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Air gap membrane distillation: A detailed study of high saline solution

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HIGHLIGHTS

- Three PTFE membranes were used to treat highly concentrated salt solutions.
- The permeate flux decline is higher than that predicted from the vapour pressure reduction.
- The energy consumption has increased when the concentration increased.

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ABSTRACT

An experimental study is used to examine the effect of high concentration of several salts, i.e., NaCl, $MgCl_2$, Na_2CO_3 and Na_2SO_4 on permeate flux and rejection factor by air gap membrane distillation (AGMD). A comparative study involving three different membrane pore sizes (0.2, 0.45 and 1.0 μm) were performed to investigate the influence of pore size on energy consumption, permeate flux and rejection factor. The permeate flux decline is higher than that predicted from the vapour pressure reduction. Furthermore, the energy consumption was monitored at different membrane pore size and was found to be increased when the concentration increased.

1. Introduction

Salinity is one of the most pressing environmental economic problems in arid countries. Desalting systems have long proven effective in the arid countries, such as in the Arabian Gulf. Water desalination can be performed using different techniques, such as thermal and membrane processes. Membrane distillation (MD) have the benefits of thermal and membrane technologies, as it is considered a thermally-driven separation process. Vapour molecules are only able to pass through a porous hydrophobic membrane. As a result, high purity water will be obtained from aqueous solution [1–4]. This separation process is driven by the vapour pressure difference existing between the porous hydrophobic membrane surfaces. Consequently, MD processes have vapour pressure difference as the driving force. Permeate flux, in general increases linearly with trans-membrane vapour pressure [2–7].

There have been many studies to explore the impact of high salt concentration on the membrane permeability. The influence of high salt concentration and complex solution such as produced water on the permeate flux and rejection factor was reported [8–11]. Yun et al. [10] found that, there was a noticeable variation on membrane permeability with time. As a result, it is hard to determine the permeate flux by using the existing models. They assumed that, the properties of the boundary layer solution (at the membrane surface) reaches the saturation and varies from the bulk solution. Indeed, the solution features are changed; for example, the density and viscosity increase, while the vapour pressure decreases [8,10–12]. Moreover, the boiling point and surface tension rise when the concentration increases [12–15].

In addition, Li et al. [16], indicated that the permeate flux reduction becomes significant as salt concentration exceeds 2.0 M. The permeate flux of KCl, NaCl and $MgCl_2$ solutions reduced by 44.4%, 59.6% and 86.8% as the salt concentration increased from 2.0 to 4.0 M. In addition, they pointed out that the impact of viscosity on the permeate flux could not be neglected at high salt concentration.

Moreover, Safavi and Mohammadi [9], employed VMD to treat highly saline solution. They concluded that, the permeate flux is better with decreasing the feed concentration. However, the rejection factor is not affected by the feed concentration.

Fouling is a deposition of unwanted materials such as scale, suspended solids and insoluble salts on the external surfaces of the membrane (Fig. 1). Kullab and Martin [17] pointed out that fouling and scaling lead to blocking the membrane pores, which reduces the effective membrane, and therefore the permeate flux obviously decreases. These may also cause a pressure drop, and higher temperature

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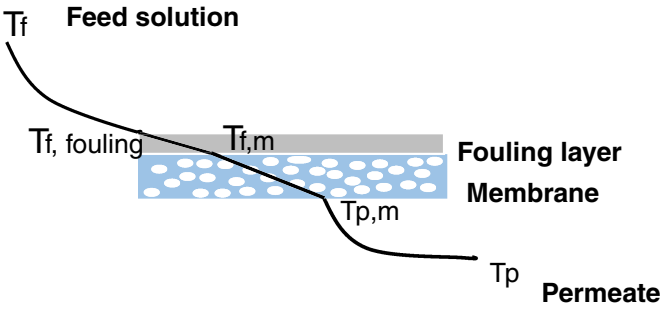

Fig. 1. Temperature profile across fouled membrane.

polarization effect. Gryta [18] indicated that the deposits formed on the membrane surface leads to the adjacent pores being filled with feed solution (partial membrane wetting). Moreover, additional mass and heat resistance will be created by the fouling layer (Eqs. 1 and 2), which is deposited on the membrane surface. As a result, the overall heat and mass transfer coefficient of the membrane decreased. For DCMD, Gryta and Goh et al. [19,20] specified:

$$J = \frac{P_f - P_{f,fouling}}{R_f} = \frac{P_{f,fouling} - P_{f,m}}{R_{fouling}} = \frac{P_{f,m} - P_{p,m,}}{R_m} = \frac{P_{p,m} - P_p}{R_p} \quad (1)$$

where $\frac{P_f - P_{f,fouling}}{R_f}$ represents the mass transfer through the feed boundary layer; $\frac{P_{f,fouling} - P_{f,m}}{R_{fouling}}$ represents the mass transfer through the fouling layer; $\frac{P_{f,m} - P_{p,m,}}{R_m}$ represents mass transfer through the membrane; $\frac{P_{p,m} - P_p}{R_p}$ represents mass transfer through the permeate.

