrios Papadopoulos, Heraclis Petropakis, Paschalis Gkoutosidis

Laboratory of Food Process Engineering, Department of Biosystems Engineering, Technological Educational Institute of Larisa, TEI Campus, 41100 Larisa, Greece

ARTICLE INFO

Article history:

Received 11 May 2009

Received in revised form 11 September 2009

Accepted 9 October 2009

Available online 7 November 2009

Keywords:

Direct osmosis

Electrodialysis

Osmotic concentration

Tomato juice

Sodium chloride brine

Osmotic medium re-concentration

ABSTRACT

A novel membrane module was developed for the purpose of concentrating tomato juice by direct osmosis at ambient temperature and low pressure. This stainless steel module was in the shape of a flat configuration consisting of two parts of a square flange screwed together, with a piece of flat membrane between them. The configuration resulted in the formation of two chambers of special morphology which allowed the flow of tomato juice and osmotic medium in the two respective sides of the membrane and enabled the osmotic transfer of pure water from the juice to the osmotic medium side.

By using this module at ambient temperature and low pressure (~4 bar), with sodium chloride as the osmotic medium, fresh tomato juice was concentrated from 5.5°Brix to the level of approximately 16°Brix, and from 4.25 to 7.5°Brix. The levels of achieved concentrations meet the standards attained by two commercially available tomato concentrates with concentration ranges 7–9 and 10–14°Brix, known as PASSATA and PIZZA SAUCE, respectively.

For re-concentration of the post-process diluted osmotic NaCl brines, electrodialysis is proposed as a viable alternative to the commonly used evaporative process. Electrodialysis is an established methodology in the chemical industry for concentrating brines up to the saturation and is far more economical than evaporation.

In summary, the use of NaCl brines as osmotic media in a combined direct osmosis–electrodialysis process operated at ambient temperature and low pressure allows concentration of tomato juice to produce tomato concentrates of commercial interest.

© 2009 Elsevier Ltd. All rights reserved.

1. Introduction

The tomato processing industry is an enormous industry worldwide, where the bulk of the tomatoes being processed results in different levels of tomato juice concentration. In Mediterranean countries, cultivation and processing of tomatoes forms an important part of the economy. In Greece for example, in an excess of fifty (50) tomato processing factories of variable capacities spread throughout the country, about 1,000,000 tons of tomatoes are processed annually, to produce tomato juice concentrates (Greek Ministry of Agriculture, 1999).

Despite efforts to update the technology of the tomato processing factories, which have led to the introduction of cutting edge technology such as aseptic packaging technology, the conventional concentration method of vacuum evaporation still remains the dominant method for obtaining the concentrate from the raw juice. However, the energy demands of this method are very high, and a

deterioration in quality seems to be unavoidable, since the processed juice is exposed to temperatures of about 65–72 °C for an extended period of time.

Attempts to replace the conventional evaporative concentration method with membrane technology have led to proposals of reverse osmosis as an alternative methodology Merson et al., 1980; Ishii et al., 1981; Watanabe et al., 1982; Pepper et al., 1985; Merlo et al., 1986a,b; Köseoglu et al., 1991). However, this method was proved to be effective only for pre-concentrating the juice up to a level of 9°Brix. At higher concentrations, the fouling problem and the high osmotic pressure of the juice sharply reduce the water flux through the membrane. Indeed, this technology has been successfully used in a cooperative factory at Piassenza – Italy, but to only pre-concentrate tomato juice (Gherardi et al., 1986). Furthermore, attempts to combine RO technology with UF or MF or even centrifugation are also presented in the literature. Cross (1988) patented a process which used UF pre-treatment of the juice and utilized hollow fiber RO in order to concentrate the clear UF permeate up to 30–60°Brix and remix it after this concentration with the UF retentate to obtain a highly concentrated juice including the

* Corresponding author. Tel.: +30 6944191500; fax: +30 2410 613153.

E-mail address: petrotos@teilar.gr (K.B. Petrotos).

pulp material. Moreover, Köseoglu et al. (1991) presented a method using conventional filtration to remove the suspended material of the tomato juice (the part so-called “pulp”) coupled with RO concentration of the clear filtrate to up to a maximum of 15.5°Brix, a method which was covered by a patent issued by Golubev et al. (1991). A similar process scheme, in which the clear tomato serum was obtained by centrifugation of raw tomato juice and RO employed to carry out its concentration was presented by Swafford (1983) but it never had any commercial follow up. According to Pepper et al. (1985), none of the above alternatives can be used commercially because they produce a low quality concentrate due to pure consistency and texture which make them susceptible to fractionation by syneresis.

Osmotic distillation (Vahdati and Priestman, 1994; Johnson et al., 1989; Mengual et al., 1993) emerges as another alternative for tomato juice concentration at low temperature and pressure (Durham and Nguyen, 1994). This technique uses porous hydrophobic polymeric membranes from PTFE or PVDF and the mechanism of achieving the concentration is based on water vapour transport through the membranes pores due to the difference of the osmotic pressure of the juice and the osmotic medium (brine or highly concentrated carbohydrate solution) established across the membrane. According to Hogan et al. (1998) and Kunz et al. (1996) the method presents lower performance in terms of permeation flux compared with RO but it does not have the concentration limitations of RO. Additionally, osmotic distillation yields a superior product compared with conventional thermal evaporation because it retains the aroma profile of the juice. However, osmotic distillation technology still faces certain problems concerning the high cost of the hydrophobic membranes used (their price is substantially higher than the RO membranes), their expected short life span, as they can easily get wetted and destroyed due to liquid penetration (Hogan et al., 1998) and finally due to the employment of expensive thermal evaporation to manage the reinforcement by re-concentration of the post-process diluted osmotic medium.

