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Performance Evaluation of Solar Assisted Membrane Distillation for Seawater Desalination Using Solar Simulator

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Abstract: The increase in freshwater demand and environmental pollution is leading to an increase in the use of renewable energy for the seawater desalination system. The emerging potential in seawater desalination technology is a solar assisted membrane distillation (SAMD) where thermal energy is supplied from the solar thermal collector to the membrane module. The objective of this study is to evaluate the performance of in-house made SAMD system for seawater application in terms of the permeate flux and salt rejection using solar simulator. In this work, Flat Plate Solar Thermal Collector (FPSC) system was designed to preheat the simulated and actual seawater as the feed solution for indoor assessment. 2.5 wt.% of sodium chloride (NaCl) was used represents the standard seawater. The heat radiation intensity remained constant during the experiment by using the tungsten lamps which are widely used as a solar simulator. During simulated seawater testing, the initial permeate flux of 3.86 kg/h.m² was obtained, then increased up to 5.39 kg/h.m², with almost 39.4% increment. This shows a similar trend with seawater MD processes. Nonetheless, the flux slightly decreased until 4.06 kg/h.m², showing about 24.7% flux reduction. Then, the flux remains decreased at a slower rate down to 3.90 kg/h.m². The declining trend in permeate flux can be attributed to the low evaporation area affected by the NaCl crystallization due to the partial membrane pore blockage. Nevertheless, the membrane still obtained 99% salt rejection in all experiments.

Keywords: Solar powered membrane distillation, Integrated system, Renewable Energy, Solar energy, Desalination

Introduction

Desalination plants usually separate the sea water into two separate streams which are retentate and permeate. The retentate is a stream with a high salt concentration (brine or concentrate) while the permeate consists of a freshwater stream with almost free of salt content (Tyszer et al., 2021). The fresh water normally called as permeate in reverse osmosis (RO) and condensate in membrane distillation (MD). Every desalination technology requires energy for the separation process, which is supplied to the system by thermal or mechanical means (generally as electrical power). The thermal desalination process technologies are based on evaporation and the subsequent condensation of the steam. Concerning pressure-driven desalination, RO is powered by electricity, thus, energy supplied from power grid is required. The RO system typically needs a high osmotic pressure (maximum operating pressure for RO is typically around 80 bar) to separate the seawater (Davenport et al., 2018). This system is not practical in rural regions because of the high energy needs to be provided to overcome osmotic pressure. In addition, severe fouling was observed during the RO desalination process. The system has high operation and maintenance costs and is difficult to integrate into the solar energy system.

Over the last decade, it is proven that MD has gained interest from the researchers and academicians to be involved in this area mainly for the water desalination process. The main advantages of the MD process over

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other desalination processes are its simplicity, less sensitivity to feed salinity, a small tendency of fouling, the capacity to utilize low-grade thermal energy, needs only a small temperature difference to run, and high quality of freshwater (Muhamad et al., 2019). However, the existing MD modules operate the system by using fully electrical energy generated from power generation station through the grid power supply (Hanoin et al., 2019). Most of the power generation in Malaysia significantly depends on three major fossil fuel sources, namely coal, natural gas, and fuel oil to generate electricity. These fossil fuel-based power generations cause negative environmental consequences and depletion of fuel reserves. Thus, the challenge is to create sustainable solutions for freshwater providing using clean, affordable energy and eliminating or decreasing the cost of electricity. Solar powered membrane distillation (SPMD) is one potential solution to meet this challenge by utilizing available solar energy sources efficiently, thus enabling increased energy independence and reducing global warming as well.

As researchers believe, the SPMD system is capable of working on a stand-alone system with a zero-energy concept that does not require external energy and only utilizes solar energy for its operation. Other than the zero-energy concept, there is also possibility to hybrid solar energy with the common grid power supply energy. There is a technology that uses the solar energy in solar thermal collector (STC) to becomes external heater to the MD system. The system is namely as solar assisted membrane distillation (SAMD). To operate under SAMD, the MD system firstly must be operated at a similar range of temperatures obtained from low-temperature STC to produce continuous freshwater production. Thus, efforts to enhance the heat transfer efficiency on flat plate solar collector (FPSC) as an STC device through the MD module are required. Previously, the FPSC system is the common STC device used in the SPMD system other than Evacuated Tube Collector (ETC) and Compound Parabolic Concentrator (CPC) (Ma et al., 2020). Several parameters have practical relation to the thermal efficiency of a solar collector such as collector plate position, coating of collector plate, coating material, glazing material property, spacing between riser tubes concerning diameter, flow rate, the intensity of incident radiation, and bottom and side insulation thickness (Majumdar et al., 2020; Yassen et al., 2019). Among these, pipe diameter, pipe spacing, water flow rate, and radiation intensity are the major contributors affecting the collector efficiency (Hajabdollahi et al., 2022; Wang et al., 2019). Design modification is a facile way were tweaking the parameters can help improve compatibility in a solar energy harvesting device. Based on the study by Wang et al. (2019), they found that the larger the pipe diameter, the better the collector efficiency. Similar performance was observed for the smallest pipe spacing. Verma et al. (2020) conducted the experiment with variation of mass flow rate (0.01 - 0.05 kg/s) and radiation intensity (650 – 1150 W/m²). The result shows that the mass flow rate reaches optimum efficiency at approximately 0.025 kg/s, whiles thermal efficiency increases with enhanced intensity of radiation.

