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Comparative study of air gap and permeate gap membrane distillation using internal heat recovery hollow fiber membrane module

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ABSTRACT

Air gap membrane distillation (AGMD) and permeate gap membrane distillation (PGMD) were investigated and compared through self-developed hollow fiber membrane modules with internal energy recovery. The effects of the feed temperature, the coolant temperature, the flow rate, the gap thermal conductivity, and the gap width on the flux and the gained output ratio (GOR) were evaluated experimentally. The gap between the membrane and the condensing surface was a key factor affecting the flux and the GOR in both AGMD and PGMD. It was found that the improvement of gap thermal conductivity using brass net was useless in improving flux and GOR. The permeate water filled in the gap changed the process of mass and heat transfer in the gap which gave rise to the increase in the flux and thermal recovery. The flux and GOR in PGMD increased by 7.9% and 59.82% in the gap of 0.5 mm compared to the AGMD. The salt rejection of all experiments was greater than 99.8%.

1. Introduction

Membrane distillation is a separation process, in which water vapor in the hot side spreads through the membrane microspores to the cold side and then vapor condenses, to dehydrate water-soluble substances and get pure water. The driving force of membrane distillation is the vapor pressure difference triggered by the temperature difference between the both sides of hydrophobic porous membrane [1]. There exist basically four types of membrane configurations according to different ways of condensation: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD), and vacuum membrane distillation (VMD) [2,3]. Among these four membrane configurations, AGMD is the most appropriate choice for desalination [4].

In the AGMD, higher thermal efficiency is achieved, since a stagnant air gap between the membrane and condensation surface reduces the conduction heat loss through the membrane. While the parasitic mass transfer resistance results in the decrease of the flux, and the extent of the flux decline depends on the effective width of the gap in AGMD. The decrease in the width of air gap can give rise to the increase in flux [5,6]. But the flux in AGMD falls far below that in the DCMD under the same operating conditions [7]. And Alklaibi reported that an air gap width below 1 mm had a negative effect on the thermal efficiency and a positive influence on the flux [8]. To solve the decrease in flux caused by air gap, there appeared researches about vacuum-air gap membrane distillation (V-AGMD) [7] and permeate gap membrane distillation (PGMD) [9,10] or liquid gap membrane distillation (LGMD) [11] and material gap membrane distillation (MGMD) [12,13]. D. Winter focused on experimental studies on full scale spiral wound MD-modules with a membrane surface area of 5–14 m^2 for PGMD and gave statements regarding module fabrication quality [14].

PGMD and MGMD are defined as water being filled in the gap and water together with material being filled in the gap respectively. In a PGMD module, the permeate water is separated from the coolant by a condensation surface, so the coolant can still be any type of liquid. The water in the gap can effectively reduce mass transfer resistance through the gap as vapor can condense immediately when leaving the membrane like the DCMD, meanwhile with lower heat loss theoretically. Another benefit of PGMD compared to DCMD is the direct use of feed water as coolant inside the module and therefore, no external heat exchanger is needed to heat the feed before entering the pre-heating tank. The improved flux was reported in PGMD and it seemed that the extent of the enhancement increased with the gap width increasing in the water gap width from 9 mm to 13 mm and the percentage of flux rose from 572% to 820% at 40 °C [12]. Khalifa [9] reported 90%–140% increasing percentage in flux was achieved as the gap width increased from 4 mm to 8 mm.

In this paper, considering the advantages of the PGMD above, we improved the membrane distillation process based on AGMD. The gap width we choose was below 1 mm. Hollow fiber membrane modules

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with internal heat recovery were self-developed and tested in AGMD and PGMD. PP net and brass net between the membrane and the heat exchange hollow fibers were used to fix the gap width. A brief analysis and comparison of the mechanism of mass and heat transfer in AGMD and PGMD was carried. Based on it, the effect of the feed temperature, the coolant temperature, the flow rate, the gap width and the gap thermal conductivity on the flux and GOR were studied and compared experimentally under the same operating conditions and geometric parameters during AGMD and PGMD process.

2. Theory analysis and experimental methods

2.1. Comparison of AGMD and PGMD mechanism

2.1.1. Mass transfer

Regardless of concentration polarization, in AGMD, mass transfer is divided into two sub-sections: mass transport across the porous membrane and mass transport across the gap.

Vapor transport across the membrane can be described by the Knudsen-molecular diffusion [15]:

$$J_{mem} = \frac{1}{\left(\frac{1}{k_k} + \frac{1}{k_{mol}}\right)} \times \frac{\Delta P_m}{\delta_m} = k_{mem} \times \frac{\Delta P_m}{\delta_m} \quad (1)$$

$$k_k = \frac{2}{3} \cdot \frac{1}{RT} \cdot \frac{r_p \varepsilon}{\tau} \cdot \sqrt{\frac{8RT}{\pi M}} \quad (2)$$

$$k_{mol} = \frac{1}{RT} \cdot \frac{D\varepsilon}{\tau} \cdot \frac{P}{P_{ml}} \quad (3)$$

where J_{mem} is the flux across the membrane, k_k is the overall Knudsen diffusion coefficient, k_{mol} is the overall molecular diffusion coefficient, ΔP_m is the trans-membrane partial pressure difference of the diffusing molecular, δ_m is the thickness of the membrane, R and T are gas constant and absolute temperature respectively. r_p, ε and τ are the membrane mean pore radius, membrane porosity and tortuosity respectively, M is the molecular weight of the diffusing molecular, D is diffusion coefficient of the species into air in the gap, P is the gas pressure, P_{ml} is the logarithmic mean of air partial pressure between membrane sides.

