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Air gap membrane distillation: Desalination, modeling and optimization

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A B S T R A C T

Response surface methodology has been applied for modeling and optimization of air gap membrane distillation process used in desalination. Regression models have been developed to predict the performance index and the specific performance index that takes into consideration the energy consumption as function of different variables. The developed models have been statistically validated by analysis of variance. The rejection factors were found to be greater than 99.9%. Two optimal operating conditions have been determined for each response. For the performance index the optimal solution was a cooling inlet temperature of 13.9 °C, a feed inlet temperature of 71 °C and a feed flow rate of 183 L/h. Under these conditions the experimental performance index, 47.189 kg/m^2.h, was found to be the greatest value among all performed experiments. For the specific performance index, the optimal solution was also 13.9 °C cooling inlet temperature, 59 °C feed inlet temperature and 205 L/h feed flow rate. When applying these last optimum conditions, the obtained experimental specific performance index, 188.7 kg/kWh, was also found to be the highest value. This corresponds to a specific energy consumption of 5.3 kWh/m^3. In all cases, the experimental results are in good agreement with the predicted ones by the developed models.

1. Introduction

Membrane Distillation (MD) is one of the emerging *non-isothermal* membrane separation processes known for about forty seven years but it is still need to be developed for its adequate industrial implementation [1]. It is a thermally driven transport of vapor through non-wetted porous hydrophobic membranes and the driving force is the vapor pressure difference between the two sides of the membrane pores. Simultaneous heat and mass transfer occur in this process and different *MD* configurations (direct contact membrane distillation, DCMD; sweeping gas membrane distillation, SGMD; vacuum membrane distillation, VMD; and air gap membrane distillation, AGMD can be used for various applications such as desalination.

In AGMD configuration, the membrane module contains a stagnant air gap interposed between the membrane and a condensation surface placed inside the membrane module. The temperature difference between the feed aqueous solution and the cold surface is the driving force for evaporation of water and volatile compounds at the hot liquid/vapor interfaces formed at the feed membrane surface. Mass transfer occurs according to the following four steps: (i) — Movement of the transferring species from the bulk liquid feed toward the membrane surface; (ii) — Evaporation at the liquid/vapor interface formed at the membrane pores; (iii) — Transport of the evaporated species through the membrane pores and diffusion through the stagnant gas gap; and (iv) — Condensation over the cold surface.

One of the advantages of the AGMD configuration is the low conductive heat loss through the membrane due to the presence of air in the permeate side of the membrane. However, this air space between the membrane and the condensing surface leads to an increased mass transfer resistance and reduces the permeate flux. It is to be mentioned that within the published papers up to December 2010 only 15.5% dealt with AGMD configuration [1]. However, AGMD is considered the most versatile configuration showing a great perspective for the MD future.

Alklaibi and Lior [2] carried out a comparative study of DCMD and AGMD processes showing that the process thermal efficiency of AGMD was higher than that of DCMD by about 6% due to the presence of the air gap. In addition, the permeate flux of DCMD was found to be higher than that of AGMD by about 2.3 fold and 4.8 fold for feed temperatures of 80 °C and 40 °C, respectively [2]. The same authors [3] carried out theoretical transport analysis of AGMD process by developing a two-dimensional model in which a simultaneous numerical solution of momentum, energy and diffusion equations of the feed and cold solutions were considered. It was concluded that the gap width between the membrane and the cooling surface had an important effect on the AGMD performance. By decreasing the gap width five fold, the permeate flux was enhanced 2.6 fold. Moreover, it was observed that the feed inlet temperature had also a major effect on the AGMD permeate flux and on the thermal efficiency, whereas the cooling temperature had less effects. The salt concentration of the feed solution and the feed circulation velocity had relatively small

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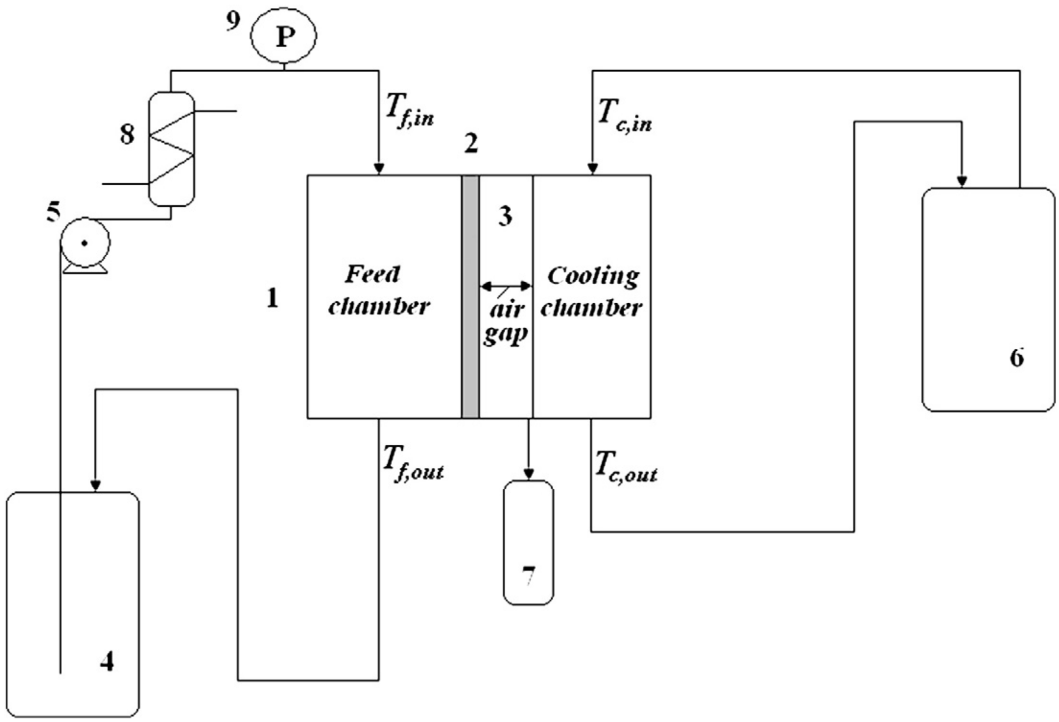

