Experimental analysis of a novel helical air gap membrane distillation system

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ABSTRACT

Membrane distillation presents one of the feasible solutions to fresh water problems. The present study aims to develop an innovative helical air gap membrane distillation (HAGMD) system and to analyze its behavior under different operating conditions. In this design the condenser is made up of a cylindrical copper tube with continuous helical fins over it, that increases the total available condensation area by almost 45% and enhances the overall heat transfer throughout the module. The presence of fins in the gap also reduces the total air gap width by almost 64% and therefore improves the flux production. A detailed experimental analysis is carried out for a better understanding of the underlying phenomenon. The effect of feed water temperature, feed flow rate, cold flow rate, coolant temperature and feed salinity on the performance of HAGMD is investigated experimentally. The analysis shows that the finned condenser results in very high flux. The maximum flux obtained from the system was 20 kg/m² hr with feed of 5 g/liter salinity and a diving force temperature difference of 45 °C.

Key words | air gap membrane distillation, cold flow rate, cylindrical module, flux, helical fins

HIGHLIGHTS

- Helical air gap membrane distillation system is developed.
- Condenser is modified with provision of helical fins on its outer surface.
- Enhanced condenser surface area results in higher flux.
- At higher flux production rate, module acts as a conductive helical gap MD system.
- A high value of flux of 20 kg/m² hr is achieved.
INTRODUCTION

The world is moving towards achieving more and more energy efficiency and reducing improper usage of resources. With an increase in population growth, industrialization and urbanization it is evident that the availability of natural resources will be diminished which poses a severe problem to humanity. Water is one of the essential elements of life. Due to the reasons mentioned above, the availability of potable water to many communities is reduced. Membrane distillation (MD) is a rate governed separation process that produces freshwater from a brackish or saline solution. The number of studies on different membrane modules, membrane properties, membrane modification and overall membrane systems are already available in the literature (Eykens et al. 2016; Mahmoudi et al. 2017a). Four basic configurations of MD systems (Khayet & Matsuura 2011a) are (i) direct contact MD (ii) air gap MD (AGMD) (iii) sweeping gas MD and (iv) vacuum MD.

The difference between them appears in the permeate side arrangement. Most studied and explored configuration out of all above is the direct contact MD (Wu et al. 2016) still, it has been shown that with renewable energy sources, AGMD is the most preferred configuration with which to go (El Amali et al. 2004). Some other new configurations are also being derived from these basic configurations and are studied nowadays. Permeate or water gap MD, material gap MD, conductive gap MD, vacuum-enhanced DCMD (VEDCMD), multi-effect MD and vacuum-multi-effect MD are some of the arrangements. Air gap MD offers an advantage in terms of lower internal conduction losses from the membrane to cold fluid, higher driving temperature difference, and ability to separate expensive solutes without dilution (Aryapratama et al. 2016). This process has excellent thermal efficiency when used with an internal heat recovery option and employing solar energy to provide thermal assistance would definitely help in establishing an energy efficient and cost-effective solution for potable water needs (Koschikowski et al. 2003). Several modifications are performed in the basic design of air gap MD to explore new configurations that can be more productive than the conventional AGMD system (Mahmoudi et al. 2017b; Lee et al. 2019;
Shahu & Thombre (2019) in terms of distillate flux and energy efficiency (Summers & Lienhard V 2013). Many studies are available that focus on feed and cold fluid conditions to affect the performance (Teoh et al. 2008; Yang et al. 2012), some studies have also concentrated on the air gap region to explore the possibilities that may help in performance improvement (Francis et al. 2013; Swaminathan et al. 2016a). Chouikh and colleagues have changed the air gap conditions by inducing air movement through the temperature difference between the top and bottom of the cavity in the gap. This resulted in enhanced hydrodynamic conditions and ultimately improved the heat and mass transfer process within the air gap. They detected a slight increase in the permeate flux (Chouikh et al. 2005). Francis and co-workers have developed a new module out of AGMD and named it material gap MD. They tested the effect of adding sand, DI water, polypropylene and polyurethane in the air gap. They demonstrated that water gap MD (WGMD) worked best and it could produce 80% more distillate flux than AGMD. They also tested the effect of gap width and showed that with an increase in gap width from 9 to 15 mm the flux increases by a minimum of 340%. The reason attributed to this is the availability of more surface area for the dissipation of latent heat of condensation (Francis et al. 2013). A novel conductive gap MD was developed by Swaminathan et al. (2016b). In this configuration the gap was filled with a conductive metal mesh along with the permeate. In this way the overall conductivity of the gap was increased, which resulted in higher thermal efficiency. The effect of permeate flow direction in the gap was also analyzed. It was asserted that the counter-flow direction of the permeate is the most suitable for higher energy efficiency (Swaminathan et al. 2016b). Khalifa and colleagues analyzed the performance of multi-stage AGMD and WGMD under series, parallel and mixed stage connections; for the feed solution with a salinity of 61,400 µS/cm it was found that multistage WGMD was superior to that of AGMD. Out of all the three arrangements, the parallel flow was the best in terms of flux production (Khalifa & Alawad 2018). Another permeate gap MD (also known as WGMD) module in a plate and frame configuration was studied and analyzed theoretically and experimentally by Mahmoudi et al. (2017a). Most of the studies have preferred plate and frame configurations, as they are easy for fabrication, operation and maintenance. But recently a design flexibility in terms of cylindrical module AGMD was studied statistically and optimized for minimum energy consumption and maximum flux conditions by Shahu and colleagues (Shahu & Thombre 2020). Another finned tubular module with vertical grooves over the metallic condenser was studied by Cheng and co-workers in small-scale and scaled-up configurations with or without the use of solar energy. They were able to achieve as high as 50 kg/m² per hour flux with 11 vertical grooves on a condenser with 5 lpm flow rates (Cheng et al. 2011). Therefore, it is clear from the literature that air gap and the condenser design can be one of the critical areas to improve the performance, however not many research studies are available concerning these issues. This motivated us to explore a different air gap and condenser design and to identify the improvements over the basic AGMD design.

