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Osmotic membrane distillation with continuous regeneration of stripping solution by natural evaporation

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Abstract. The paper presents an experimental set-up for osmotic membrane distillation, which can be operated continuously for several weeks. NaCl solutions were used as an osmotic solution. The influence of osmotic solution concentration on the obtained permeate flux is presented. The experimental set-up was equipped with a system for the regeneration of dilute brine. The regeneration was carried out using a method of natural evaporation to the air surrounding the installation. The evaporation area was created by the Białecki rings, assembled in the form of tower. The obtained evaporation rate was sufficient to maintain a constant NaCl concentration (over 300 g/L), for air with the relative humidity in the range of 30-80%. Accurel PP S6/2 hydrophobic polypropylene membranes were used in the study. The membranes exhibited 100% rejection for 600 h of the process duration.

Keywords: osmotic membrane distillation; osmotic solution; OMD pilot plant

1. Introduction

The concentration of solutions can be potentially realized by a membrane contactor technique in which a porous hydrophobic membrane separates the two aqueous solutions having different water vapour pressure (driving force for mass transfer). One surface of the membrane has a contact with a dilute solution and the opposite surface is contacted with a stripping solution (osmotic solution), e.g., cold water or brines (Gabelman and Hwang 1999, Khayet and Matsuura 2011). The membrane prevents the penetration of separated solutions into the pores, due to the hydrophobicity of the membrane material. Therefore, the membrane pores are filled only by the gas phase and the water vapour is transferred through the pores, from the feed to the stripping solution.

Different methods are used to generate the driving force for mass transfer. In direct contact membrane distillation (DCMD) this driving force is maintained by a temperature gradient between the hot feed and cold distillate (El-Bourawi *et al.* 2006, Gryta 2005, Khayet and Matsuura 2011). Using the feed temperature 353-363 K it is possible to obtained the permeate fluxes closed to the efficiency of RO process (Teoh *et al.* 2008). However, for such high temperature, the concentration of solutions containing thermally sensitive components, such as fruit juices and pharmaceuticals, is not possible (Cassano and Drioli 2004, Cassano *et al.* 2004). These solutions can be concentrated by isothermal process, known as osmotic distillation (OD) (Barbe *et al.* 1998, Petrotos and

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Lazarides 2001, Valdés *et al.* 2009). In this process, the driving force for mass transfer results from the difference in the water activity between a diluted feed and brine (osmotic solutions).

When the membranes are wetted, a high osmotic pressure is created as a result of differences in the salt concentrations. The difference in osmotic pressure was used as the driving force in a new separation process called as forward osmosis (FO). However, a problem of brine regeneration also exists in this case (Cath *et al.* 2006).

The OD process can be carried out at room temperature and under atmospheric pressure without the degradation of heat-sensitive components and losing some volatile components of liquid foodstuffs. Moreover, these solutions can be concentrated to a very high concentration (over 60° Brix). Therefore, OD is proposed as a method of removing water from liquid food such as fruit and vegetable juices, milk, instant coffee and tea, and various non-food aqueous solutions that are thermally non-resistant (Cassano and Drioli 2004, Chanachai *et al.* 2010, Petrotos and Lazarides 2001, Valdés *et al.* 2009,). However, a level of the permeate flux obtained in OD process is 10-30 fold lower than that in DCMD variant.

In order to increase the partial pressure difference some authors proposed to maintain the feed temperature a few degrees higher than the temperature of osmotic solution (El-Abbassi *et al.* 2013, Gryta 2005, Khayet and Matsuura 2011). In this case, the driving force is generated by both the transmembrane temperature gradient (DCMD effect) and the concentration gradient (OD effect). This variant combines DCMD and OD, and is called as osmotic membrane distillation (OMD).

During the separation of non-volatile solutions by DCMD, the obtained distillate is pure water ($a_D = 1$), and the partial pressure difference (Δp) can be determined using the Raoult law

$$\Delta p = p_F^0 x_F \gamma_F - p_D^0 \tag{1}$$

where p_F^0 and p_D^0 are vapour pressure of pure water at the feed/membrane and membrane/distillate interface temperature, respectively, and x_F is the molar fraction of water and γ_i is the water activity coefficient in the solution. In OMD variant both temperature and the concentration influenced on the Δp value

$$\Delta p = p_F^0 a_F - p_D^0 a_D = p_F^0 x_F \gamma_F - p_D^0 x_D \gamma_D \tag{2}$$

In the case of OD process the feed temperature is close to that of brine (i.e., $p_F^0 \approx p_D^0$), and we have

$$\Delta p = p^0 \left(a_F - a_D \right) \tag{3}$$

Hence, the driving force in OD depends not only on Δa, but also on the temperature, a function of which is p^0. Therefore, a high permeate flux can be obtained using high temperature osmotic distillation for the concentration of temperature non-sensitive solutes (Gryta 2011).

