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Performance improvement on distillate flux of countercurrent-flow direct contact membrane distillation systems

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HIGHLIGHTS

- A roughened-surface device of countercurrent-flow DCMD was developed theoretically.
- Experimental study indicated its feasibility with 42% of performance enhancement.
- The pure water productivity with the expense of energy consumption is discussed.
- A heat-transfer coefficient correlation of roughened-surface channels is obtained.

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ABSTRACT

The theoretical predictions of pure water productivity in a parallel-plate direct contact membrane distillation (DCMD) module using roughened-surface flow channel for enhancing heat transfer enhancement were obtained under countercurrent-flow operations. The device performance improvements with increasing the pure water productivity in saline water desalination were achieved as compared to the concurrent-flow operation. The roughened surface was fabricated using siphonic-blasting with aluminum oxide (Al_2O_3) sand grains and arc spraying for Ni film coating, and the experimental data were correlated in a simplified expression to predict the heat transfer coefficient for the DCMD device. The pure water productivity and temperature distributions of both hot and cold feed streams are represented graphically with the fluid flow rate and inlet saline temperature as parameters. Both flow-pattern and roughened-surface effects have demonstrated the technical feasibility in the roughened-surface channel device and up to 42.11% of the device performance enhancement was achieved for the countercurrent-flow DCMD system. The influences of operation and design parameters on the pure water productivity with the expense of energy consumption are also discussed.

1. Introduction

Membrane distillation (MD) has been recognized as an economically feasible technology for desalination processes [1,2] in its simplicity and the low energy demand. The rejection of dissolved solids is nearly 100% [3]. The direct contact membrane distillation (DCMD) device in this study is a MD system for which hot saline and cold liquids directly contact both membrane surfaces with a small temperature-driving force in providing a phase-change process, which results in a vapor pressure difference in between to allow only the vapor transport across a hydrophobic porous membrane where water is the permeating flux. Other application of membrane-based separation processes includes juice concentration and waste water treatment [4–7].

The membrane distillation process analysis of countercurrent-flow operations is to develop a mathematical model considering both heat and mass transfer mechanisms for evolving a heat transfer coefficient correlation interpolated by experimental data. The permeation rate of pure water in direct contact membrane distillation DCMD is governed by the heat transfer resistances among the hot liquid, membrane, and cold liquid, called temperature polarization [8,9], as well as the mass transfer resistance in the membrane. Attempts to reduce the effect of temperature polarization were made implementing eddy promoters [10,11] to improve the heat and mass transfer rate by inserting channel spacers [12,13]. The new design of roughened-surface channels [14] was fabricated using siphonic-blasting with aluminum oxide (Al_2O_3) sand grains and arc spraying for Ni film coating by arc spraying process in aiming to promote the eddy turbulence of the hot saline feed stream. The arc spraying for Ni layer on aluminum oxide (Al_2O_3) has gained key importance in structural applications because of corrosion resistance [15].

This study investigates the heat and mass transfer of the countercurrent flow in DCMD processes with the eddy promoter to achieve the heat-transfer correlation equation incorporated with the experimental runs, and the results show that a good agreement is obtained between

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the experimental results and theoretical predictions. Once the temperature distributions and the amount of vapor flux across the membrane are calculated, the correlated equation is expressed as a function of relative roughness and can be used for predicting the heat transfer coefficient under operating the device roughened-surface channels. The mass flux enhancement accompanying with the penalty of the friction loss increment due to employing roughened-surface channels was correlated experimentally [16] and the extra power consumption was calculated in terms of the relative surface roughness. The improvements of device performance were considerably achieved under the countercurrent-flow operation roughened-surface channels as compared. The influences of operation and design parameters on the pure water productivity improvement are also discussed.

2. Theoretical model

Fig. 1 shows a DCMD module with inserting a hydrophobic microporous membrane of thickness δ_m into a parallel conduit of width B and length L, and with the same thickness d for both hot and cold feed streams to conduct a double-flow countercurrent operation. The distillate flux of pure water production is collected by an overflow tank into a beaker as the distillation process proceeds and measured using a timer and weighted on an electronic balance. The thermal boundary layers on both liquid streams build up a temperature differences between bulk fluid and membrane surfaces. The water vaporization occurs on the membrane surface in the hot saline stream and then the vapor is transferred through the membrane pores with the condensation of permeate on the other side of the membrane surface in the cold feed stream thereafter.

