European Water 58: 529-534, 2017.

Wastewater treatment by solar air gap multi-stage membrane distillation

I.J. Siddique[1], R. Bahar[2*], S. Ibrahim[3] and M.H.F. Al Hazza[1]
[1] *Department of Manufacturing and Materials Engineering, International Islamic University Malaysia, Jalan Gombak, 50728 Kuala Lumpur, Malaysia*
[2] *Department of Mechanical and Materials Engineering, Lee Kong Chian Faculty of Engineering and Science, University Tunku Abdul Rahman (UTAR), Sungai Long, Cheras, Kajang 43000, Malaysia*
[3] *Department of Civil Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia*
[*] *e-mail: rbahar@iium.edu.my*

Abstract: Scarcity of fresh water and availability of solar irradiation constitute the perfect condition for developing small-scale solar waste water treatment plants. One of the suitable low energy process applicable is Membrane Distillation (MD). MD is a relatively lower temperature process which does not need to operate under high pressure like Reverse Osmosis (RO). A hydrophobic membrane maintains a barrier between hot feed water and coolant flowing outside. The vapour generated due to partial pressure difference crosses the pores of this hydrophobic membrane and travels toward the cooler side to condense and produce distillate. In this paper, performance of a solar assisted multi-stage MD system has been analysed. Our previous experimental multi-stage MD setup gave a hike of 5.6 times in production per kWh of energy input compared to a single stage. In this study, an average annual solar radiation of 1571 kWh/m^2 has been incorporated in the multi-stage MD system with a narrow air gap between the coolant and feed. It has been observed that using smaller sized multiple chambers in the process can enhance the production of fresh water compared to a bigger sized chamber with a single large membrane. Association of solar heat into the MD module can contribute to further energy savings and producing up to 220 l/day of freshwater in hot tropical climate.

Key words: Air Gap Membrane Distillation, Multi-stage Membrane Distillation, Solar Energy, Wastewater Treatment

1. INTRODUCTION

The demand of alternate water distillation methods has been ever rising with the world tending to lean on renewable energy sources rather than land and energy extensive methods. Among these alternate methods membrane distillation (MD) has shown a great potential. Since MD requires least amount of space and energy, has ability to use renewable energy and can produce pure distillate from high concentration of wastewater (Raluy et al., 2012), thus MD has the option to be used as household water treatment facility as well as industrial wastewater treatment plant (Gryta et al., 2006).

MD is a thermally driven separation process in which only vapour molecules pass through a microporous hydrophobic membrane due to the vapour pressure difference between the two sides of the membrane by flowing hot and cold solution on each side of the membrane (Lawson and Lloyd, 1997). The nature of the membrane restricts the aqueous solution in the pore openings. The vapour transferring through the membrane is then cooled by different methods to get the pure distillate. Depending on this cooling method MD can be classified to Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweep Gas Membrane Distillation (SGMD) and Vacuum Membrane Distillation (VMD). In AGMD instead of directly letting the distillate mix with cold side an air gap is used to separate them. The permeate vapour is cooled by the coolant plate which is in direct contact with the circulating cold solution. Figure 1 shows how AGMD works.

One of the main drawbacks of MD is lower flux compared to RO processes, thus optimization and improvement is needed in MD to make it competitive with RO. Over the time many modification is made to MD technology (Zhani et al., 2015) and it has been observed that with optimum design MD can produce fluxes more than conventional systems. (Chafidz et al., 2016) has reviewed some of the major solar powered membrane distillation (SPMD) systems. It can be seen that either the distillate production rate or the quality is low, and if both of the parameters are satisfactory the energy consumption is higher due to complex machinery. With the recent trends of green technology, people have shown a tendency to use multi-staging in MD process as well to extract more available energy (Bahar et al., 2014), as introducing multistaging helps better mixing of the working fluid in successive stages and improves flux production. In this paper we have presented the performance of a solar assisted multi stage AGMD and compared with the performance of a single stage MD module.

