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Performance of asymmetric hollow fibre membranes in membrane distillation under various configurations and vacuum enhancement

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ABSTRACT

Hollow fibre membrane distillation (MD) modules have a more compact structure than flat sheet membrane modules, providing potentially greater advantage in commercial applications. In this paper, a high-flux asymmetrically structured hollow fibre MD module was tested under various conditions. The results show that increasing velocity and temperature are positive for flux, and salt rejection was more than 99% over the entire experimental range. The hollow fibre module also showed great variation in flux when altering the hot feed flow from the lumen side to the shell side of the fibre, and this phenomenon was analysed based on the characterisation of the asymmetric structure of the hollow fibre. The largest mass transfer resistance was determined to be in the small pore size skin layer on the outer surface of the membrane, and having the hot feed closest to this surface provided the greatest vapour pressure difference across this high resistance mass transfer layer. The results also show that placing the suction pump on the permeate outlet increased the flux by lowering the pressure within the pore and hence increased the rate of vapour mass diffusion. A maximum flux of 19 L m^{-2} h^{-1} was obtained at 85 °C when hot feed was entering the shell side, and the mass transfer coefficient was relatively constant across the entire temperature range when operated at high velocities. These outcomes suggest that asymmetric hollow fibre MD modules should be operated with hot brine feed closest to the high resistant skin layer, and that vacuum enhanced MD further increases vapour transport and flux.

1. Introduction

Membrane distillation is a developing technique for desalination. Its driving force is a vapour pressure difference across a membrane, which is quite different from other membrane processes in which an absolute pressure difference, a concentration gradient or electrical potential gradients are the driving force for mass transfer. It has 100% theoretical rejection of non-volatile components and can utilise low grade heat sources of 40–80 °C. Its flux is not sensitive to salt concentration in the feed, since vapour pressure is not greatly affected by the salinities found in practical water treatment. Thus, it is a potential commercial desalination technique if it can be combined with solar energy, geothermal energy or waste heat available in power stations or chemical plants. It could also be an effective method to reduce the volume of waste discharges or even convert a reject stream to a higher value concentrated liquid. Therefore, MD can be combined with conventional reverse osmosis processes to minimise high concentration brine discharge.

Fig. 1 shows a tubular hollow fibre module (a) and a flat sheet module (b), which are the most popular configurations employed for membrane distillation. In comparison with the flat sheet module, the hollow fibre module has larger effective area per unit volume.

In the MD process, the force preventing process liquid wetting the membrane pores results from both the hydrophobicity of membrane material and the liquid surface tension. The lowest wetting pressure, the Liquid Entry Pressure (LEP) [1] can be calculated from:

$$\mathrm{LEP} = \frac{-2B\gamma_l \cos\theta}{r_{\max}} \quad (1)$$

where B is a geometric factor, γ_l is the surface tension of the solution, θ is the contact angle between the solution and the membrane surface, and r_{max} is the largest membrane pore size. If the maximum pore size of membrane is 1 μm [2], the LEPs of membranes with the contact angles of 95° and 140° calculated from Eq. (1) are 23 and 204 kPa, respectively, which would be the upper application pressure limits of such membranes. These calculations demonstrate the large effect that contact angle of the membrane has on the LEP, and subsequently on the maximum operating pressures and velocities in MD modules. In a commercial application, the effective membrane area will be tens or hundreds of times of that of laboratory

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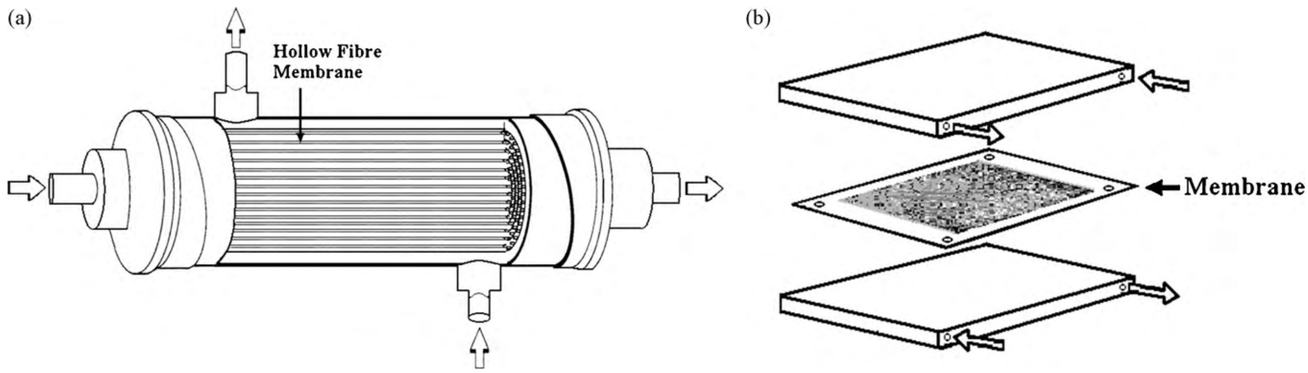

Fig. 1. Configurations of MD module. a. Tubular hollow fibre module b. Flat sheet module.

scale tests, and a reasonable flow velocity needs to be maintained to reduce temperature polarisation [3]. Therefore, to avoid wetting, the hydrophobicity of membrane material and hydraulic resistance of the module with turbulence enhancing structure will be very important for commercial design. From Fig. 1, we observe that it is easier to put more effective area into the hollow fibre module with less restriction than that of the flat sheet module, however, turbulence promoters are likely to be required to reduce temperature polarisation.

