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Study on air-bubbling strengthened membrane distillation process

Wu Chunrui, Jia Yue, Chen Huayan, Wang Xuan, Gao Qijun, Lu Xiaolong*

State Key Laboratory of Hollow Fiber Membrane Materials and Processes, Institute of Biological and Chemical Engineering, Tianjin Polytechnic University, Tianjin 300160, P.R. China
Tel./Fax: +86-22-24528201; email: wuchunrui79@yahoo.com.cn

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ABSTRACT

In this work, a novel air-bubbling vacuum membrane distillation (AVMD) process was constructed on the basis of traditional vacuum membrane distillation (VMD) process. Compressed air was pressed into the lumen side of the hollow fiber membranes together with the hot feed solution just at the inlet of membrane module. So gas/liquid two-phase flow was formed in membrane lumen. Hydrophobic polyvinylidene fluoride (PVDF) hollow fiber microporous membranes were employed in this work. The effects of operating conditions, such as the feed air flow rate, the feed temperature and concentration on the performance of AVMD process were studied. The surface morphology of the PVDF membranes used in the VMD and AVMD process was characterized by scanning electronic micrograph (SEM). The results showed that the permeate flux increased as the air flow rate and/or feed temperature enhanced. The permeate flux of VMD process was 22 kg/m^{2}h when tested at 75°C with a feed flow rate of 120 l/h and a vacuum pressure of 0.085 MPa. While, the flux of AVMD process reach 40 kg/m^{2}h with the aid of a gas flow rate of 60 l/h. The flux of the two processes both declined gradually as the feed concentration increased from 3.5 g/l to 300 g/l, but that of AVMD was much slower. The conductivity of the product water was kept lower than 3 μS/cm. SEM paragraphs showed that there's much more salt deposition on the surface of the membrane used in VMD process than that used in AVMD process.

Keywords: Air-bubbling vacuum membrane distillation (AVMD); Polyvinylidene fluoride (PVDF) hydrophobic membrane; Two phase flow; Desalination

1. Introduction

Membrane distillation (MD) is the combination of membrane technique and traditional distillation process. MD is a promising technology for desalination [1]. In MD, only vapor molecules could pass through the porous hydrophobic membranes. It has advantages including lower operating temperature and pressure, high rejection for non-volatiles, high water production rate, possibility for the treatment of solutions with high concentration, and so on. While the disadvantages, such as the relatively low permeate flux and the flux decay due to the concentration and temperature polarization during MD process, are main barriers preventing it from real application [2,3].

Many researchers devoted to develop variable method to improve MD flux, decrease polarization and fouling. Phattaranawik [4] and Martinez [5] placed spacers in membrane module and got enhanced flux and reduced polarization effect during MD experiment. Toeh twisted the membranes into wavy shape, and specially designed membranes membrane modules with baffles and spacers [6]. Li designed rectangular cross flow modules for MD purpose [7]. These special designs on membrane modules improved the flowing turbulence and surface shear, so higher fluxes were obtained.

*Corresponding author.

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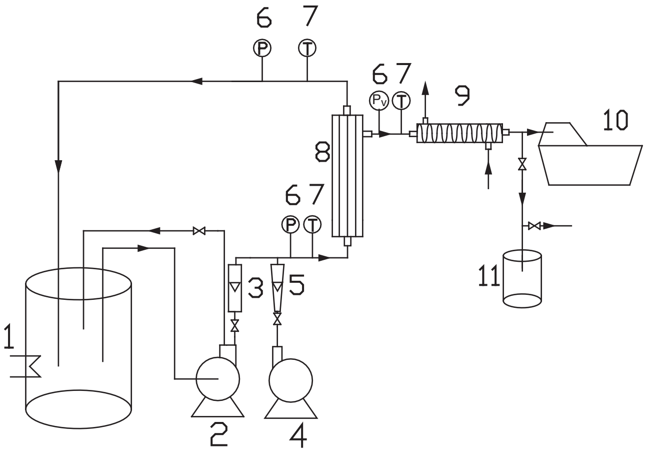
Flowing turbulence and surface shear could also be enhanced by two-phase flow, which could be obtained by introducing air bubbles into the feed solution. The introduction of gas/liquid two-phase flow by air bubbling has been testified significantly enhanced the membrane performance in microfiltration and ultrafiltration [8,9]. Two-phase flow has also been introduced into pervaporation to reduce the polarization effect [10]. As a relatively easy method comparing to module design and membrane twisting, two-phase flow by air bubbling may be a variable method for the polarization reduction and flux enhancement in MD process.

In this work, a novel air-bubbling vacuum membrane distillation (AVMD) process was constructed on the basis of traditional vacuum membrane distillation (VMD) process. The effects of operating conditions, including the feed air flow rate, the temperature and concentration of the feed solution on the performance of AVMD process were studied. The SEM photo was used to characterize the surface morphology of membranes used in VMD and AVMD processes.



