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Enhanced air gap membrane desalination by novel finned tubular membrane modules

Li-Hua Cheng[a,b], Yu-Hung Lin[b], Junghui Chen[b,*]

[a] Department of Environmental Engineering, Zhejiang University, Hangzhou 310027, China
[b] R&D Center for Membrane Technology and Department of Chemical Engineering, Chung-Yuan Christian University, Chung-Li 32023, Taiwan, ROC

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ABSTRACT

To increase the permeate flux of air gap membrane distillation (AGMD) process, two novel tubular membrane modules: small and large, are designed and tested for desalination. The small module having a membrane surface area of 166 cm^2 is basically composed of a nonporous finned copper tube for cold flow and the grooves outside of the tube for both the air and the permeate. The modules with air gap thickness of 1, 2 and 2.3 mm, and grooves number of 4, 6 and 11 are compared for their permeate flux, respectively. The effects of operating conditions including the feed flow rate, feed temperature, cold temperature, and temperature difference between the hot feed and cold solution are investigated on the permeate flux. It is found that the permeate flux higher than 50 $kg\,m^{-2}\,h$ can be obtained in the proposed AGMD-based finned tubular membrane module with 11 grooves when the operating conditions are controlled at both hot feed and cold water flow rates of 5 L/min, hot and cold temperature of 353 K and 303 K, respectively. The flux is about 2–5 folds of the experimental results reported for AGMD modules in literature. The module under solar driven operation are further studied for the periodic variation of permeate flux, i.e., the desalination energy of which is supplied entirely by solar thermal collector. The large module composed of 10 finned tubes with a membrane surface area of 1661 cm^2 is finally tested for the scale-up effect at the lab.

1. Introduction

Membrane distillation (MD), in which only vapor molecules are transported through porous hydrophobic membranes, has advantages in its lower operating temperature and hydrostatic pressure, insensitivity to salt concentration, as well as in utilizing low-grade waste and/or alternative energy sources such as solar energy [1]. Air gap membrane distillation (AGMD), as one of the four basic configurations of MD, exhibits the highest thermal efficiency. AGMD has not only been applied for separation of non-volatile components from water like desalination as other MD configurations, but also been specifically suitable for separation of some volatile substances which can not be removed in direct contact membrane distillation (DCMD), e.g., alcohols from an aqueous solution. However, the air gap between membrane and condensation surface results in lower permeate flux of AGMD since its configuration presents a new resistance to heat and mass transfer.

In order to achieve a breakthrough in the performance of AGMD and thus appreciably reduce both the costs and the energy consumption of the MD system, theoretical modeling on the AGMD has been explored for the limiting factors affecting AGMD performance. Generally, it is admitted that the air/vapor gap has by far the strongest effect on the mass transfer resistance of the process domain. The effect of the air gap thickness, when using the flat membrane, is usually investigated in the region between 1 mm and 5 mm. Alklaibi and Lior found that decreasing air/vapor gap thickness from 5 mm to 1 mm increases the permeate flux by 2.6-fold, and the thermal efficiently was still 93% high for the air gap thickness of 1 mm [2]. It appears that narrower air gaps are favorable because they not only increase the permeate flux, but also make the system more compact. Patents in 1986 also deduced that an air gap thickness of 0.2–1.0 mm was needed in order to achieve both a high flow rate and a low loss of perceptible heat [3]. However, the air gap width should not be reduced without considering the gap bridging effect due to the limited space for the condensed water vapor [4]. For the reported plate and frame AGMD process, the increase of the inlet velocity or the decrease of the inlet temperature of cold solution has smaller effect on the flux when comparing with the effects of both hot solution conditions and the air gap thickness. For the AGMD-based hollow fiber module, our previous modeling work also shows that both productivity and thermal efficiency of the module can be maximized by adjusting the tube ratio of the hot feed fibers to cold fibers and thus changing the thickness of the air gap and the relative flow rate ratio of hot feed to cold solution [5].

* Corresponding author. Tel.: +886 3265 4107; fax: +886 3265 4199.
E-mail address: jason@wavenet.cycu.edu.tw (J. Chen).

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Experimental studies on the fabrication of highly permeable membranes and design of optimized membrane modules have been reported for the flux enhancement. For example, an electrospun polyvinylidene fluoride nanofiber membrane in AGMD was explored to produce potable water, and the membrane flux obtained of 11 kg m^{-2} h was found comparable to those obtained by commercial microfiltration membranes of 5–28 kg m^{-2} h at temperature differences ranging from 25 °C to 83 °C [6]; Liu et al. carried out experimental investigations on plate and frame AGMD modules of different aqueous solutions with the permeate flux of 5–25 kg m^{-2} h [7]. Hanemaaijer et al. proposed a module, which could be made up of essentially parallel non-porous fiber membranes for the feed stream and parallel porous fiber membranes for the retentate stream [8]. Guijt et al. performed an experiment with a cylindrical test module containing a single hollow fiber membrane in the center and a well-defined air gap situated around the fiber based on the Memstill concept tubular AGMD module [4]. All those work on AGMD has indicated a research tendency to evolve from the flat-sheet membrane in plate and frame modules to hollow fiber modules. Hollow fiber-based membrane devices for MD are likely to be of considerable utility because they are simple, potentially scalable, and they can pack a large membrane surface area per unit volume without any need of a supporting structure [9]. However, unlike DCMD [10–12], to our best knowledge, no hollow fiber or tubular module has been truly prepared and reported for AGMD in open literature except our pervious modeling work [5]. The fabrications of the dual layer hydrophobic hollow fibers, the hydrophobic PVDF hollow fiber with narrow size distribution and ultra-thin skin, and different hollow fiber modules designs with baffles, spacers and modified hollow fiber geometries have been reported for the flux enhancement in DCMD [13–15] but not for AGMD.