Fig. 1. Experimental AGMD set-up: 1 — AGMD module; 2 — flat-sheet membrane; 3 — condensation chamber; 4 — feed tank; 5 — circulation peristaltic pump; 6 — cooling tank; 7 — permeate tank; 8 — heat exchanger; 9 — pressure indicator (manometer).

effects on the permeate flux and on the thermal efficiency [3]. It was found that the thermal efficiency (η) was affected slightly by varying the feed flow rate because the AGMD permeate flux as well as the heat transferred by conduction through the membrane and the heat associated to mass transfer all increased with increasing the feed flow rate [3].

Guijt et al. [4] used a hollow fiber module for AGMD and found that the energy efficiency (typically 85–90%) approached the theoretical values (95–98%). It was also observed that a reduction of the air gap pressure down to a pressure equal to the water vapor pressure of the feed aqueous solution increased the AGMD permeate flux by a factor up to 2.5 to 3 compared to the obtained AGMD permeate flux at atmospheric pressure [4]. In this case the thermal efficiency was increased from 78% to 95%. This result was attributed to the decrease of the heat transfer loss by conduction through the membrane by reducing the air gap pressure.

It is noted that the reported AGMD experimental studies are carried out varying one of the independent parameters maintaining the others fixed [1]. Following this classical or conventional method of experimentation many experimental runs are necessary and interaction effects between operating parameters are ignored. For example, in AGMD studies the permeate temperature varies generally between 7 °C and 30 °C and a slight decrease of the permeate flux is observed with the increase of this temperature due to the decrease of the partial pressure gradient, which is the driving force [5]. Moreover, the rate of evaporation is strongly affected by the feed temperature and exponential trends between the AGMD permeate flux and the feed temperature are observed. By increasing the feed temperature from 40 °C to 80 °C, maintaining fixed all other AGMD operating parameters, the permeate flux can be enhanced nine fold [3,5,6].

Response surface methodology (RSM) that involves statistical design of experiments (DoE) in which all factors are varied simultaneously is a possible method permitting to study the interaction effects between parameters and to optimize the AGMD process. A quadratic RSM model was developed for desalination by AGMD modules using Fortran code in Aspen Plus® platform [7]. The considered response was the produced water per unit of feed liquid flow rate and auxiliary heat input, whereas the considered variables were only two, the feed temperature and the feed flow rate. Optimum separation efficiency (i.e. ratio of produced water to the feed) of 5.8% was predicted. Special attention should be devoted to optimize the different AGMD systems in order to study rigorously the interaction effects between parameters, increase the AGMD performance and decrease energy consumption.

The present study deals with the application of statistical experimental design and RSM in AGMD to investigate the mutual effects of factors on the AGMD performance taking into account energy consumption and to determine the optimal operating conditions of the experimental system used.

2. Experimental

The AGMD experimental set-up is presented schematically in Fig. 1. The feed salt solution is supplied from the feed tank (4) to the feed chamber of the plate-and-frame AGMD module Filtron Minisette™ (1) by a circulation pump (5) MasterFlex 7529-20. The retentate is turned back to the feed tank. A commercial porous hydrophobic membrane (2) (TF-450, Gelman Science) is employed in this study. This membrane is made of polytetrafluoroethylene (PTFE) supported by a polypropylene (PP) net. Its principal characteristics, as specified by the manufacturer, are 178 μm membrane thickness, 0.45 μm mean pore size, 80% fractional void volume and 137.8 kP liquid entry pressure of water.

A cooling agent is recycled from the cooling tank (6) to the cooling chamber of the membrane module. The evaporated water molecules at the liquid/membrane interface cross the membrane pores and the air gap chamber (3) to finally condense over the cooling stainless steel metallic plate. The thickness of the air gap is 5.6 mm. Pt-100 sensors connected to a digital multimeter FLUKE HYDRA are used to measure the temperature at the inlets and outlets of the membrane module for both the feed and cooling agent. In order to avoid membrane pore wetting, the pressure at the feed inlet membrane module was measured by a manometer. The energy consumption in each AGMD test was measured using the energy meter (Valleman) that