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Original paper

FRESH WATER PRODUCTION IN COASTAL AND REMOTE AREAS BY SOLAR POWERED LIQUID-LIQUID MEMBRANE CONTACTOR

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ABSTRACT

Liquid-liquid membrane contactor (LLMC) is a new desalination process using microporous hydrophobic membrane. The temperature difference at two solution-membrane interfaces gives rise to a trans membrane vapor pressure difference that drives the flux. In this work, the effect of process parameters on LLMC performance has been done. The process parameters consist of feed and permeate temperatures, cross flow velocity, feed concentration and mode of operation. In addition, this paper focuses on the development of LLMC by using solar and wind as energy sources. In this experiments micro porous hydrophobic hollow fiber polypropylene membrane with 0,2 μm was used as a contacting device. The experiment were conducted at temperature of 25-80^{o}C, cross flow velocity of 0.02-0.2 m/s and solute concentration of 0-110.000 mg/L. Results show that the flux was influenced by the feed and permeate temperatures, the cross flow velocity and the concentration of solute. The increase of feed temperature increases the flux exponentially, whereas the flux seems to increase linearly with the increase of cross flow velocity. On the other hand, the flux was not significantly affected by the solute concentration. Furthermore, the flux in the counter current mode was lower than in the co-current mode. The average pure water fluxes obtained were in the range of 2-3 l/(m^{2}h), whereas the products concentrations were in the range of 2-5.3 mg/L depending on the feed concentration. The operation of solar powered LLMC up to 10 days shows a very stable performance.

Key words: flux, liquid-liquid membrane contactor, wind and solar energy

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INTRODUCTION

Nowadays, desalination process of seawater, brackish water or highly salinity water has become a necessity especially in coastal and remote regions. This condition is caused by the limitation of water resources and the growing population. Freshwater, which can be used by man, accounts for only 2.5% of all water resources on the earth while the other 97.5% are seawater and salty lake water (Takenaka Corp., 2001). This fact shows that most potential water resources are salty. Liquid-liquid membrane contactor

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(LLMC) is one of membrane technologies, whose high potential for drinking and/or pure water production from seawater or brackish water especially for small and medium scale. The main advantages of this process are shown from the fact that no pressure is needed and its suitability to be implemented in rural areas because of possibility in using solar and wind as an energy sources. This technology is also suitable for drinking water production in "FINISI", an old fashion Indonesian ship with no engine.

LLMC is a membrane distillation process in which both liquid feed and liquid permeate are kept in contact with the hydrophobic microporous membrane. The temperature difference between the two solutions gives rise to a trans membrane vapor pressure difference that drives the flux. Due to their hydrophobicity the liquid can not penetrate into membrane pores, but the vapor can pass the pores.

The process scheme of LLMC is shown in **Figure 1**. In LLMC, the distillation is performed at ambient pressure and at maximum temperature of 90°C. Operating costs are extremely low because the process can be driven by low temperature heat source e.g. solar heat or waste heat (Takenaka Corp., 2001; Bier and Plantikow, 1995; Scarab, 1999 (a); Scarab, 1999 (b); Drioli et.al., 1985). Researches to increase LLMC performance have been done (Drioli and Wu, 1985; Gostoli and Sarti, 1989; Kubota et.al., 1998; Lawson et.al., 1995; Lawson and Lioyd, 1996 (a); Lawson and Lioyd, 1996 (b); Scheneider et.al., 1988; Schofield et.al., 1987). This paper presents the process parameters affecting LLMC performance and develop-ment of LLMC using solar and wind as an energy sources.

