



Study on the heat and mass transfer in air-bubbling enhanced vacuum membrane distillation



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HIGHLIGHTS

- MD flux could be improved 100% by air-bubbling and gas–liquid two phase flow method.
- Two phase flow pattern is the key factor affecting the performance of MD process.
- Mathematic model based on flow pattern was built and AVMD performance was explained.

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ABSTRACT

Air-bubbling vacuum membrane distillation (AVMD) process was designed to boost the heat and mass transfer in membrane distillation (MD). Both effect of flow pattern on the performance of AVMD process and the heat and mass transfer mechanism in this process were studied in this paper. The results showed that the performance of VMD was improved obviously by air-bubbling method. The flux was doubled at certain feed velocity and gas/liquid proportion. The study showed that flow pattern was the key factor affecting the mass and heat transfer efficiencies. The heat transfer coefficients, corresponding to the two main flow patterns in AVMD process, bubbly flow ($h_{f_{bub}} = 1.7527Re_{tp}^{0.4215}Pr^{1/3}(\mu_b/\mu_w)^{0.14}\lambda/d$) and slug flow ($h_{f_{slu}} = 0.0632Re_{tp}^{1.0420}Pr^{1/3}(\mu_b/\mu_w)^{0.14}\lambda/d$), were obtained and employed in the modeling of AVMD process. The modeling results showed that the theoretical prediction of flux aligned with experimental results well, in which the error was within $\pm 5\%$. Both variations of Temperature Polarization Coefficient (TPC) and Concentration Polarization Coefficient (CPC) in AVMD process were studied based on the obtained correlations. And the result showed that both TPC and CPC were significantly influenced by the flow patterns.

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1. Introduction

Membrane distillation (MD), an innovative separation process which combines distillation and membrane technology, has gained worldwide attention and been developed rapidly since it was invented in 1960s [1–3]. Compared to other desalination technology such as Reverse Osmosis and Multi-Flash, MD has quite a few distinctive advantages such as the ability of treating extra-high concentration solutions, high rejection for nonvolatile components, lower operating temperature and pressure, less distillation space requirement and the ability of using low grade heat [2,3]. Many processes and configurations of MD have been developed, and widely employed in sea and brackish water desalination, industrial wastewater treatment, food industry, petro chemistry, chemical engineering, et al. [4–8]. In MD process, water

molecules or other volatile components evaporate at the membrane pore entrance (feed side), cross the membrane pores in vapor phase, and finally condense in the cold side or be removed as vapor from the membrane module [9]. However, concentration and temperature polarization caused by liquid boundary layer are the major barriers inhibiting heat and mass transfer from the bulk stream to pore interface [10–13]. To solve the problem, different techniques have been developed. Teoh et al. [14] achieved 20–28% flux increase by adding baffles and spacers in membrane channel, and modifying the geometry of the hollow fiber in direct contact membrane distillation (DCMD) process. Yang et al. [15] achieved great flux increase by modifying hollow fiber membrane configurations in DCMD experiments in which the modules with undulating membrane surfaces (curly and spacer-knitted fibers) achieved up to 300% flux enhancement in laminar flow region. Liu et al. [16] designed coiled hollow fiber membrane modules for sweeping gas membrane distillation (SGMD) and the flux was improved by about 200%. Zhu et al. [3] obtained 25% flux enhancement by using ultrasonic technology in air gap membrane distillation (AGMD). Li et al. [17,18] found that cross-flow hollow fiber module could ensure a high heat transfer

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coefficient at low Reynolds number (Re) in both vacuum membrane distillation (VMD) and DCMD processes. By modifying the hot feed flow direction and the air gap configuration, Tian et al. [19] boosted the permeation flux up to 2.5-fold in comparison with the conventional design.

Gas/liquid two phase flow technology has been well developed to minimize the boundary layer effect in microfiltration, ultrafiltration, membrane bioreactor and other traditional membrane separation processes [20–27]. Recently, Chen et al. [28] incorporated gas bubbling into DCMD process, and studied both its effect on reducing the concentration polarization and temperature polarization, and influence of bubble size distribution on the gas-bubbling performance [29]. Ding et al. [30] also found that the membrane fouling in DCMD for concentrating the extract of Chinese traditional medicine can be effectively controlled by optimizing gas bubbling parameters.

Many models [1,13] have been developed to research the heat and mass transfer mechanism in MD. However, these models only studied single phase flow on either side of the membrane. Therefore, those models cannot be employed to explain the phenomenon in MD process that both gas and liquid phase exit in one stream (hot and/or cold stream). Influence of gas/liquid two phase flow on heat transfer has been established [31–33] in conventional heat transfer studies. However, in these researches, the mass transfer occurred simultaneously with heat transfer in MD has not been investigated. Although previous works confirmed experimentally in DCMD process that gas/liquid two phase flow was able to minimize boundary layer effect and enhance heat and mass transfer, there is no systematically theoretical study on the heat and mass transfer mechanism for bubbling-enhanced MD process, especially for VMD process. Therefore, it is necessary to develop the heat and mass transfer model suitable for bubbling-enhanced VMD process. In this paper, an air-bubbling enhanced vacuum membrane distillation (AVMD) process designed by our team [34,35] was studied experimentally and theoretically, and heat and mass transfer in this process was modeled.

