DIRECT CONTACT MEMBRANE DISTILLATION: A POTENTIAL TECHNOLOGY FOR HYPER-SALINE WATER TREATMENT

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ABSTRACT

A direct contact membrane distillation (DCMD) module was built to investigate the treatment capability towards hyper-saline water. Both experimental and theoretical work were carried out based on the heat and mass transfer and energy balance. The feed inlet temperature was the most affected factor in freshwater production compared to feed concentration. Regarding feed concentration, the experimental results showed a trivial decrease of 5.5% in freshwater production when the feed concentration varied from 20 ‰ to 40 ‰. However, this drop was significant with up to 54.7% when the feed concentration reached 175 ‰.

Keyword: - *Direct contact membrane distillation, hyper-saline water, spacer, heat transfer, mass transfer*

1. INTRODUCTION

Over the past twenty years, the basic needs for unpolluted water have steadily risen due to population growth [1]. The available limitation in drinking water has long been a worldwide issue, leading to the development of desalination technologies aimed at processing seawater. Two types of technologies can be applied in desalination, including membrane or thermal techniques. Membrane distillation (MD) integrates both techniques and is characterized as a thermal membrane process driven by simultaneous mass and heat transfer through a hydrophobic membrane [2]. The hydrophobic characteristic of the membrane prevents the liquid from entering the pores [3]. The temperature difference of solutions between feed-membrane and permeate-membrane surfaces leads to the partial vapor pressure gradient, which serves as MD's driving force [4]. Generally, four MD configurations can be considered, including direct contact membrane distillation (DCMD), vacuum membrane distillation (VMD), air gap membrane distillation (AGMD), and sweeping gas membrane distillation (SGMD) [5]. The DCMD process has been frequently evaluated due to its simple operation and its treatment capability towards hyper-saline water [6, 7].

In the present work, A DCMD module was built to investigate the treatment capability of the system in producing freshwater from hyper-saline water on lab-scale. The research employed highly saline water up to 175 ‰. Both experimental and theoretical work were carried out at different operating conditions, including feed inlet temperature, and volume flow rate.

2. HEAT AND MASS TRANSFER IN SPACER-FILLED DCMD

2.1. Heat transfer

According to [4], the mechanisms of heat transfer in spacer-filled DCMD happen in three regions: (1) in the feed channel; (2) through the hydrophobic membrane; and (3) in the permeate channel. The heat flux in each region can be described by Equation (1), (2), and (3):

In the feed side:

$$Q_f = h_f \times \left(T_{b,f} - T_{m,f}\right). \tag{1}$$

Through the hydrophobic PTFE membrane:

$$Q_m = \frac{k_m}{\delta}(T_{m,f} - T_{m,p}) + J\,\Delta H_v \tag{1}$$

And on the permeate side:

$$Q_p = h_p(T_{m,p} - T_{b,p}) \tag{2}$$

The effective thermal conductivity of the PTFE membrane is calculated according to the Maxwell model [8-12], and km is assumed constant over the investigated temperature range.

$$k_m = \frac{k_g\left[1 + 2\beta\varphi + \left(2\beta^3 - 0.1\beta\right)\varphi^2 + 0.05\varphi^3 \exp\left(4.5\beta\right)\right]}{1 - \beta\varphi}.$$

$$\beta = \left(k_p - k_g\right) / \left(k_p + 2k_g\right). \tag{4}$$

$$\varphi = 1 - \varepsilon_m.$$

At steady-state conditions when Qf = Qm = Qp = Q, based on the energy balance and iterative model, the membrane surface temperature at the feed side (Tmf) and at the permeate side (Tmp) can be described [4]:

$$T_{m,f} = \frac{k_m\left(T_{b,p}\,\frac{h_f}{h_p}T_{b,p}\right) + \delta(h_f T_{b,f} - J\,\Delta H_v)}{(k_m) + h_f\left(\delta + \frac{k_m}{k_p}\right)} \tag{5}$$

$$T_{m,p} = \frac{k_m\left(T_{b,f}\,\frac{h_p}{h_f}T_{b,p}\right) + \delta(h_p T_{b,p} + J\,\Delta H_v)}{(k_m) + h_f\left(\delta + \frac{k_m}{k_f}\right)} \tag{3}$$

In the case of spacer-filled DCMD, the internal heat transfer coefficient at both sides (hf, hp) can be evaluated according to the aforementioned studies [12-14].

