해수담수화를 위한 직접 접촉 막증류 (Direct Contact Membrane Distillation, DCMD) 모듈의 모델링

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Modeling of a direct contact membrane distillation (DCMD) module in a desalination process for various operation conditions

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1. Introduction

Membrane Distillation (MD) is an emerging alternative separation technology being investigated worldwide. By using direct contact membrane distillation (DCMD) for desalination, the water vapor molecules are transported through a hydrophobic micro-porous membrane from the hot liquid feed side to the cold permeate side [1]. The most common approach to modeling MD, as found in the literature, is by assuming the process as one-dimensional and applying empirical heat and mass transfer coefficients. The aim of this study is to develop an accurate two-dimension model for the DCMD process. In this paper a commercially available hydrophobic, porous PTFE membrane was used for DCMD for both co-current and counter-current flow modes. A two dimension model equations are derived by integrating the permeate flux across the membrane with the mass, momentum and energy balances on both feed and permeate sides by using comsol multiphysics. The modeling results were compared with experimental results for different operating conditions.

2. Theoretical model

In modeling the DCMD process, three transport processes were considered – two-dimensional energy and momentum transport and one-dimensional mass transport. Three layers including the feed channel, the membrane layer, and the permeate channel were modeled. For simulation with reasonable computational expense, the following assumptions for the transport equations were made: (i) Steady incompressible flow; (ii) Laminar flow; (iii) Momentum of the permeate flow through the membrane was ignored; (iv) Negligible heat loss to the ambient environment; (v) Steady state convection and conduction model for energy balance; (vi) Dusty gas model for mass transfer equations; and (vii) The concentration polarization was ignored to simplify the calculation procedure and save CPU time.

Main equations:

The following equations in terms of pressure (P_h), velocity (u_h), and temperature (T_h) were derived for feed channel.

$$\rho_h(u_h \cdot \nabla)u_h = \nabla \cdot [-P_h I + \eta(\nabla u_h + (\nabla u_h)^{T_h})] \quad \textbf{(1)}$$

$$\nabla \cdot u_h = 0 \quad \textbf{(2)}$$

$$\rho_h\, Cp_h\, u_h \cdot \nabla T_h - \nabla \cdot (k_h \nabla T_h) = 0 \quad \textbf{(3)}$$

The following equations were derived for the membrane layer,:

$$J = \frac{1}{L}\int_0^L C_{(x)}(P_{(T1_{(x)})} - P_{(T2_{(x)})}) \quad \textbf{(4)}$$

$$\rho_m Cp_m u_m \cdot \nabla T_m - \nabla \cdot (k_m \nabla T_m) = 0 \quad \textbf{(5)}$$

The following equations in terms of pressure (P_c), velocity (u_c), and temperature (T_c) were derived for permeate channel.

$$\rho_c (u_c \cdot \nabla) u_c = \nabla \cdot [-P_c I + \eta(\nabla u_c + (\nabla u_c)^{T_c})] \quad \textbf{(6)}$$

$$\nabla \cdot u_c = 0 \quad \textbf{(7)}$$

$$\rho_c Cp_c u_c \cdot \nabla T_c - \nabla \cdot (k_c \nabla T_c) = 0 \quad \textbf{(8)}$$

where, ρ is the liquid density; C_p is the specific heat capacity; and k is the liquid thermal conductivity, $C_{(x)}$ is the mass transfer coefficient, P is the vapor pressure of the membrane surface, respectively.

3. Experimental

A commercially available hydrophobic porous PTFE membrane manufactured by ChangQi co. Ltd. (Ningbo, China) was used for the experiments. The membrane characteristics are showed in Table 1. The DCMD experimental setup is similar with previous studies [2]. The feed and permeate were separated the membrane with the effective area of 0.06 m^2.

Table 1 Membrane characteristics

Material	Thickness	Pore size	Porosity	Liquid entry pressure
PTFE	0.12 mm	0.7 μm	88%	90 kPa

4. Results

4.1 Comparison co-current and counter-current flow mode

The temperature distribution profiles of permeate side and feed side are parallel to each other in count-current flow mode, which is different from the curves of the co-current flow mode in which the curves approach each other (not shown in the paper). Fig. 1 compares the experimental and modeling results for the effect of flow rate on flux for both co-current and count-current flow modes. The experimental results show good agreement with the modeling results for both the co-current and count-current flow modes, and the fluxes for count-current mode were slightly higher than co-current.