The effective thermal conductivity of the membrane can be determined by taking account of the contributions on the gas inside the membrane and solid part of the membrane [17]. The energy balance equations among the three heat fluxes and for the bulk fluids in Fig. 1 give

$$q = q_h = h_h(T_h - T_1) \quad (1)$$

$$= q_c = h_c(T_2 - T_c) \quad (2)$$

$$= q_m = N''\lambda + \frac{k_m}{\delta_m}(T_1 - T_2) \quad (3)$$

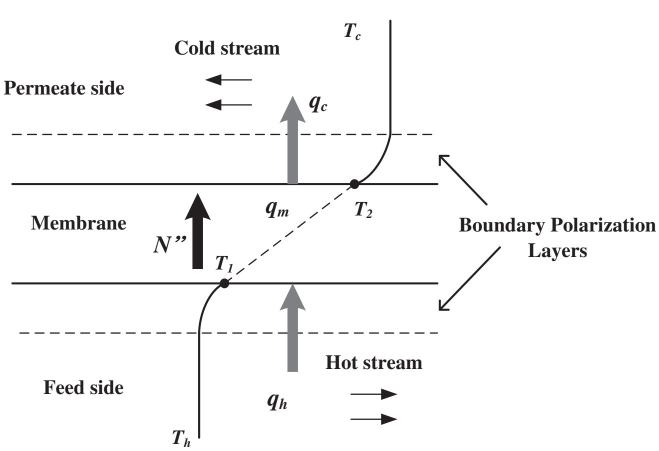

Fig. 1. Heat and mass transfer in countercurrent-flow DCMD systems.

$$\frac{dT_h}{dz} = \frac{-Wq}{Q\rho_h C_{ph}} \quad (4)$$

$$\frac{dT_c}{dz} = \frac{-Wq}{Q\rho_c C_{pc}}. \quad (5)$$

The heat loss associated with the vaporization process due to conductive heat transport across the membrane has been considered as the second term in the right-hand side of Eq. (3) and k_m is the effective thermal conductivity of microporous membrane, and was estimated by the combination of the gas and solid conductivities [18]

$$k_m = \varepsilon k_g + (1-\varepsilon)k_s \quad (6)$$

In general, the mass flux of the condensate water was expressed using a membrane permeation coefficient (C_m) and the across-membrane saturation vapor pressure difference (ΔP)

$$N'' = c_m \Delta P = c_m\left[P_1^{sat}(T_1) - P_2^{sat}(T_2)\right] \quad (7)$$

where $P_1^{sat}(T_1)$ and $P_2^{sat}(T_2)$ are the saturated pressure of water on the membrane surfaces in hot and cold streams, respectively. The saturated pressure of water on the membrane surface in the hot stream was correlated with water activity coefficient $a_w = 1 - 0.5x_{NaCl} - 10x_{NaCl}^2$ as follows:

$$P_1^{sat} = y_w P = x_w a_w P_w^{sat}. \quad (8)$$

There are three essential membrane coefficient models, the Knudsen diffusion model, Poiseuille flow model, and molecular diffusion model that can be used to describe the mass flux across the hydrophobic porous membrane. Many researchers used the expressions of interfacial temperature in terms of bulk temperature with specified empirical correlations of heat-transfer coefficients [19,20] due to the uncertainty of microporous membrane morphology in the molecular diffusion model (say the effective gas diffusivity) leading to inaccuracy calculation of the mass transfer [21]. Moreover, the trans-membrane temperature difference creates the pressure difference across membrane owing to the existence of saturated pressure difference across the membrane, resulting in Poiseuille flow occurrence if the mean free path is much smaller than the pore size. The membrane coefficient including the tortuosity (τ) of the porous hydrophobic PTFE membrane was proposed by Schofield et al. [21–23] by inspection of the Knudsen diffusion model (due to the larger mean free path of vapor molecules than the membrane pore size) and Poiseuille flow model to describe the water vapor flux through a deaerated microporous membrane in a semi-empirical equation, this is

$$c_m = c_k + c_p = 1.064\frac{\varepsilon r_p}{\tau\delta_m}\left(\frac{M_w}{RT_m}\right)^{1/2} + 0.125\frac{\varepsilon r_p^2}{\tau\delta_m}\frac{M_w P_m}{\eta_v RT_m}. \quad (9)$$

Therefore, the combination of Knudsen diffusion and Poiseuille flow models was proposed in the present study and validated by the theoretical predictions as compared to experimental runs.

The mass flux and the temperature distributions of hot stream, cold stream, and membrane interfaces along the flow direction were achieved using the finite difference techniques of the Runge–Kutta method in solving Eqs. (4) and (5), as illustrated in Fig. 2.

The value of the standard deviation calculated for the previous study [24] indicates that the best agreement between the experimental permeate flux and calculated permeate flux was achieved with four times higher in comparison with other correlations including Grashof number [25] when Eq. (10) was used for the determination of the convective heat-transfer coefficients in the countercurrent MD model. The heat fluxes transferred across the thermal boundary layers to the membrane