By combining the basic mechanism of MD process and the method of fitting gas/liquid two phase flow heat transfer correlations, the heat and mass transfer model suitable for AVMD process was established. Using the obtained heat and mass transfer correlations, the variations of TPC and CPC were studied at different patterns.

2. Theory

In the gas/liquid two phase flow system, gas only intensifies mixing of feed solution and enhances surface shear rate, but the liquid boundary layer on the membrane surface still exists [36]. Furthermore, in the MD process, the liquid phase protrudes into the pores as a lid due to the hydrophobicity of the membrane [37], which makes the air bubble isolated from the pores. Therefore, it can be assumed that gas bubbles will not interfere with the mass transfer in membrane pores and alter the main principle of transmembrane mass transfer in AVMD process. Since liquid boundary layer still exists in the gas/liquid two phase flow system, the law of heat and mass transfer between the bulk phase and membrane interface in VMD process is also applicable to AVMD process.

2.1. Heat and mass transfer

For VMD process, both Knudsen diffusion and Poiseuille flow make contributions to transmembrane mass transfer [38] and the MD flux J can be calculated as:

$$J = \left(1.064 \frac{r\varepsilon}{\tau\delta} \sqrt{\frac{M}{RT_m}} + 0.125 \frac{r^2\varepsilon MP_m}{\tau\delta \mu RT_m} \right) \cdot [P(T_{fm}) - P(T_p)] \quad (1)$$

where r is the membrane pore radius; ε is the membrane porosity; δ is the membrane thickness; τ is the pore tortuosity; μ is the dynamic viscosity of water vapor; M is the molecular weight of water; R is the gas constant; $P(T_{fm})$ and $P(T_p)$ are the vapor pressure as function of T_{fm} and T_p ; T_{fm} and T_p are the membrane interface temperature on the feed and the permeate sides; T_m is the average temperature in membrane pores, $T_m = (T_{fm} + T_p) / 2$; P_m is the average vapor pressure in membrane pores, $P_m = [P(T_{fm}) + P(T_p)] / 2$; $P(T_{fm})$ and $P(T_p)$ can be calculated using the Antoine's equation (Eq. (2)) [13]:

$$P(T_{fm(p)}) = \exp \left(23.238 - \frac{3841}{T_{fm(p)} - 45} \right) \quad (2)$$

With the measurable J and $P(T_p)$ as well as other membrane parameters, the unknown parameter T_{fm} can be calculated via the combination of Eqs. (1) and (2) [9].

In MD system, the heat flux across the liquid boundary layer (feed side), Q_f , can be expressed as Eq. (3):

$$Q_f = h_f A_f (T_f - T_{fm}) \quad (3)$$

where h_f is heat transfer coefficient of the bulk phase; T_f is the temperature of the bulk phase, $T_f = (T_{in} + T_{out}) / 2$; A_f is the effective inner surface area of the hollow fiber membranes, $A_f = \pi L d$; L is the effective length of the membrane module; d is the inner diameter of hollow fiber membrane. The inlet temperature T_{in} can be measured and the outlet temperature T_{out} can be calculated via the combination of Eqs. (4) and (5):

$$C_p m (T_{in} - T_{out}) = J A_m \Delta H \quad (4)$$

$$m = \rho_l V_l = \rho_l U_l A_{sec} = Re_{tp} \frac{\mu_g}{\mu_l} + \frac{U_g \rho_g}{U_l \rho_l} \frac{A_{sec}}{d} \approx Re_{tp} \mu_l A_{sec} / d \quad (5)$$

where C_p is specific heat of the feed; m is the mass flow rate of the feed solution; A_m is the effective area of the transmembrane heat transfer, $A_m = \pi L (D - d) / \ln(D/d)$, D is the outer diameter of hollow fiber membrane; A_{sec} is the cross section area of the hollow fiber membranes based on the inner diameter of hollow fiber membrane; ρ_g and ρ_l are densities of air and water; U_g and U_l are superficial velocities of air and water; μ_g and μ_l are dynamic viscosities of air and water. ΔH is the latent heat of vapor at temperature of T_{fm} and it can be calculated via Eq. (6):

$$\Delta H = 2258.4 + 2.47 (373.0 - T_{fm}) \quad (6)$$

The overall heat-transfer flux across the membrane, Q , is expressed as Eq. (7):

$$Q = J \Delta H A_m + \frac{h_m}{\delta} A_m (T_{fm} - T_{pm}) \quad (7)$$

where h_m is the thermal conductivity of hollow fiber membrane, $h_m = (1 - \varepsilon)h_s + \varepsilon h_g$; h_s and h_g are separately the thermal conductivity of polymer and gas (usually air); T_{pm} is the membrane surface temperature in the permeate side.

Similar to VMD process, the contribution of the heat conduct through the membrane matrix in AVMD (i.e., $h_m A_m (T_{fm} - T_{pm}) / \delta$) can be neglected due to the high vacuum degree in the permeate side [17]. Therefore, Eq. (7) can be simplified to Eq. (8):

$$Q = J \Delta H A_m \quad (8)$$

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