From our own analysis, we found that a pipe collector with a tube diameter of 3/4-inch achieved 3.5% and 9.4% higher thermal performance and collector efficiency respectively, compared to a tube diameter of 3/8-inch due to a larger contact area with the surface. With the same tube diameter (3/4 inch), pipe spacing of 18.5 cm tends to attain higher thermal performance and collector efficiency by 4.3% and 12.6%, compared to pipe spacing of 27 cm. An optimal working condition can be achieved at 0.03 kg/s of mass water flow rate and 1050 W/m² of heat radiation intensity for the highest average temperature in the water tank (Hanoin et al., 2021). In this study, no experimental work was conducted to investigate the effectiveness of the in-house made FPSC in supporting the MD system. Therefore, the objective of this study is to evaluate the performance of the integrated FPSC and MD system in producing freshwater from saline water and seawater. In this work, a solar simulator was used to control the radiation intensity at 1050 W/m². The SAMD system was evaluated based on feed water temperature, permeate flux and salt rejection.

Methodology

As shown in Figure 1, a schematic layout of the SAMD system involves an integration of serpentine-shaped FPSC system to DCMD modules was presented. There are three loops in the system; solar, feed and permeate loops. In view of the solar loop, the FPSC plays a vital role to gain solar radiation and convert it into thermal energy. In this area, a solar simulator was used to supply the heat radiation intensity to the serpertine-shaped FPSC system as shown in Figure 2. The detailed methodology can be found in our previous work (Hanoin et al., 2021). The FPSC system was operated early until the water temperature of the outlet collector achieved 75±1˚C. In this work, the same water inside the FPSC was circulated using coiled in the feed tank of the MD system. The FPSC turns into heat exchanger device to heat the feed solution. This is where the solar energy being used to substitute the non-renewable energy sources. However, it must be pointed out that the power supply box and battery supply are still needed to drive the electrical equipment (ex: two hydrostatic pumps, chiller, and weight balance) in the MD system. The FPSC just covered the thermal energy required of the feed solution. In terms of

MD system, two different loops are required for the process; namely as feed (hot solution) loop and permeate (cold solution) loop. The feed loop transmitted the thermal energy of the feed solution into the membrane module for the MD process while the permeate loop is used to acts as the condensing medium inside the membrane module. As MD is operated based on the vapor pressure difference between both solutions, the two loops will serve their role in order to obtain the freshwater from seawater.