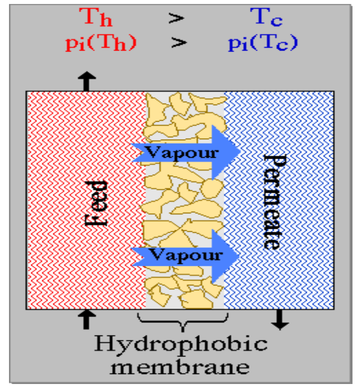

Fig. 1. Schematic representation of LLMC

MATERIALS AND METHODS

Variables

The process variables observed were the feed and permeate temperatures, the cross flow velocity, the feed concentration and the mode of operation. The effects of feed and permeate temperatures on flux and product quality were studied by varying the temperature from 25 to 80°C, while the effect of feed velocity on flux was studied in the range of 0.02 to 0.2 m/s. In all experiments, the feed and permeate velocities were kept in the same value. The experiments were also conducted by varying the solute concentrations from 0 (pure water) to 110000 mg/L to study the effect of feed concentration on flux. The experiments were conducted in co-current and counter current modes to understand which operation mode is the best in respect to flux.

Materials

In this study, microporous hydrophobic hollow fiber polypropylene was used as a membrane material. The specifications of polypropylene membrane are pore diameter 0.2 μm, porosity 70%,

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outter diameter 540 μm, inner diameter 390 μm, fiber length 0.2 m. NaCl aqueous solution and pure water were used as the feed and permeate, respectively.

Experimental apparatus

The experimental apparatus to study the effect of process parameters on LLMC performance is shown in **Figure 2**.

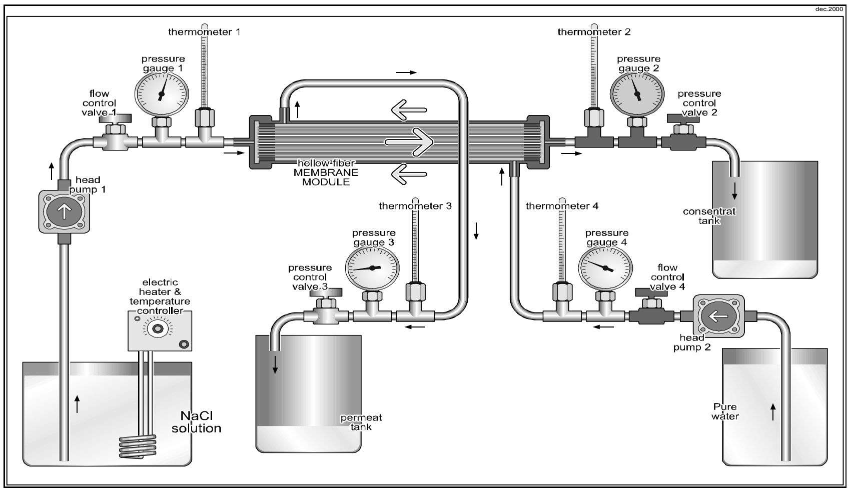

Fig. 2. Schematic representation of experimental apparatus

Solar powered liquid-liquid membrane contactor experimental

The development of LLMC by using solar and wind energy was conducted for possible implementation in coastal or remote areas where electrical energy is not available. The use of solar and wind is expected to solve the problem of the unavailability of electricity supply. The main equipment of this prototype consists of a membrane module, a solar collector, a wind generator and shell and tube heat exchanger. The schematic representation of solar and wind powered LLMC is presented in **Figure 3**.