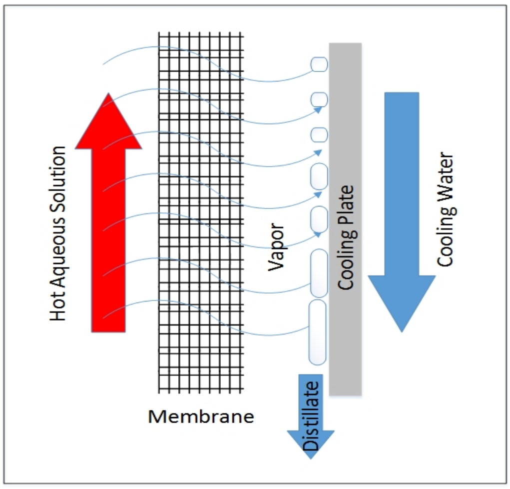

Figure 1. Working method of AGMD.

2. EXPERIMENTAL SETUP AND PROCEDURE

The designed module was made out of grade 'A' polycarbonate sheets having thickness 5 mm and the hot and cold chamber had these dimensions 162.4 x 162.4 x 106.6 mm. It consisted of six parts: 1) Hot solution Chamber, 2) Membrane, 3) Membrane Ramp, 4) Air gap frame with hole on the bottom surface to collect distillate, 5) Coolant plate, 6) Cold solution chamber. The overall 3-D design of the module can be seen in Figure 2. The three modules were connected in series and the schematic diagram is shown in Figure 3. Instead of directly feeding the salty water from solar heater to the hot chamber a heat exchanger has been used to protect the solar heater from corrosion. Module performance parameters like permeate flux, gained output ratio (GOR), rejection factor and specific energy consumption for feed heating were evaluated using equation (1) – (5) respectively,

Permeate flux, J (L/m^2h):

$$J = \frac{V}{At} \tag{1}$$

Gained output ratio (dimensionless):

$$GOR = \frac{\Delta h_{evap} * m_d}{Q_{input}} \tag{2}$$

$$Q_{input} = m_f * C_{pf} * (T_f - T_o) \tag{3}$$

Module separation efficiency:

$$\%\ Separation = \frac{C_f - C_p}{C_f} \tag{4}$$

$$\text{Specific energy consumption} = \frac{m_f C_{pf}(T_f - T_0)}{m_d} \quad (5)$$

Here V (L) is the volume of the permeate collected, A (m^2) area of the membrane used, Δh_{evap} is the latent heat required to evaporate the water produced and the Q_{input} is input energy supplied to the system. C_f and C_p are the feed and permeate concentrations respectively, m_f and m_d (Kg/s) are the mass flow rates of the feed and permeate waters, T_f and T_o are the temperature of the feed entering the feed channel and leaving the feed channel for each stage and C_{pf} (4.1 KJ/Kg ºC) is the specific heat capacity of water. The reason behind taking the feed inlet and exit temperature at each stage as a parameter in GOR and specific energy consumption calculation is that the feed chambers were not insulated, so much of the heat has been lost to the environment.

The system presents the following main characteristics:

- Permeate flux 6 - 13 L/m^2h
- Membrane material polytetrafluroethylene (PTFE), 0.45μm pore size
- Membrane effective area 0.013 m^2/stage
- Air gap thickness 11 mm
- Feed temperature at inlet 40-70 ºC
- Coolant water temperature 20-30 ºC
- Solar field area 2 m^2, tank capacity 180 L, with efficiency 85%
- Location Selangor, Malaysia
- Pump energy requirement 10 W
- Feed and coolant flow rate 1 L/min
- Feed concentration 14.625 g/L of NaCl
- Permeate quality 9-12 $\mu S/cm$
- Operational hours 8h
- GOR 0.5-7.88
- % Separation 99.96%
- Specific energy consumption was 0.0794 – 0.819 kWh/kg

