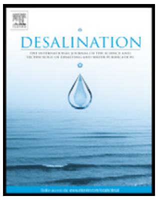
Desalination 396 (2016) 48–56

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal



Study on the performance of double-pipe air gap membrane distillation module

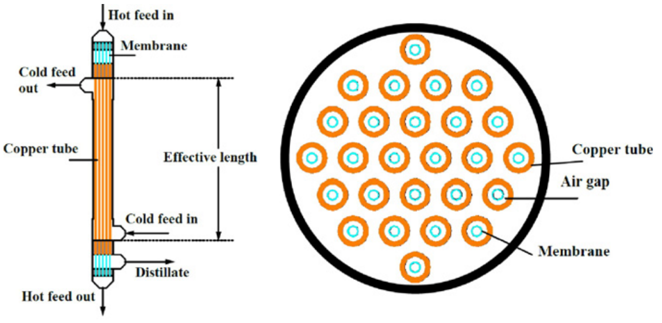
Zhiyu Liu [a,b,c], Qijun Gao [a,b,*], Xiaolong Lu [a,b,c,**], Lihua Zhao [a,b,c], Song Wu [a,b,c], Zhong Ma [a,b,c], Hao Zhang [a,b,c]

[a] *State Key Laboratory of Separation Membranes and Membrane Processes, Tianjin Polytechnic University, Tianjin 300387, PR China*
[b] *Institute of Biological and Chemical Engineering, Tianjin Polytechnic University, Tianjin 300387, PR China*
[c] *School of Material Science and Engineering, Tianjin Polytechnic University, Tianjin 300387, PR China*

HIGHLIGHTS

- A novel double-pipe air gap membrane distillation module was developed successfully.
- The air gap width of the module can be evenly distributed and easily regulated.
- The concept of equivalent membrane distillation flux (J_{AGMD}) was firstly introduced.
- The maximum value of J, GOR and J_{AGMD} could reach 11.4 kg/(m^2·h), 6.6 and 29.6 kg/(m^2·h), respectively.

GRAPHICAL ABSTRACT



(a) Configuration (b) Cross section

Configuration of DP-AGMD-M.

ARTICLE INFO

Article history:
Received 28 January 2016
Received in revised form 22 March 2016
Accepted 25 April 2016
Available online 14 June 2016

Keywords:
Air gap membrane distillation
Double-pipe module
Air gap width
Equivalent membrane distillation flux
PVDF hollow fiber membrane

ABSTRACT

Air gap width has an important influence on the performance of air gap membrane distillation (AGMD) process. In this study, a novel double-pipe AGMD module (DP-AGMD-M) consisted of PVDF hollow fiber membrane and heat exchange capillary copper tubes was successfully developed. The evenly distribute and easily control of the air gap width in DP-AGMD-M can be implemented. The effect of the air gap width (d_a), hot feed temperature (T_1), hot feed flow rate (Q), temperature difference (ΔT) between the hot feed outlet temperature and the cold feed inlet temperature, and the effective membrane module length (L) on the performance of DP-AGMD-M were experimental studied. The concept of the equivalent membrane distillation flux (J_{AGMD}) was firstly introduced in this paper and used to evaluate the comprehensive performance of DP-AGMD-M. The optimal performances, including membrane distillation flux (J), gained output ratio (GOR) and J_{AGMD} were obtained. Within the experimental range, the maximum J arrived at 11.4 kg/(m^2 · h), the maximum GOR reached 6.6 and the maximum J_{AGMD} was 29.6 kg/(m^2 · h).

1. Introduction

Membrane distillation (MD) technique is a kind of membrane separation technology combines with traditional distillation process. The driving force for mass transfer is the vapor pressure difference of volatile molecules across the hydrophobic micro-porous membrane [1]. Compared to other separation techniques, MD has some unique advantages:

---

[*] Correspondence to: Q. Gao, State Key Laboratory of Separation Membranes and Membrane Processes, Tianjin Polytechnic University, Tianjin 300387, PR China.

[**] Correspondence to: X. Lu, School of Material Science and Engineering, Tianjin Polytechnic University, Tianjin 300387, PR China.

E-mail addresses: gqj2005@aliyun.com (Q. Gao), luxiaolong@263.net (X. Lu).

http://dx.doi.org/10.1016/j.desal.2016.04.025
0011-9164/

higher rejection and concentrating multiple, and lower operating temperature. With these advantages, MD has great potential on the application for wastewater resource utilization, water conservation and emission reduction, especially in the field of deep concentration of industrial wastewater [2–6]. MD process has be divided into five basic configurations depending on the ways to collect or remove the transported vapor from the permeate side: (i) direct contact membrane distillation (DCMD), (ii) air gap membrane distillation (AGMD), (iii) vacuum membrane distillation (VMD), (iv) sweeping gas membrane distillation (SGMD) and (v) osmotic membrane distillation (OMD) [7–12].

However, the biggest barrier in the large-scale application of MD process is the high thermal energy consumption required for evaporation. The energy efficiency of an evaporation-based separation process (such as multiple effect distillation (MED) and MD) is commonly measured as “gained output ratio” (*GOR*). The *GOR* of typical thermal desalination techniques (such as MED) can reach more than 15.0 [13,14]. Unfortunately, the value of *GOR* for traditional MD process is just 0.2–1.0 [15,16]. Besides, MD needs to consume a large amount of cooling water to condense vapor into fresh water completely. The high consumption of energy and cooling water severely restricts the development and industrialization of MD technique. Therefore, it became the focus of research to find ways of recovering the vapor latent heat to improve the energy efficiency of MD process in recent years. Lu [17–19] referred the principle of vapor latent heat recovery of MED process and developed a new MD process, namely multiple effect membrane distillation (MEMD). MEMD possesses two mainly technical advantages of efficient separation (MD) and effective heat recovery (MED), and thus has been became a hot-spot of MD technology research.

