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Modeling and optimization of air gap membrane distillation system for desalination

Qingfeng He, Pingli Li *, Hongxin Geng, Chunyao Zhang, Juan Wang, Heying Chang

Tianjin Key Laboratory of Membrane Science and Desalination Technology, Tianjin University, Tianjin 300072, China
State Key Laboratory of Chemical Engineering, Tianjin 300072, China
School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, PR China

HIGHLIGHTS

- A regression model was established by RSM.
- The regression model was able to predict J and GOR accurately.
- Optimal operating parameters were determined by NSGA-II.
- The maximum value of J and GOR reached 5.07 L/m^2·h and 8.78 respectively.

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ABSTRACT

In this paper, the experiments of desalinating the NaCl aqueous solution were carried out using an air gap membrane distillation module with energy recovery. Response surface methodology (RSM) was applied to develop a regression model relating operating parameters with performance indicators of the AGMD system. Operating parameters including cold feed inlet temperature (T_1), hot feed inlet temperature (T_3) and feed-in flow rate (F) were considered and distillate flux (J) and gained output ratio (GOR) were selected as the performance indicators. The regression model developed by RSM was tested by analysis of variance (ANOVA). Based on the regression model, it was found that T_3 has the highest positive effect on both J and GOR, and there was a trade-off between J and GOR when T_1 and F varied. Non-dominated sorting genetic algorithm II (NSGA-II) was firstly used to maximized J and GOR simultaneously. Under the optimum condition, the maximum GOR and J could reach 8.78 and 5.07 L/m^2·h respectively.

1. Introduction

Membrane distillation (MD) is a thermally driven separation process in which only vapor molecules can transport through the membrane. The driving force for vapor molecules transfer is the vapor pressure difference between the two sides of the membrane. In MD process, microporous hydrophobic membrane was utilized to provide the vapor–liquid interface. Most of the membranes used in MD process were made from polypropylene (PP), polyvinylidene fluoride (PVDF) and polytetrafluoroethylene (PTFE) [1–3]. Comparing with conventional separating process, MD has the advantages of low operating temperature and pressure, insensitivity to salt concentration and the ability to use low-grade heat or waste heat [4,5]. Thus, its potential of desalination has been well recognized [6,7]. Based on the various modes that vapors condense in the cold side, MD process can be divided into direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), vacuum membrane distillation (VMD), and sweep gas membrane distillation (SGMD). Among these four configurations, DCMD is the most studied MD configuration due to its ease of handling. However, DCMD has the lowest energy efficiency because of the heat loss by conduction. In AGMD, a stagnant air gap is interposed between the membrane and a condensation surface, which increases the thermal energy efficiency of the process inherently.

The thermal efficiency of MD could be measured by “gained output ratio” (GOR), which is defined as the quotient of the amount of latent heat needed for the evaporation of the produced water and the amount of heat provided from external heat sources. GOR of a traditional MD process ranges from 0.2 to 0.9 [8–10]. However, when a MD system is equipped with an energy recovery device in which the latent heat of condensation is able to be reused to preheat the cold feed, GOR of this process could be improved significantly. Yao et al. [11] conducted

* Corresponding author at: Tianjin Key Laboratory of Membrane Science and Desalination Technology, Tianjin University, Tianjin 300072, China. Tel.: +86 22 27405902; fax: +86 22 27404347.
E-mail address: tdlpl@163.com (P. Li).

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experiments using a hollow fiber AGMD module within which a heat recovery unit was inserted. The highest GOR was 13.8 which was comparable to that of evaporation-based separation process such as multi-stage flash evaporation (MSF) and multi-effect distillation (MED) [12]. Our team has recently developed a hollow-fiber based AGMD module with an internal energy recovery unit which gained a distillate flux of 5.30 $kg/m^2 \cdot h$ and the GOR was 5.7 [13].

In most of the reported MD studies, conventional methods of experimentation were performed, in which one of the MD operating parameter varied while maintaining the others constant [14]. These conventional methods of experimentation involve many experimental runs, ignore interactions between the operating parameters of the process, and lead to low efficiency of optimization. The limitations of these conventional methods of experimentation can be avoided by applying statistical design of experiments. Statistical designs of experiments such as response surface methodology (RSM) and Taguchi experimental design have been reported to be used in the field of membrane distillation [15–17]. In reference [15], the Taguchi method was performed in SGMD to determine the effects and contribution of each of the operating parameters on the distillate flux and to reveal the interactions between the operating variables. On the other hand, RSM was applied to model and optimize the DCMD [16] and SGMD [17] system to determine the optimum operating parameters for the distillate flux.

