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Experimental Study on a Multi-stage Air Gap Membrane Distillation (AGMD) Unit

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Graphical abstract

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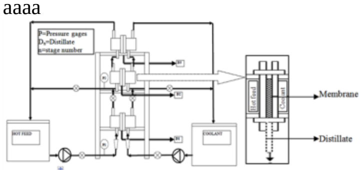

Abstract

Membrane distillation (MD) is a separation process that involves vapour transport through a hydrophobic membrane. The evaporation is caused by the partial pressure difference between a hot fluid and cold fluid/surface. In this study, an air gap MD (AGMD) process is utilized to produce freshwater from saline solution. A multi-stage AGMD unit with 0.45 μm pore size Polyvinylidene Fluoride (PVDF) membranes is built and experiments have been carried out with different operating variables including feed temperature, coolant temperature, air gap width and feed inlet concentration.A maximum of 12.9 kg/m^2 of distillate flux was obtained per kWh energy input from the multi-stage MD unit while for a previously built single-stage MD unit, the highest water/power ratio obtained was only 2.3 kg /m^2 kWh. This variation indicates that multistaging is necessary for efficeint energy use in MD system.

Keywords: Air gap membrane distillation (AGMD); hydrophobic membrane; PVDF membrane; multi-stage membrane distillation; energy efficiency; water/power ratio

■1.0 INTRODUCTION

Membrane Distillation (MD) is an emerging technology for water purification because of its low energy and simple infrastructure requirement. Unlike reverse osmosis (RO), it does not need high pressure and the process can produce distillate at a temperature even as low as 45ºC at ambient pressure and temperature.

The driving force for MD is the partial vapour pressure difference between two dissimilar temperature fluids. In this method, vapour is generated from the higher temperature fluid and is allowed to pass through a hydrophobic membrane. Later, the vapour is condensed and collected. Based on the method of collecting and condensing the vapor, MD process is classified into 2 major types: i) direct contact MD (DCMD) where the generated vapor condenses directly in the cooler fluid stream ii)air gap MD (AGMD), where the vapor travels through an air gap and condenses on a coolant plate.The other available MD processes are sweep gas MD (SGMD) and vacuum MD (VMD). In sweep gas MD, the produced vapor is carried out by a gas stream to condense outside while in VMD, the evaporation occurs in lower pressure than the atmosphere. Among these categories, AGMD has the advantage of reducing the heat loss occured in DCMD between the two dissimilar temperature streams by providing a thin air gap between them.The main drawback of the air gap is that it offers additional resistance to mass transfer. However, with maintaining a very narrow air gap, this deficiency can be overcome to a certain extent. Besides, AGMD process provides the freedom of using any coolant as the coolant does not come in contact with the condensate. Dealing with membrane leakage therefore has some flexibility, as in case of membrane damage, the process can be shut down for a while. Whereas in case of a DCMD process, for such a situation, all the distillate would be contaminated at once.

In this study, a multi-stage AGMD set up has been built and experiments have been conducted with different operating variables. The multi-staging is supposed to maximize utilization of the available energy and also increase the total production from the AGMD test rig. Multi-staging of MD has been proposed since the beginning of this process in the late 60's [1] and continued alongwith the development of the process over the 4 decades [2,3]. However, the trend of production from each stage was not reported properly. Also, effect of multi-staging on the total energy consumption or the limit for the numbers of stages were among the issues that have not been addressed yet. This work includes investigation on the production rate individually from each stage and also on improvement in energy utilization by implementing multi-staging. Operating variables like feed /coolant temperature, air gap width and feed inlet concentration were varied to observe the effect of multi-staging. The results were compared with results from single stage experiments to observe the enhancement in production and energy utilization.

2.0 EXPERIMENTAL

A multi stage AGMD rig was built with Polyvinylidene Fluoride (PVDF) 0.45 µm pore size flat sheet membrane from Millipore Singapore. Further properties of the membrane are tabulated in Table 1.