In the present study a cylindrical helical AGMD (HAGMD) system was developed that resembles a shell and tube heat exchanger in its design. It has a hollow copper condenser with helical fins over it. Copper was used as the condenser material here because copper has very high thermal conductivity that can help to achieve higher thermal efficiency as well as higher flux. Its higher corrosion resistance properties make it a perfect option for using with brines. Besides this, copper is known for imparting beneficial antioxidant and antimicrobial properties and is an essential micronutrient for human health (Dietrich et al. 2004), making copper the ideal choice to be used with a desalination system to provide potable water. The presence of fins increases the overall surface area available for condensation. The fins in the gap reduces the air gap width. Thus, the overall heat transfer in the module increases and helps in achieving higher flux. It was stated by Swaminathan et al. that the effect of increased conductivity of the gap was similar to the reduced air gap thickness (Swaminathan et al. 2018), therefore using fins further facilitates flux production by inducing the impact of lower air gap thickness.

The feed to be treated flows at higher temperatures in the outer shell, and is maintained on one side of the membrane. Polytetrafluoroethylene (PTFE) hydrophobic membrane was used as the separating medium. The membrane was wrapped over the helical finned condenser so the fins also act as a
support for the membrane. On the other side of membrane an air gap exists and after the air gap, comes the condenser tube. The condenser tube is maintained at a lower temperature by a continuous flow of cold water through it. The membrane experiences temperature difference on its both sides and therefore the difference in vapor pressure builds up across the membrane. To balance this difference, hot feed evaporates on the feed membrane interface and only the vapors travels through the membrane. After the membrane the vapors encounters the air gap and the finned copper condenser tube. The vapors become condensed over the fins and the condenser tube. The fins are continuous with constant pitch that forms a helical passage for condensing vapors to flow from top to bottom of the condenser. The length of the active membrane module is \( L = 270 \text{ mm} \) as shown in Figure 1. The height of the fin is 3 mm, and the same as the air gap. The condensed vapors experience a small centrifugal action while traveling downwards through the fins, creating an additional inertial suction effect on the incoming vapors from the membrane. Although this suction effect is very small it helps the vapors to diffuse quickly through the membrane and further facilitates the vaporization at the membrane surface. The effect of feed temperature, feed and cold flow rate, coolant temperature and feed salinity are analyzed on the performance of the helical AGMD system. A maximum flux of 20 kg/m² per hour was achieved with this HAGMD system for a feed with 5 gm/liter salinity and for a diving force temperature difference of 45 °C. The present experimental facility is not equipped with an energy recovery method, and therefore the present study is not intended for energy studies.