Based on theoretical modeling and experimental results, few demonstration projects with the integration of solar heat into desalination processes are developed using the AGMD configuration. It has been found that MD will be more competitive relative to reverse osmosis when low cost heat energy is available [1]. The so-called “compact systems” and ‘two loop system’ of the spiral-wound AGMD module have been developed for autonomous operation with a lack of electricity but with high solar irradiation [16,17]. In both those systems, the cold outlet stream is further heated and then flows as the inlet feed stream by a heat exchanger, resulting that the feed water passes the condenser channel in a counter-flow from its inlet of 20 °C to its outlet of 75 °C while the hot water passes the evaporator channel from its inlet of 80 °C to its outlet of 25 °C [18]. Although the heat recovery from the permeate to the feed is an effective way to improve the energy efficiency of the whole system [19], the low temperature difference across the membrane, about 5 °C resulting from the heat recovery occurred between the cooling of the hot feed stream and the warming up of the cold streams, makes the permeate flux no more than 10 kg m^{-2} h and thus the low thermal efficiency of the module. Our previous modeling work on the AGMD has shown that the permeate flux is a function of not only the absolute temperature of the membrane at the feed side, but also the transmembrane temperature difference at both sides [5]. If both of those temperature values can be maintained at their high levels by the module design, the performance of the module might be improved. Nevertheless, the availability of the industrial MD modules is up to now one of the limitations for MD process implementation, and the module for AGMD is not an exception.

Due to the fact that MD is a non-isothermal process, the design of the MD modules must not only provide good flow conditions, low pressure drop and high packing density but also guarantee a good heat recovery function and thermal stability. Among various module configurations, flat-sheet membrane in plate and frame modules shows the highest permeate flux, but the specific surface area of the membrane per module is the lowest. Hollow fiber module has the highest packing density, but the pressure drop along the fiber is the biggest because of the high ratio of fiber length to the fiber diameter. Moreover, an important aspect of the hollow fiber module is the deficiency in fluid flow along the side of effective mass transfer area, i.e., the randomness of fiber packing in shell side can lead to transmembrane flux reduction by up to 58% [1]. The spiral wound membrane module with heat recovery from the cold stream to the feed stream demonstrates a much lower temperature difference across the membrane, resulting also in lower permeate flux [16,17]. For the tubular module with moderate tube diameter and tube length, however, the criteria for the module design might be met for the flux enhancement as much as possible. In addition, the issue of energy cost is of secondary importance if free heat is available as pointed by Song et al. [20] Therefore, the design objective of novel finned tubular AGMD module integrated with solar heat is considered for the flux enhancement and its effect of scale-up in this laboratory.

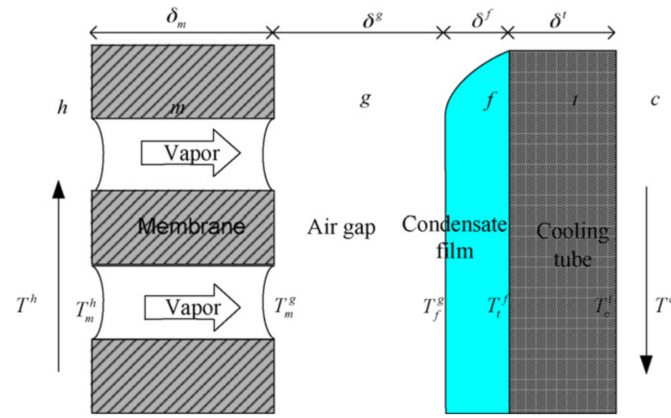

Fig. 1. Schematic representation of the AGMD process (domains of the AGMD process include the hot feed solution (*h*), the membrane (*m*), the air/vapor gap (*g*), the condensate film (*f*), the cooling tube (*t*), and the cold fluid (*c*)).

In this article, we are demonstrating finned tubular modules designed especially for flux enhancement in AGMD. The configuration of the finned tubular AGMD-based module and membrane material are introduced in Section 2. The experimental set-up for the AGMD-based desalination with the electric heat and solar heat as the energy is introduced in Section 3. In Section 4, the modules consisted of a single finned tube but with various air gap thickness and groove number are compared for their permeate flux; the effects of operating conditions including the feed flow rate, feed temperature, cold flow rate, cold temperature, and temperature difference between the hot feed and cold solution are investigated on the permeate flux. The two modules with both a single finned tube and 10 finned tubes are further studied by solar driven for the periodic variation of permeate flux, respectively. Finally, concluding remarks are made.

2. Configuration of the tubular AGMD module

In an AGMD process as shown in Fig. 1, the vapor from the feed of a higher temperature penetrates through the hydrophobic membrane and then the air gap, and condenses on the cooled surface. Since the permeate flux is a function of both the absolute temperature of the membrane at the feed side and the transmembrane temperature difference, in order to achieve a breakthrough in the performance of AGMD and thus appreciably reduce both the costs and the energy consumption of the system, the design of AGMD module must allow (1) thin air gap but smooth flow of the permeate ($\delta^g + \delta^f$), (2) high feed flow rate (υ^h) and feed temperature (T^h),