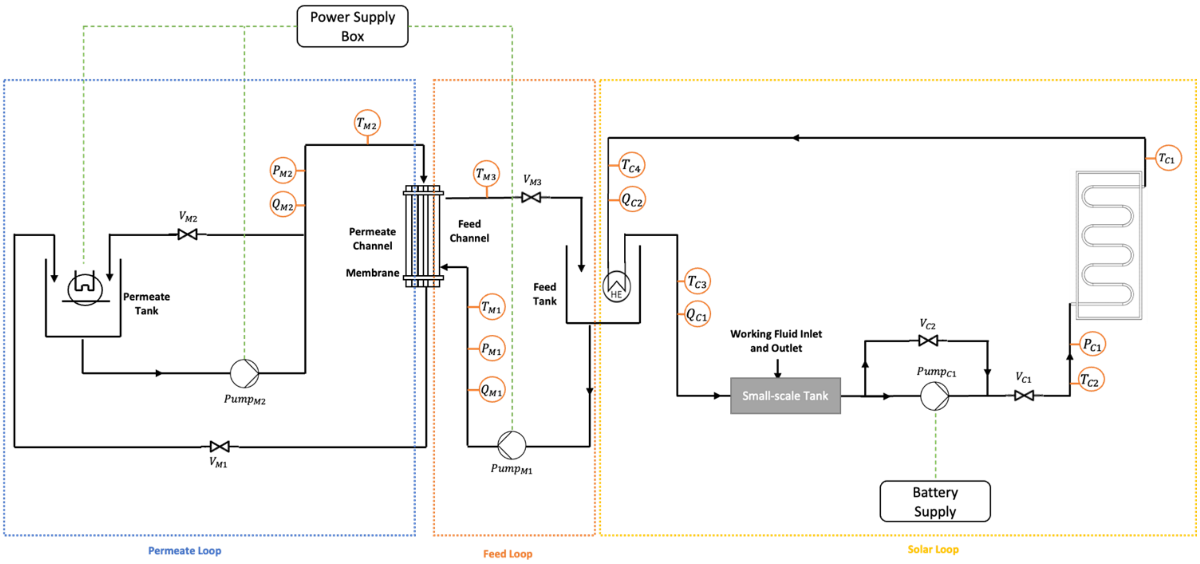


Figure 1. Schematic flow diagram of the SAMD system

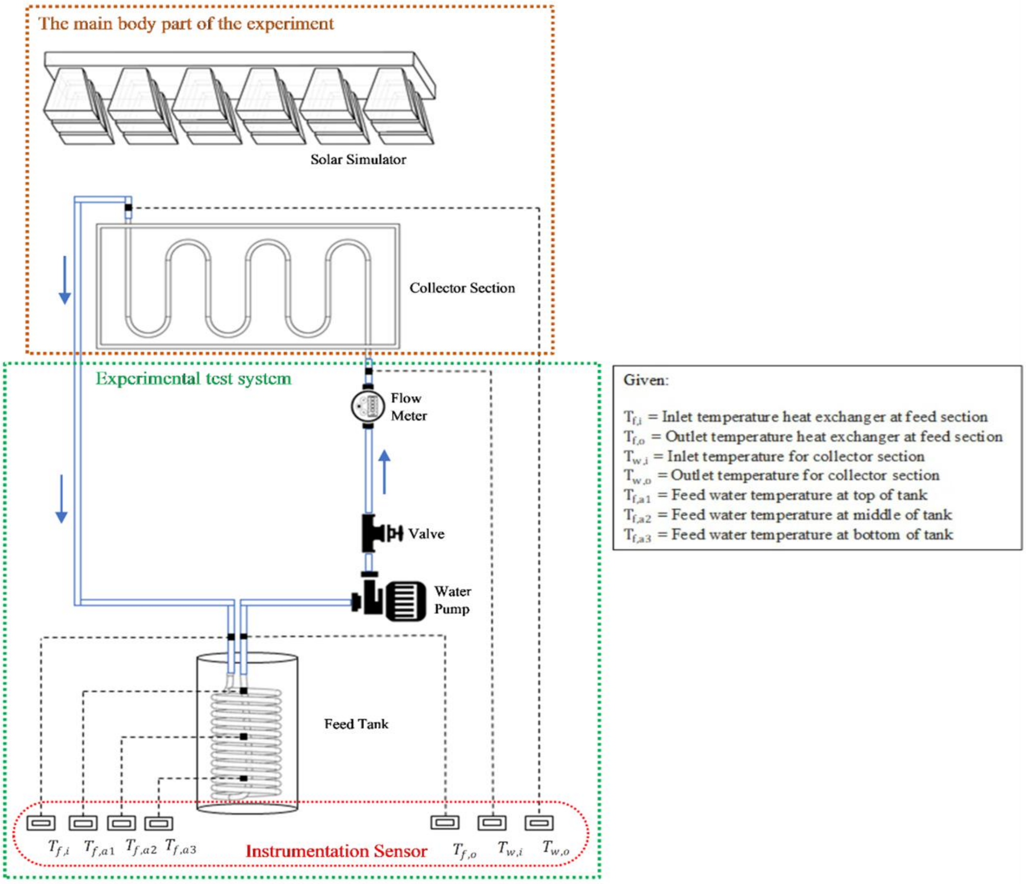


Figure 2. Schematic diagram of the FPSC system

In this study, the DCMD module was integrated with the FPSC system to investigate the overall SPMD system performance. A stainless-steel module containing 20 strands of hollow fiber membrane was prepared and used to determine the performance of the membranes during the process. Polyvinylidene fluoride (PVDF)-bentonite hollow fiber membrane as a previous research product was used for the study. The membrane consisted of 12 wt.% of PVDF with the addition of 0.5 wt.% of bentonite powder. The membrane has a contact angle of 90.63±0.67˚ with a membrane porosity of 69.23%. The DCMD system is designed to have two circulating streams, i.e., the hot stream also known as feed stream (circulated through the membrane shell-side) and cold stream (fed through the lumen side of the hollow fiber membrane). In order to maintain the bulk feed temperature inside the feed tank at 75±1˚C, an electric heater (830, PROTECH) was used to support the system. Meanwhile, a recirculating chiller (RT2, VIVO) was used to cool down the water temperature in the permeate tank. The system was maintained at feed and permeate temperatures of 60±1˚C and 