**MATERIALS AND METHODS**

**Design and principle of HAGMD system**

The design of HAGMD module is similar to a shell and tube heat exchanger as shown in Figure 2. In this system, the shell forms a passage for hot feed flow and, condenser tube forms a passage for cold-water flow. The shell houses the condenser tube. Helical fins are provided on the cylindrical copper condenser tube and a flat sheet PTFE membrane is wrapped over the finned condenser tube. The height of the fins forms the air gap, the shape of the fins is trapezoidal and fin tips act as the support for the membrane. On one side of the membrane, there is a hot foods and on other side there is an air gap followed by a helical condenser.

The fins create a continuous helix on the condenser surface, therefore the total condenser length \( L \) is now divided into ‘n’ number of smaller length regions with number of smaller condensate films. As the length of condensate film \( L_a \) is reduced, it ultimately increases the overall condensation heat transfer coefficient as per the Nusselt theory of condensation for vertical plate (Swaminathan et al. 2016b). It is assumed that all the ‘n’ sections will behave in the same manner as far as the heat and mass transfer is concerned. The heat and mass transfer in one finned section is shown in an enlarged view in Figure 3. The condensed liquid droplets over the fin and on the wall of condenser tube wall are also represented in the same figure. In this event the downward traveling vapors induce a suction effect on the incoming vapors, however this effect may be very small compared to the overall mass transfer process through the diffusion. This suction effect may also produce additional vaporization at the membrane surface as the
diffusion through the membrane is accelerated by this suction effect on the incoming vapors.

HAGMD module preparation and membrane arrangement

The dimensions of the HAGMD module are given in Table 1.

The membrane used in the present study is PTFE hydrophobic membrane in the form of a flat sheet, which is wrapped over the finned condenser tube. The length of the condenser tube is 500 mm. The length of condenser over which the membrane is wrapped is termed as the active length of the module and is 270 mm. The extra length of the condenser is given before and after the membrane to facilitate a fully developed flow at the membrane surface. The properties of the membrane used in this study are given in the Table 2.
The vertical ends of the membrane are pasted together to form a cylindrical shape. The membrane is also pasted to the fin tips, so that condensed fluid does not skips away from between the membrane and the fin tips, but travels along the helical path from the top to bottom. The thermal conductivity of the compound used to stick the membrane to the fins is very low, therefore the fins are considered as insulated at the tips. The membrane is also pasted to the condenser tube at the top and bottom ends, to ensure that hot feed does not leak into the distillate side of the membrane and vice versa. Pressure testing is done to ensure the perfect sealing and a leak-proof setup. The module is placed vertically to gain the gravity advantage. The hot feed flows from the bottom to the top to ensure that the membrane is always submerged in the feed water. The coolant also flows in the upwards direction whereas the permeate flows in the downward direction to take the advantage of counter-flow (Swaminathan et al. 2016b). The details of operating parameters varied during the investigation are given in Table 3.

After passing through the membrane, some vapors get condensed over the fin surface and remaining travel through the air gap and condense over the vertical wall of the condenser surface. Condensate formed by both ways gets merged and travels downwards through the continuous helical fins and leaves through the permeate tapping at the condenser’s bottom.

The driving temperature difference (ΔT) in HAGMD is that between the membrane surface temperature at hot feed side (Tfm) and the permeate film temperature over the condenser surface (Tfilm), as shown in Figure 4. The hot feed and cold water, both travel upwards in parallel flows.

![Figure 4 | Vertical cross-sectional view of HAGMD module.](https://example.com/figure4.png)

### Table 1 | Dimension details of HAGMD module

| Module parts                  | Dimension |
|-------------------------------|-----------|
| Active length (L)             | 270 mm    |
| Overall length of shell       | 500 mm    |
| Condenser material            | Copper    |
| Number of finned sections (n) | 35        |
| Inner diameter of the condenser tube | 15 mm |
| Width of air gap              | 3 mm      |
| Diameter of finned portion    | 26 mm     |
| Inner diameter of shell       | 34 mm     |

### Table 2 | Properties of flat sheet membrane used in this study

| Membrane property | Value                  |
|-------------------|------------------------|
| Polymer           | Polytetrafluoroethylene (PTFE) |
| Structure         | Unsupported             |
| Thickness         | 175 μm                 |
| Width             | 85 mm                  |
| Length            | 270 mm                 |
| Pore size         | 0.2 μm                 |
| Porosity          | 80%                    |
| Active membrane area | 0.012 m²            |

### Table 3 | Experimental values of variable parameters

| Parameter | Feed water | Coolant water |
|-----------|------------|--------------|
| Temperature | 45–75 °C  | 27–30 °C     |
| Salinity  | 5–30 gm/liter | Tap water   |
| Flow rate | 1–3 lpm    | 1–9 lpm    |

Not controllable as direct tap water is used as a coolant.
Therefore maximum $\Delta T$ is experienced at the bottom of the membrane and it diminishes as we move upwards and the minimum $\Delta T$ exists at the top consequently the permeate production varies accordingly along the length and the maximum vapors are formed at the bottom.