In MD process only water passes through the membrane. Therefore, the solute concentration near the membrane on the feed side is larger than that in the bulk, whereas the solute concentration on the extract side is lower than that in the bulk. This phenomenon is termed as the concentration polarization and caused a reduction of the driving force across the membrane (El-Bourawi *et al.* 2006, Barbe *et al.* 1998, Gryta 2005). Moreover, during the solution concentration the water evaporation decreases the interfacial temperature of the layers adjacent to the membrane surfaces (temperature polarisation) while vapour condensation increases this temperature. This phenomenon also decreases the driving force. The created temperature gradient causes in OD process heat

(a) (b)

Fig. 1 Temperature profile in: (a) OD process; (b) OMD process:
T – temperature, Q_V – specific heat, and Q_C – heat conducted through the membrane

conduction from brine to feed, which reduces the temperature polarization effect. Moreover, a variable interfacial temperature also induces the heat transfer between the membrane surfaces and bulk solutions. As a consequence, the feed temperature decreases and the brine temperature increases, which is presented in Fig. 1(a). The resulting temperature difference causes a further decrease in the driving force formed by the concentration difference. In OMD variant, the feed temperature is always higher than the temperature of osmotic solution (Fig. 1(b)), and the heat conduction from feed to brine through the membrane occur. This creates, similarly to DCMD, heat losses and decreases the partial pressure difference (Gryta 2005).

The permeate flux in OMD is proportional to the reciprocal of the pore length; therefore, the membranes should be as thin as possible (Martìnez and Rodrìguez-Maroto 2008). On the other hand, the application of thin membranes facilitates the possibility of membrane wetting, which results in the decline of both the permeate flux and separation performance (Gryta 2008). In order to evaluate the intensity of wetting phenomenon, a long-term study of OMD should be performed. This type of study should also be conducted in order to determine a deterioration of the membrane properties caused by fouling (Gryta 2008, Qu *et al.* 2009).

The negative phenomena described above usually occur slowly and with a low intensity. Therefore, in order to better understand these phenomena it is advisable to use OMD installations that can be operated automatically for several weeks and to use large membrane modules having a size comparable to those used in the industrial applications.

Maintaining a constant concentration of brine is a major problem in larger experimental OD/OMD installations (Cassano *et al.* 2004, Kozàk *et al.* 2008). The water absorbed from the feed lowers the concentration of the applied stripping solution which leads to a fast decline of permeate flux. The larger is the area of the membranes in a given module, the more quickly brine becomes diluted**.** For this reason a dilution of osmotic solution may result in the introduction of certain error into the obtained results.

The concentration of salt solutions is often carried out using the thermal methods, such as multi-stage flash evaporation (MSF), multi-effect distillation (MED), and vapours compression (VC). Taking into account a high level of energy consumption in the evaporation the possibility of using the natural energy sources is investigated (Valsaraj 2002). Atmospheric evaporation (natural evaporation) is proposed for the concentration of diluted solutions in several countries (Al-Shammiri 2002). This process is especially suitable for the disposal of brine in arid and semi-arid areas due to the abundance of solar energy. The same experiments demonstrated that the rate of water evaporation is directly proportional: to the difference between the saturated vapour pressure of water body (P_W) and partial pressure of water vapour in the surrounding air (ϕP_A), to the surface area of plane of evaporation, and inversely proportional to the relative humidity (ϕ) of air into which the water will evaporate (Al-Shammiri 2002, Valsaraj 2002). P_A is the saturated vapour pressure of water in air at a process temperature.

The climatic parameters and boundary layer conditions (turbulent flow) significantly affect the atmospheric evaporation efficiency in traditional ponds technology. At the initial period of natural evaporation of liquid the heat transport to the evaporating surface is smaller than a heat lost associated with the mass transport and the solution temperature decreases until equilibrium condition is reached. As the evaporation interface is in equilibrium, the net heat flow rate is zero and the solution temperature reaches the temperature of wet thermometer, which is a characteristic temperature of solution during an atmospheric evaporation. In this process the mass transport is linked with the heat transfer from air to solution surface and the conditions of the heat transport are the factors controlling the evaporation rates. In OMD process the heat is transferred to the brine with the permeate flux (vapour condensation) and by conduction from heated feed. As the brine temperature is a higher than that of air, the heat transfer mechanism is different in comparison to pond methods. In this case, the heat induced inside the OMD installation is the major source of energy required for water evaporation.

The objective of this research was to develop a system of a pilot plant for OMD process coupled with self-regeneration of osmotic solution. The presented design solution uses the concentration of brine through its natural evaporation, which allows to carry out the OMD study for several weeks while maintaining a constant concentration of the osmotic solution.