20±1˚C, respectively. It must be pointed out that the feed temperature is measure based on the inlet temperature of the membrane module. The pressures for feed and permeate were fixed at 8 psi and 2 psi. Meanwhile, the feed and permeate flow rates were controlled at 2.2 LPM and 0.5 LPM, respectively.

The feed tank and permeate tank will be filled with 1000 mL of simulated or real seawater. A 35 g of sodium chloride (NaCl) mixed with 1000 mL of deionized water will be prepared as the simulated seawater. For the permeate tank, 1000 mL of deionized water will be used. The weight of the permeate tank will be measured every 15 minutes using a digital balance. The samples of water inside the permeate tank will be taken out every 15 minutes for further analysis of the salt rejection rate. The parameter that can be used to compare proportionally the performance of the DCMD unit is the permeate flux. The MD flux, J, during the test (kg/h.m²) is characterized by:

$$J = \Delta W/(A.\Delta t) \tag{1}$$

where ΔW (kg) is the weight of permeate collected over a predetermined time t (h) of process and A (m²) is the effective membrane area. To identify the rejection, R (%) of the membrane, the following equation was employed:

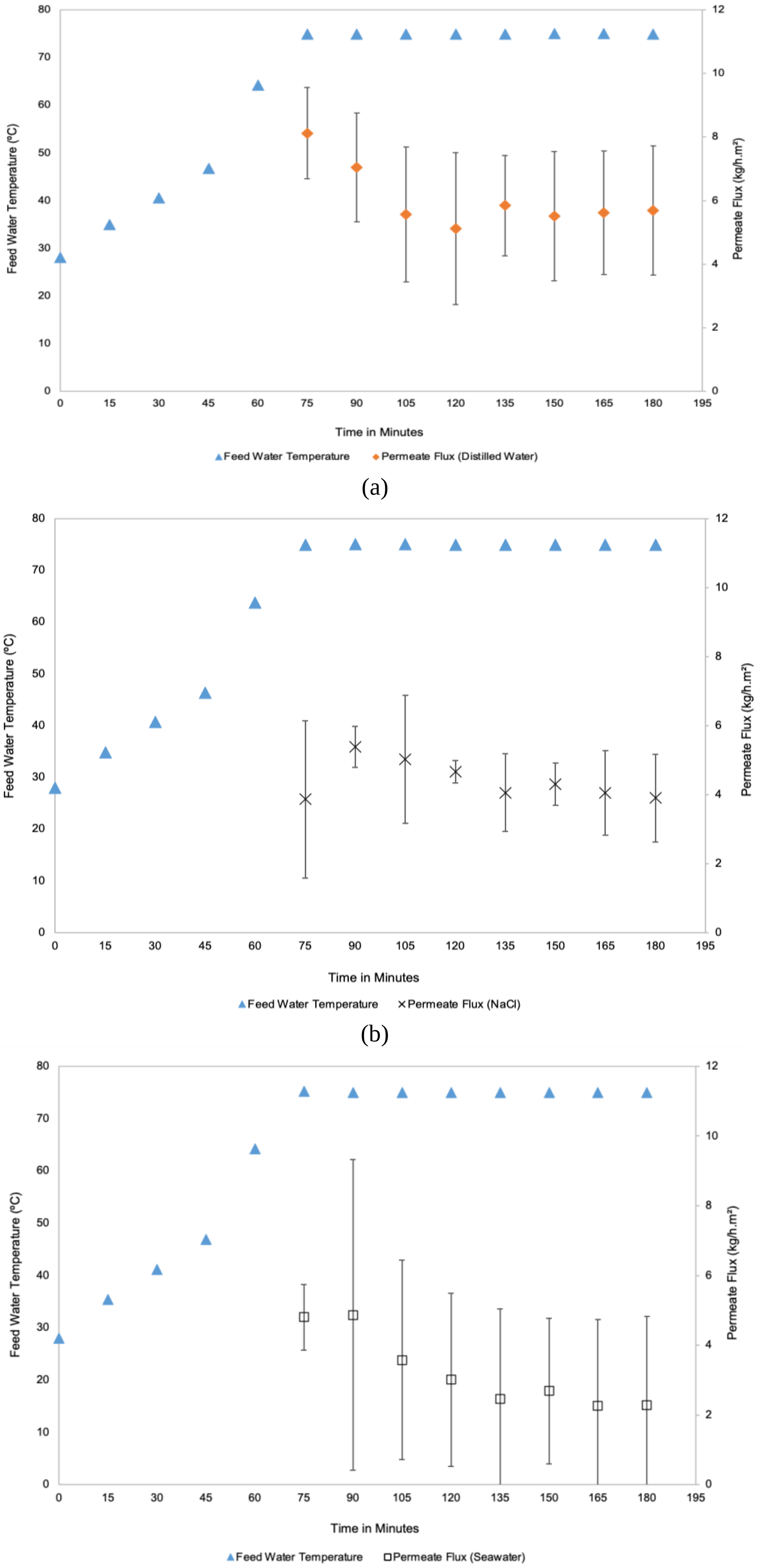
$$R\ (\%) = (1 - C_p/C_f) \times 100 \tag{2}$$