Over the last two decades yet another alternative to conventional vacuum evaporation has emerged. This is the method of direct osmosis concentration and promises concentration of tomato juice at ambient or even sub-ambient temperatures and low pressure. The technology was developed in the USA by Osmotek Inc. and details of its application to the concentration of juice are

presented in a number of publications, both, by the Osmotek group, and several authors (Beaudry and Lampi, 1990a,b; Wrolstad et al., 1993; Herron et al., 1994; Anonymous, 1993; Petrotos et al., 1998, 1999). According to Anonymous (1993), the method of Osmotek is capable of producing a concentrate of 22°Brix. The serious drawback of this method is the re-concentration of the osmotic medium after its dilution. The suggested by Osmotek use of evaporative concentration to overcome this problem would result in a sharp increase in the cost if this technology was to be used in the production of tomato concentrate. This could be the reason that this technology has not yet been widely adopted and there are no reports of installations of such kind.

The aims of the present work are (a) to investigate whether the technology of direct osmosis can serve as an alternative to the current conventional evaporative technology for the concentration of tomato juice, and (b) to suggest an economically viable solution to the inherent problem of re-concentration of the post-process diluted osmotic media.

2. Materials and methods

The experimental rig used to carry out the experimental work is shown in Fig. 1. It consisted of the tomato juice stock tank, the osmotic medium stock tank, two plastic pneumatic membrane pumps for circulating the two liquids and the square shaped osmotic module that supported the membrane. All components were connected by plastic reinforced pipes.

The direct osmosis module was a 1 ft × 1 ft square flange constructed from 316 stainless steel (Orfanidis Mechanical Constructions Co., Thessalonica, Greece) with a membrane sheet (Ecofilter reverse osmosis membrane, Ecofilter Co., Greece) inserted between the two flange parts. The membrane was a reverse osmosis type thin film composite polyamide membrane, with 99% rejection as NaCl, total thickness of 260 μm , 120 μm backing material thickness, and water permeation coefficient, A , equal to 4.47 $\text{l/m}^2 \text{ h atm}$. The membrane backing material was also sent to the European Membrane Institute in Twente and analyzed for porosity (ϵ) using a density meter and tortuosity factor (τ) by using a method introduced by Mackie and Meares (1955). The porosity factor of the membrane was measured $\epsilon = 0.498$ while its tortuosity was $\tau = 3.02$. One part of the flange (Fig. 2, Part A) had a 1 mm deep

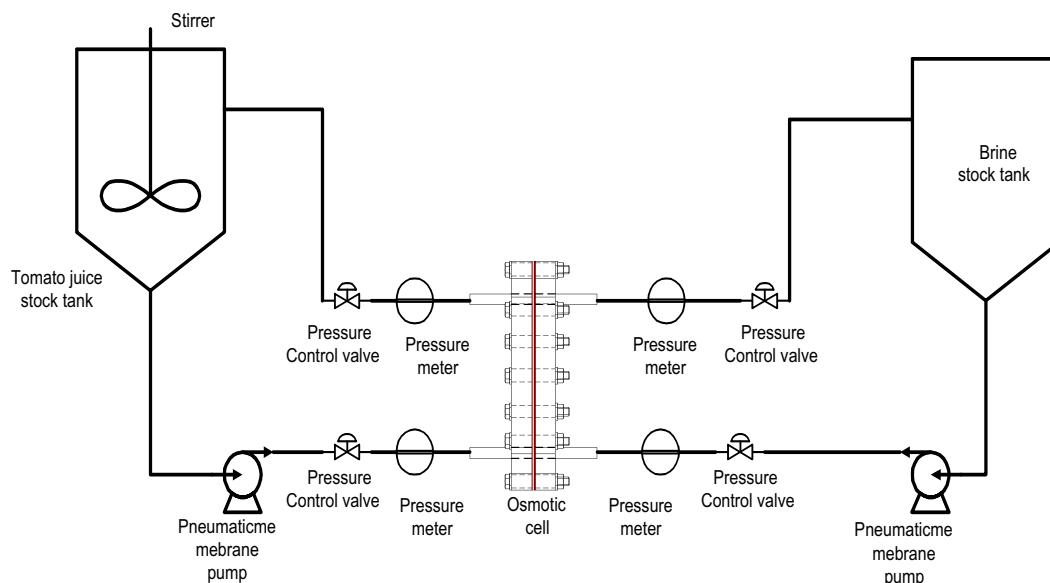


Fig. 1. The direct osmosis experimental rig.

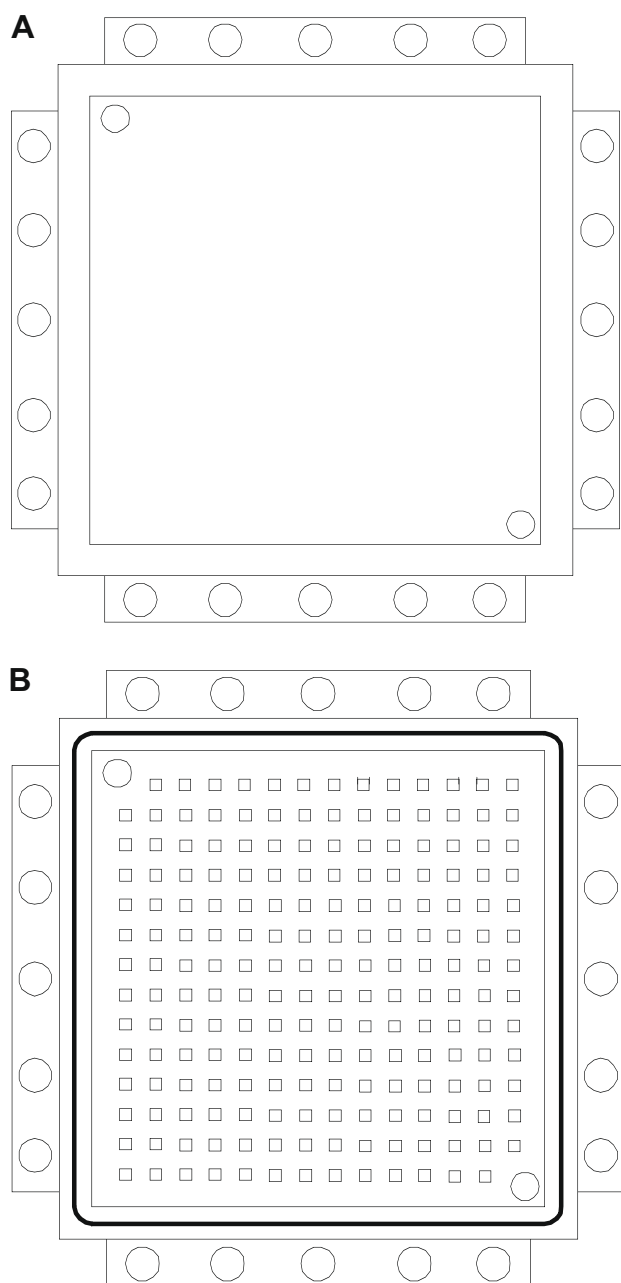


Fig. 2. Graphical representation of the two parts, A and B, of the osmotic cell.