2. Experimental

The experimental set-up used in the studies is schematically presented in Fig. 2. A pilot plant was assembled from industrial components, owing to which it can be operated continuously and safely. The installation was constructed using PVC (1/2“) tubes and water solutions were pumped using acid-resistance centrifugal pumps (TE-3-MD-HC, manufactured by Little Giant Pump, USA).

A sodium chloride osmotic solution was circulated in a brine loop from a brine tank (20 L) on a shell side of the OMD module. The feed was circulated in the feed loop from the supply tank (5 L) through the bore of the capillary membrane. Distilled water was used as the feed, which allowed to limit the influence of polarization phenomenon on the lumen side of the membrane. The temperatures brine and feed entering the module were in the range of 290-313 K. The flow rates within the range 0.168-0.71 L/s m^2 (membrane area) were used for operating the OMD installation. The pressure of both circulating osmotic solutions and feed was measured by a pressure gauge. The largest measured values (for a maximum flow rate) were: 0.35 bar - osmotic solution and 0.36 bar - feed. The stream temperatures were measured using electronic thermometers with ± 0.1 K accuracy.

The flux of permeate obtained during the OMD process was calculated on the basis of changes in the water volume in the feed tank. For this purpose, after starting the pilot plant and achieving the constant parameters of its operation (temperature, flow rate), the feed tank was filled-up with water and the feed level was read from a pipette scale (8 - Fig. 2). During the OMD process the water evaporated through the membranes, and the feed loss was refilled usually once a day in the

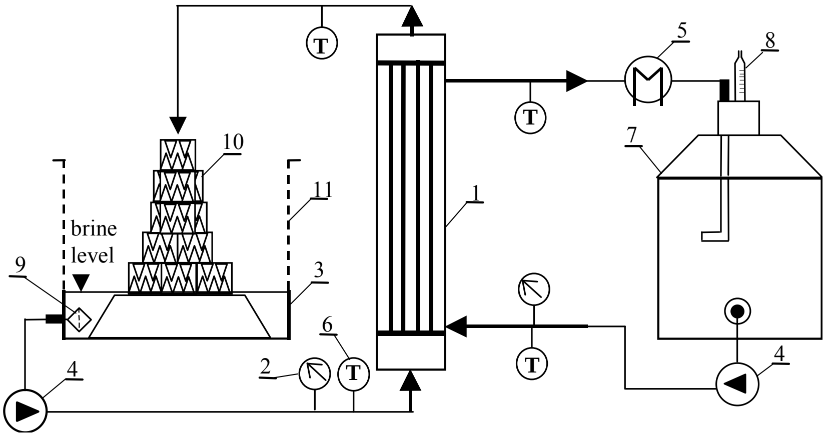

Fig. 2 The OMD pilot plant: 1 – OMD module; 2 – manometer; 3 – brine tank; 4 – pump; 5 – heat exchanger; 6 – thermometer; 7 – feed tank; 8 – pipette; 9 – filter; 10 – Białecki rings; 11- net

feed tank, which also enables the determination of the average permeate flux over the period of experiment duration.

A capillary OMD membrane module with the diameter of 0.021 m and the effective length of 0.83 m was assembled in a vertical position. The module was equipped with 18 hydrophobic capillary polypropylene membranes (Accurel PP S6/2, Membrana GmbH – Germany). The capillaries had an internal diameter of 1.8 mm and an outer diameter of 2.6 mm, and the porosity of 73% (the manufacturer's data). The membranes were located in every second mesh of six sieve baffles, arranged across the module housing within 0.15 m. The total surface area of the membranes for the mass transfer was calculated for the internal capillary diameter and amounted to 0.084 m^2.

The pilot OMD installation was operated in two modes: without the regeneration of the osmotic solution and with a system for the regeneration (concentration) of brine. The system consisted of a tower composed of 17 Białecki rings (80 mm in diameter and high) that was placed in the osmotic solution tank, over the liquid level (Fig. 2). For the used ring dimension the packing density is 2160 rings/m^3. The osmotic solution (NaCl) after leaving the module was directed towards the top of the tower where it was sprayed on the surface of the first Białecki ring (top of tower). The evaporation surface created by the Białecki rings (0.4 m^2) was found to be large enough to maintain a constant concentration of brine through natural evaporation. The external and internal surfaces of rings were taken for the calculation as an effective evaporation area. Such calculated area was five times larger than the membrane area in used capillary module. The used Białecki rings (DOLSIN, Poland) have open-work design, which significantly improve the parameters of the column fillers, e.g., they have the flow resistance two or three times lower than the Rashing rings.

The solute concentration expressed as the total dissolved solids (TDS - NaCl mode) and electrical conductivity of water was measured with 6P Ultrameter (Myron L Company, USA). An air temperature and the relative humidity were measured by electronic hygrometer AZ8829 (AZ-Instruments, Poland) connected with computer program TRLOG v.3.4.