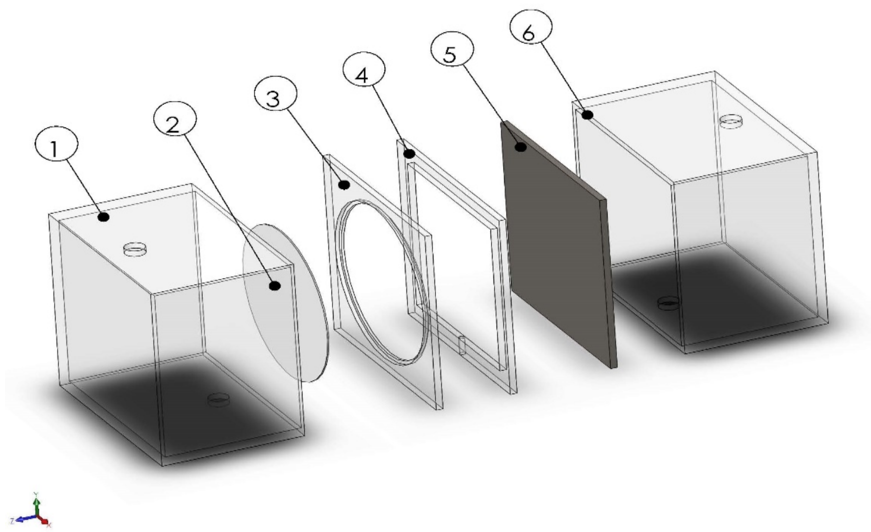

Figure 2. 3D image of the MD module.

3. RESULTS AND DISCUSSION

The system was operational during the daytime and was shut down at night, but it remained operational even during the rainy days. The solar heater used had a water storage tank which helped during these hours. The permeate flux obtained was tested by a conductivity meter to check the distillate quality. Also food colour was mixed with the feed solution to check if there is any serious leak in the MD module.

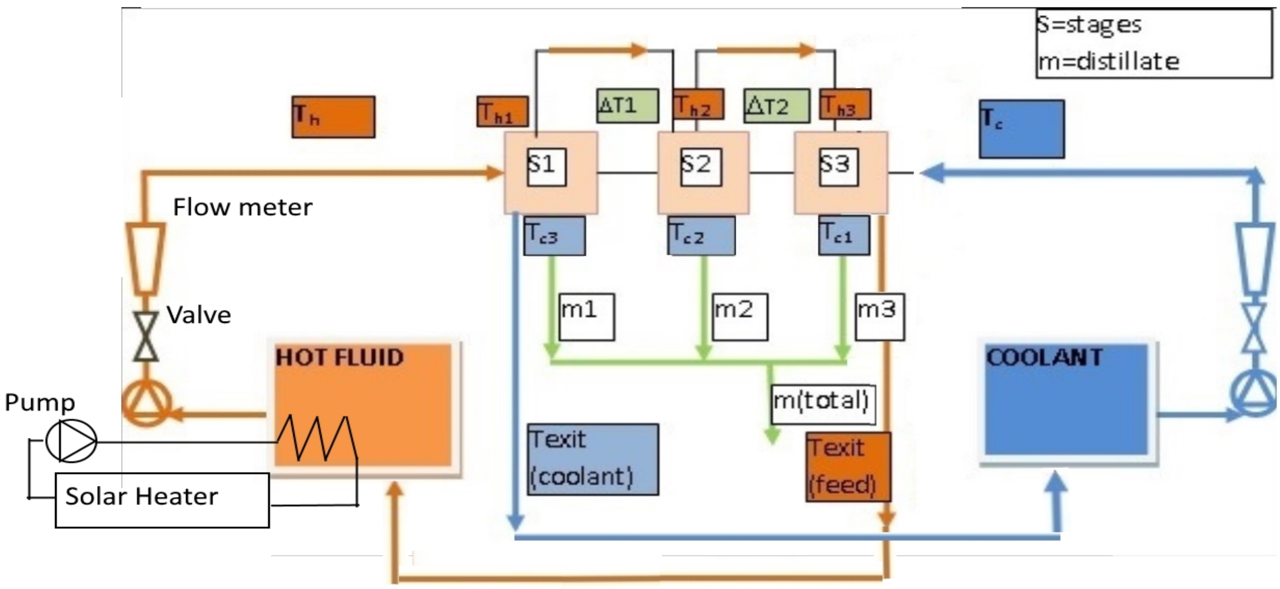

Figure 3. Schematic of the Multi Stage MD module.