Table 1
Range of concentration of single salts used in the filtration experiments.

Single salt	NaCl	$MgCl_2$	Na_2SO_4	Na_2CO_3
Lowest concentration (ppm)	5844	4760	4260	5300
Highest concentration (ppm)	180,000	95,210	142,000	106,000

R_f, $R_{fouling}$, R_m, R_p are the resistance in the feed boundary, fouling layer, membrane and permeate boundary respectively.

$$h_f(T_f - T_{f,foulig}) = \frac{k_{fouling}}{\delta_{fouling}}(T_{f,fouling} - T_{f,m}) = \frac{k_m}{\delta}(T_{f,m} - T_{p,m}) + J\Delta H_v = h_p(T_{p,m} - T_p) \quad (2)$$

where $k_{fouling}, \delta_{fouling}$ *and* $T_{f,fouling}$ are the fouling layer thermal conductivity, thickness, and fouling layer temperature, respectively.

El-bourawi [21] proposed that scale formation and deposition at membrane surfaces may diminish the membrane hydrophobicity and cause water logging of some membrane pores. Tun et al. [22] examined the effect of high concentration of NaCl and Na_2SO_4 on the permeate flux. The flux gradually decreases during the MD process, until the feed concentration reaches the supersaturation point, and then the flux decreases sharply to zero. The membrane was completely covered by crystal deposits.

The influence of high concentrations on permeate flux, salt rejection factor, and energy consumption was examined in this work. In addition, the effect of pore size on the permeate flux and rejection factor was analysed too.

2. Experimental procedure and material

The influence of a wide range of concentrations of NaCl, $MgCl_2$, Na_2CO_3 and Na_2SO_4 on permeate flux, salt rejection factor, and energy consumption was examined as shown in Table 1. In addition, the effect of pore size was investigated by three commercial membrane pore sizes (0.2, 0.45 and 1.0 μm). The experimental tests were achieved by AGMD module, as shown in Fig. 2. Three types of flat sheet polytetrafluoroethylene (PTFE) microporous hydrophobic membranes were used in this work. PTFE has excellent chemical resistance (nonreactive) being unaffected by almost all chemicals. Moreover, it is insoluble and thermally stable to high temperatures (up to 260 °C) [23]. These membranes, manufactured by Sterlitech corporation, were used to filter high saline solutions. The membrane cell was maintained in a horizontal position. The feed solution was maintained in direct contact with the membrane surface. Furthermore, the heat was supplied to the feed by a heating coil. The feed reservoir was insulated to minimize the heat losses. The feed temperature can be manipulated and controlled by an Autotune temperature controller. The feed flow rate was heated and

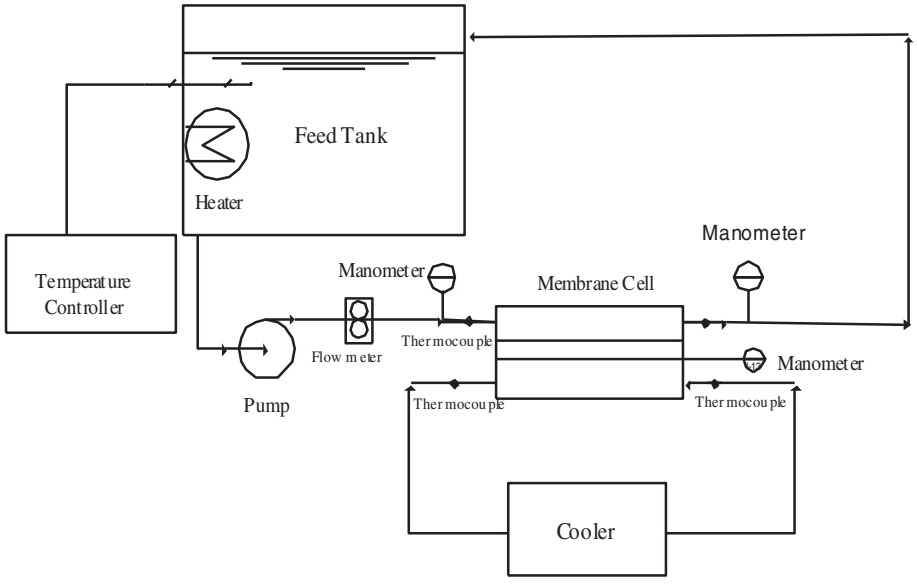

Fig. 2. Schematic diagram of the AGMD used in this work.

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