1. water bath; 2. pump; 3. liquid flowmeter; 4. gas pump; 5. gas flowmeter; 6. manometer; 7. thermometer; 8. hollow fiber membrane module; 9. condenser; 10. vacuum pump; 11. product collection

Fig. 1. Flow chart of AVMD process.

2. Experimental

Polyvinylidene fluoride (PVDF) hydrophobic hollow fiber membrane with a porosity of about 80%, pore size of 0.16 μm, inner diameter of 0.8 mm and membrane thickness of about 0.15 mm was prepared in our lab and used for VMD experiment. The hydrophobic hollow fiber membranes were fixed in a shell-and-tube membrane module, using a plastic cylinder with an inner diameter of 28 mm and length of 23 mm as the shell. The effective membrane area in each module is 0.025 m^2.

The flow chart of AVMD experiment is shown in Fig.1. Feed solution temperature was maintained constant with a heating bath. 1.0 g/l NaCl aqueous solution was used as the feed, which was circulated through the lumen side of the hollow fiber membranes, with a circulation pump. Compressed air was introduced into the feed before the inlet of the module. The feed velocity of the hot solution and air was controlled and measured with flowmeter, separately. Vacuum pump with pressure controller was connected to the shell side of the module to remove the permeate vapor.

Electrical conductivity meter (DDS-11A, Shanghai Leici Instrument Works, China) was used to measure the electrical conductivity of the feed and product solutions. Electrical balance with a sensitivity of ±0.1 g was used to measure the weight of the product water of the system. Scanning Electron Microscopy (SEM, JSM-5600LV, JEOL Co., Japan) was used for the analysis of the surface morphologies of the membranes.

Each experiment continued 40 min. The product water was weighed and the permeate flux (N) was calculated as:

$$N = W / (S \cdot t) \quad (1)$$

where W (kg) is the weight of product water during the operating time of t (h) and S (m^2) the membrane area based on the fiber inside diameter.

The turbulence of the feed two-phase flow could partly be described by the Reynolds number, Re, which could be calculated as:

$$Re = \frac{U_m D}{V_1} = \frac{(qV_Q + qV_L)D}{AV_1} \quad (2)$$

where U_m is the average velocity of the two-phase flow, m/s; qV_Q and qV_L are the feed flow rate of the liquid and gas, l/h; A, the cross section area of the flowing channel, m^2; V_1, the viscosity of the liquid phase, Pa·s; D, the equivalent diameter, m.

3. Results and discussion

3.1. Effect of gas flow rate

Firstly, the effect of feed gas flow rate on MD flux was studied. The experiments were carried out with feed temperature of 70°C, feed liquid flow rate of 120 l/h, and 0.085 MPa vacuum degree on the cool side. The results were shown in Fig. 2.

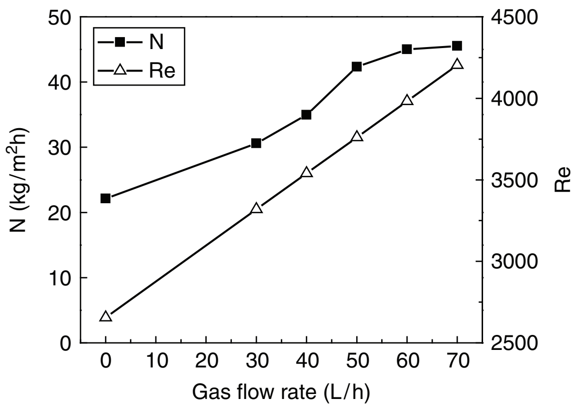


Fig. 2. Effect of feed gas flow prate on the performance of AVMD process.

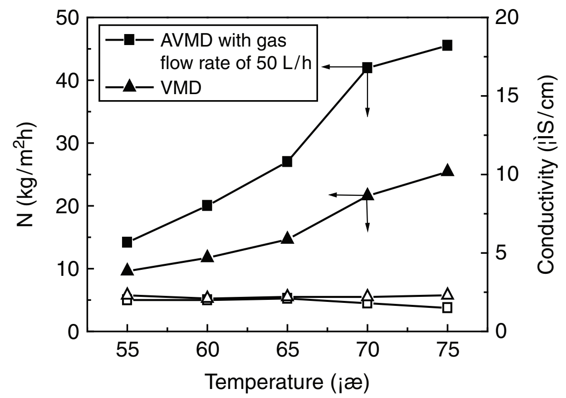


Fig. 3. Effect of feed temperature on the performance of VMD and AVMD processes.

From the figure, one can see that, the permeate flux of MD process enhanced obviously with the feed gas flow rate increased. When there's no air pressed in the system, a traditional VMD process, the permeate flux was about 22 kg/m^{2}h. As air being pressed into the feed solution, the flux increased and exceeded 40 kg/m^{2}h, when the gas flow rate reached 60 l/h.