The hot and the coolant fluid temperatures were maintained and circulated by re-circulators. The hot re-circulator supplied the feed through a reinforced PVC pipe to the MD module feed chambers where the membrane was placed. On the way to the first chamber, the feed flow rate was measured and controlled by a variable area flowmeter and a globe valve. After the feed came in contact with membrane, it evaporated at the membrane-liquid interface and the vapour passed through the membrane pores. On the other side, the coolant supply was maintained with the help of the cold re-circulator bath using the same orientation as the hot side. The generated vapour travelled through the air gap and condensed on the coolant plate. In between the two chambers, the air gap was maintained by a flange with a slot cut at the bottom. Through that slot, the condensed distillate came out and was collected inside a graduated tube. The tube was connected with the slot by flexible piping. The air gap was varied using flanges with different thicknesses. The feed and the coolant were led back to the re-circulators where the same supply temperatures were maintained according to the set value. There were 3 stages for this set up and between the first and second stages, there was provision for by-passing the flow to the re-circulator to run the setup in single stage mode when necessary. The fluid entered the bottom module first on both sides and then passed through the next modules before it was returned back to the re-circulator baths again. The distillate was collected separately to ensure the specific product quality from each stage. Pressure gages and thermocouples were inserted in different points of the 3 modules. Figure 1 shows the schematic of the existing multistageAG MD setup while Table 2 summarizes the operating variables.

For the experimental measurement of the mass flux,

$$\dot{M}_{exp} = \frac{\text{distillate collected(kg)}}{\text{membrane area(m}^2) \times \text{time(s)}}$$

3.0 RESULTS AND DISCUSSION

Instead of letting the hot feed escape from the MD module with the remaining energy, it was designed to be circulated through multiple stages before the exit temperature lowers to a certain value. By using multi-stage, two purposes were served. Firstly, the possible available energy was extracted before the feed reaches the exit. Secondly, the membrane area was increased, thus total amount of flux was increased. In addition, the polarization of temperature and concentration were reduced as a result of better mixing of the feed compared to that of a bigger chamber with same membrane area. The only extra energy needed was that by the circulation pumps which are not significant as MD process does not require high pressure.

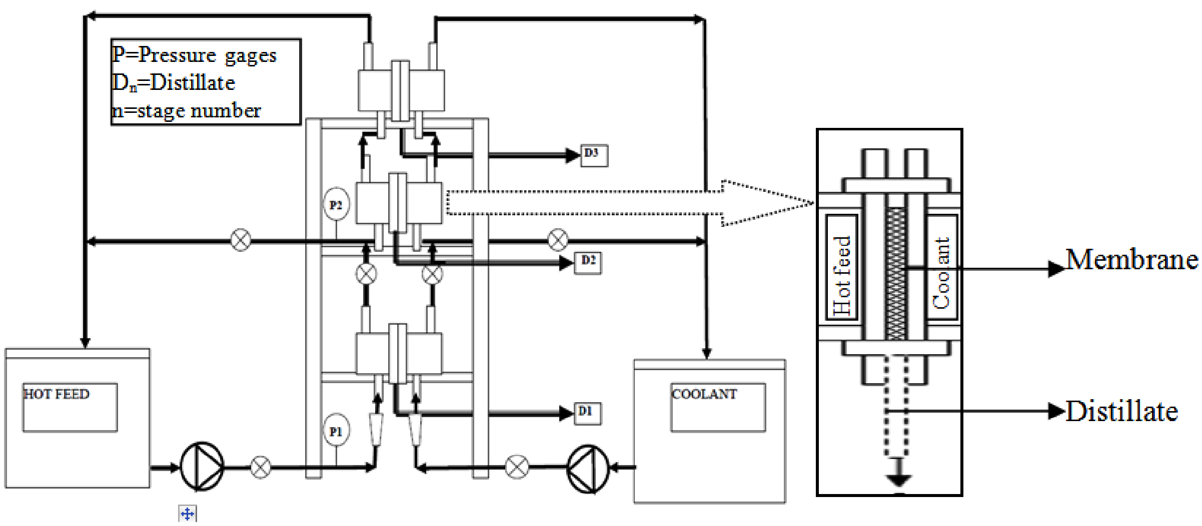

Figure 1 Schematic diagram of the multi-stage AGMD rig

Table 1 Properties of Durapore membrane

Water Flow Rate(ml/min/cm^2)	35
Bubble Point (bar)	≥ 0.56
Thickness (µm)	125
Effective membrane area (cm^2)	88.2
Membrane porosity	0.75