In AGMD configuration, a thin stagnant air gap is interposed between the membrane and the cooling surface, which can weaken the heat loss by conduction [20,21]. Therefore, AGMD has higher thermal efficiency than other MD configurations [22]. Compared with flat-sheet membrane, hollow fiber membrane has higher specific surface area and packing density. The advantage has encouraged researchers to design several tubular AGMD modules by using parallel polypropylene (PP) hollow fiber membranes and PP hollow fiber heat exchange tubes [23–26]. And experiment results proved that these modules have exhibited excellent performance of heat recovery.

The efficiency of vapor latent heat recovered by cold flow in the heat exchange tubes plays a decisive role in AGMD module, which can both determine the total energy efficiency of whole AGMD process (i.e., *GOR*) and the vapor pressure difference across the membrane (i.e., mass transfer driving force). Obviously, AGMD is a synergic process composed of heat and mass transfer, and which is mainly controlled by heat transfer. However, the stagnant air gap increases the resistance to the heat transfer. Consequently, the reduction of the heat transfer resistance (i.e., air gap width) plays an important role in enhancing the heat transfer efficiency of AGMD process. But there exists the problem that the air gap width distributed unevenly and controlled difficultly in tubular AGMD modules. The cross-section of tubular AGMD module shown in Fig. 1a, it is obviously that the distance between porous membrane and dense wall tubes are uncertainly. On the one hand, larger air gap width leads to larger heat transfer resistance. On the other hand, condensed water vapor in limited space can easily form a water bridge [22,27] when air gap width is too small. Both can weaken the performance of AGMD process significantly.

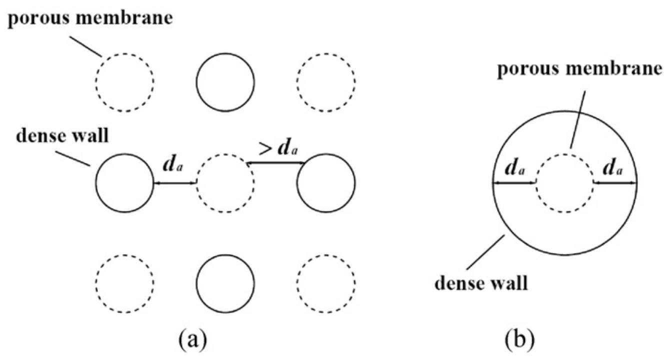


Fig. 1. Schematic diagram of the cross-section of (a) tubular and (b) double-pipe AGMD modules.

The purpose of this paper is to introduce a novel double-pipe AGMD module (DP-AGMD-M). The DP-AGMD-M consisted of hydrophobic polyvinylidene fluoride (PVDF) hollow fiber membranes and heat exchange capillary copper tubes. In this design, each membrane was inserted into the corresponding copper tube to constitute an independent AGMD unit. Then a certain number of the units were assembled to make up a DP-AGMD-M. And the gap between the outer surface of porous membrane and the inner surface of copper tube acted as the air gap. The air gap width can be evenly distributed and easily regulated in DP-AGMD-M, as shown in Fig. 1b. Thus the heat and mass transfer resistance in AGMD process can be controlled effectively. Meanwhile, another problem in AGMD process is that high membrane distillation flux (J) and high *GOR* cannot be obtained simultaneously, the true performance cannot be reflected by only J or *GOR*. So the equivalent membrane distillation flux (J_{AGMD}) was firstly introduced in this paper and used to evaluate the comprehensive performance of AGMD process. Tap water was used as feed solution in the experiments. The effect of various parameters on the performance of DP-AGMD-M were experimental investigated. The parameters including the air gap width (d_a), hot feed temperature (T_1), temperature difference (ΔT) between the hot feed outlet temperature and the cold feed inlet temperature, hot feed flow rate (Q) and the effective length of membrane module (L). J, *GOR* and J_{AGMD} were used to evaluate the performance of DP-AGMD-M.

2. Experimental

2.1. Membranes and modules

The hydrophobic PVDF porous hollow fiber membranes with an average pore size of 0.16 μm, porosity of 85% and contact angle of 78° were produced by our research group. The detail information of the membrane properties and preparation process have been described in the previous reports [12,28]. The inner and outer diameters of the membrane are 0.8 mm and 1.1 mm, respectively. The capillary copper tubes were provided by Shanghai Yongkun Refrigeration Equipment Co., Ltd., China. Table 1 shows the parameters of DP-AGMD-Ms. The configuration of the module is shown in Fig. 2. Tap water had an electrical conductivity of 530 μS/cm.

2.2. Experimental apparatus

The schematic diagram of the AGMD experimental apparatus is depicted in Fig. 3. And Fig. 4 shows the mass and heat transfer process in DP-AGMD-M unit.

The whole feed circulatory system was wrapped with thermal insulation cotton, in order to reduce heat loss to surrounding. The feed was heated to a constant temperature T_1 in the thermostat, then pumped into the inlet of hollow fiber membranes at the top of the module. The flow rate Q was adjusted by the rotameter 1. After the vapor evaporated from the feed and diffused across the porous membrane wall, the temperature of the hot feed dropped to T_2. Then the feed leaving the module and flowed into an external condenser, and thus its temperature dropped to T_3. And then the feed was allowed to flow into the shell side of the copper tubes at the bottom of the module as cold feed. The cold feed flowed counter-currently with the hot feed in the module, as shown in Fig. 4. The cold feed recovered the vapor heat and gradually warmed up to T_4. At the same time, the vapor was condensed into distillate water. Finally, the feed with T_4 flowed back into the thermostat.