3. Results

3.1 Yield of natural evaporation

At the initial stage of the presented study the effectiveness of Białecki ring's tower used for the concentration of brine by natural evaporation was investigated. In the experimental set-up (Fig. 2) the membrane module was disconnected and only a loop with the osmotic solution was working. At the starting moment, a solution temperature was equal to the air temperature. The obtained experimental results for NaCl solutions were presented in Fig. 3. The salt solution were circulated through the evaporation tower and then were contacted with surrounding air, and as a result of water evaporation the temperature of brine was decreasing. During the concentration of solution the heat required for water evaporation is taken from a liquid surface. This heat must be supplied to the solution/air interface at an equal rate to prevent a temperature drop. A heat source is mainly the surrounding air. However, the temperature gradient is required to achieve the heat transfer from air to the liquid surface, therefore, the brine temperature is established 3-6 K below air temperature (wet thermometer effect).

Dissolved solids reduce the vapor pressure over the solution, thus causing a decrease of the evaporation rates. The effect of salinity in these experiments was also observed. However, the observed decrease in the evaporation rate was relatively low and the process efficiency obtained for a concentrated solution was higher than that presented by other authors (Al-Shammiri 2002, Armenta-Deu 2002). As was shown in Fig. 3 for air humidity equal to 47-50%, the evaporation rate decreases from 3.4 to 2.6 kg/m^{2}h when the salt concentration increases from 138 to 223 g NaCl/L. For humidity of 50-54%, the evaporation rate decreases from 2.3 to 1.5 kg/m^{2}h when the salt concentration increases from 42 to 233 g NaCl/L. These results also indicated that the evaporation rates decreases with increasing the relative humidity. An increase of the humidity from 47 to 60% caused that the evaporation rate decreased more than two times.

According to the actual daily weather, the air temperature and humidity changes around the OMD installation. The changes of these values during the study were presented in Fig. 4. The measured values fluctuated from 293 to 299 K, corresponding to the changes in the relative

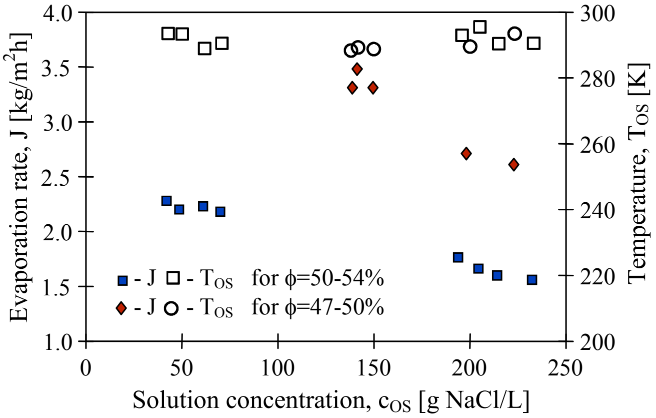

Fig. 3 The influence of osmotic solution concentration on the evaporation rate and equilibrium brine temperature for different values of air humidity (ϕ). Air temperature: 297-298.5 K

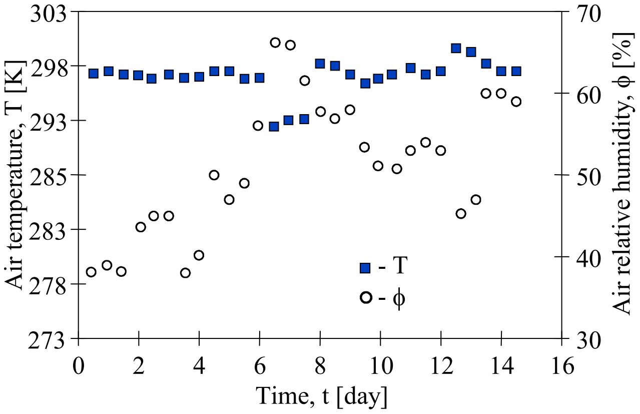

Fig. 4 Changes of air temperature and relative humidity during the study of natural evaporation presented in Fig. 3

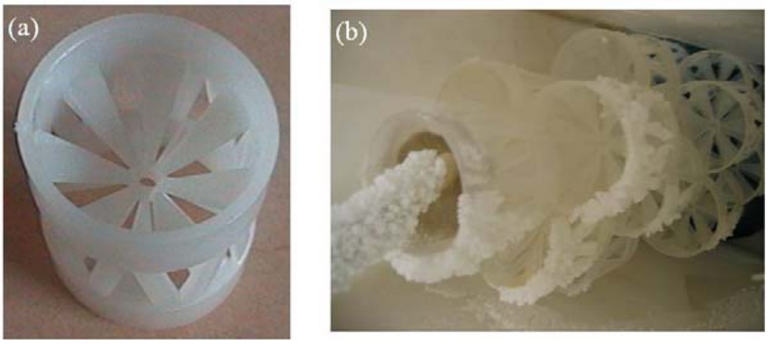

Fig. 5 The images of used rings: (a) Białecki ring; (b) rings covered by NaCl deposit

humidity from 38 to 65%. Similar fluctuations were observed during three months of the OMD studies. In the presented study, the average evaporation rate of water from surface the tower packed with Białecki rings (Fig. 5) was 0.4-0.6 kg/h. These values were significantly larger than obtained OMD permeate fluxes, therefore, the saturation state of osmotic solution was maintained during a long term study of OMD process.