Table 2 Operating variables during experiments on the multi-stage AGMD rig

Variable Parameter	Range
Feed temperature	40 to 60 ºC @5ºC
Coolant temperature	10 to 25 ºC@5ºC
Air gap	2.5,5,6,7.5 and 8.5 mm
Concentration	tap water to 45000 ppm @15000 ppm.

3.1 Effect of Temperature and Air Gap

The feed temperature was varied from 4 0 to 60°C and between each stage the temperatures were measured. For implementing 3 stages, there was an average temperature drop of 2°C at the entry and exit of the integrated module. A similar temperature difference across the membrane-air gap was observed in each module.

As seen in Figure 2(a),distillate produced from the first stage had a higher volume than those from the other two stages, by about 1.5 times; although the temperature difference across the membrane in each stage did not vary significantly with each other. Further investigation revealed that the orientation of stacking of the modules was responsible for this enhanced production. The modules were vertically stacked and the static pressure exerted by the upper modules influenced the production from the lower stage. The distillate from this module was carefully monitored and some dye was mixed with the feed to sense the instantaneous leakge through membrane due to extra pressure. Long time running did not show any visible trace of leakage through the membrane (i.e. colour change of the distillate). However, when the conductivity of distillate from each stage was measured, some difference in the quality was detected. [Discussed in section 3.3].

Figures 2(b) illustrates the trend and total production for increasing feed temperature. As expected from the previous experiments on the single-stage [4], the production was dominated by feed temperature rather than coolant temperature. As seen in the figure, changing the feed temperature increased total distillate at a steeper rate compared to changing the coolant temperature for which the flux production lines are more closely spaced, as seen in Figure 2(b).The air gap dominated the production significantly because of influence of the mass transfer resistance on production. A highest rate of about 18 kg/m^2hr of distillate flux was obtained for a feed temperature of 60°C, coolant temperature 10°C and air gap of 2.5 mm as seen in the graph in Figure 2(c).

3.2 Effect of Feed Inlet Concentration

It has been observed [5,6] that MD is not very sensitive to feed concentration compared to the other desalination processes as the evaporation does not involve boiling point elevation(BPE) . However, for the multi-stage production, it was seen that the total production dropped from 7.5 kg/m^2hr for tap water to 5 kg/m^2hr for feed NaCl concentration of 45000 ppm, which gave approximately 33% reduction in production, as seen in Figure 3(a). The reason may be that for a more concentrated feed Raoult's law of partial pressure was not valid because the solution could not be considered as dilute solution anymore. Hence, the effect of boiling point elevation would be dominant for higher concentration value in the subsequent stages.

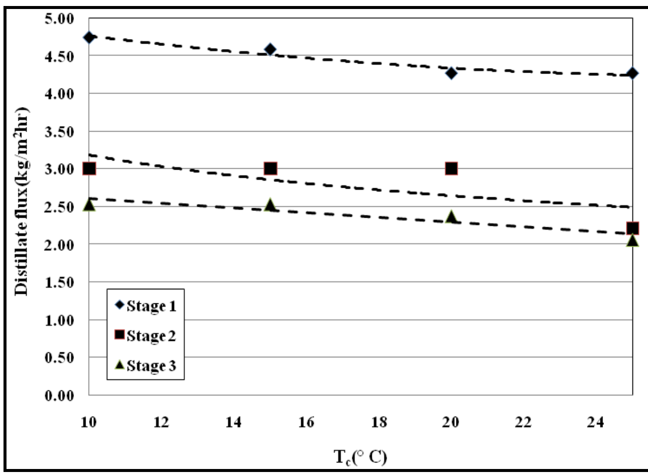

Figure 2(a) Distillate production from individual stages (air gap=2.5 mm, T_h=60°C)