Mass transport across the gap which is similar to the molecular diffusion Eq. (3) is the main mass transfer resistance:

$$J_a = \frac{D}{RT} \cdot \frac{P}{P_{ml}} \cdot \frac{\Delta P_a}{\delta_a} = k_a \times \frac{\Delta P_a}{\delta_a} \quad (4)$$

ΔP_a and δ_a are the pressure difference between the cold side of the membrane and the condensation surface, air gap thickness respectively.

The AGMD flux will be:

$$J = \Delta P / \left(\frac{1}{k_a} + \frac{1}{k_{mem}}\right) \quad (5)$$

The PGMD flux J_p differs from AGMD for no air gap resistance: $J_p = J_{mem} > J$.

2.1.2. Heat transfer

The heat transfer in the AGMD is generally divided into six parts: (a) Heat transfer through the thermal feed side boundary layer by convection; (b) Heat transfer across the membrane by conduction and latent heat of evaporation; (c) Heat transfer through the air gap by conduction and latent heat of evaporation; (d) Heat transfer through the flux by conduction; (e) Heat transfer through the condensation film by conduction; (f) Heat transfer through the cold side boundary layer by convection.

While in PGMD, the process c and d were replaced by heat transfer through permeate water by latent heat of evaporation and conduction.

Table 1
Parameters of iPP hollow fiber membrane.

Outer diameter (mm)	Inner diameter (mm)	Porosity	Average pore size (μm)	Contact angle (°)	Tortuosity factor
0.66	0.44	68%	0.2	110	2.56

2.2. Membrane materials

Polypropylene (PP) hollow fiber membrane provided by Tianjin Chemical Separation Technologies Co. Ltd., China, was used. The TIPS-iPP hollow fiber membranes had a mean pore size of 0.2 μm with a porosity of 68% and contact angle of 110°. The inner and outer diameters of the hollow fiber membrane measured by the high resolution optical microscope were 0.44 mm and 0.66 mm respectively. All these membrane parameters were shown in Table 1. The iPP heat exchange hollow fibers with inter diameter of 0.40 mm and outer diameter of 0.63 mm were also provided by Tianjin Chemical Separation Technologies Co. Ltd.

2.3. Module fabrication

The structure of membrane module was shown in Fig.1. Firstly, four layer sheets were assembled: net, membrane, net and heat exchange hollow fibers layered sheet in a large flat of table; secondly, the sheets were sealed at one edge, and were tightly packed where four layer sheets were wrapped around the edge in a spiral fashion. The net between the membranes and the exchange heat fibers was used to fix the gap width and change the thermal conductivity in the gap. Thirdly, ends of the fiber bundle together with Acrylonitrile Butadiene Styrene (ABS) plastic tube were sealed with solidified epoxy resin to compose a membrane module. Then the hollow fibers were cut open at both ends to accommodate the feed channel and the condensation channel.

Four hollow fiber membrane modules with internal energy recovery were assembled and the major parameters of the modules were shown in Table 2. Each membrane module contained 240 hollow fiber membranes and 480 heat exchange hollow fibers. The number ratio of hollow fiber membranes to heat exchange hollow fibers decided by previous experiment [16] was 1:2 (the surface ratio of hollow fiber membrane taken by inner surface area to heat exchange hollow fibers taken by outer surface area was 0.35).

2.4. Experimental procedure and equation

The schematic diagram of this experimental set-up of AGMD was shown in Fig. 2. While in PGMD the module was inverted by collecting water from the top, hydrostatically forcing the gap region to be flooded with permeate water as seen in the Fig. 3. And Fig. 3 showed how the flows pass through the module for AGMD and PGMD. During the experiment, the preheating NaCl solution (20 °C, 30 °C, 40 °C) as condensate water was pumped into the bottom of heat exchange hollow fibers channel by the magnetic pump A for internal heat recovery. Then the feed from the top of heat exchange hollow fibers flowed into thermostatic water bath B and was heated up to the pre-set temperature (60 °C, 70 °C, 80 °C) and would be pumped into the top of membrane channel by the magnetic pump B. The concentrated feed out from the bottom of membrane channel flowed into the concentrated tank. All experiments were operated in a counter-current flow.

The flow rate in the system was regulated with the rotameter that has a measuring range of 0–60 L/h. In all experiments, the feed flow rate was equal to the coolant flow rate. The water produced was collected on a measuring cylinder and recording the value in each 10-minute period for three times after the system ran stably. The temperatures of inlets and outlets of feed and coolant (T_1, T_2, T_3, and T_4)