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Condensation, re-evaporation and associated heat transfer in membrane evaporation and sweeping gas membrane distillation

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ABSTRACT

Vapor transport through membranes is very important in many industrial processes such as membrane distillation (MD), membrane condensation and flue gas dehydration. In this study, we explore the condensation, re-evaporation and associated heat transfer in membrane evaporation and sweeping gas membrane distillation (SGMD) at low gas flow rates. It is found that both condensation and re-evaporation are closely related to the membrane properties. Condensation is more severe for the membrane with lower mass transfer resistance. The condensation layer takes place between the separation layer and the bulk gas in the module. The re-evaporation rate is determined by the total surface area of the droplets, the gas stripping velocity and the gas temperature. The overall mass transfer coefficient increases significantly with the increases of the gas flow rate, while the liquid flow rate has limited effect on the overall mass transfer coefficient. The overall mass transfer coefficient decreases with the increase in the evaporation temperature. The traditional way to quantify temperature polarization effect may not be applicable for SGMD at low gas flow rates because of vapor condensation. The increase in the gas flow rate or evaporation temperature can effectively improve evaporation efficiency (EE) in SGMD, while the liquid flow rate has limited effect on EE.

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1. Introduction

Water vapor transport through membranes is of great importance in many industrial processes. Applications can be found in membrane distillation (MD) [1–3], membrane evaporation [4], membrane condensation [5,6], drying of natural gas [7] and flue gas dehydration [8]. Utilizing low-grade heat, MD is often considered to be an efficient desalination alternative as it offers higher salt rejection but consumes less energy when compared with the leading desalination technology—reverse osmosis (RO) [1,3,9,10]. MD can be carried out with four major configurations: direction contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD) and sweeping gas membrane distillation (SGMD), depending on the method by which water vapor is recovered on the permeate side of the membrane. Among them, SGMD is the least studied configuration, likely because that an external condenser is required to collect the permeate which will incur extra cost by complicating the system [2].

Essentially, membrane evaporation has the same process principle as MD in terms of mass and heat transfer [11]. The difference

between membrane evaporation and MD is in that membrane evaporation is used for the concentration of thermo-sensitive solutions [4,12,13], while MD aims to obtain high quality water from the vapor [2,3]. Contrary to MD, there is no need to recover the water vapor on the permeate side in membrane evaporation.

A number of researchers have done numerous studies on MD, particularly on DCMD [1–3,14–21]. Only few people have reported results for SGMD [2]. Khayet et al. conducted a series of experimental and modeling work to explore the influences of operational parameters on the process performance in SGMD [22–25]. Until recently, the fundamental mass transfer mechanisms in SGMD are reported. We find that mass transfer in SGMD with low sweeping gas velocity has four consecutive processes: (1) vapor transport through the active layer, (2) condensation and droplets formation on the gas side, (3) droplet re-evaporation under the condition of gas stripping, and (4) water vapors and/or droplets are swept out of the module by the stripping gas [11].

In fact, condensation associated with water vapor transfer is a common problem in membrane contactors and it can adversely reduce the module mass transfer performance [5]. However, this important phenomenon has received little attention in the membrane research community. Fang et al. believe that vapor condensation could occur in the bulk gas phase or at the gas–membrane surface [5]. Our previous study has proved that condensation does occur on the

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gas side by comparing the vapor-holding capability (e.g. saturation humidity) of the gas and the cross-membrane vapor flux [11].

The objective of this study is to further explore the condensation, re-evaporation and associated heat transfer in membrane evaporation and SGMD. We attempt to clarify the relationship between condensation and membrane properties, the location of vapor condensation, and some factors influencing re-evaporation and heat transfer in SGMD.

2. Theory

2.1. Condensation and re-evaporation in SGMD

In the membrane module, when the water vapor transfer rate through the membrane is higher than the vapor-holding capability of the sweeping gas, the gas becomes super-saturated and vapor condensation occurs on the gas side [11]. As a consequence of condensation, droplets form at the pore-sweeping gas interface in the module. Simultaneously, the latent heat associated with condensation will release to the gas. Under the condition of gas stripping, the droplets will be re-evaporated. The evaporation rate (E) of the droplets can be expressed by a common formulation [26,27]

$$E = ku(e_s - e) \quad (1)$$

where k is a mass transfer limiting term, u is the gas flow velocity, e_s is the saturation vapor pressure at the droplets surface, and e is the vapor partial pressure of the gas.