recess for the positioning of an approximately 1 mm thick mesh, i.e. of about the same thickness as the depth of the recess. The space between this construction and the membrane formed the osmotic medium chamber. The plastic mesh acted both as a spacer and a flow distributor allowing the osmotic medium to spread evenly over the membrane surface. The space between the membrane and the second part of the flange formed the chamber for the circulation of tomato juice. This part (Fig. 2, Part B) had a recess about 4 mm deep and the surface inside the recess was equipped with orthogonal baffles about 2 mm high. The construction on the tomato juice side of the flange was intended to evenly distribute the flow over the membrane surface, and to promote turbulence. Installation of the membrane in the module was in five consecutive steps as follows:

STEP 1: The plastic mesh was placed in the 1 mm recess of the first piece of the flange.

STEP 2: A piece of permanite gasket was applied peripherally to this part of the flange.

STEP 3: A square 1 ft × 1 ft piece of membrane was placed with the smooth side upwards over this part of the flange and aligned against its ends.

STEP 4: A piece of permanite gasket identical in shape to the first one was set over the membrane.

STEP 5: The second part of the flange was placed over the construction, the bolts were inserted in the peripherally shaped holes and the corresponding nuts were screwed diagonally in order to avoid sleeping of the two pieces of flange and to ensure alignment.

For membrane cleaning, the P3 Ultrasil 10 alkaline detergent (supplied by Henkel, Ecolab, Greece) was used at approximately 1% concentration in distilled water. Prior to its use, the membrane was cleaned for 1 h at 55 °C with the detergent solution, and rinsed with distilled water for at least 20 min in order to remove residuals of the membrane preservative. After each experimental run the following membrane cleaning regime was followed:

- Initially, the membrane system was rinsed with cold water for 20 min with purpose to remove the tomato concentrate residual.
- After that a P3 Ultrasil 10 alkaline detergent 1% w/w in water was passed through the system at 55 °C for 1 h.
- Consequently, a rinse with cold water was performed for 20 min.
- Finally, the membrane cell was filled with a 0.5% w/w sodium bisulphate solution in water in order to prevent contamination of the membranes and preserve the cell sterile till the next run would occur.

The liquid tomato juice was freshly squeezed “cold-break” juice supplied by the Cooperative Factory of Omospondia (Gefira, Thessalonica). The juice was obtained from the stock tank just after the finisher, cooled and put in 5 kg tins which were seamed and carried to the University Lab within the next hour. Six kilograms of this juice were used in each experimental run.

The osmotic medium was sodium chloride (NaCl) brine which was prepared from industrial grade cooking salt supplied by Kallas, Thessalonica, Greece in 1 kg plastic bags. The salt was diluted in distilled water to obtain the appropriate brine concentration. The importance of cleanness of the salt needs to be stressed here, because otherwise a cloudy brine may result.

The experimental procedure consisted of the following steps:

- (a) Six kilograms of fresh tomato juice were poured into the juice stock tank and kept agitated at 30 rpm.
- (b) The osmotic medium tank was filled with 10 kg of freshly prepared concentrated sodium chloride (NaCl) brine.
- (c) Tomato juice circulation was initiated, while the hydraulic pressure was set at approximately 4 bar.
- (d) The NaCl brine circulation was initiated and the hydraulic pressure was set at about 1.5 bar.
- (e) Both the tomato juice and the osmotic brine were sampled at frequent time intervals and the samples were retained to be tested at the end of each experimental run, which lasted approximately 11 h.
- (f) The respective sample concentrations were measured by using the Stanley & Bellingham RFM340 high precision digital refractometer.

The relative concentrations of the tomato solutions were directly taken by operating the refractometer at the °Brix scale. The concentration of the NaCl solutions, C, was measured indirectly,

Table 1
Summary of experimental conditions for runs A and B.

Experimental run	A	B
Raw material	Fresh tomato juice	Fresh tomato juice
Tomato juice temperature (°C)	26.9	28.0
Tomato juice flow rate (kg/h)	150	152
Temperature of osmotic brine (°C)	25.9	27.0
Osmotic brine flow rate (kg/h)	50	52
Tomato juice input pressure (bar)	4.14–4.52 pulsing	4.25–4.99 pulsing
Tomato juice output pressure (bar)	3.86–4.17 pulsing	3.96–4.75 pulsing
Osmotic brine input pressure (bar)	1.8–2.7 pulsing	1.98–2.80 pulsing
Osmotic brine output pressure (bar)	0.95	0.8–1.10 pulsing
Total membrane area (m ²)	0.0797	0.0797
Duration of the run	11 h 22 min	10 h 8 min
Initial quantity of tomato juice (kg)	6	6
Initial quantity of osmotic brine (kg)	10	10
Tomato juice initial concentration (°Brix)	5.5	4.25
Brine initial concentration (% w/w)	22.23	9.73

by measuring the refractive index, *RI*, and converting the value into concentration using the following equation:

$$C\% \text{ (w/w NaCl)} = 561.17 \times RI + 0.1082 \quad (1)$$

Eq. (1) is a linear formula developed by using *C* versus *RI* data as reported by Weast (1974).

All results were average values of triplicate determinations to ensure accuracy.

The osmotic pressure values (*Π*) of tomato juice and tomato concentrates expressed in (atm) were calculated using the formula (Dale et al., 1982):

$$\Pi = 20.5X_s \quad (2)$$

where *X_s* is the weight fraction of total dissolved solids in the tomato juice.

