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Osmotic concentration of liquid foods

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Abstract

Vast amounts of liquid food are industrially concentrated in order to reduce storage, packaging, handling and transportation costs. Vacuum evaporation is the predominant method used by the food industry to produce liquid food concentrates, despite serious drawbacks (poor product quality, high energy demand). This paper describes the research efforts to develop alternative techniques that could be applied on an industrial scale to overcome the disadvantages of currently used concentration methods. A major part of these attempts is focused on the application of osmotic membrane techniques, namely direct osmosis, membrane distillation and osmotic distillation. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Evaporative concentration of fluid foods presents major drawbacks. First is the heat induced deterioration of sensory (colour, taste, aroma) and nutritional value (vitamins, etc.) of the finished product (concentrate). It is well known that, in the first few minutes of evaporative concentration, most of the aroma compounds contained in the raw juice are lost and the aroma profile undergoes an irreversible change (Lazarides, Iakovidis, & Schwartzberg, 1990).

An additional drawback in the use of vacuum evaporation is the high energy demand, despite the use of energy saving systems (i.e. thermocompression, mechanical compression, etc.).

The results of several experimental studies were published in the area of applying reverse osmosis to concentrate liquid foods. Most of the research activity was in the area of fruit juices, tomato juice and vegetable juices (Merson & Morgan, 1968; Merson, Paredes, & Hosaka, 1980; Sheu & Wiley, 1983; Merlo, Rose, Pedersen, & White, 1986; Merlo, Rose, Pedersen, White, & Nicholson, 1986; Ishii, Konomi, Kojima, & Kai, 1981; Watanabe, Ohtani, & Kimura, 1982; Pepper, Orchard, & Merry, 1985;Gherardi, Bazzarini, Trifiro, Lo Voi, & Palamas, 1986). Despite the extensive research efforts, it appears that reverse osmosis cannot be used by itself, as the potential of the method is only to pre-concentrate and not to achieve final concentration. For example, in tomato juice, which is one of the most popular concentrated food commodities, it has been shown that only a concentration of approximately 9°Brix can be (economically) achieved by reverse osmosis. Efforts to achieve higher concentration values met with problems of fouling and a severe reduction in permeation fluxes. An additional limitation is imposed by the limited resistance of reverse osmosis membranes to hydraulic pressure. Most of the new generation membranes are capable of resisting maximum 60–80 atm, which indicates that the obtained concentrate has to have an osmotic pressure less than this limit, in order for a driving force to exist.

These inherent problems of concentration by reverse osmosis have forced some of the researchers to design combined concentration processes. Dale, Okos, and Nelson (1982) evaluated financially four different alternative schemes of combined technologies for concentrating tomato juice. Using the Complex algorithm for optimization along with the net present value criterion to evaluate projects, they found that the most economical way to concentrate tomato juice is a scheme incorporating centrifugation, partial concentration of juice serum by reverse osmosis up to 16%, a final concentration of the reverse osmosis concentrate in a vacuum

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evaporator with mechanical recompression and re-mixing serum concentrate and tomato pulp. Koseoglou, Lawson, and Lusas (1991) performed a pilot scale concentration of tomato and vegetable juices (carrot, cucumber etc.) using a scheme of combined juice pre-treatments (filtration, microfiltration and ultrafiltration) and reverse osmosis. The juices were initially passed through filtration, microfiltration and ultrafiltration membranes. The retentates were kept separately. The permeate (juice serum) from ultrafiltration (the last step of pre-treatment) was consequently concentrated to the highest possible level by reverse osmosis. The highest level which was attained was approximately 16°Brix. Finally, the collected permeates were re-mixed under high pressure with the reverse osmosis concentrate to yield the final tomato or vegetable juice concentrate. This approach reduced the effect of fouling of the reverse osmosis membrane, because of the juice clarification step. It also improved the permeation flux through the reverse osmosis membrane. A few years earlier, Cross (1988) used the same approach but, by utilizing a much higher pressure (over 120 atm) inhollow fibre reverse osmosis membranes, obtained much higher concentrations (up to 60°Brix). Despite the fact that the above combined scheme appears to be very attractive, the separation of the juice into two fractions seems to negatively affect the rheological characteristics of the juice concentrate (Pepper et al., 1985). In fact, the finished product appears to have higher fluidity and lower consistency compared to commercial products. This is an obvious disadvantage as the concentrate is more susceptible to syneresis.