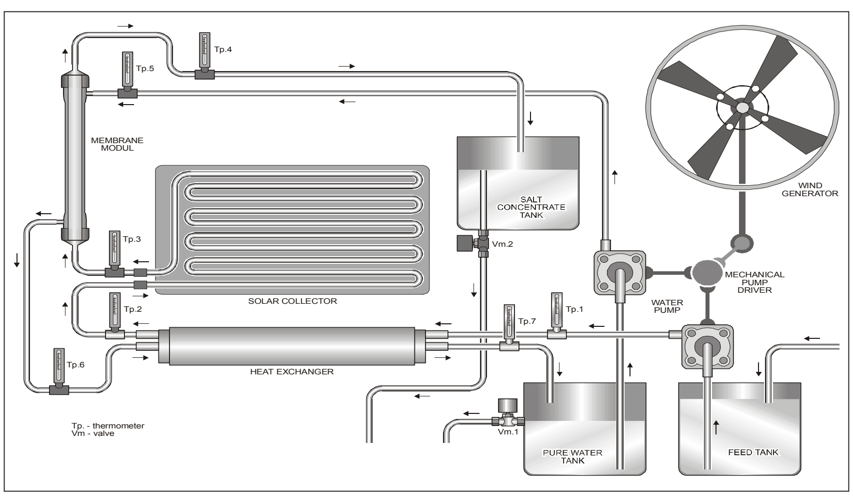

Fig. 3. Schematic representation of LLMC powered by solar and wind energy

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The liquid in the feed tank is sent to the system using a pump powered by wind generator. The liquid feed is heated in heat exchanger using warm fluid from permeate outlet to increase its temperature. Furthermore, the liquid feed is further heated in solar collector. The purpose of this heating is to increase the feed temperature before entering the membrane module. From the solar collector, the liquid feed is flowed to the membrane module in lumen side. On the other side, pure water as permeate fluid is circulated through shell side of the membrane module. Because of the difference in vapor pressure between liquid and permeate which are separated by a porous hydrophobic membrane, vapor evaporating from the feed is transported through the pores of the membrane and condensed in the permeate side. In the case of seawater, brackish water or salty water, the component evaporated is mainly water.

RESULTS AND DISCUSSION

The Effect of Feed and Permeate Temperatures on Flux

The experiments were conducted by varying the feed and permeate temperatures from 25 to 80 ^{o}C. The feed and permeate velocities were 0.05 m/s. The feed concentration was 30000 mg/L. The experimental result of the flux profile as functions of feed and permeate temperatures is shown in **Figure 4**.

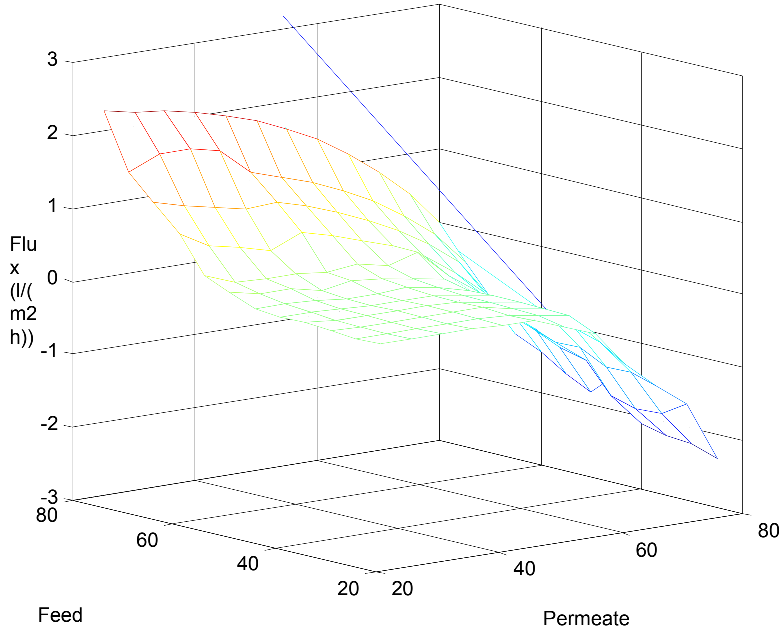

Fig. 4. The flux profile functions of the feed and permeate temperature at v = 0.05 m/s and NaCl = 30000 mg/L

Figure 4 explains that the increasing feed temperature increases the flux exponentially; on the contrary the increasing permeate temperature decreases the flux. The same temperature difference between feed and permeate did not result in the same flux. This phenomenon can be explained based on the partial vapor pressure as the mass transfer driving force in LLMC. The vapor pressure of water can be calculated from the Antoine equation (Foust,1980). The relationship between the water vapor pressure and temperature was an exponential function. Because of this relationship, the flux obtained was also an exponential function to the feed temperature. Furthermore, the same temperature increase in different temperature did not result in the same increase in flux. In addition, **Figure 4** shows that the lower the permeate temperature the higher the flux. Another observation suggests that there were negative fluxes in LLMC. It means that the flux occurs from permeate side to feed side. It is caused by the vapor pressure in the permeate side which was higher than in the feed side. This indicates that there was a minimum temperature difference to be considered in order to cause the flux occurs from feed side to permeate side. This minimum temperature difference was called the threshold temperature difference.