One of the main impediments of the hollow fibre module is its typically low flux, which is generally 1–4 $L\,m^{-2}\,h^{-1}$ at 40–60 °C [4–6]. This is much lower than that of the flat sheet membranes with fluxes of 20–30 $L\,m^{-2}\,h^{-1}$ [7]. However, the recent renewed interest in membrane distillation has led to improved hollow fibre membranes and modules.

1.1. Force balance analysis at pore entrance

Fig. 2 shows the force balance at the entrance of pore, in which P_f and P_p are respectively the gauge pressure of the feed flow and permeate flow, P is the total gauge pressure in the pore, F is the force from surface tension, H is the water protrusion into the pore and θ' is the angle between the water and membrane material. Additionally, θ' cannot be more than θ before wetting, and the initial P equals zero gauge pressure (atmospheric pressure).

In considering Fig. 2, it can be speculated that the pressure in the pore will remain almost constant, assuming the membrane material is not compressible. When P_f and/or P_p are higher than zero and increasing in value relative to P, the depth of protrusion will also increase (H and θ' will become greater to balance the increased liquid pressure). When either feed or permeate pressure is less than zero, the higher pressure in the pore will cause air to bubble into the lower pressure liquid, until P equals this lower pressure. Furthermore, assuming a membrane with pore size of 1 μm and contact angle of 150°, based on Eq. (1) the maximum protrusion H is 0.3 μm. When considering a typical membrane thickness of 10–50 μm, this protrusion will have a negligible effect on the air volume within the pore.

1.2. Mass transfer in DCMD

Fig. 3 shows the heat and mass transfer processes in direct contact membrane distillation (DCMD). The liquid feed and cooling flow are not in contact with each other, but are physically separated by the membrane and gas trapped within the pores. The feed temperature, T_f drops across the feed side boundary layer to T_1, as water evaporates and is transported through the membrane and heat is conducted through the membrane to the permeate side. The permeate temperature, T_p, increases across the permeate boundary layer to T_2 as the permeate flow condenses into the fresh water stream and gains heat from the feed side. The real driving force is

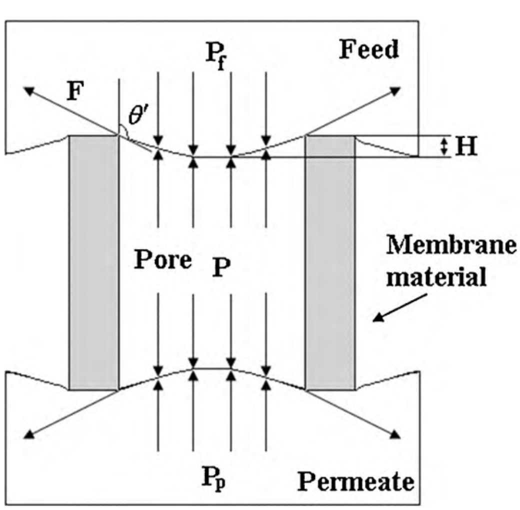

Fig. 2. Schematic of force balance in the pore.

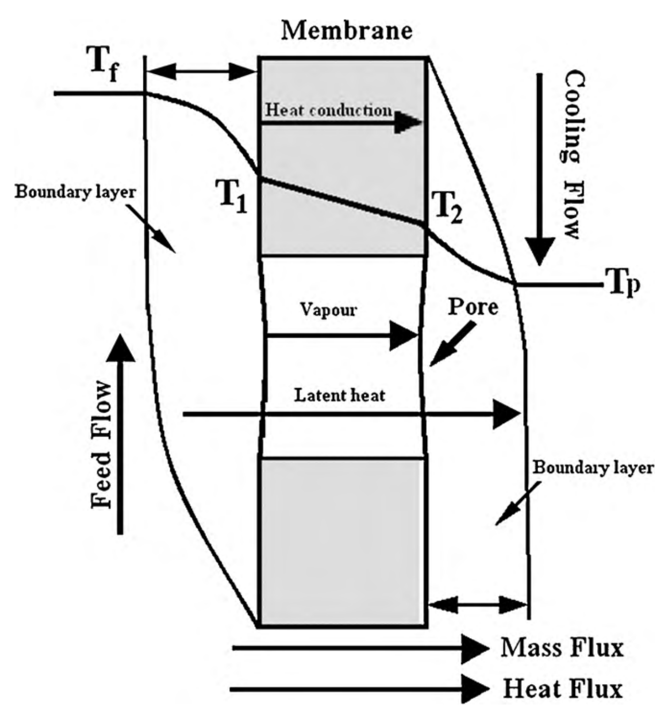

Fig. 3. Heat transfer and mass transfer through membrane.