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Persian Gulf desalination using air gap membrane distillation: Numerical simulation and theoretical study

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HIGHLIGHTS

- Persian Gulf desalination using AGMD was modeled with MATLAB.
- TPC reduced while thermal conductivity of the membrane material decreased.
- TPC also decreased with feed temperature.
- Permeate flux increased exponentially with feed bulk temperature.
- The predicted data were in good agreement with the experiments.

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ABSTRACT

A simultaneous heat and mass transfer model in air gap membrane distillation has been developed and validated with experimental data using MATLAB, in order to enhance its performance in desalination of Persian Gulf and to get more flux. The effect of operating parameters including feed temperature, concentration and velocity, condensate fluid temperature and velocity, thickness of air gap of permeate side, heat transfer coefficient (HTC) on permeate flux has been considered. The influence of some membrane characteristics including its thickness, tortuosity, porosity, and pore size distribution on permeate flux has also been studied. The results revealed that increase of feed temperature and velocity, HTC, membrane porosity and pore size distribution has improved the permeate flux. In contrast, the permeate flux decreased with feed concentration and air gap distance as operation parameters, and thickness and tortuosity as membrane characteristics. The temperature polarization coefficient decreased with feed temperature and reduced while thermal conductivity of the membrane material decreased. At elevated temperatures, increasing of HTC affects more strongly on permeate flux; i.e. a 25% increase in flux at 70 °C reduced to 14% at 50 °C. Comprising to experimental data, just about 6% average deviation was observed for this ultra-simple model.

1. Introduction

Membrane distillation (MD) is a process mainly suited for applications in which water is the major component present in the feed solution [1]. MD is a thermally driven process, in which only vapor molecules are transported through porous hydrophobic membranes. The liquid feed to be treated by MD must be maintained in direct contact with one side of the membrane without penetrating its dry pores unless a transmembrane pressure higher than the membrane liquid entry pressure is applied. The hydrophobic nature of the membrane prevents liquid solutions from entering its pores due to the surface tension forces. As a result, liquid/vapor interfaces are formed at the entrances of the membrane pores. Various MD modes differing in the technology applied to establish the driving force can be used. The differences between them are localized only in the permeate side as can be seen in Fig. 1.

The MD driving force may be maintained with one of four possibilities applied in the permeate side. As seen in Fig. 1f, a stagnant air gap is interposed between the membrane and a condensation surface. In this case, the evaporated volatile molecules cross both the membrane pores and the air gap to finally condense over a cold surface inside the membrane module. This MD configuration is called air gap membrane distillation (AGMD) [1,2].

To solve the problem of heat loss by conduction through the membrane, which leads to relatively low efficiency of the MD process, an air gap was placed inside the membrane module between the permeate side of the membrane and the condensing surface. This reduces considerably both the heat loss by conduction and temperature polarization, thereby improving the separation effect. However, the permeate flux has to overcome the air barrier and therefore it is drastically reduced