3.2 Periodic regeneration of osmotic solution

A batch variant of osmotic distillation was used in the first stage of the research. A brine tank was filled with 6 dm^3 of concentrated NaCl solution. After the installation was started, the temperature of the streams was progressively increased until it reached the values that were stabilized after several hours of operation (Fig. 6). The initial increase of the streams temperature was caused by a heat release of a part of energy used for pumping the solutions (centrifugal pumps). Finally, the feed temperature was lower than that of the brine, which is in accordance with the temperature profile presented in Fig. 1(a).

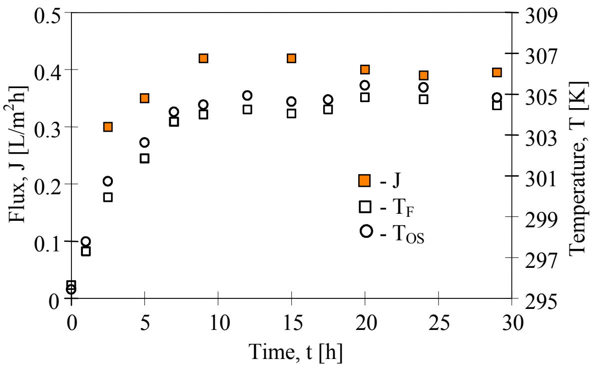

Fig. 6 Changes in streams temperature and process efficiency during the OD process; The initial concentration of osmotic solution: 286 g NaCl/L

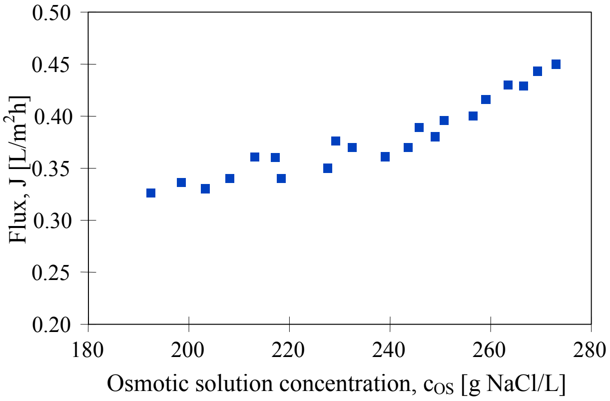

Fig. 7 The influences of osmotic solution concentrations on a variation of permeate flux. Feed temperature: 304-305.5 K; Brine temperature: 304.5-306 K

The temperature of osmotic solution was stabilized at approximately 0.5-0.6 K above the feed temperature. This effect results from a principle of the course the OD process - feed was cooled through the evaporation and latent heat of vapour (condensation) heated the brine. The obtained temperature values were also affected by heat exchange between the installation and the ambient air (295-298 K). In order to limit the magnitude of heat loss, the installation was placed in a fume hood thermostated with heating cables. As a results, the air temperature around the installation during the experiments were 301-303 K, therefore, the heat exchange with the air was reduced.

The temperature of streams in the OMD installation were stabilized within the initial 10 h of measurements (Fig. 6), and the process was then continued for another 120 h. During this period, the feed temperature was in the range of 304-305.5 K and the brine temperature was on average higher by 0.5 K, than the feed temperature. As a result of water vapour transport through the membranes the NaCl concentration in the osmotic solution decreased from 275 to 192 g/L, which also decreased the permeate flux from 0.45 to 0.33 L/m^{2}h. The influence of NaCl concentration on the value of obtained permeate flux was presented in Fig. 7. These results indicated, that a larger decrease of the flux occurred when a more concentrated solution was diluted. It is due to a partial pressure decrease, and this effect is more noticeable for higher process temperature (Fig. 8), because the vapour pressure increases exponentially with temperature.

A large tank of brine (20 dm^3) was assembled in the pilot installation, which allowed to obtain the ratio of volume to the module area of 0.24 m^3/m^2 (maximum). In the above-discussed case the initial brine volume was 6 dm^3 (0.072 m^3/m^2). An increase of this volume could cause a slower change of NaCl concentration in the solution, but ultimately the regeneration of the stripping solution is still necessary to be applied. In a batch mode of process operation, diluted brine is concentrated in the evaporators and the system is then filled with regenerated brine. The course of installation operation in such a mode (from the beginning of its exploitation) is presented in Fig. 9. In the investigated cases, the concentration decrease from 280 to 230 g NaCl/L caused a more than two-fold drop in the efficiency. These results confirm a significant influence of the stripping solution concentration on the obtained permeate flux.