3.1 Effect of Temperature

Before coupling the MD system with the solar heater it was tested experimentally to obtain the performance parameters. The feed temperature was varied from 40 ºC to 70 ºC and the corresponding flux was plotted. The result is shown in Figure 4. The flux increases almost linearly. From the figure we can see that permeate flux for multi stage becomes almost double than single stage at 70 ºC. The data for single stage was obtained from a theoretical model developed by (Alsaadi et al., 2015). Their result matched with our laboratory experiment and thus helped in scaling up the membrane area.

Figure 5 represents the relationship between flux and cold solution temperature. Flux gradually decreases with the increase of cold solution temperature, this is well established from the literature and it can be seen that flux doesn't change as steeply as it does when feed temperature is changed meaning that flux has less sensitivity to cold solution temperature.

3.2 Water Production using the solar heater

The solar heater was used to obtain the average temperature during the day time and was coupled with MD system. The results were used to obtain the water production during the day (8 hours runtime) if the membrane area was 2 m^2 which is equivalent to a small scale plant. Figure 6 shows the water production during the month of February, 2017. It is clear that with this system pure water production of 220L per day is achievable. And even in the cloudy seasons producing 90 L of water is possible.

4. CONCLUSION

The permeate flux achieved is quite high compared to some of the previous experiment running similar parameters mainly because of using simple string support instead of net like support (Guillén-Burrieza et al., 2011) which reduces the flux heavily. But at the same time experiments on multi-effect membrane distillation shows even more improved flux (Pangarkar et al., 2016). Thus both of these systems need to be compared with the same specification to achieve an optimized MD system. The system tested in this paper could have been improved more if air gap thickness and pressure (Alsaadi et al., 2015) were reduced, also adding internal heat recovery and spacers/baffles to reduce polarization in the feed chamber would greatly increase the distillate production rate.

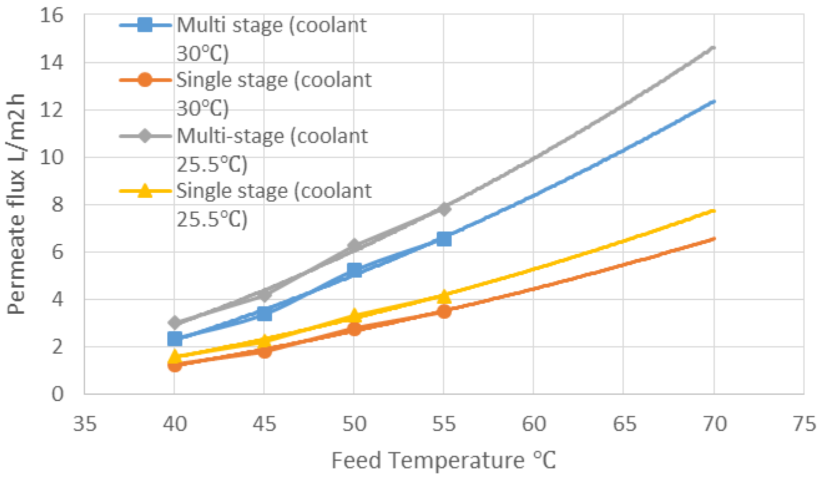

Figure 4. Relationship with permeate flux with feed temperature.

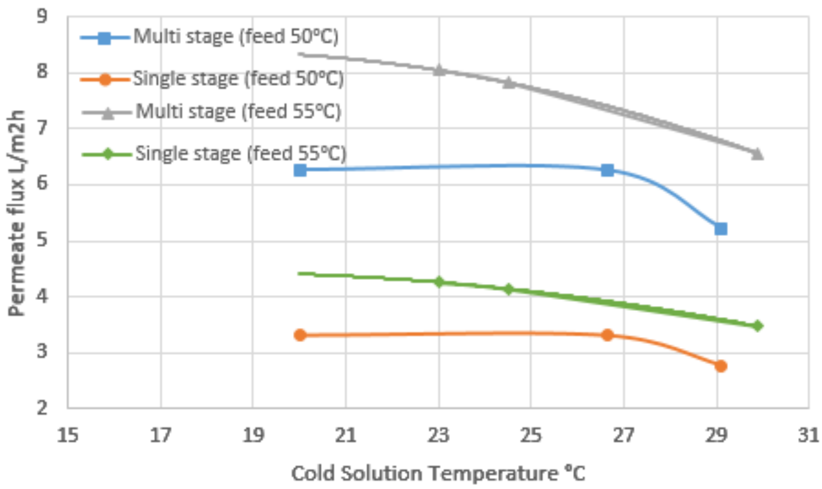

Figure 5. Relationship with permeate flux with cold solution temperature.