As air being pressed into the feed liquid solution, gas-liquid two phase flow formed. The flowing turbulence of the feed solution increased as gas flow rate (gas/liquid proportion) enhanced. This could be partly testified by the increasing trend of *Re* (also shown in Fig. 2). The shearing force on solution/membrane interface increased. The flowing boundary layer, the temperature and concentration polarization phenomenon weakened by the disturbance of two-phase flow.

3.2. Effect of feed temperature

The effect of feed temperature on the AVMD was studied, comparing to that on traditional VMD process. The experiments were carried out with feed liquid flow rate of 120 l/h, and 0.085 MPa vacuum degree on the cool side. The results were shown in Fig. 3.

Fig. 3 shows the permeate flux increased as the feed temperature enhanced, in both of VMD and AVMD processes. The conductivity of the product water was kept lower than 3 μS/cm. As the feed temperature increased, the vapor pressure on the hot side of MD process enhanced, and the mass transfer driving force of MD process increased, so an increased flux was observed [2].

From the figure, we can also find that the difference between the two fluxes was also enhanced with feed temperature. At higher temperature, the concentration polarization is much severe, owing to the relatively higher MD flux [3]. Bubbling and gas/liquid two-phase flow facilitated the mixture of the feed bulk flow, and so restrained the polarization on solution/membrane interface. Much severe the polarization phenomenon is, much obvious the effect of bubbling and two-phase flow. This could partly explain the increasing difference between AVMD and VMD processes.

3.3. Effect of feed concentration

The effect of the concentration of feed NaCl aqueous solution on the performance of the two processes was studied, and the results were shown in Fig. 4.

Fig. 4 shows that, the permeate fluxes of the both processes declined as the feed NaCl concentration increased. The flux declination of AVMD process was much slow than that of VMD process. The flux of VMD decreased 56% (from 34 kg/m^{2}h to 15 kg/m^{2}h), as the concentration of feed NaCl solution increased from 3.5 g/l to 300 g/l. While the flux of AVMD process only declined 17% (from 42 kg/m^{2}h to 35 kg/m^{2}h) at the same time. The

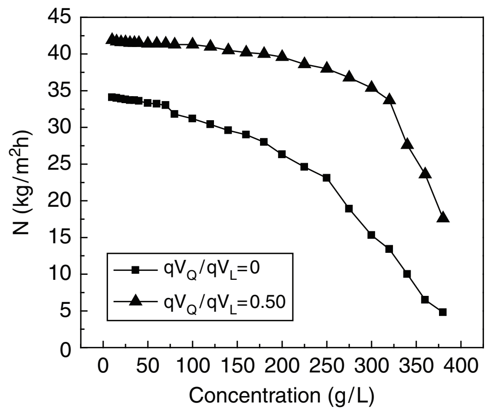


Fig. 4. Effect of feed NaCl concentration on the performance of AVMD process.

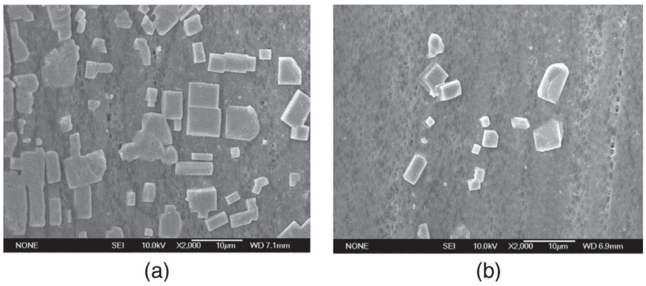


Fig. 5. SEM photograph of membranes used in VMD (a) and AVMD (b) process.

difference between the two fluxes also increased as the feed concentration enhanced. It increased from 8 kg/m^{2}h to 20 kg/m^{2}h as the feed concentration increased from 3.5 g/l to 300 g/l. The effect of bubbling and gas/liquid two-phase flow is much obvious when the concentration of feed solution is higher.

Fig. 5 gives the SEM photographs of the inner face of membranes used in VMD and AVMD processes, using 300 g/L NaCl aqueous solution as the feed. From the pictures we can see that only few NaCl crystals deposited on the membrane sample used in AVMD process. While, as for the membrane used in VMD process, much more deposition was observed on the membrane sample. The comparison of the two pictures further testified that the gas/liquid two-phase flow obtained by bubbling method can restrain concentration polarization and membrane fouling in MD process.

4. Conclusion

On the basis of traditional VMD process, a novel process, AVMD was constructed. The new process uses air bubble and gas/liquid two-phase flow method to strengthen the mass and heat transfer in the hot solution, and restrain polarization and membrane fouling. The effects of operating conditions on the performance of AVMD process were studied. The morphology of the membrane inner surface was characterized by SEM. The results showed that the flux of AVMD process increased obviously as the air flow rate, feed solution temperature increased, but declined as the feed concentration enhanced. The effect of bubbling and two-phase flow is much obvious when the feed temperature or the feed concentration is higher.

Acknowledgement

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