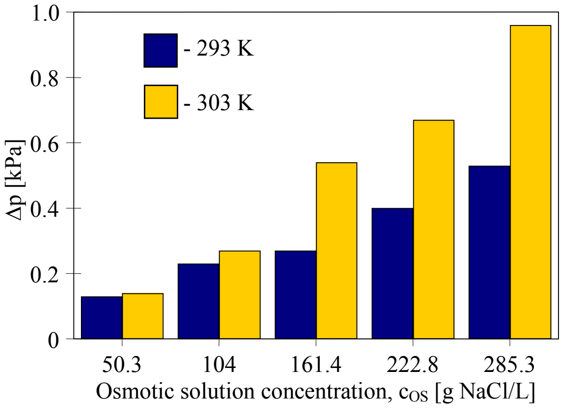

Fig. 8 Partial pressure difference between water and brine with different salt concentration; $T_F = T_{OS} = 293$ and 303 K; The calculations were performed based on data presented in Lide (1997)

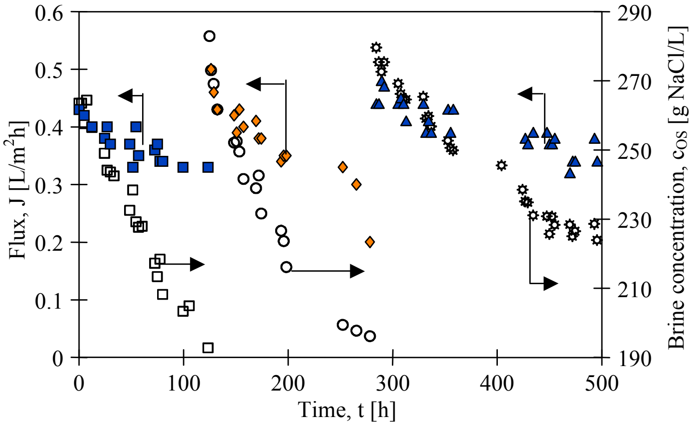

Fig. 9 Changes of the permeate flux and brine concentration during OD process with a periodic exchange of osmotic solution

The highest yield of installation can be obtained when the concentration of osmotic solution will be permanently close to the saturated state. Therefore, in order to increase the installation efficiency it is advantageous to use any method of brine regeneration that in order to maintain its concentration high over the entire operating period OD/OMD process. In the last series (Fig. 9 from 284 h) a cover was removed from the osmotic solution tank, which allow the water evaporation into the atmosphere. In this case, the brine concentration decreased from 280 to 221 g NaCl/L and the permeate flux decreased from 0.44 to 0.343 L/m^{2}h during OD. As a result, the osmotic solution was diluted by less than 10% in a comparison with the two previous series that were carried out without the evaporation, although this series was conducted by over 60% longer.

The influence of water evaporation from the stripping solution on the course of process was presented in Fig. 10. When the brine tank was opened, a decrease in the concentration of the stripping solution was stopped and its concentration was stabilized at 165 g NaCl/dm^3. Moreover, the values of permeate flux at the end of series without evaporation (J_1) is significantly lower than the values of J_2 obtained for similar brine concentration. This was caused by the difference in temperature of streams. The evaporation of water from brine requires energy; therefore, the brine undergoes a natural cooling as a result of evaporation. In the investigated case the brine temperature decreased from 304 to 302 K, which reduced the magnitude of temperature polarization (Fig. 1(a)) and increased the value of the driving force (Eq. 2 and Fig. 3).

Unfortunately, a colder brine during the flow through the OMD modules cools the feed, which reduces the driving force of mass transfer. As a result, the values of J_2 were decreased from 0.27 L/m^{2}h (76 h) to 0.258 L/m^{2}h (90 h - Fig. 10). However, the total effect of brine cooling through the evaporation is positive and a slightly higher efficiency was obtained in this case in comparison to that in the system without evaporation (Fig. 10, 68 and 90 h).

3.3 OMD with continuous brine regeneration

The obtained result indicates that the application of osmotic solution regeneration by natural evaporation may be an interesting alternative to classical evaporation methods. In Fig. 10, due to natural evaporation, the brine concentration was stabilized at a level of 165 g NaCl/L. This is an equilibrium value between the given operational conditions of the installation, the free surface of