The osmotic pressure (*Π*) of the NaCl osmotic brine solutions expressed in atm was calculated by using the following third order polynomial formula:

$$\Pi = 10512 * X_s^3 - 83.765 * X_s^2 + 807.29 * X_s \quad (3)$$

where *X_s* is the weight fraction of NaCl solids in the brine.

The analytical form of Eq. (3) was derived using NaCl osmotic pressure data for a range of various salt in water concentrations which were obtained by Perry and Chilton (1973). Then these data were best fitted in the formula:

$$\Pi/X_s = a_0 + a_1X_s + a_2X_s^2$$

and after suitable rearrangement Eq. (3) was obtained.

The permeation flux values versus time, graphically presented in Figs. 5–7, were calculated by using the following method: firstly, a best fitting of the measured experimental data of brine or tomato juice concentration *C*(*t*) versus time (*t*) to a suitable third order polynomial function was performed. Then the derived analytical (with calculated, known coefficients) equation was used in order to produce the corresponding derivative function *dC*(*t*)/*dt* and calculate its value at any experimental observation time. The permeation flux value was then obtained at any experimental point by substituting its corresponding *C*(*t*) and *dC*(*t*)/*dt* values in Eq. (4):

$$\text{Flux}(t) = (m_o \times C_o/A) \times (\pm dC(t)/dt) \times (1/C^2(t)) \quad (4)$$

where *m_o* is the initial brine or tomato juice mass in kg, *C_o* the initial brine or tomato juice concentration at (*t* = 0) divided by 100 and *A* the membrane area (*m*²) = 0.0797 m².

The development of Eq. (4) was based on the following mathematical procedure:

Tomato juice or salt (dry solids) material balance: $m_o \times C_o = m(t) \times C(t)$.

$$\begin{aligned} \text{Flux}(t) &= dm/A \times dt = d(m_o \times C_o/C(t))/A \times dt = (m_o \times C_o/A) \times (-1/C^2(t)) \times (dC(t)/dt) \\ \text{or Flux}(t) &= dm/A \times dt = d(m_o \times C_o/C(t))/A \times dt = (m_o \times C_o/A) \times (-dC(t)/dt) \times (1/C^2(t)) \\ \text{for brine or Flux}(t) &= dm/A \times dt = d(m_o \times C_o/C(t))/A \times dt = (m_o \times C_o/A) \times (dC(t)/dt) \times (1/C^2(t)) \text{ for tomato juice.} \end{aligned}$$

This method of calculation was used in order to smooth potential experimental errors, that could affect the accuracy of the calculation of flux, if this calculation was performed for each small time interval around the run instead.

A typical stainless steel Bostwick consistency meter was used in order to be determined the Bostwick consistency of the tomato concentrates at the proper dilution. For the colour measurements a HunterLab®-USA colorimeter along with the calibration tiles (red, white and black) was used.

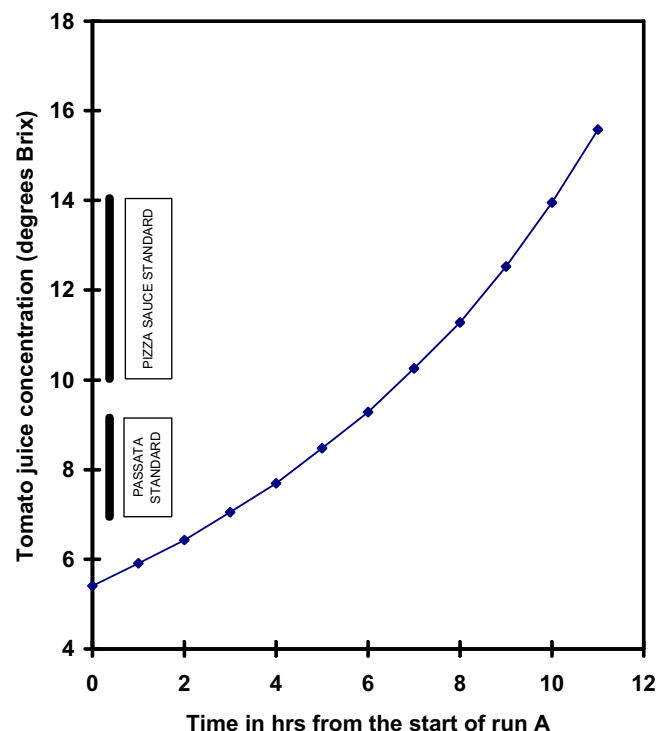


Fig. 3. Concentration of tomato juice versus time in experimental run A.

3. Results and discussion

Two separate experiments, A and B, were conducted. The average experimental condition values are given in Table 1.

In experimental run A, freshly squeezed tomato juice with concentration 5.5°Brix was used. By utilizing osmotic medium sodium chloride brine initial concentration of 22.23% w/w NaCl, after 11 h 22 min of operation, a concentration of tomato juice equal to 15.88°Brix was attained. The concentration curve for the tomato juice throughout experimental run A is presented in Fig. 3.

Triplicate values of the osmotic brine refractive index at regular time intervals along run A are presented in Table 2. Table 2 also shows the average refractive index value derived from these determinations and the respective % w/w concentration of sodium chloride as calculated from Eq. (1).

The value of flux, calculated by material balances, with data from both osmotic brine dilution and tomato juice concentration also appears in Table 2. The two flux values, tomato juice value 4.43 kg/m² h and brine value 4.46 kg/m² h, were close enough to prove that the preservation of the membrane integrity throughout the run was maintained. Although the membrane used in this study (260 μm) was thicker than the 25–80 μm special construction direct osmosis membranes of Osmotek Co., the calculated value of flux is comparable with values of osmotic flux published by Herron et al. (1994) in the disclosure section of the US Patent No. 5,281,430. This can be explained by the significant advantages of the sodium chloride brine used in this study, as compared to the glucose syrups used by Herron et al. (1994) and Petrotos et al. (1998). The maximum obtained concentration of 15.88°Brix is higher than the required concentrations of 7–9 and 10–14°Brix of the two first commercially accepted concentrates, known under the brand names PASSATA and PIZZA SAUCE, respectively. It can be claimed that the osmotic apparatus developed for this study achieved “cold” – ambient temperature concentration of tomato juice up to the second commercially accepted limit at low pressure.