The Effect of Feed Velocity on Flux

The experiment to understand the effect of feed velocity on flux was conducted by varying the feed velocity at various feed concentrations and feed temperatures. Due to the limitations on pumping rate, the feed velocity varied from 0.02 to 0.2 m/s. The experimental result is shown in Figure 5.

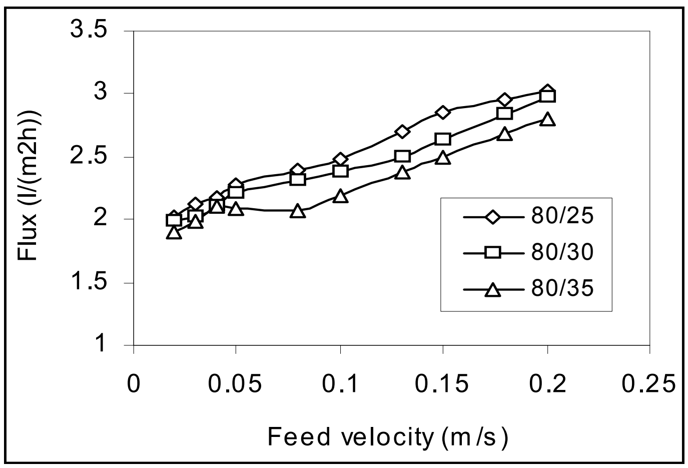

Fig. 5. The effect of feed velocity on flux at various Tf/Tp with feed concentration of 30000 mg/L

Figure 5 explains that the increase of the feed velocity increases the flux linearly. The increase in feed velocity by 10 times increases the average flux by 1.5 times. These phenomena can be explained by explaining the influence of feed velocity on fluid turbulence, temperature and concentration polarizations phenomena, and the decrease of temperature along the membrane module. The increase in feed velocity increased the heat and mass transfer coefficients. Consequently, this increases the water vapor flux, which is transported from feed to permeate sides. The feed velocity influenced the temperature and concentration polarizations in membrane interface. The higher the feed velocity the lower the temperature and the concentration polarizations. The decrease in the temperature polarization increased the vapor pressure difference between feed and permeate. The increase in feed velocity decreased concentration polarization in interfacial membrane at feed side, so the membrane wall concentration was being lower and resulted in higher vapor pressure. However, the increase in vapor pressure caused by the decrease in concentration polarization was very small.

The Effect of Feed Concentration on Flux

The study of the effect of feed concentration on LLMC flux was conducted in the range NaCl concentration of 0-110000 mg/L. Figure 6 shows the experimental results.

Figure 6 shows that the flux was not significantly affected by the solute concentration. The presence of solute in feed influenced the colligative property and activity solution, heat and mass transfers coefficient. The degree of the decrease in the three parameters mentioned was influenced by the number of solute in feed in mole fraction and density. The mole fractions of solute corresponded to such range of concentration was in the range of 0 to 0.037, while the feed density was between 980 to 1050 kg/m^3 and the decrease of the feed vapor pressure was in the range of 99% to 93%. The higher the feed concentration the lower the vapor pressure. However the decrease in the vapor pressure was insignificant; consequently, the flux was relatively stable. In addition, the decrease in vapor pressure because of the presence of solute also influences the thermal conductivity and heat capacity. In the range of concentrations used, the influence on these parameters was very small. Therefore, the decrease of flux because of the decrease in heat transfer was insignificant.