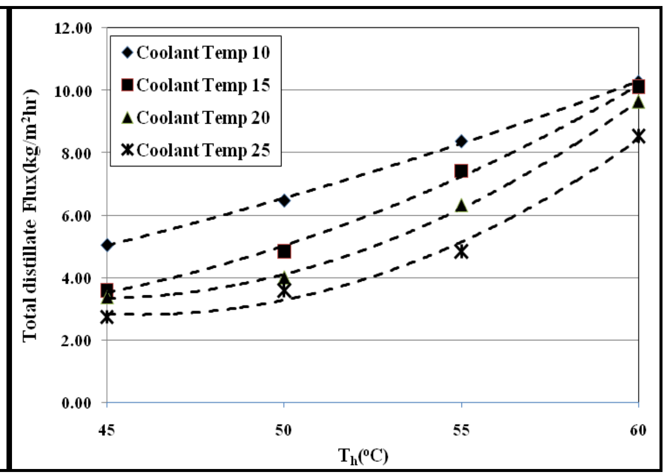

Figure 2(b) Total distillate production from multi-stage MD with varying feed temperature (air gap=6 mm)

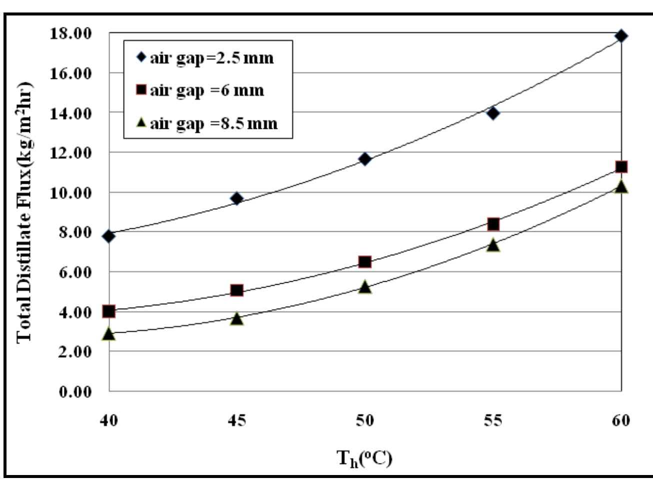

Figure 2(c) Total distillate production from multi-stage MD with varying air gap (T_c=10°C)

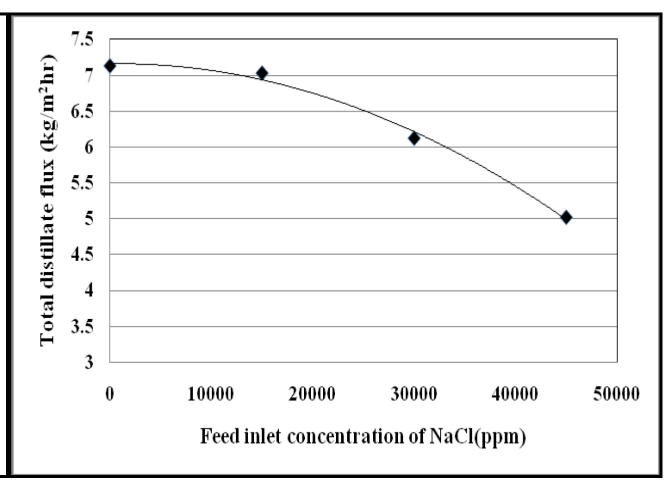

Figure 3(a) Distillate vs concentration (T_h=55°C,T_c=20°C,air gap=6 mm)