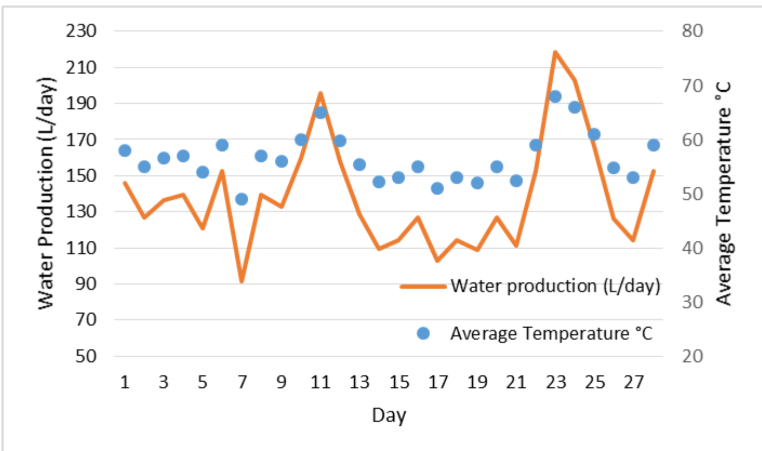

Figure 6. Expected water production during the month of February, 2017.

ACKNOWLEDGEMENT

The work is jointly supported by Fundamental Research Grant Scheme (FRGS-14-118-0359) and IIUM-UM joint grant (CG015-2014) by providing necessary financial and technical assistance.

REFERENCES

Alsaadi, A. S., Francis, L., Maab, H., Amy, G. L., & Ghaffour, N. (2015). Evaluation of air gap membrane distillation process running under sub-atmospheric conditions: Experimental and simulation studies. Journal of Membrane Science, 489, 73–80.

Bahar, R., Hawlader, M. N. A., Nga, K. C., & Haw, Y. J. (2014). Experimental study on a multi-stage air gap membrane distillation (AGMD) unit. Jurnal Teknologi (Sciences and Engineering), 69(9), 89–92.

Chafidz, A., Kerme, E. D., Wazeer, I., Khalid, Y., Ajbar, A., & Al-zahrani, S. M. (2016). Design and fabrication of a Portable and Hybrid Solar-Powered Membrane Distillation System. Journal of Cleaner Production, 133, 631-647.

Gryta, M., Tomaszewska, M., & Karakulski, K. (2006). Wastewater treatment by membrane distillation. Desalination, 198(1–3), 67–73.

Guillén-Burrieza, E., Blanco, J., Zaragoza, G., Alarcón, D.-C., Palenzuela, P., Ibarra, M., & Gernjak, W. (2011). Experimental analysis of an air gap membrane distillation solar desalination pilot system. Journal of Membrane Science, 379(1–2), 386–396.

Lawson, K. W., & Lloyd, D. R. (1997). Membrane distillation. Journal of Membrane Science,124(1), 1–25.

Pangarkar, B. L., Deshmukh, S. K., & Thorat, P. V. (2016). Experimental study of multi-effect membrane distillation (MEMD) for treatment of water containing inorganic salts, 11(4), 765–773.

Raluy, R. G., Schwantes, R., Subiela, V. J., Peñate, B., Melián, G., & Rosa, J. (2012). Operational experience of a solar membrane distillation demonstration plant in Pozo Izquierdo-Gran Canaria Island (Spain). DES, 290, 1–13.

Zhani, K., Zarzoum, K., Bacha, H. Ben, Koschikowski, J., Pfeifle, D., Zarzoum, K., Pfeifle, D. (2015). Autonomous solar powered membrane distillation systems : state of the art. Desalination and Water Treatment, 57(48-49): 23038-23051.