The problems encountered with the above-mentioned processing schemes (which have reverse osmosis as a core process) have not permitted their application on a commercial scale. From the range of the above-mentioned process schemes, only plain reverse osmosis has had a commercial follow-up, strictly for the pre-concentration of fruit juices and tomato juice. On top of quality problems, the complexity of combined process schemes has probably prohibited their commercial application in place of conventional vacuum evaporation.

A potential solution to the above problems and an attractive alternative to evaporative concentration could be offered by a purely osmotic technique. This paper is an effort to review the research developments with regard to these techniques, namely, direct osmosis, membrane distillation and osmotic distillation.

2. Direct osmotic concentration

Direct osmosis utilizes low pressure and low temperature, thus preserving the quality character of the concentrated liquid food.

The use of direct osmotic techniques to produce concentrated foodstuffs is not a recent invention. According to Cussler (1984), a long time ago East European farmers used to prepare a range of juice concentrates by simply immersing a bag made of semi-permeable material and full of freshly squeezed juice into concentrated sodium chloride brine. In that way, water was forced by osmosis to move from juice to the osmotic brine. Although a highly concentrated juice was obtained, the process was very slow, as the bags had to remain in the brine overnight in order to guarantee a satisfactory osmotic dehydration.

Based on the traditional method, Scott (1975) developed a commercial process. The process consisted of filling a bag made of semi-permeable material with the liquid foodstuff and then passing the bag through a bath of osmotic medium at an elevated temperature. In the disclosure section of the patent awarded for this process, a description is given of the operating conditions and of several materials used for bag construction (cellulose, polysulphones, animal intestines, etc.). In addition, a number of potential applications concerning fruit juices, milk and dairy products are presented. Bag movement resulted in much higher water fluxes and a significant reduction in the time required to obtain highly concentrated foodstuffs compared to the traditional way of plain immersion of the bag into the osmotic medium.

The first attempt to use more sophisticated techniques in order to take advantage of the extremely large overall driving force which appears in purely osmotic applications was made by Popper, Camirand, Nury, and Stanley (1966). They used first generation reverse osmosis membranes, made of cellulose acetate and similar materials, in both a flat and tubular configuration. Two different membrane housings were used: a tubular configuration to accommodate the tubular membranes and a plate and frame configuration for flat membranes. The latter came from a suitable modification of a commercial filter press allowing circulation of the fruit juice and osmotic medium across the flat sheet membrane. An average osmotic flux of about 2.5 kg/(m^2 h) was reported by this team and they claimed the production of highly concentrated fruit juices.

Beaudry and Lampi (1990a,b) revisited the same process, which was named by Popper et al. (1966) "dialysis". They changed the name of the process from dialysis into "direct osmosis" and improved some of the engineering aspects. They also utilized improved, new generation thin film composite (TFC) reverse osmosis membranes, which were properly modified. Through additional developmental work, these membranes became thinner (overall membrane thickness 25–85 μm), while the membrane's top selective layer remained similar to that of tight reverse osmosis membranes (MWCO less than 100 Da), thus allowing no passage of other food ingredients besides water. Furthermore, a tubular membrane module of specific design was constructed to provide housing for the sensitive ultrathin direct osmosis membranes. It enhanced turbulence and allowed an increase in the osmotic flux, minimizing fouling. The module configuration formulated a flow path (inside the membrane) with a continuous change in flow direction, providing at the same time effective support to the membrane. A similar module of flat geometry was also developed to be used with inexpensive flat sheet membranes. These new developments were covered by a US patent awarded to Herron, Beaudry, Jochums, and Medina (1994). In the patent document some theoretical aspects of this method are discussed along with tips on its practical application concerning membrane type, membrane module configurations, suitable ways to support the thin sensitive membranes etc. A magnitude of osmotic flux 5–6 l/(m^2 h) seems to be the maximum achieved with several kinds of foodstuffs, according to information included in the relevant patent document.