In other words, a concentration factor of approximately $V = 3$, i.e. a reduction of the initial volume of tomato juice by three times was achieved.

During experimental run B a significantly lower concentration of osmotic brine as compared to run A was used (9.73% w/w NaCl initial brine concentration or average concentration for the overall run 8.8% w/w NaCl). The measured refractive indices of the osmotic brine during the run, and equivalent % w/w concentration of NaCl are presented in Table 3.

In Fig. 4, the tomato juice concentration curve is presented. As seen in Fig. 4, a final concentration of tomato juice of approximately 7.5°Brix was achieved at the end of the experiment, which is within the limits of 7–9°Brix for the first commercially accepted tomato concentrate, known as PASSATA.

The proximity of the calculated osmotic flux values, 3.26 kg/m² h on the tomato juice side and 3.03 kg/m² h on the osmotic brine side, as in the case of experimental run A, also verify maintenance of membrane integrity. The lower flux value compared to that of run A was not unexpected due to the lower strength of the osmotic brine used in this run.

Herron et al. (1994) and Beaudry and Lampi (1990a,b) reported that the problem of membrane fouling is not significant for direct osmosis membranes. According to them, the low pressure which is employed in the DO operation along with the lower concentration polarization leads to the elimination of the problem, probably due to lower deposition potential on the membrane and substantially lower compaction of the deposition. Thus, the membrane restores its capacity for separation after careful cleaning through successive cycles of use. In order to verify or reject this claim, after a series of experiments using the membrane which lasted more than two months, the experimental run A was repeated under the same experimental conditions and for a sufficiently long time period (9 h, run C) in order to make a direct comparison with the results of the initial run A and clarify whether or not the membrane performance had been affected by continuous use. The calculated

Table 2
Measured values of refractive index of osmotic brine and calculated flux values along experimental direct osmotic concentration run A.

No. of sample/time (min)	1st test	2nd test	3rd test	Average	Conc. ^a % w/w NaCl
0	1.37241	1.37241	1.37241	1.372410	22.23
15	1.37153	1.37153	1.37151	1.371523	21.73
30	1.37105	1.37104	1.37104	1.371043	21.46
45	1.37061	1.37060	1.37061	1.370607	21.22
60	1.37031	1.37024	1.37024	1.370263	21.02
75	1.36982	1.36982	1.36985	1.369830	20.78
90	1.36945	1.36947	1.36947	1.369463	20.58
105	1.36908	1.36909	1.36910	1.369090	20.37
120	1.36873	1.36875	1.36873	1.368737	20.17
150	1.36805	1.36806	1.36807	1.368060	19.79
180	1.36739	1.36739	1.36741	1.367397	19.42
210	1.36677	1.36677	1.36679	1.366777	19.07
240	1.36625	1.36622	1.36623	1.366233	18.76
270	1.36568	1.36565	1.36565	1.365660	18.44
300	1.36513	1.36515	1.36514	1.365140	18.15
330	1.36468	1.36460	1.36466	1.364647	17.87
360	1.36420	1.36422	1.36421	1.364210	17.63
390	1.36378	1.36375	1.36379	1.363773	17.38
420	1.36337	1.36340	1.36340	1.363390	17.17
450	1.36302	1.36302	1.36302	1.363030	16.96
480	1.36264	1.36263	1.36265	1.363640	16.75
510	1.36233	1.36231	1.36233	1.362323	16.57
540	1.36206	1.36199	1.36203	1.362027	16.40
570	1.36176	1.36175	1.36175	1.361753	16.25
600	1.36149	1.36150	1.36149	1.361493	16.10
630	1.36121	1.36124	1.36126	1.361237	15.96
673	1.36109	1.36110	1.36110	1.361097	15.89
Osmotic flux calculated from the tomato juice side (kg/m ² h)		4.43	Osmotic flux calculated from the osmotic brine side (kg/m ² h)		4.46

^a Calculated from Eq. (1).

Table 3
Measured values of refractive index of osmotic brine and calculated flux values along experimental direct osmotic concentration run B.

No. of sample/time (min)	1st test	2nd test	3rd test	Average	Conc. ^a % w/w NaCl
0	1.35009	1.35010	1.35009	1.350093	9.73
15	1.34997	1.34996	1.34994	1.349957	9.65
30	1.34984	1.34985	1.34985	1.349847	9.59
45	1.34972	1.34974	1.34975	1.349737	9.53
68	1.34958	1.34958	1.34960	1.349587	9.44
83	1.34949	1.34949	1.34948	1.349487	9.39
98	1.34935	1.34935	1.34933	1.349343	9.31
113	1.34922	1.34924	1.34925	1.349237	9.25
128	1.34913	1.34913	1.34914	1.349133	9.10
158	1.34881	1.34880	1.34879	1.348800	9.00
188	1.34870	1.34869	1.34872	1.348703	8.95
218	1.34854	1.34854	1.34854	1.348540	8.85
248	1.34834	1.34833	1.34835	1.348340	8.74
278	1.34815	1.34816	1.34819	1.348167	8.64
308	1.34800	1.34800	1.34800	1.348000	8.55
338	1.34787	1.34790	1.34791	1.347893	8.49
368	1.34770	1.34769	1.34769	1.347693	8.38
398	1.34756	1.34756	1.34758	1.347567	8.31
428	1.34742	1.34742	1.34743	1.347423	8.23
458	1.34729	1.34730	1.34730	1.347297	8.16
488	1.34717	1.34717	1.34718	1.347173	8.09
518	1.34702	1.34699	1.34699	1.347000	7.99
548	1.34692	1.34693	1.34692	1.346923	7.95
578	1.34682	1.34684	1.34684	1.346833	7.90
608	1.34672	1.34672	1.34672	1.346720	7.83
Osmotic flux calculated from the tomato juice side (kg/m ² h)		3.26	Osmotic flux calculated from the osmotic brine side (kg/m ² h)		3.03

^a Calculated from Eq. (1).