In the case of hollow-fiber based AGMD module equipped with internal energy recovery unit, the distillate flux (J) and gained output ratio (GOR) are of the same importance. Therefore, they should be optimized simultaneously. However, these two objectives cannot be compared simply. Meanwhile, they cannot be combined into a single, meaningful scalar objective function. Therefore, it is a two-objective optimization problem to optimize the AGMD system. There is no single optimal solution, but rather a set of alternative solutions which are known as Pareto optimal set or Pareto front to the two-objective optimization problem. The Pareto optimal set is useful since it narrows down the choices and helps the decision-maker to select a desired operating point from the set rather than from a much larger number of possibilities. A multi-objective evolutionary algorithms, called non-dominated sorting genetic algorithm II (NSGA-II) can be used to obtain the Pareto optimal set [18]. NSGA-II is an effective multi-objective genetic algorithm based on fast elitist non-dominated sorting. It can search the feasible area in a parallel mode by population evolution, and can get a lot of Pareto solutions without bias in one run. As for genetic algorithm (GA), it is a non-traditional search and optimization method, which mimics the principles of genetic and Darwinian principle of natural selection. Cheng et al. [19,20] have applied GA to optimize hollow fiber DCMD module and AGMG module design for desalination. Based on the two objective functions, J and GOR, NSGA-II can be used to search through the space which is composed of the operating parameters of the experiments to determine the optimal combination of these operating parameters for the optimization of the newly designed AGMD module.

In the present study, RSM was used to model the desalination of sodium chloride (NaCl) aqueous solution based on our newly designed hollow-fiber based AGMD module. For this purpose, the RSM was used to fit mathematical equations between the system inputs including cold feed inlet temperature (T_1), hot feed inlet temperature (T_3) and feed-in flow rate (F) and the system outputs including distillate flux (J) and cold feed outlet temperature (T_2). Based on the regression models, the effects of these operating parameters on the performance (J and GOR) of the AGMD system were evaluated by three dimensional plots. To maximize the distillate flux and GOR simultaneously, NSGA-II was firstly used to search the Pareto optimal set to determine the optimum operating parameters for J and GOR.

2. Materials and experimental methods

2.1. AGMD module

The TIPS-iPP hollow fiber membranes were provided by Tianjin Chemical Separating Technologies Co. Ltd. The characteristics of the membrane were shown in Table 1. The tortuosity of membrane was calculated according to reference [21,22]. The dense-wall iPP fibers with an inner diameter of 0.4 mm and an outer diameter of 0.5 mm were also provided by Tianjin Chemical Separating Technologies Co. Ltd.

Experiments were carried out using a hollow-fiber based AGMD module which was able to reuse the condensation heat. The hollow fiber membrane module was designed and built in our lab and the parameters of the AGMD module were chosen based on our previous work [13]. Fig. 1 shows the schematic diagram of the hollow-fiber based AGMD module. In the AGMD module, 700 iPP hollow fiber membranes and 1400 dense-wall iPP hollow fibers were arranged in parallel in a rectangular housing which has a length of 0.8 m, a width of 0.12 m and a height of 0.08 m. Within the rectangular housing, the hollow fiber membranes and dense-wall hollow fibers were separated by a PP net which has a thickness of 5 mm to provide the air gap. At each end of the housing, the hollow fiber membranes and dense-wall hollow fibers were separated into two set and were potted into epoxy. The module has an effective membrane area of 0.8 m^2.

2.2. Setup of the AGMD system

The schematic diagram of the laboratory scale AGMD system for this study is shown in Fig. 2. The AGMD module was placed vertically during the operation after pressure-tested by pure water to assure no leakage of the module. The cold feed sodium chloride (NaCl) aqueous solution, with a concentration of 35 g/L, was prepared in the Thermostat A with a constant predetermined temperature between 0 and 50 °C (±0.1 °C). It was then pumped into the inlet of dense-wall iPP fibers at the bottom of the AGMD module by a magnetic centrifugal pump. Adjusting by a rotameter, the cold feed feed-in flow rate varied between 10 L/h and 100 L/h. After flowing out of the dense-wall iPP fibers at the top of the AGMD module, the feed flowed into the Thermostat B which heated the preheated feed to a higher temperature usually between 60 and 100 °C (±0.1 °C). Then the hot feed prepared in the Thermostat B was pumped into the inlet of hollow fiber membranes at the top of the AGMD module with an equal flow rate to the cold feed. The temperatures of the feed at four points (two inlets and two outlets) were measured with thermometers Pt100 with 0.1 °C sensitivity, and the pressure of the inlet feed was monitored by pressure gauges (0–0.1 MPa).

A good thermal insulation was used to prevent heat loss from AGMD system to the surrounding environment. After the whole system was running at steady state, the distillate water was collected and measured by a volumetric cylinder every 10 min. The conductivity of the permeate water was monitored by an electrical conductivity meter (DDSJ-308A, Shanghai Leici Instrument Factory, Shanghai, China). Each experiment was repeated at least three times under the same condition, and the results presented in this paper were the average values.

Table 1
Characteristics of the iPP hollow fiber membrane used in the present study.

Bubbling pressure (MPa)	Pore size (μm)	Tortuosity	Outer diameter (mm)	Inner diameter (mm)	Porosity (%)	Contact angle (°)
0.105	0.20	2.56[a]	0.83	0.51	68	112.7

[a] From reference [21,22].