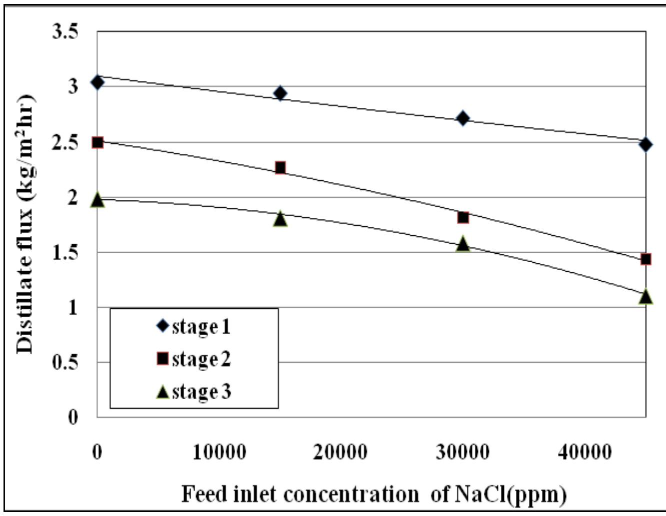

Figure 3(b) Distillate vs concentration for each stage (T_h=55ºC,T_c=20ºC,air gap=6 mm)

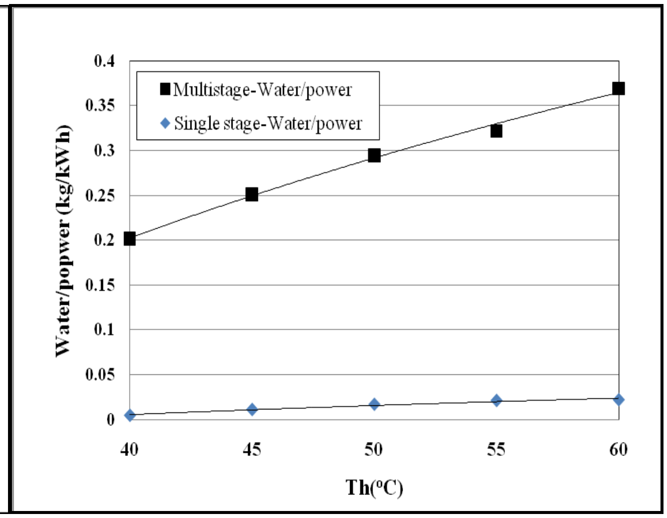

Figure 4 Water and power ratio (for coolant temperature 10ºC, air gap 2.5 mm)

Further investigation on the production rate from each stage separately added some more observations. It is seen in Figure 3(b) that the production from the second and third stages tend to decrease more quickly at an elevated feed concentration compared to the first stage. The reason for such variation may be attributed to the fact that the feed was getting more concentrated as it reached subsequent stages and consequently the production dropped due to higher concentration brine.

3.3 Power Consumption and Water Quality

The power consumption, water quality and membrane condition were studied to have a clear practical impressionabout the MD process.Figure 4 shows the trend of product water (kg) per kWh. Although the power requirement was highest for maintaining coolant temperature of 10ºC, yet the highest water/power ratio obtained was for the coolant temperature of 10ºC. A maximum of 0.37 kg of distillate was obtained per kWh energy input for the multi-stage MD unit while it is seen that for single-stage, the highest ratio obtained was only 0.021 kg per kWh energy input. Although the multi-stage MD unit had three times higher membrane area than the single-stage. This variation indicates that multistaging is necessary for efficeint energy use in MD system. Considering membrane specific area, it was possible to obtain maximum 13 kg/m^2 of distillate per kWh of energy input from the multi-stage rig.

The distillate from each stage was tested using the conductivity meter. Table 3 summarizes the results.

Table 3 Water quality from three stages using stainless steel coolant plate (Feed inlet concentration 45,000 ppm)

	1st Stage	**2nd Stage**	**3rd Stage**	**Tap water**
Conductivity (mS/cm)	0.45	0.21	0.20	0.275
ppm	288	134	128	176

It is seen from the results that the water produced was of good quality. However, static pressure on the first stage did have some adverse effect on the product water quality with the conductivity higher than those of the subsequent stages.

■4.0 CONCLUSION

A detailed experimental study was carried out on a multi-stage AGMD rig. A highest distillate flux of 18 kg/m^{2}hr was obtained from the multistage MD unit with a feed temperature of 60ºC and air gap of 2.5mm. A maximum of 0.37 kg of distillate was obtained per kWh energy input for the multi-stage MD unit; which was 5.6 times higher than the performance of the single-stage. Multi-staging in MD therefore is a viable option for building energy efficient pure water supply system.

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