DO flux values versus time since the beginning of the run for the two runs A and C are graphically presented in Fig. 7 and provide evidence that the membrane remained intact during its performance. In addition, in Fig. 8, a calculation of the overall mass transfer coefficient k_m throughout the runs A and B for 10 h of operation and the graphical representation of this parameters versus the corresponding time elapsed from the start of each respective run leads to the conclusion that only a 6% reduction of mass transfer coefficient over 10 h appeared in run B and about 20% in run A. However, it can be observed in Fig 8 that a major part of the k_m versus time reduction can be attributed to the expected increase of the resis-

tance in mass transfer of the tomato juice boundary layer, as the juice gets more concentrated with time and thus becomes more viscous and certainly not all of this is caused by fouling effects. In conclusion, any fouling effect is reversible as the DO membrane repeatedly restored its performance after it had been given a proper cleaning while only a small and commercially acceptable flux reduction appeared after long course runs.

The concentrates produced by runs A and C were packed after their production in 720 ml glass jars and were thermally deaerated, open, at 72 °C. Then the jars were covered with lids and given a 1 h thermal processing in boiling hot water at 100 °C in order to preserve them. The content of these jars were used within one week of production to test colour and Bostwick consistency and the results are presented in Table 4, along with the measurements taken for the conventionally produced industrial concentrate from the same raw material. From the obtained analytical data, it is con-

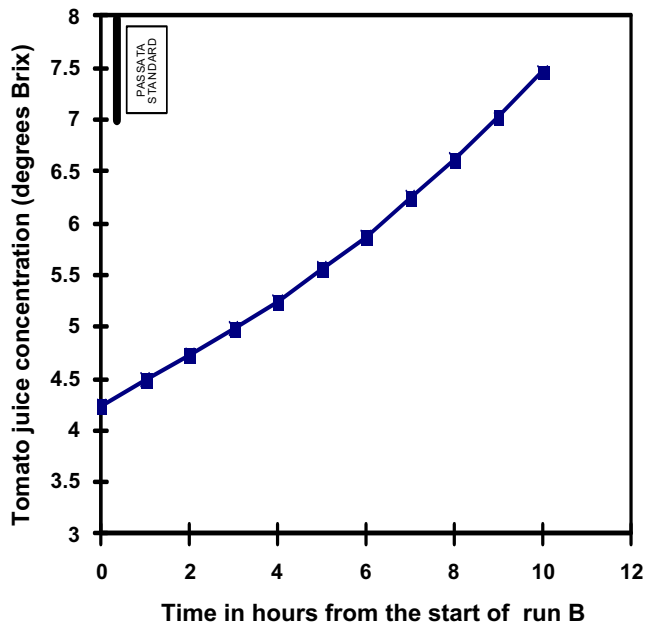


Fig. 4. Concentration of tomato juice versus time in experimental run B.

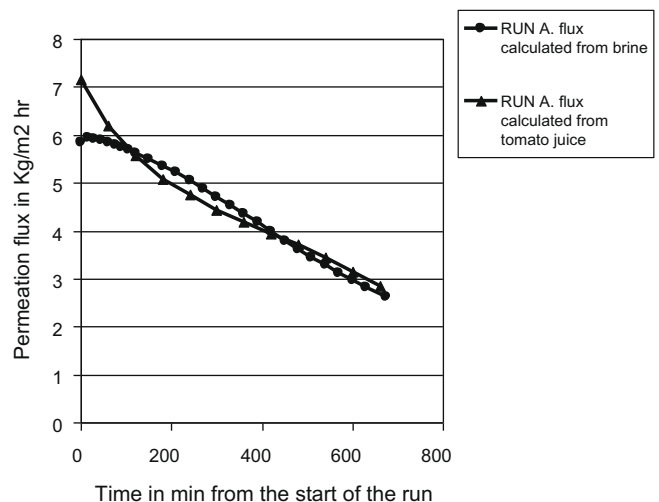


Fig. 5. Permeation flux versus time throughout run A.

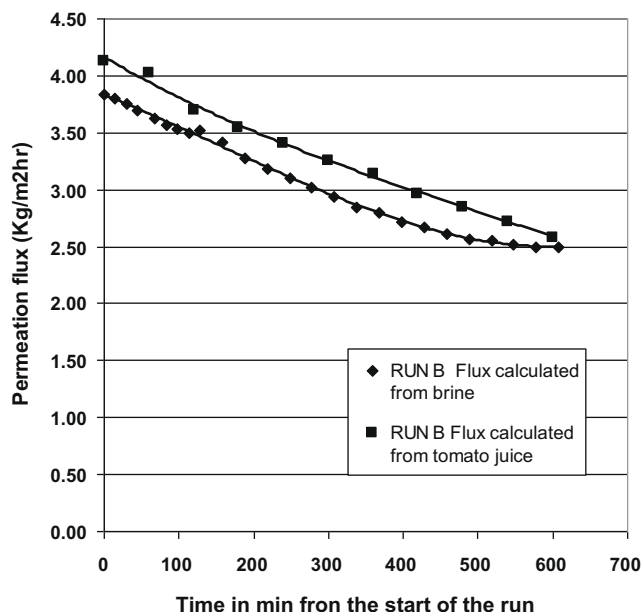


Fig. 6. Permeation flux versus time throughout run B.

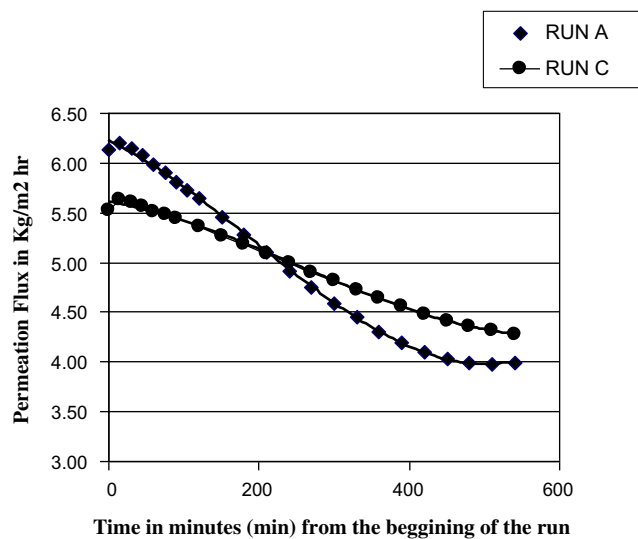


Fig. 7. Flux versus time for runs A and C.