The space between the helical pitch provides enough space to accommodate the higher permeate coming from the membrane as well as permeate traveling from the fins above.

As the flux production rate changes according to the operating conditions, the resulting permeate accumulation inside the air gap also varies. This process results in different MD configurations to get established in the HAGMD system as discussed here.

**HAGMD module configuration at lower permeate production**

When the flux production rate is lower, such as that with lower driving force temperature difference and low flow rates, there may be some air always available in the upper portions of the air gap, but the lower most gaps will be mostly filled with permeate only. It is because, at the bottom, vapors from two regions become merged, that is the travels condensed vapors traveling downwards, as well as vapors diffusing through the membrane. However, the air gap region will be randomly occupied with air and water droplets along the length of helical fins. Therefore, it will be considered as a mixed HAGMD configuration. In this case the heat transfer through the gap may be higher than AGMD configuration but less than DCMD configuration and therefore the thermal efficiency may be lower than AGMD.

**HAGMD module configuration at higher permeate production rate**

When the permeate production rate is high, such as with higher driving force temperature difference and higher flow rates, the air gap may be completely filled with the permeate and results in a conductive gap configuration (Swaminathan et al. 2016b). The velocity of the condensate traveling downwards will be higher than that in the previous case. This process will further increase the heat and mass transfer coefficient in the air gap that facilitates more permeate production. The conductive heat transfer will also be higher due to the flowing permeate in the gap, which may increase energy consumption and reduce the system’s thermal efficiency, if heat recovery is not used. Therefore, the thermal efficiency may be lower than AGMD. The presence of permeate in the air gap further facilitate increased area for the latent heat of condensation to dissipated and resulting in increased flux production. All these factors result in higher permeate production in the conductive HAGMD configuration.

**Experimental methods**

Numbers of experimental runs were performed to determine the performance of the HAGMD module under different operating conditions. The experimental setup is shown schematically in Figure 5. The whole setup is divided into three circuits or channels for better control and understanding: a feed channel, a coolant channel and a permeate channel. The temperatures at the inlet and outlet of the HAGMD module were measured using PT-100 thermocouples having $\pm 0.01$ °C accuracy. The flow rate in feed and coolant...
channels were maintained using centrifugal pumps and measured with rotameters. The salinity of the feed and permeate was measured using an electrical conductivity check instrument having an accuracy of 0.01 μs/cm. The weight of the permeate was measured using a balance with ±0.01 gm accuracy. For each parameter change, the readings are taken after the steady-state is reached which took about 1–2 hours of operation.

Feed circuit

The feedwater is heated in a thermostatically controlled heater. It is then sent to the HAGMD module by a saline centrifugal pump (TAHA PMD30). The hot feed enters the shell of the module from the bottom end and flows over the membrane. It comes out from the top end, and is again sent back to the feedwater heater.

Some make-up feed is added to the heater tank at regular intervals to maintain the feed supply’s desired salinity. The saline feed water is prepared in the laboratory by adding the required amount of NaCl to tap water. The outer shell of the module is insulated using rock wool insulation to reduce the heat loss from the module to the environment.

Coolant channel

Due to easy availability, tap water is used as the coolant, and for this reason, the temperature of the coolant was not controllable. The temperature of the coolant was always maintained in the range of 28–30 °C. The cold tap water is stored in a tank, and from there, it flows through a small centrifugal pump to the module. After the module, the cold water is sent to a small cooling tower where extra heat is rejected, and the cold water returns to its initial temperature. A small laboratory scale cooling tower was used for maintaining the coolant temperature within the considered range. This cooled water is again sent to the cold-water tank, and this completes the coolant channel. Any loss of cold water is compensated by adding make-up water from the tap.

Permeate channel

The permeate formed over the condenser surface (finned surface of the tube) flows to the bottom of the tube, from where it is taken out and collected in a small container. The copper condenser tube with fins and a hole for condensate removal is shown in Figure 6. The experiment is performed for a fixed time; the quantity of condensate collected in the container is weighed. The total flux is calculated using the following formula:

\[ J = \frac{W}{A_m \cdot t} \]  

where \( J \) is the total flux for that particular parameter set (kg/m².hr), \( W \) is the weight of the permeate (kg), \( A_m \) is the membrane area (m²) and \( t \) is the total time (hr). The quality of the permeate is measured by checking its salinity with the help of a conductivity check apparatus (Systronics-306).