Wrolstad et al. (1993) completed a detailed quality study of a particularly heat sensitive material red raspberry juice. The study suggested that the direct osmosis concentrate is of premium quality, compared to that obtained by conventional evaporation. Herron et al. (1994) also provided evidence that the direct osmosis concentrate is of superior quality in comparison to that yielded by a conventional vacuum evaporator. These studies were an answer to earlier claims for a negative effect of direct osmotic process on the quality of the osmotic fruit juice concentrates (Bolin & Salunke, 1971). In those days, the prolonged processing times resulting due to the poor process performance were probably the reason behind the observed deterioration in quality.

Petrotos, Quantick, and Petropakis (1998, 1999) used a tubular membrane module to study the effect of several processes and membrane parameters on the performance of direct osmosis in the concentration of tomato juice. In the context of these investigations, it was proved that the membrane thickness and the viscosity of the osmotic fluid are of paramount importance in determining permeation flux. The main conclusion was that a thinner membrane and a low-viscosity osmotic medium (like NaCl brines) are expected to yield a better performance. The findings indicated that the use of viscous carbohydrate syrups as osmotic media has to be abandoned in favour of highly osmotic and low-viscosity salt brines. The clarification of the juice by either plain filtration, microfiltration or ultrafiltration was also found to have a significant effect on the value of the observed osmotic fluxes. The ultrafiltrates gave the best performance of all other filtrates.

Petrotos, Petropakis, and Poirazis (2000) developed a new osmotic apparatus with a flat configuration (Fig. 1) The core of this apparatus is an osmotic cell of special configuration to promote turbulence. The two parts of this custom designed osmotic cell are presented in Fig. 2. Test work has already been completed with one of the most popular concentrated juices worldwide, namely tomato juice. Using a commercially available reverse osmosis membrane with an overall thickness of 260 μm, a tomato juice concentrate of approximately 16°Brix was produced at low pressure and ambient temperature. The average osmotic flux was as high as 4.5 kg/(m^2 h), which is close to the values given by Herron et al. (1994), despite the fact that the used membrane was much thicker than the special direct osmosis membranes used by Herron et al. (1994).

3. Membrane and osmotic distillation

Parallel to the development of direct osmotic concentration which utilizes hydrophilous wettable membranes, another osmotic concentration process was also investigated. This process is called "osmotic distillation" or "membrane distillation", depending on the nature of the physical parameter creating the driving force for water separation. This parameter can be either temperature (membrane distillation) or concentration (osmotic distillation). In both cases a vapor pressure differential is

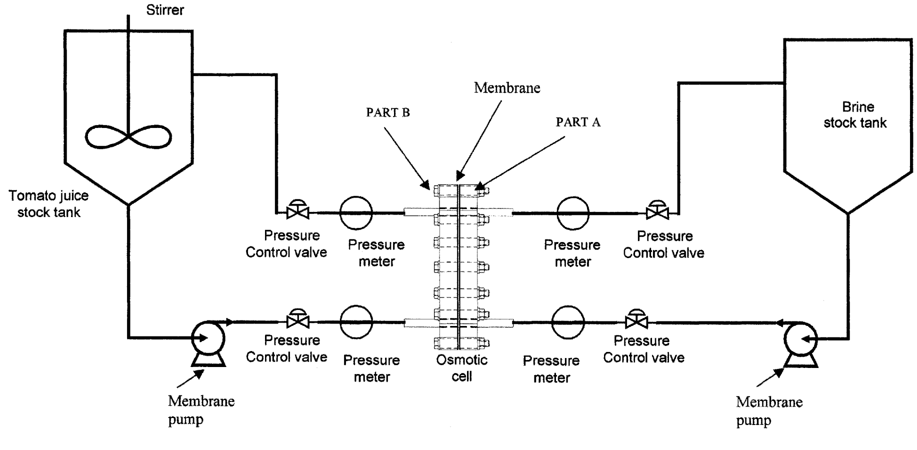

Fig. 1. Experimental set-up for the direct osmotic concentration of tomato juice in flat membrane module configuration.