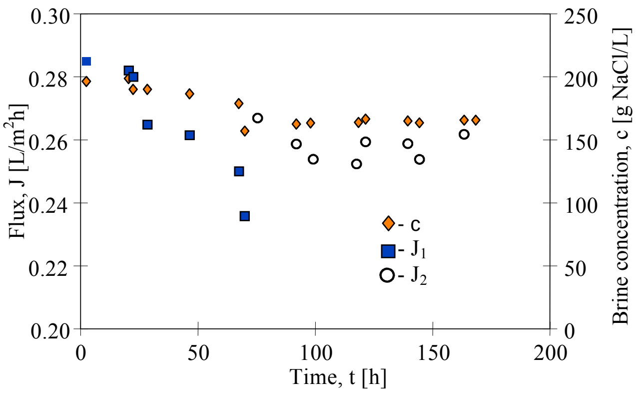

Fig. 10 The course of OD process without evaporation (J_1) and with evaporation (J_2) of the osmotic solution

the osmotic solution and the relative humidity of air over liquid surface in the tank. In order to increase the degree of brine concentration, it is necessary to increase the area of water evaporation.

In this work was utilized the experience from the design of absorption columns, where the mass transfer area and process intensity can be increased by the use of structural elements. In the present case the Białecki rings were used for this purpose (Fig. 5(a)). These rings were made of polypropylene, i.e., from the same material as the membranes. It is important for the filler to be made of a brine resistant material. In our case the 17 rings forming a tower were placed inside the stripping solution tank (Figs. 2 and 5(b)). The osmotic solution flowing out of the OMD module was subsequently flowing down the rings and was than collected at the bottom of the tank, from where it was recycled to the installation. The evaporation in this system was found to be so effective that brine in the tank became supersaturated and a partial crystallization of salt was observed. In order to prevent the pumps from sucking in crystals, a net filter (50 mesh) was installed at the inlet of the suction conduit (9, Fig. 2).

The concentration effectiveness of osmotic solution during the OMD with simultaneously water evaporation on the surface of the Białecki rings was presented in Fig. 11. At the initial period the feed was heated to 305-306 K. Although the brine was simultaneously diluted by the absorbed permeate (water), the salt concentration was progressively increasing (OMD time axis) until it reached the concentration of 318 g NaCl/L. This result confirmed that the presented pilot plant could be used for continuous OD/OMD study with a constant concentration (close to saturation state) of osmotic solutions. It should be noted that the presented design can be applied only for those solutions of salts for which the vapour pressure of the saturated solution is lower than the water vapour in the ambient air. Otherwise, such solutions will be not concentrated; on the contrary, the absorption of humidity from the air will dilute it.

Similar to OD process, also in OMD the feed temperature and the concentration of osmotic solution has a significant influence on the permeate flux (Fig. 11). The three last experimental points in Fig. 11 show the results obtained without feed heating. In this case, the feed temperature in the installation was stabilized at a level of 299.5-300.6 K, and the brine temperature was equal to 297.6 K. When heating was switched on (heat exchanger, 8 - Fig. 2), the feed temperature increased to 305-306.3 K. Due to the mass transfer as well as the thermal conduction through the

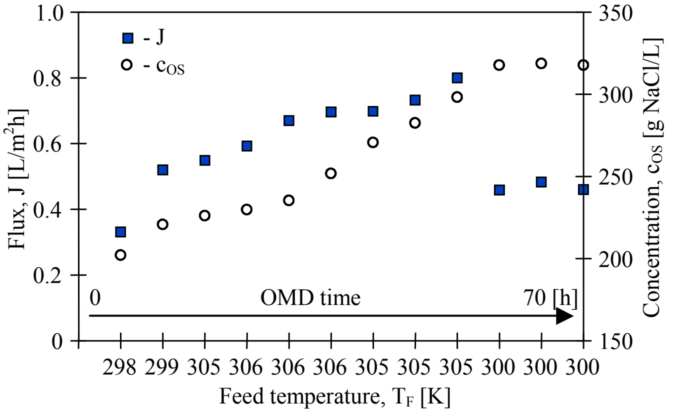

Fig. 11 The influence of feed temperature and osmotic solution concentration on the permeate flux in OMD process

membranes in the OMD module, the energy was transferred from the feed to the osmotic solution and as a result, its temperature increased to 302 K. In both cases (with/without feed heating), the temperature profile formed inside the OMD module was similar to present in Fig. 1(b). Caused by feed heating the slight increase in the streams temperature significantly enhanced the OMD process yield and the rate of brine evaporation. In case investigated (Fig. 11), the brine concentration was increased from 202.3 to 318 g NaCl/L after only 50 h of the process duration. This is considerably faster than in the case without feed heating, where a similar salt concentration was obtained during 170 h of OMD process duration (Fig. 12, from 50 to 220 h).