where C_p and C_f are for permeate and feed concentration (mg/L), respectively.

Results and Discussion

Figure 3 presents the data of the hybrid system between FPSC and MD in terms of feed water temperature and permeate flux. In this study, the feed water temperature is the temperature detected in the feed tank. Initially, the hybrid system is started alone with the FPSC operation. For first 60 minutes, the fabricated solar collector was exposed to the solar simulator under radiation intensity of 1050 W/m² until the outlet collector temperature reached 75±1˚C. After that, MD system will take next action in purying the feed solution for 2 hours continuously. Figure 3(a) shows the permeate flux of the SAMD system when tested with distilled water as feed solution. The purpose of this test is to determine the vapor permeate flux of the SAMD system without foreign elements in the feed solution. Normally, this testing is required to set the benchmark for other types of feed solutions. As shown in Figure 3 (a), the initial permeate flux is 8.12 kg/h.m². Nonetheless, the fluxes decreased rapidly, with approximately 36.9%, until 5.12 kg/h.m² at 120th minutes. The decreasing permeates fluxes because of temperature polarization, then decreases the temperature difference between the feed and permeate side. This happens due to higher temperature difference between hot and cold solution, as the feed temperature has a strong influence on permeate flux (Mokhtar et al., 2015). The higher permeate flux was achieved at higher feed temperature as described by the Antoine equation that reflects the liquid temperature relationship with the related vapor pressure equilibrium which is the major MD process driving force (Qtaishat et al., 2008). Moreover, the difference of partial pressure occurs across the membrane and both water vapor and volatile species start to permeate through the membrane pores.

The simulated seawater through the MD process was presented in Figure 3(b). The initial permeates flux of 3.86 kg/h.m² was obtained, then increased up to 5.39 kg/h.m², with almost 39.4% increment. This shows a similar trend with seawater MD processes. Nonetheless, the flux slightly decreased until 4.06 kg/h.m², showing about 24.7% flux reduction. Then, the flux remains decreased at a slower rate down to 3.90 kg/h.m². The evaporation of the hot feed could contribute to the NaCl crystallization on the membrane surface if the experiment is continued for a long time and this can decrease the water flux due to the partial membrane pores blockage. Furthermore, membrane hydrophobicity will be reduced due to the NaCl crystals deposition on the surface of the membrane which reduces the salt rejection rate (Hubadillah et al., 2018).



(a)

(b)

(c)

Figure 3. Permeate flux and average temperature of different feed water: (a) distilled water, (b) Simulated seawater (35g of NaCl mixed with 1000mL of deionized water), and (c) seawater

Figure 3(c) used seawater as feed water during the MD process. Result shows that the initial permeate flux of MD which recorded at around 4.80 kg/h.m² tended to increase until the highest average permeate flux achieved at 4.87 kg/h.m². However, the flux decreased rapidly until 2.45 kg/h.m², showing approximately 49.5% flux reduction. From 150th to 180th minutes, the flux of the membrane continued to drop, but at a moderate rate. Although the feed water temperature is constant due to continuously generated electricity from the electrical heater, the cold solution tended losses to the surrounding. Therefore, the temperature difference is decreasing rapidly. The decreasing trend is also caused by the severe deposition of solutes on the outer surface of membrane at the beginning of the separation process, leading to surface pore blocking and increased water vapor transport resistance. The reduction in the flux could be due to an increase in salt concentration as a result of declining vapor pressure, which is commonly observed in MD processes because the coefficient activity of water tends to be lower at higher solute concentration (Liu & Wang, 2013).