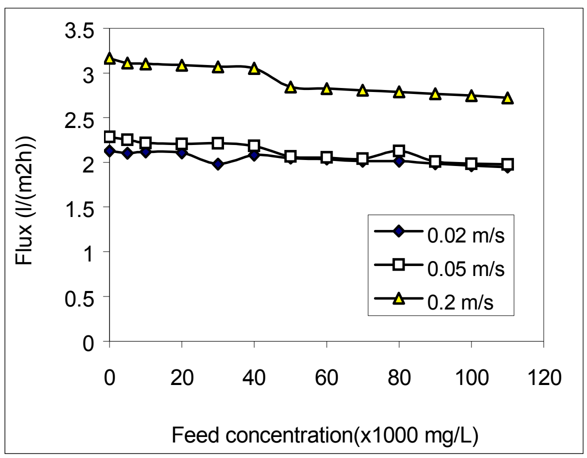

Fig. 6. The effect of feed concentration on flux at various feed velocities and Tf/Tp = 80/30^{o}C

The Effect of Operation Mode on Flux

Hollow fiber module enabled operation in counter current and co-current systems. In many cases, the counter current mode was commonly used than the co-current mode. In LLMC not only heat transfer but also mass transfer occurs in membrane; consequently, the operation mode determines the flux. The experiment was performed to determine which operation mode results in the preferable flux at feed concentration 30000 mg/L. The experimental result is shown in Figure 7.

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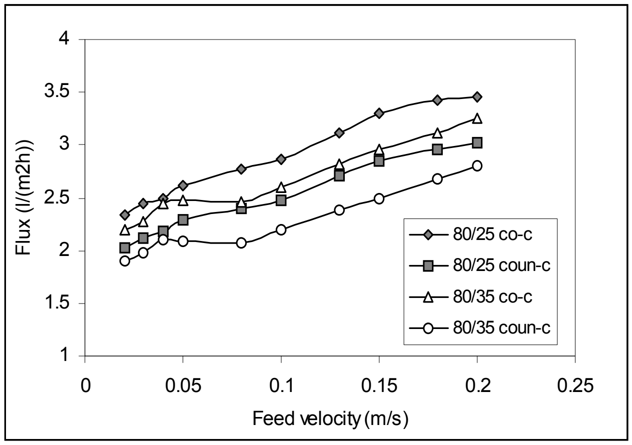

Fig. 7. Flux comparison between co-current and counter current modes at feed concentration of 30000 mg/L

From **Figure 7**, it can be seen that, the flux obtained in the co-current mode was higher than in the counter-current mode. This can be explained by examining the mean vapor pressure difference between the inlet and outlet of the feed and permeate. The arithmetic mean vapor pressure difference in co-current and counter-current modes can be calculated based on the inlet of feed temperature 80°C and permeate temperature 25°C corresponded to vapor pressure of 47 and 3 kPa respectively at feed concentration 30000 mg/L. In the counter current operation mode, the feed and permeate temperatures out from the membrane module were 62°C (22 kPa) and 42°C (8 kPa) respectively, resulted in the mean vapor pressure difference of 29 kPa. Furthermore in the co-current operation mode, the feed and permeate outlet temperatures are 65°C (35 kPa) and 38°C (7 kPa) respectively, resulted in the mean vapor pressure difference of 31 kPa. Therefore, the flux in co-current mode was higher than in counter-current mode. In addition, in LLMC the heat transfer by conduction was the heat loss, which was an undesirable process. In the counter current process the heat transfer by conduction was higher than in the co-current process.

The effect of feed temperature on product quality

Other than the flux, the product quality is a parameter, which can be used as an indicator of LLMC performance. In this experiment, product quality in LLMC was determined by measuring product concentration at different feed temperature and feed concentration. The feed temperature was varied from 40 to 80°C and the salt concentration used were 5000 and 30000 mg/L at velocity of 0.05 m/s. The permeate inlet temperature was kept constant at 25°C. The experimental result is shown in **Figure 8**.