An increase of the feed temperature from 300 to 305 K caused that the permeate flux in OMD variant increases from 0.4 to 0.8 L/m^{2}h. This yield is almost two times higher than that obtained for OD at a similar level of temperature (Figs. 6 and 7). When a concentrated feed does not lose its properties as a result of contact with the heating surface (its temperature is in a principle much higher than that of the heated feed), its is advisable to take into consideration an OMD option of process realization. The fact should also be noted that the increase of efficiency resulted in the introduction of a much larger amount of water into the brine, but even then its regeneration was faster than in the process conducted without heating. If the feed was not heated, the feed temperature was stabilized at a level of 300 K. At lower feed temperature the permeate flux was reduced to 0.4 L/m^{2}h (Fig. 11), however, it was still higher than the flux obtained for similar process conditions in the OD variant (Fig. 2, 6 h). This resulted from a fact, that the application of natural evaporation on the Białecki rings enables to obtain the OMD temperature profile also in this case.

The intensity of natural evaporation is affected by air humidity (Fig. 1). The air surrounding the installation had a relative humidity in the range of 30-50%. During a long-term rainfall the humidity increased to 60-80%, but the brine was concentrated even under these conditions (Fig. 12). The evaporation area of tower, composed by used Białecki rings, was five times larger than the membrane surfaces in OMD module, what enables to obtain the saturated brine also in the case when the outside conditions were unfavorable for the natural evaporation of water.

When brine flows down the surface of the Białecki rings, both a liquid film and small droplets are formed. Some droplets migrated outside the tank with osmotic solution causing the contamination

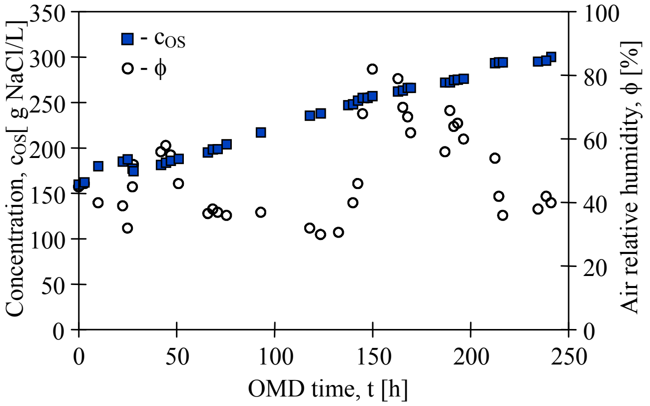

Fig. 12 OMD process with a simultaneous concentration of osmotic solution using the method of natural evaporation from Białecki rings surface

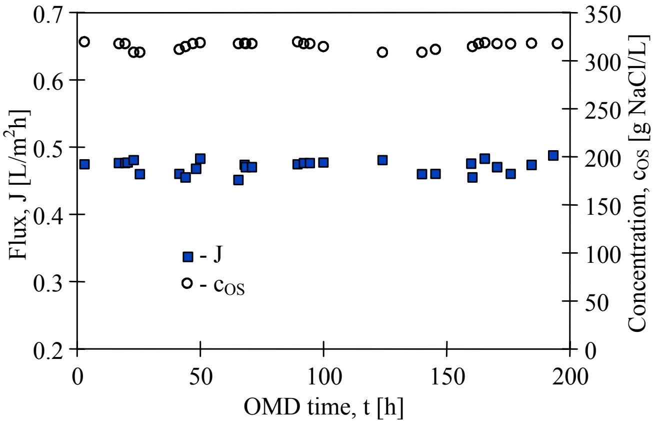

Fig. 13 Changes of the permeate flux and concentration of osmotic solution during OMD with natural evaporation of brine

of the environment of OMD installation. This effect was eliminated by extending the tank walls by mounting a flange made of a net (net mesh of 0.1 mm) – (11, Fig. 2). Sprinkling droplets settled on the inner surface of the net and flowed inside the tank. The presence of protecting net did not affect the stripping solution concentration, which was close to that of the saturated solution during the entire process (Fig. 13). This fact allowed to conduct a long-term study of the OMD installation for several months at a practically constant concentration of brine. Periodically, small amounts of distilled water were added to the brine tank, as the evaporation efficiency was slightly higher than that of the OMD module. Moreover, the maintenance work of the installation was carried out three to four times per year, which included washing, exchange of the stripping solution and removal of salt dust from the installation surface.

The water conductivity in the feed tank was systematically measured during the investigations. Its value did not exceed 10 μS/cm. Taking into consideration the fact that the brine was flowing on the other side of the membranes, it can be concluded that the membranes demonstrated practically 100% degree of separation. This indicates that the used membranes exhibited a good resistance to wettability by the concentrated NaCl solutions.

4. Conclusions

It was demonstrated that the concentration of salt solutions using the natural evaporation can be an efficient method of maintaining a constant concentration (close to saturation state) of the osmotic solution in OMD process.

The extension of evaporation surface using structural packing, such as the application of the Białecki rings, allows to construct small, but efficient OMD installations useful for long-term pilot studies.

The presented system allows to evaluate the usability of a given kind of membranes for the OMD process. In the study case, the applied polypropylene membrane was not wetted and exhibited a good resistance for the osmotic solution.

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