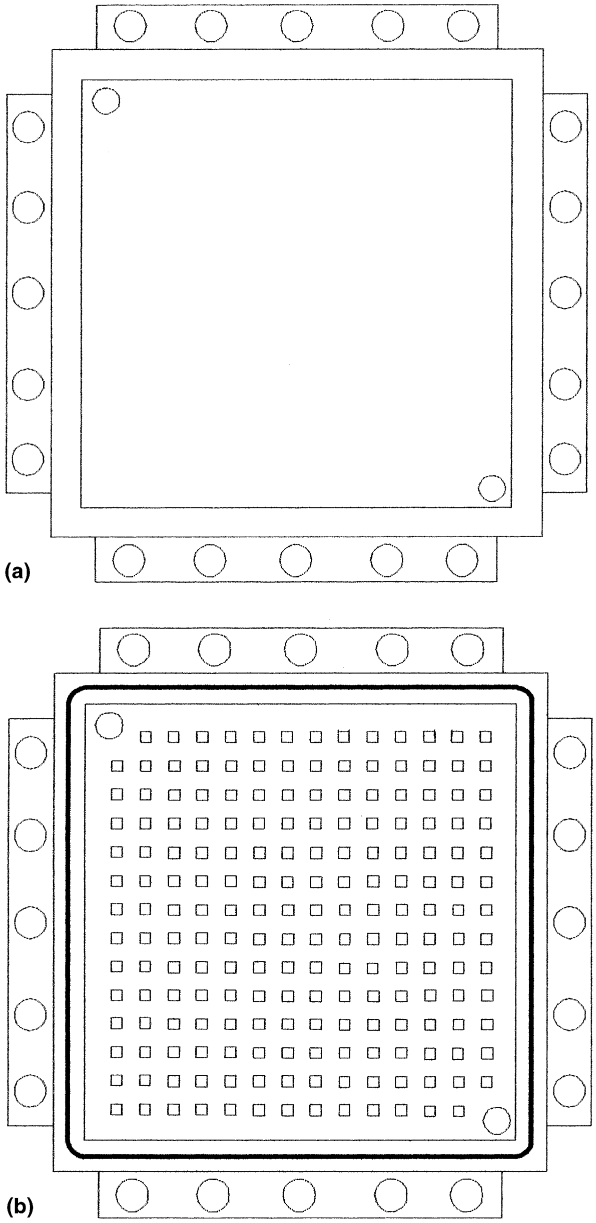

Fig. 2. Geometry of Parts A and B of the osmotic cell.

set up across the membrane. This differential acts as a driving force for water vapour transfer across the clearly porous, hydrophobic, non-wettable membranes used in such processes.

The theoretical aspects of these processes are extensively discussed in a series of publications (Lefebvre & Serge, 1986; Schofield, Fane, & Fell, 1987; Johnson, Volks, & Lefebvre, 1989; Lefebvre & Piper, 1992; Mengual, Zarate, Pena, & Velazquez, 1993; Vahdati & Priestman, 1994; Vazquez-Gonzalez & Martinez, 1994; Drioli, Calabro, & Jiao, 1994). In all cases, the membranes used were of hydrophobic nature, non-wettable and were constructed by Poly Vinyl-DiFluoride (PVDF) or Poly-TetraFluoroEthylene (PTFE). The size of the pores in the membranes can vary from 0.2 to 1.0 μm, the porosity from 60% to 80% and the overall thickness from 80 to 250 μm, depending on the absence or presence of support.