cluded that the concentrates produced by the runs A and C appeared to show similar Bostwick consistency values, typical for a “cold break tomato concentrate”, but much higher *a/b* (red to yellow) colour ratio (2.6 for both runs A and C compared with 2.3 and 2.2 for the corresponding industrial concentrates). This implies a

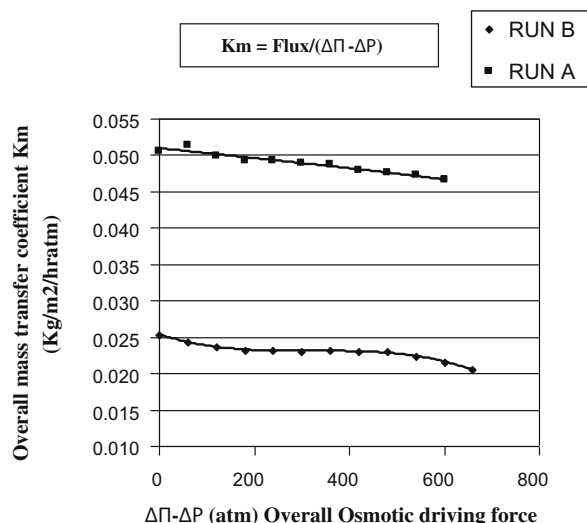


Fig. 8. Overall mass transfer coefficient versus time along the runs A and B.

much better red colour for the concentrate produced by direct osmosis. Additionally, visual and sensory test of the A, C run produced and thereafter preserved concentrates, verified that there were no signs of contamination and microbiological activity proving the effectiveness of the applied membrane cleaning regime and the absence of fermentation.

From runs A and B, it is clear that sodium chloride brines can be successfully used to concentrate tomato juice. The selected initial brine concentration depends on the final desired tomato juice concentration and affects the process performance. However, the important issue as in any direct osmotic concentration procedure is to determine the method to be used for osmotic reinforcement of the post-process diluted osmotic medium. In the present study, the use of sodium chloride brine as an osmotic medium will allow the brine to be re-concentrated by the economical and well established method of electro dialysis. According to Lacey and Loeb (1979), sodium chloride brines can be concentrated up to 23% w/w by electro dialysis. Electro dialysis has been used for years by the chemical industry, especially in Japan, to obtain the required concentrated brines for a number of chemical processes. The energy consumption in electro dialysis (Lacey and Loeb, 1979), is very low (20–30 Btu/lb water removed), whereas in direct osmosis the comparative figure is 5 Btu/lb water removed (Anonymous, 1993). Therefore, the expected energy expenditure in the case of combining direct osmosis and electro dialysis is 25–35 Btu/lb water removed, which in fact is one tenth of the required energy for conventional evaporation and approximately the same as reverse osmosis concentration (Köseoglu et al., 1991). Lower concentrations of diluted brine as in the case of run B, will even allow for the use of high pressure reverse osmosis in hollow fiber modules to obtain the re-concentrated brine.

Table 4

Comparative quality characteristics of the concentrates produced by direct osmosis (runs A and C) and by vacuum evaporation using the same raw material.

Tomato concentrate	Packaging	Bostwick consistency value	Colour <i>a/b</i> value (redness index)
Run A	Preserved in glass jars 720 ml	11.3	2.6
Industrially produced by vacuum evaporation	Preserved in metal tins of ½ kg	11.4	2.3
Corresponding in run A (same raw material)			
Run C	Preserved in glass jars 720 ml	11.5	2.6
Industrially produced by vacuum evaporation	Preserved in metal tins of ½ kg	11.6	2.2
Corresponding in run C (same raw material)			

Another potential alternative will be to reconcentrate the diluted brines by using a solar ponding technique, which could produce concentrated brines at a low cost. Even more an attractive proposal is to use sodium chloride brines which come as by-products of water desalination plants to serve as one-way (not being reconcentrated) osmotic media for nearby established direct osmosis concentration units. Such brines, in evaporative desalination, have a concentration of about 23% w/w NaCl or 9% w/w NaCl when they are derived by reverse osmosis desalination units. This proposal seems to have a great deal of potential for applications coastal areas and on islands, for example in the Mediterranean Sea. Along to recommended herein, well known and long time used electro dialysis process all the above mentioned methods can also serve in order to solve the problem of reinforcement of the post-process diluted brines. However, in each respective case an optimum method has to be decided probably by testing on a pilot plant scale and carrying out a cost evaluation in order to be decided the most cost efficient method.

4. Conclusions

An osmotic concentrator of flat membrane geometry developed in the context of the present work which was tested and proved effective in concentrating fresh tomato juice up to a concentration of approximately 16°Brix, substantially higher than the specified concentrations of two commercially available concentrates, known as PASSATA (7–9°Brix) and PIZZA SAUCE (10–14°Brix). The highest concentration (16°Brix) was achieved by using a TFC reverse osmosis membrane called ECOFILTER which had a total thickness of about 260 µm and 99% rejection coefficient, while the osmotic medium was sodium chloride brine of initial concentration approximately 22% w/w NaCl. It was also demonstrated that a tomato concentrate of a lower concentration of 7.5°Brix (typical PASSATA), can be obtained by using, as raw material, tomato juice concentration (4.25°Brix) and a significantly lower initial concentration of brine (9.73% w/w).

An effective and economical combination of direct osmosis to concentrate the tomato juice and electro dialysis to reconcentrate the diluted NaCl brine was proposed. This would reduce the energy demand at only 25–35 Btu/lb water removed and ensure low pressure and temperature operation to obtain tomato juice concentrates. Other methods to reconcentrate the brine, such as reverse osmosis at low brine concentration or solar ponding, can also put forward as possible alternatives while on the other hand, a very favourable process sequence to produce low Brix tomato juice concentrates by utilizing osmotic brines from the by-products of water desalination plants was experimentally demonstrated as being suitable for the particular conditions existent on islands in the Mediterranean Sea and coastal areas.

Acknowledgement

The authors of this paper wish to express their sincere gratitude to the Greek National Fellowship Institute (I.K.Y) which kindly supported this research by providing a grant awarded to the first of the aforementioned authors.