2.2. Mass transfer

The mass transport through the hydrophobic membrane can be expressed based on Darcy's law [4]:

$$J = B_m \Delta P_m = B_m(p_{m,f} - P^0_{m,p}) \tag{4}$$

The partial pressure at the membrane-feed interface is affected by the salinity of the feed solution and it is calculated by [4]:

$$p_{m,f} = \alpha_{w,f} P^{0}_{m,f} \tag{5}$$

Where $a_{\omega,f}$ is the water activity. For an aqueous solution of sodium chloride (NaCl), there is a relationship between water activity and the molar fraction of the solute, as can be described [4, 7]:

$$a_{\omega,f} = 1 - 0.5X_{NaCl} - 10(X_{NaCl})^{2} \tag{6}$$

$P^{0}_{m,f}$ and $P^{0}_{m,p}$ are the vapor pressure of pure water evaluated via the Antoine equation at the membrane surface temperatures $T_{m,f}$ and $T_{m,p}$, respectively [7]:

$$P^{0}_{m,f} = exp\left(23.1964 - \frac{3816.44}{\left(T_{m,f} - 46.13\right)}\right) \tag{7}$$

$$P^{0}_{m,p} = exp\left(23.1964 - \frac{3816.44}{\left(T_{m,p} - 46.13\right)}\right) \tag{8}$$

The permeability coefficient (Bm) can be evaluated by using Phattaranawik's model [15], as mentioned in a previous study [10]

$$B_{m} = \frac{1}{RT_{m}\delta}\left[\frac{P_{a}\tau}{M\varepsilon PD} + \frac{3\tau}{2\varepsilon r}\left(\frac{\pi M}{8RT_{m}}\right)^{1/2} + \frac{1}{\left(\frac{2\varepsilon r}{3\tau}\left(\frac{8RT_{m}}{\pi M}\right)^{1/2} + \frac{M\varepsilon PD}{P_{a}\tau}\right)}\right]^{-1}. \tag{12}$$

3. EXPERIMENTAL SET-UP

A DCMD module with an effective membrane area of 225 cm2 and a 4mm channel height was built to investigate the treatment capability of hyper-saline water. The hydrophobic PTFE membrane with pore size and porosity of 0.22µm and 75% was applied, respectively. In the feed loop, the feed solution was heated up to the experimental temperatures by a combination of the hot urn and temperature controller. In the permeate loop, the freshwater was cooled down to a fixed temperature by implementing both a chiller and heat exchanger. Both the feed and permeate solutions were pumped counter-currently into the DCMD channels at a similar volume flow rate. The temperatures at the inlet and outlet of both DCMD sides were measured by WZP - PT100 temperature sensors. The volume flow rates were detected by flowmeter sensors (YF-S201). DI-2108 data logger was used to collect all the experimental data. The experimental setup is illustrated in **Error! Reference source not found.**.

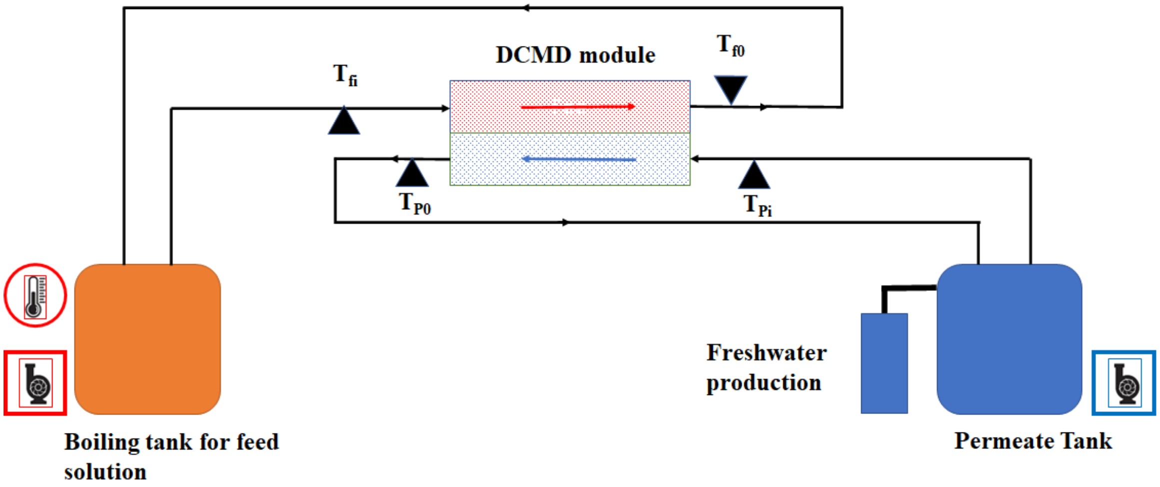

Fig -1. Diagram illustrating the experimental setup for the DCMD process in lab-scale

4. RESULTS AND DISCUSSIONS

The performance of the DCMD process was greatly influenced by the experimental conditions. Various experiments were carried out to investigate how the feed concentration and feed inlet temperature impacted the amount of freshwater production.