The application of membrane distillation in the concentration of foodstuffs has its origin in Australia. Sheng, Johnson, and Lefebvre (1991) reported data on the effect of three process parameters (juice flow rate, juice concentration and juice temperature) on the osmotic distillation flux of orange, apple and grape juice. In this application, sodium chloride brine close to its saturation limit was used as an osmotic medium. A PTFE membrane with pore size of 0.2 μm and an overall thickness of 100 μm was used. Thompson (1991) reported the application of the osmotic distillation process in the wine industry to obtain premium quality wine. Drioli, Jiao, and Calabro (1992) experimented with membrane distillation to concentrate orange juice. Additionally, Durham and Nguyen (1994) carried out osmotic distillation experiments to concentrate tomato juice. A fouling effect, due to some lipid constituents of the tomato juice, was reported. Furthermore, several membrane cleaning regimes were tested, on the grounds of both effectiveness and membrane durability. A flux value about 5 $l/(m^2\ h)$ (similar to that of direct osmosis) was observed in the membrane/osmotic distillation of foodstuffs. The cost of the hydrophobic membranes is far higher than that of hydrophilic direct osmosis membranes. Their life cycle appears to be an additional problem. Based on published data, it seems that there is much greater potential for the direct osmosis process on both operational and financial grounds. However, it is very possible that new developments in these two processes will remain a secret, until the intellectual property rights are duly protected by patents.

4. Osmotic solution management

A serious problem with commercial applications of both osmotic techniques is the management of the diluted osmotic medium. It is essential to re-use the medium several times before it is removed from the process. Beaudry and Lampi (1990a,b) and Herron et al. (1994) reported the use of a classic evaporator in order to re-concentrate the diluted osmotic medium. In that way, it is only the (inert) osmotic medium (and not the liquid food) which is thermally processed. The food concentrate retains the freshness of the raw material. In addition to heat evaporation, some other approaches were tried for the concentration of the osmotic medium. Thompson (1991) reported that solar ponding or even reverse osmosis and pervaporation could be used to re-concentrate osmotic media in order to restore their osmotic ability. Petrotos et al. (2000) suggested the use of electrodialysis as the most suitable way to reinforce the osmotic NaCl brines which they used in their osmotic apparatus. The latter method is well known to the chemical industry, especially in Japan, where electrodialysis is used to concentrate brines for certain chemical processes. The main characteristic of the electrodialysis process is the extremely low energy consumption (Lacey & Loeb, 1979) combined with high durability of the membranes, which have a shelf-life of from six to ten years.

5. Conclusions

Conventional evaporative concentration techniques present major drawbacks with respect to high energy consumption, and inferior quality (colour, taste, aroma, nutritional value) of the finished product.

Reverse osmosis technology emerged as an alternative to classical evaporation, but it is used as a pre-concentration step rather than as a full concentration process. A combination of high pressure reverse osmosis and ultrafiltration has also been used with limited success.

The application of purely osmotic techniques such as direct osmosis and membrane or osmotic distillation in liquid food concentration has been under investigation for a long time. These techniques do not impose similar limitations (as reverse osmosis) in achieving a finished product of high concentration. Besides, the energy expenditure is quite low, since there is no substantial hydraulic pressure involved. The whole process runs at low temperature, which is very important for product quality.

Process efficiency needs to be improved through production of more suitable membranes with improved diffusional characteristics.

The effective, environmentally friendly handling of the diluted osmotic medium is still a problem to be faced. The suggested use of evaporation would negatively affect the operational cost of the process. An alternative, such as electrodialysis, could provide a solution, but it needs to be carefully evaluated in terms of efficiency and economics. In addition, the osmotic flux values should be increased, by carefully changing the diffusional characteristics of the membranes and producing more suitable membranes.

A preliminary evaluation of the two kinds of purely osmotic membrane processes, direct osmosis and osmotic or membrane distillation, reveals certain advantages of direct osmosis. Such advantages include substantially cheaper membranes and a longer life cycle of direct osmosis membranes compared to hydrophobic membranes of osmotic or membrane distillation.

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