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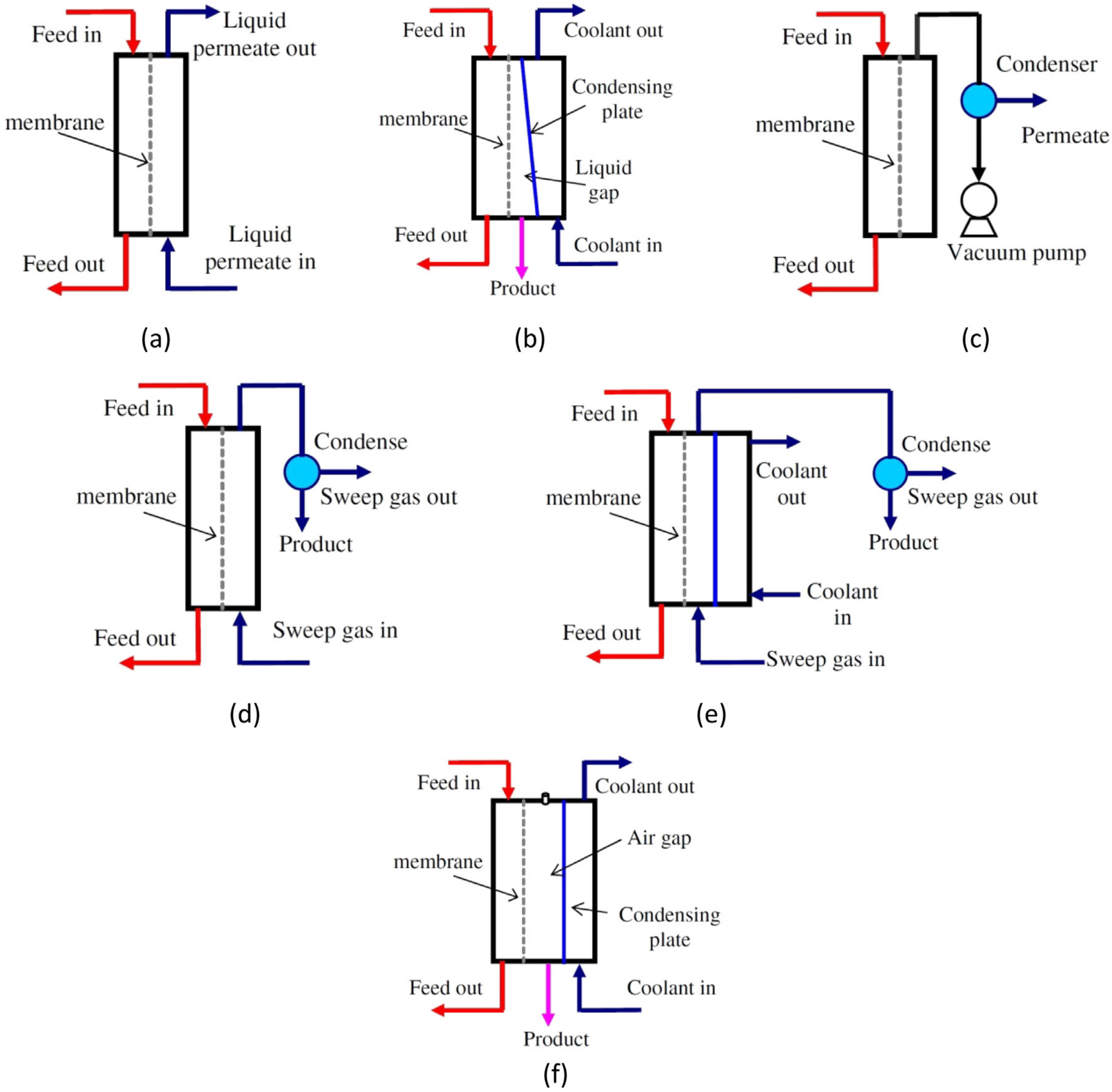

Fig. 1. MD process configurations: (a) direct contact MD (DCMD); (b) DCMD with liquid gap; (c) vacuum MD (VMD); (d) sweeping gas MD (SGMD); (e) thermostatic SGMD; (f) air gap MD (AGMD) [*].

depending on the effective air gap width. On the other hand, because permeate is condensed on a cold surface rather than directly on membrane surface, AGMD can be applied in fields where the direct contact membrane distillation (DCMD) is limited such as the removal of organic compounds from aqueous solutions [1,3,4].

Desalination is one of the potential applications of AGMD technology for production of high-purity water, especially from sea water [1,5–7]. The AGMD permeate fluxes are as high as the DCMD permeate fluxes. For both MD modes very high rejection factors ranging from 99 to 100% could be obtained but the AGMD production is higher than that of DCMD, using the same membrane [8]. Experiments on seawater desalination by AGMD were conducted by Kubota et al. [9] temperature drop and local water vapor permeate flux distribution have considered by Pingli Li et al. [46] using a porous Polytetrafluoroethylene (PTFE) membrane. The obtained AGMD permeate fluxes of the PTFE membrane were as high as a maximum flux of 10 kg·h. Temperature drop and local water vapor permeate flux distribution have been considered by Li et al. [46] which showed that the local flux drop and temperature drop of water vapor permeate were much larger at the upper part than those at the lower part of the membrane module in the hot feed side.

In AGMD process, the heat transfer occurs by two major mechanisms: (i) the latent heat transfer accompanying the transmembrane vapor flux, and (ii) heat transferred by conduction through the membrane matrix [17,30]. Consequently, there is rather complex relationship between both heat and mass transfer. This is related and involved with the presence of an unstirred boundary layer that adjoins the membrane surface at the feed side [11]. Temperature of the membrane surface is lower than the bulk phase. This creates temperature gradients in the liquid film adjoining the membrane surface [11]. In other words, this temperature gradient is due to the heat flux through the liquid layer, which is needed to provide the required heat for evaporation at the membrane interface [11]. This phenomenon is called temperature polarization [17,30–33].

The Persian Gulf is certainly one of the most vital bodies of water on the planet, as gas and oil from Middle Eastern countries flow through it, supplying much of the world's energy needs. A lot of waste heat is produced by the refineries and petrochemical industries located close to the Persian Gulf, which would be able to be applied for the enhanced process such as AGMD to produce distilled water from seawater. The wider application of the desalination process could be used by companies to produce distilled water for industrial processes.

In previous works, simultaneous heat and mass transfer models for DCMD [10] and vacuum membrane distillation (VMD) [11] systems have been developed and validated with experimental data.