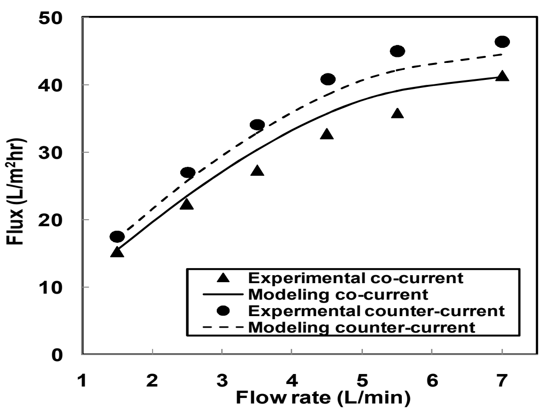

Fig.1. Comparison modeling and experimental results for both co-current and count-current flow modes. (Hot inlet temp. of 60°C; cold inlet temp. of 20°C; feed NaCl conc. of 1%)

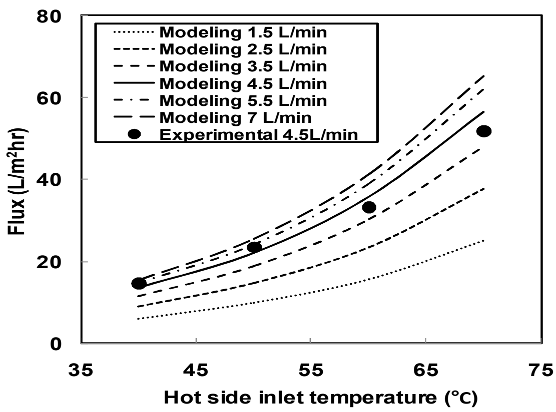

Fig.2. Effect of temperature on flux for different flow rate conditions for both modeling and experimental results. (Flow rate of 4.5 L/min; feed NaCl conc. of 1%; count-current)

4.2 Effect of temperature

Fig. 2 shows the effect of hot side inlet temperature on flux at a series of different flow rate conditions. The permeate flux increased with an increase in temperature. The experimental results show good agreement with the modeling results. It is widely understood that a temperature difference across an MD membrane will induce water vapor to pass and some amount of permeate to be generated. Therefore, a significant temperature difference should lead to greater desalination production rates [3].

4.3 Effect of flow rate

Fig. 3 shows the effect of flow rate on flux for both the experimental results and modeling results under different feed inlet temperature conditions. The fluxes exhibit higher values when operated at higher flow rate. The flux increased with an increase in flow rate, and seems to reach maximum values asymptotically for high velocity. This is due to the reduction of the boundary layer thickness when the Reynolds number increased, approaching a limiting value [4]. The modeling results show good agreement with the experimental results.

4.4 Effect of NaCl concentration

Fig. 4 shows the effect of salt concentration on permeate flux for both modeling and experimental results. The permeation flux decreased from 39.03 to 29.7 L/m^{2}hr when the NaCl concentration increased from 1 to 10%. The reason attributed to membrane surface temperature polarization and concentration polarization. Polarization layers formed on either side of membrane reduce water permeation in MD process. This reduction is higher when the concentration increased [5]. The modeling results show good agreement with the experimental results.

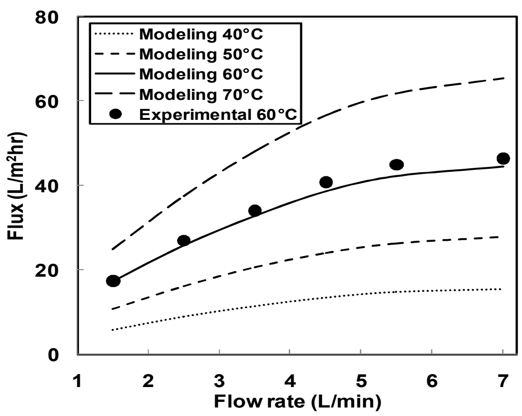

Fig. 3. Effect of flow rate on flux for different temperature conditions. (Cold inlet temp. of 20°C; feed NaCl conc. of 1%; count-current)

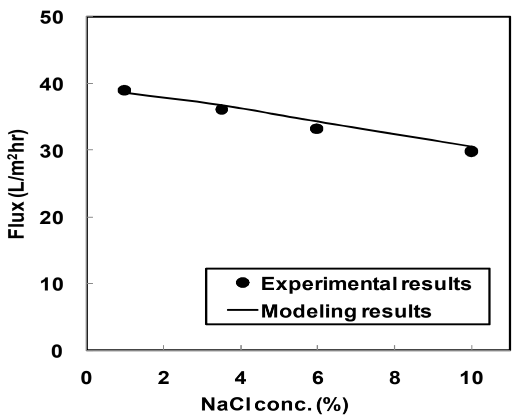

Fig. 4. Effect of NaCl concentration on flux for modeling and experimental results. (Hot inlet temp. of 60°C; cold inlet temp. of 20°C; count-current)

5. Conclusions

A two dimension model was developed by integrating the permeate flux through the membrane with mass, energy and momentum balances. The modeling results showed good agreement with the experimental results for different conditions. The permeate flux for count-current flow mode show little higher than co-current mode. The permeate flux increase with the increase of temperature and flow rate, but decrease with the increasing of feed concentration. For all the experiments permeate salt rejections were higher than 99.99%.

6. Acknowledgement
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7. References

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