Actually, the evaporation rate is also closely related to the droplet radius (r) in addition to the gas velocity (u). The evaporation rate of a water droplet in a steady state is given by [28]

$$E = \frac{4\pi MrD_{eff}}{R} \left(\frac{P_\infty}{T_\infty} - \frac{P_{sat}}{T_a} \right) \quad (2)$$

where M is the molar mass of water, R is the universal gas constant, D_{eff} is the effective gas diffusion coefficient, P_∞ is the ambient water partial pressure, P_{sat} is equilibrium vapor partial pressure, T_∞ is the ambient temperature, and T_a is the droplet temperature.

2.2. Heat transfer in membrane distillation

2.2.1. Resistance-in-series model for heat transfer

Generally the heat transfer across a porous membrane in traditional MD can be explained by three different mechanisms: (1) heat

transferred between the bulk solution and the boundary layer, which is related to the temperature polarization effect on both sides of the membrane [9]; (2) heat conduction across the membrane matrix and the gas filled pores; (3) latent heat flow caused by vaporization [17]. The overall heat transfer resistance as a combination of the boundary layer resistance and the resistance across the membrane can be illustrated by a serial and parallel resistance model (Fig. 1). Based on the resistance-in-series model, the overall heat transfer coefficient H can be obtained from the following equation [1]:

$$\frac{1}{H} = \frac{1}{H_f} + \frac{1}{H_m + N\Delta H_v / \Delta T_m} + \frac{1}{H_p} \quad (3)$$

Therefore, the total heat flux (Q) transferred across the membrane can be expressed as follows:

$$Q = H\Delta T = \left[\frac{1}{H_f} + \frac{1}{H_m + N\Delta H_v / \Delta T_m} + \frac{1}{H_p} \right]^{-1} \Delta T \quad (4)$$

where ΔT is the bulk temperature difference between the feed and permeate, ΔT_m is the temperature difference across the membrane, H , H_f , H_m and H_p are the heat transfer coefficients of the bulk, feed side, membrane and permeate side, respectively. N is the molar flux, and ΔH_v is the molar heat of vaporization.

2.2.2. Temperature polarization (TP)

In traditional MD, mass transfer and heat transfer occur simultaneously as shown in Fig. 2. On the hot liquid side, the feed temperature (T_f) decreases across the boundary layer to T_1 at the membrane surface. On the cold side, the permeate temperature (T_p) increases across the boundary layer to T_2 at the membrane surface. Mass transfer is facilitated by the heat transfer across the boundary layers. Therefore, boundary layers play significant roles in both heat transfer and mass transfer. The magnitude of the boundary layer resistances to the total heat transfer resistance can be presented by the temperature polarization coefficient (TPC). TPC is generally used to evaluate the process efficiency of MD and it is defined as follows:

$$\text{TPC} = \frac{T_1 - T_2}{T_f - T_p} \quad (5)$$

TPC decreases with the increase of the feed temperature although higher feed temperature will cause an exponential increase in the permeate flux [18,24,29,30]. For a well designed MD system, TPC is in the range of 0.4–0.7 [1].

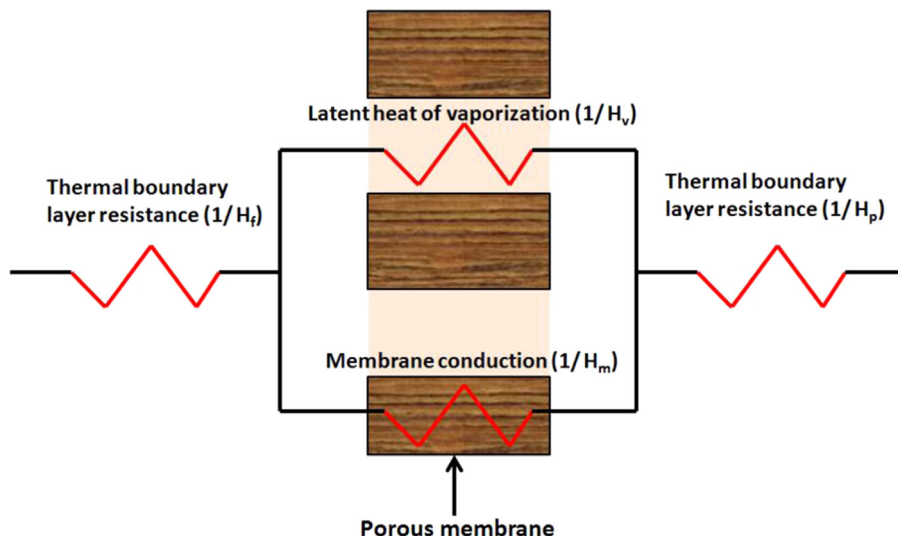


Fig. 1. A series and parallel heat transfer resistance model in membrane distillation.

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