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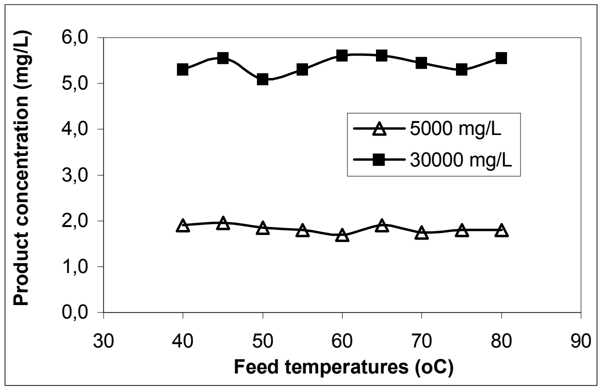

Fig. 8. The effect of feed temperature on product quality at permeate temperature of 25°C and feed velocity of 0.05 m/s

Figure 8 shows that the increase in feed temperature did not influence the product quality. The membrane material used was polypropylene, which is a hydrophobic material. This hydrophobicity prevented the liquid penetration into the membrane pores, so that the product quality only depends on water vapor quality evaporated at the membrane surface. The total dissolved solid concentration of pure water was 2 mg/L for feed concentration 5000 mg/L and 5.3 mg/L for feed concentration 30000 mg/L correspond to rejection coefficients of 99.96 to 99.98 %. This shows that very high selectivity can be obtained by using this technology.

Solar Powered Liquid Liquid Membrane Contactor

The experiment using solar and wind powered LLMC unit was performed by the apparatus as shown in Figure 3. Experiment was conducted at feed concentrations 30000 mg/L and 100000 mg/L, the feed velocity was 0.2 m/s and the feed and permeate temperature were 80°C $\pm$ 5 and 25°C $\pm$ 5 respectively. The mode of operation was co-current. The experimental result is shown in Figure 9.

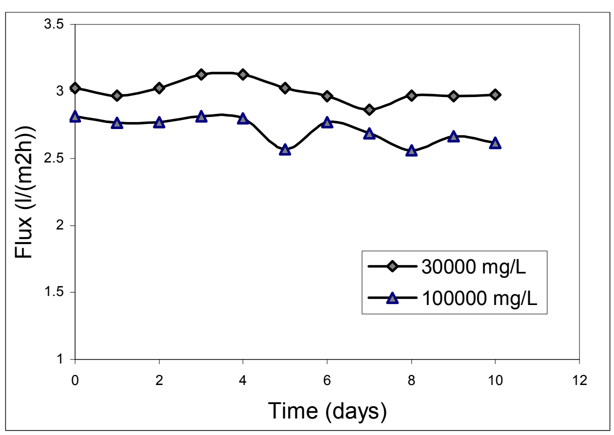

Fig. 9. The flux stability on operation time at Tf/Tp = 80/25°C and feed velocity 0.2 m/s

Figure 9 shows that at both feed concentration 30000 and 100000 mg/L, the fluxes were relatively stable up to 10 days. This indicates that no fouling phenomenon occur in LLMC. In LLMC the membrane material was highly hydrophobic allowing only vapor to pass through the membrane pores. Because of its high mobility, no accumulation of vapor occurs in the membrane pores. The presence of liquid in the membrane pores was known as one of the main reason for the decrease of flux in LLMC. In addition, although the feed concentration was increased up to 100000 mg/L, crystallization on membrane surface does not occur. This again indicates that concentration polarization can hardly take place. This is the superiority of LLMC compared to the other membrane processes where fouling is usually very severe.

CONCLUSION

The study of the effect of process parameters on LLMC performance has been done. The experimental results show that the increase in feed temperature increases the flux exponentially; on the contrary the increase in permeate temperature decreases the flux. The increase in feed velocity by 10 times (from 0.02 to 0.2 m/s) increases the averages flux by 1.5 times. The flux was not significantly affected by the increase in feed concentration up to 110,000 mg/L. The co-current operation mode resulted in higher flux than the counter current operation mode. The concentrations of pure water products were in the range of 2 to 10 mg/L. The continuous operation of solar powered LLMC up to 10 days shows very stable flux. LLMC is a membrane technology that has potential application in desalination process, concentration of fruit juice and sugar solution, separation of azeotrope mixture, separation of propane/propylene mixture and in biotechnological applications.

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