Experimental study on vacuum membrane distillation based on brine desalination by PVDF

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Abstract Based on polyvinylidene fluoride (PVDF) hollow fiber hydrophobic porous membrane, vacuum membrane distillation desalination test bench was built to study the effects of operating parameters such as temperature of feed solution, flow rate of feed solution, concentration of feed solution and vacuum degree on the performance of vacuum membrane distillation process. Experimental results showed that with an increase in the vacuum degree and temperature of the flux of membrane is increased. While with an increase in the concentration of feed solution of the flux of membrane is decreased and retention rate were essentially the same, with an increase in the flow rate of feed solution of he flux of membrane changed slowly (increase slightly). When temperature of the feed solution was 88℃, the flow rate of feed solution was 270cm/min, the vacuum degree was 0.081MPa, the concentration of feed solution was 5%, the flux of membrane was 14.1kg/ (m².h), the retention rate was 99.8%, the electrical conductivity of fresh water was maintained at 12us/cm.

1. Introduction
Membrane distillation (MD), which is a hybrid between thermal desalination and microporous hydrophobic membrane, generally the aqueous solution of non-volatile substances was distilled. When the aqueous solution in different temperature is separated by a hydrophobic microporous polymer membrane, aqueous solution of both sides can't permeate the membrane pores due to the surface tension, while water vapor at high temperature permeates membrane pores into the low temperature side under water vapor pressure difference on both sides of membrane and then is condensed to realize the separation process. Evaporation, mass transfer, condensation process in the process are very similar with conventional distillation, so it is called membrane distillation[1].Comparing with the method of thermal desalination, feed solution is not need to be heated to boiling point in the MD process, it is driven by vapor pressure difference on both sides. Membrane distillation is almost conducted under atmospheric pressure, simple equipment needed, operated easily, without high pressure compared with reverse osmosis desalination device, in the region of weak technical force also has the possibility of implementation.

MD basically has the following four forms: direct contact membrane distillation (DCMD), vacuum membrane distillation (VMD), sweeping gas membrane distillation (SGMD), air gap membrane distillation (AGMD) [2].The study found that one side of the membrane which was called hot side contact with the feed solution directly in vacuum membrane distillation, pressure of the other side is lower than the hot side, water vapor is pumped out from membrane module to condense. The higher vapor pressure difference on both sides of the membrane, the greater flux.
Despite membrane distillation has many advantages, however its industrialization is effected by low thermal efficiency and low flux [3-6], what's more the application of membrane distillation on large-scale desalination of sea water is scarce, in order to develop the potential of the desalination process, reduce the cost of desalination, alleviate the water crisis, it is necessary to carry out research work about low-cost seawater desalination technology. In this paper polyvinylidene fluoride PVDF hollow fiber hydrophobic porous membrane was used, focuses on water desalination via VMD. The effects of vacuum, temperature of feed solution, flow rate of feed solution and the concentration of feed solution on the membrane distillation process were studied.

2. Experiment

2.1. Experiment system
Hollow fiber vacuum membrane distillation assembly used in the present study came from Tianjin MOTIMO Membrane Technology CO., LTD. The membrane module shell was made of organic glass, the size was , the inside diameter of membrane was 0.5mm, thickness 0.25mm, average pore size was 0.18, the porosity was 86%, the effective area was 0.8m².

Vacuum membrane distillation experiment system diagram as shown in Figure 1, which was mainly composed of hot side, vacuum side and hollow fiber membrane, thermostatic hot water bath, magnetic pump, rotometer flow meter, thermometer, pressure gauge and control valve were included on hot side, the vacuum side includes water ring vacuum pump, freshwater collection tank, electronic balance.

NaCl solution was heated to the predetermined temperature, then was pumped into the hollow fiber membrane module using magnetic circulating pump after the flow was adjusted by rotameter, Due to the vapor pressure difference on both sides, water vapor on the hot side through the hydrophobic porous membrane into the vacuum side, then water vapor was pumped outside from membrane module by vacuum pump to be condensed by the condenser.

2.2. Calculation parameters
The weight of collected fresh water was measured continuously to calculate the VMD flux,

\[ J = \frac{Q}{St} \]  

where \( J \) is the VMD flux, kg/(m²·h), \( Q \) is the weight of vapor across the membrane, kg; \( S \) is the effective membrane area, m², and \( t \) is the experimental running time, h.

\( \eta \) describes the salt rejection for the permeation selectivity of aqueous NaCl solution.
\[ \eta = \left(1 - \frac{C_p}{C_F}\right) \times 100\% \quad (2) \]

where, \( \eta \) is the salt retention rate \(^\text{%}\), \( C_F \) is the concentration of feed solution %, \( C_p \) is the concentration of permeation solution %.  