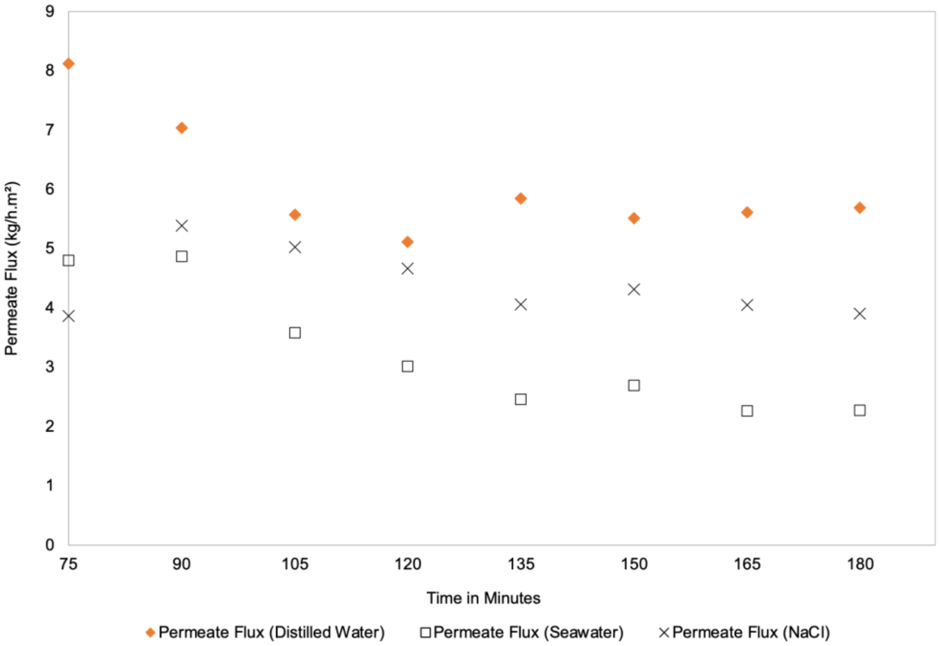


Figure 4. Comparatives permeate flux of feed solution between distilled water, simulated seawater (NaCl) and seawater

Figure 4 shows the comparative permeate flux between distilled water, simulated seawater (NaCl), and seawater. As can be seen from this figure, the permeate fluxes of distilled water were always higher than simulated seawater (NaCl) and seawater. The feed salinity affects the permeate flux and can be attributed to a decrease in the transmembrane driving force resulted from the decrease of the vapor pressure of water with increasing salt concentration. At elevated temperature, the vapor pressure of a solute will be lower than that of the distilled water at the same temperature because the polar interaction between water molecules and solute ions is stronger than the hydrogen bonding between the water molecules (Sharqawy and Zubair, 2010). Also, the increase in solute concentration increases the temperature and concentration polarization effects. In terms of salt rejection, it was observed that almost 100% rejection was achieved in experimental works with simulated seawater and seawater. The findings proved that NaCl in the feed solution has very little impact on the performance of membrane with respect to separation characteristics. The analysis is in agreement with the previous studies that using the stand alone SPMD system or hybrid SAMD system.

Conclusion and Future Outlook

Nowadays, the sea or brackish water desalination has gained attention due to the scarcity of water. The utilization of solar energy through desalination processes indicated the capability of further growth, from the point of view of energy conservation and/or cost-cutting approaches. Numerous researchers have examined the integration of solar energy and MD for eco-friendly water desalination. In this study, the self-fabricated FPSC was examined using simulated seawater and real seawater. From the analysis, almost 100% salt rejection was obtained in all experiments indicating the potential of using SAMD as the water purifier. In terms of thermal energy supply from the FPSC, the system managed to store solar energy and transfer to the feed solution and supported the MD system. Meanwhile, the MD system shows different performance evaluation between seawater and NaCl solution. The lower permeate flux achieved by the seawater solution is presumed due to the high concentration of inorganic salts in the seawater. The variation of inorganic matters and other pollutants in the seawater may affect the overall performance.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to authors.

Acknowledgements

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