References

Anonymous, 1993. Osmotek's DOC Technology profile.

- Beaudry, E.G., Lampi, K.A., 1990a. Membrane technology for direct-osmosis concentration of fruit juices. *Food Technology* 44 (6), 121.
- Beaudry, E.G., Lampi, K.A., 1990b. Osmotic concentration of fruit juices. *Flüssiges Obst* 57, 652–656, 663–664.
- Cross, S., 1988. Achieving 60° Brix with membrane technology. Paper presented at Annual Meeting, Institute of Food Technologists, New Orleans, La., June 19–22.
- Dale, M.C., Okos, M.R., Nelson, P., 1982. Concentration of tomato products: analysis of energy saving process alternatives. *Journal of Food Science* 47 (6), 1853–1858.
- Durham, R.J., Nguyen, M.H., 1994. Hydrophobic membrane evaluation and cleaning for osmotic distillation of tomato puree. *Journal of Membrane Science* 87, 181–189.
- Gherardi, S., Bazzarini, R., Trifiro, A., Lo Voi, A., Palamas, D., 1986. Pre-concentration of tomato juice by reverse osmosis. *Industria Conserve* 61 (2), 115–119.
- Golubev, V.N., Oleshko, A.Y., Bondar, S.N., Kostinskaya, L.I., Talanov, V.P., Lemer, V.I., Ogurtsov, V.V., Krushkovskaya, G.M., 1991. USSR Patent SU1655449A1.
- Greek Ministry of Agriculture, 1999. Circular to the tomato processing industry.
- Herron, J.R., Beaudry, E.G., Jochums, C.E., Medina, L.E., 1994. US Patent 5,281,430, January 25.
- Hogan, P.A., Canning, R.P., Peterson, P.A., Jonhson, R.A., Michaels, A.S., 1998. A new option: osmotic distillation. *Chemical Engineering Progress* 7, 49–62.
- Ishii, K., Konomi, S., Kojima, K., Kai, M., 1981. Development of a tomato juice concentration system by reverse osmosis. In: Turbak, A.F. (Ed.), *Synthetic Membranes: Volume II – Hyperfiltration, Ultrafiltration Uses*, ACS Symposium Series, vol. 154. ACS, Washington, DC, p. 1.
- Johnson, R.A., Valka, R.H., Lefebvre, M.S., 1989. Osmotic distillation. A low temperature concentration technique. *Australian Journal of Biotechnology* 3 (3), 206–207, 217.
- Köseoglu, S.S., Lawson, J.T., Lusas, E.W., 1991. Vegetable Juice produced with membrane technology. Process combining ultrafiltration and reverse osmosis yields fresh-tasting, clarified juices. *Food Technology* 45 (1), 124, 126–128, 130.
- Kunz, W.A., Behables, Aim, R.B., 1996. Osmotic evaporation through macroporous hydrophobic membranes: a survey of current research and applications. *Journal of Membrane Science* 121, 25–36.
- Lacey, R.E., Loeb, S., 1979. *Industrial Processing with Membranes*. Robert E. Krieger Pub. Co., Huntington, New York.
- Mackie, J.S., Meares, P., 1955. The diffusion of electrolytes in a cation – exchange resin membrane. I. Theoretical. *Proceedings of Royal Society London Series, A* 232, 498–509.
- Mengual, J.I., Ortiz de Zarata, J.M., Pena, L., Velazquez, A., 1993. Osmotic distillation through porous hydrophobic membranes. *Journal of Membrane Science* 82, 129–140.
- Merlo, C.A., Rose, W.W., Pedersen, L.D., White, E.M., 1986a. Hyperfiltration of tomato juice during long term high temperature testing. *Journal of Food Science* 51 (2), 395–398.
- Merlo, C.A., Rose, W.W., Pedersen, L.D., White, E.M., Nicholson, J.A., 1986b. Hyperfiltration of tomato juice. Pilot plant scale high temperature testing. *Journal of Food Science* 51 (2), 403–407.
- Merson, R.L., Paredes, G., Hosaka, D.B., 1980. *Concentrating fruit juices by reverse osmosis*. In: *Ultrafiltration Membranes and Applications*. Plenum Publishing Co. Inc., New York, p. 405.
- Pepper, D., Orchard, A.C.J., Merry, A.J., 1985. Concentration of tomato juice and other fruit juices by reverse osmosis. *Desalination* 53, 57–166.
- Perry, R.H., Chilton, C.H., 1973. *Chemical Engineer's Handbook*, fifth ed. McGraw Hill Inc., Chemical Engineering Series, Tokyo, Japan.
- Petrotos, K., Quantick, P., Petropakis, H., 1998. A study of the direct osmotic concentration of tomato juice in tubular membrane – module configuration. I. The effect of certain basic process parameters on the process performance. *Journal of Membrane Science* 150, 99–110.
- Petrotos, K., Quantick, P., Petropakis, H., 1999. Direct osmotic concentration of tomato juice in tubular membrane – module configuration. II. The effect of using clarified tomato juice on the process performance. *Journal of Membrane Science* 160, 171–177.
- Swafford, T.C., 1983. New concepts for juice concentration use centrifugation and membrane filtration. *Food Engineering* (April), 153–154.
- Vahdati, M.M., Priestman, G.H., 1994. Enhancement of the performance characteristics of membranes in osmotic distillation. In: *Biotechnology 94'ICHEM Symposium*, pp. 94–96.
- Watanabe, A., Ohtani, T., Kimura, S., 1982. Performance of dynamically formed Zr (IV)-PAA membrane during concentration of tomato juice. *Nippon Nogeikagaku Kaishi* 56 (5), 339.
- Weast, R.C., 1974. *Handbook of Chemistry and Physics*, 55th ed. CRC Press Inc., New York, USA, pp. D-215, D-231, E-1.
- Wrolstad, R.E., McDaniel, M.R., Durst, R.W., Micheals, N., Lampi, K.A., Beaudry, E.G., 1993. Composition and sensory characterization of red raspberry juice concentrated by direct-osmosis or evaporation. *Journal of Food Science* 58 (3), 633–637.