3. Results and discussion

3.1. Effect of feed temperature

The concentration of feed solution was set to 0, 6%, 10%, 13%, vacuum degree was 0.080MPa, the flow rate of feed solution was 250cm/min, and the influence of feed temperature on the flux was investigated. The results were shown in Figure 2. The concentration of feed solution was 10%, inlet flow rate was 250cm/min, the vacuum degree was 0.054MPa, 0.063MPa, 0.072 MPa, 0.084MPa, the influence of feed temperature on the flux was investigated, as shown in Figure 3. The concentration of feed solution was 10%, vacuum degree was 0.080MPa, the flow rate of feed solution was 200 cm/min, 250 cm/min, 270 cm/min, the influence of the temperature on the flux was investigated, as shown in Figure 4.

\[ \text{Figure 2. Effect of feed fluid temperature on flux flux(different feed fluid concentration)} \]

\[ \text{Figure 3. Effect of feed fluid temperature on flux(different vacuum)} \]

\[ \text{Figure 4. Effect of feed fluid temperature on flux(different flow)} \]

Figure 2 showed that the flux increased with the increasing of temperature, and decreased with the increasing of concentration of feed solution. Figure 3 showed that the flux increased with the increasing of vacuum, increased with the increasing of temperature of feed solution.

No matter what kind of operating conditions, the flux increased with the increasing of feed temperature, this is mainly because the saturated pressure of water would increase along with the temperature rises, the driving force was water vapor pressure difference on both sides in the process of vacuum membrane distillation, increasing steam partial pressure on the feed side or increasing the
vacuum degree of the permeate side (VMD) both make the vapor pressure difference of both sides increased and increase the driving force, eventually make the flux of membrane also increased.

3.2. Effect of vacuum degree

It can be predicted from Figure 3, the flux would increase with the increasing of vacuum degree. The concentration of feed solution was 10%, inlet velocity was 250 cm/min, the feed temperature was 68 °C, 73 °C, 80 °C, 88 °C. The influence of the vacuum on the flux was investigated, the results were shown in Figure 5. The concentration of feed solution was 10%, the temperature was 80 °C, the flow rate of feed solution was 200 cm/min, 220 cm/min, 250 cm/min, 270 cm/min, the influence of the vacuum on the flux was investigated, the results were shown in Figure 6.

The influence of vacuum and feed temperature on flux were the same, the efficiency of the membrane distillation process could be improved by increasing the vapor pressure difference on both sides of the membrane. In the process of industrial applications, increasing the feed temperature made experimental equipment simpler, the cost lower compared with increasing vacuum, without additional vacuum equipment, feed solution was preheated by condensed steam at the same time. The system could recover the latent heat of vaporization and reduce the heat input.

3.3. Effect of feed solution flow rate

Figure 7 showed that the flux variation with flow rate of feed solution, when the feed temperature was 80°C, the feed solution concentration was 10%, the vacuum degree was 0.054 MPa, 0.063 MPa, 0.072 MPa, 0.084 MPa. Figure 8 showed that the flux variation with flow rate of feed solution, when vacuum degree was 0.080 MPa, the temperature was 68 °C, 73 °C, 80 °C, 88 °C. From the two figures above it could be seen the flux increased with the increase of flow rate in any condition, but the curve relatively flat, namely the influence of flow rate of feed solution on flux was very small, increasing feed solution flow rate led to boundary layer disturbance enhanced, also enhanced heat and mass transfer. Once a stable flow pattern was formed, the influence of velocity was negligible, considering the mechanical properties of the membrane module, the flow rate of the material liquid couldn’t be increased unlimited.
Figure 7. Effect of feed fluid flow on flux (different vacuum)

Figure 8. Effect of feed fluid flow on flux (different feed fluid temperature)

3.4. Effect of feed solution concentration

The temperature of the feed solution was 80 °C, the vacuum degree was 0.080MPa, the feed rate was 250cm/min, the influence of the concentration of feed solution on the retention rate was studied. Results were shown in Figure 9 and Figure 10. With the increasing of concentration of feed solution, retention rate decreased, because the greater the feed concentration, the smaller the water vapor partial pressure of the hot side, this made vapor pressure difference decreased and reduced driving force. With the concentration of the feed solution increasing, the curve decreased rapidly, it can be explained that concentration polarization will appear in the membrane separation interface when the concentration of the feed solution up to a certain value. Effect of the concentration of feed solution on retention rate was very small, but if membrane was contaminated large fluctuation of the curve would appear.
Figure 9. Effect of feed fluid concentration on flux and concentration rate

Figure 10. Effect of feed concentration on flux and concentration rate

4. Conclusion
In this paper PVDF hollow fiber hydrophobic porous membrane was used to carry out experimental research on the process of vacuum membrane distillation, focused on the effect of temperature of feed solution, flow rate of feed solution, vacuum degree and centration of feed solution on the flux and concentration rate of VMD process. The results showed that the efficiency of the VMD process can be increased by increasing the temperature of the feed solution, the vacuum degree, flow rate of feed solution appropriately, all of its essence were to enhance the driving force of membrane distillation by increasing vapor pressure difference across the membrane. Which method was used to improve the MD process should be considered comprehensively such as characteristics of feed solution, the material of the membrane module and so on. It was found that the maximum flux reached 14.1 kg/(m².h) in this system, which was larger than reverse osmosis with the same scale, so the membrane distillation has a very broad prospect for the desalination of sea water.

5. References
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