4.1. The effect of feed concentration

Error! Reference source not found. illustrates the impact of feed concentration on the amount of freshwater production. In this experiment, the feed inlet temperature was 550C while the permeate inlet temperature was 200C. The volume flow rates were adjusted equally on both sides of DCMD at 2 L.min-1. The experimental results showed that the freshwater production dropped by only 5.5 % as the salt concentration increased from 20 ‰ to 40 ‰. However, this decrease was significant when the feed concentration was higher up to 54.7% when the feed concentration ranged from 40‰ to 175‰. These experimental results were coincident with the previous studies [6, 16]. They indicated that there was up to a 56% drop in freshwater production when the feed concentration reached 177.5‰.

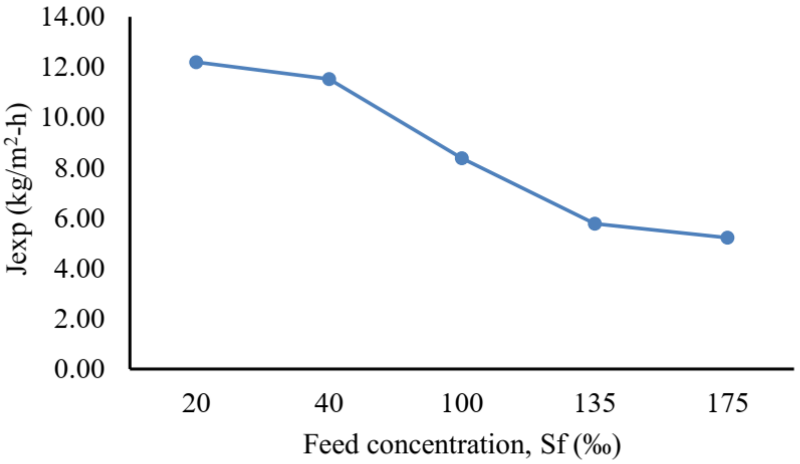

Fig -2. The effect of feed concentration on the experimental freshwater production

Error! Reference source not found. illustrates how the feed inlet temperature influenced the amount of freshwater production. The feed inlet temperature varied from 450C to 550C, while the permeate inlet temperature was fixed at 200C. The feed concentration was 100‰, and the feed and permeate volume flow rates were 2 L.min-1. When the feed inlet temperature went up from 400C to 500C, the freshwater production rose by approximately 5.3%.

However, this increase was significant when the feed inlet temperature reached 550C. In comparison to 400C, the amount of freshwater produced at 550C increased by nearly 38%. In this case, the partial vapor pressure increased exponentially with temperature based on the Antoine equation was the dominant factor.

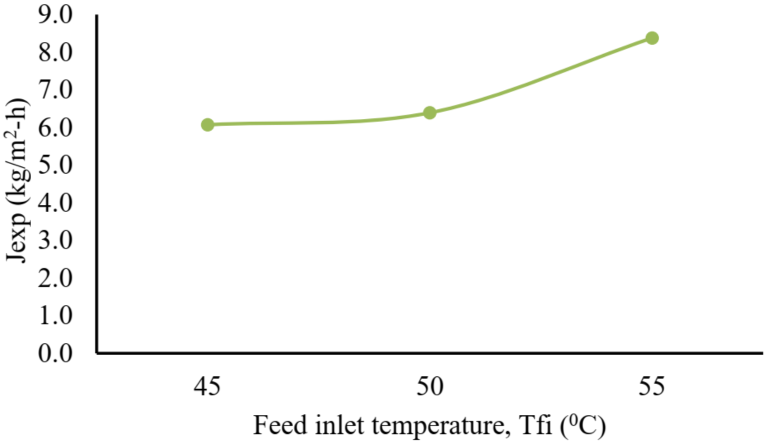

Fig -3. The effect of feed inlet temperature on experimental freshwater production

5. CONCLUSIONS

Heat and mass transfer were investigated in spacer-filled DCMD configuration. In this study, the hyper-saline water with various concentrations of (20‰ - 175 ‰) was applied. The experimental results showed that the amount of freshwater decreased significantly up to 54.7% when the feed concentration was 175‰. In comparison with the feed concentration factor, the feed inlet temperature had more influence on the freshwater production in the same operating conditions.

ACKNOWLEDGMENT

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