RESULTS AND DISCUSSION

A HAGMD module is developed and analyzed in the present study. The performance of the HAGMD system can be indicated by the flux as the end product. The current experimental setup is not designed with an energy recovery option and energy efficiency studies is not the scope of current study. The effect of different operating parameters on the flux production will now be discussed in detail.

Figure 6 | Condenser tube with helical fins and tapping for permeate removal.
Feed temperature

Feed temperature (FT) is the most crucial parameter that affects the performance of any MD system (Khalifa & Lawal 2016). Higher the temperature difference across the membrane, higher will be the driving vapor pressure difference. For this reason, higher FTs are always desirable. But they impose a very strong constraint of increased energy cost on the system, unless a stand-alone renewable energy system is used for the overall energy supply. The effect of FT on the flux for different feed flow rate (FFR) is shown for the HAGMD system in Figure 7. The salinity (S) of the feed is constant at 20 gm/liter and cold-water temperature is maintained constant at 29 °C.

It is shown that the distillate flux increases with FT exponentially. It is because of the exponential relationship between the FT and the flux explained by the Antoine equation (Bouguecha et al. 2005; Khayet & Matsura 2017b). When the FT increases, the total driving force increases, the vapor pressure increases at the feed side and the evaporation rate increases at a given pressure. With an increase in the FT, the viscosity of the feed also reduces, which helps in reducing the thickness of the boundary layer formed near the membrane and facilitates the vapor diffusion through the membrane and ultimately increase the flux (Liu et al. 2016). For higher feed flow rate, the flux is higher because, the higher turbulence in the feed side further encourages the heat transfer and mass transfer coefficients. When the FT was increased by 15% from 65 °C to 75 °C, the flux for 2 lpm FFR was increased around 30% from 9.80 kg/m² hr to 13.1 kg/m² hr, and when the FT was increased 1.7 times from 45 °C to 75 °C, the distillate flux was increased 3.3 times from 4.5 kg/m² hr to 14.85 kg/m² hr. In both cases the temperature of cooling water is constant to 25 °C. This shows that higher will be temperature difference higher will be the flux, and also that the flux increases exponentially with FT (Elhenawy et al. 2020).

Figure 8 shows the variation of flux with FT for different values of salinities (S) of feed solution. The cold temperature is maintained constant at 29 °C. Feed flow rate as well as cold flow rate are maintained at 2 lpm. This figure shows that, with an increase in salinity, the flux reduces at any FT because of the reduction in vapor pressure and thus the driving force. At 55 °C as the salinity is increased by six times from 5 gm/liter to 30 gm/liter, the flux is reduced by two times from 8.7 kg/m² hr to 4.35 kg/m² hr, this facilitates the use of HAGMD even for very high salinity feed solutions. This result is in accordance with the previous published literature (Chouikh et al. 2005; Mahmoudi et al. 2017b).
Feed flow rate

The effect of feed flow rate on flux is shown in Figure 9. Here distillate flux is plotted against the feed flow rate for different values of FT. The feed salinity was maintained at 20 gm/liter. The cold flow rate is maintained at 2lpm. The cooling water temperature was maintained at 29 °C. It can be seen from the figure that the flux increases with an increase in the feed flow rate. The increased turbulence in the feed channel improves the overall heat and mass transfer rate. Further because of the increased flow rate, the turbulence increases and thus is reduced the temperature polarization. This process increases the temperature available at the membrane surface and therefore the driving force across the membrane, and results in higher flux (Alsalhy et al. 2018). Also for higher feed flow rates the retention time of the feed reduces and therefore the evaporation temperature available at the membrane surface increases that results in higher driving force and thus the higher flux (Liu et al. 2016). With higher feed flow rate and FT the flux is higher. The results are found in accordance with the literature as far as the behavioral trend of AGMD is concerned (Singh & Sirkar 2012; Khalifa et al. 2015; Aryapratama et al. 2016; Liu et al. 2016). Higher feed velocities also wash away the saline layer near the membrane and reduces the concentration polarization on the membrane surface, thus making more surface area available for permeation. However, this effect is negligible to be considered in laboratory scale module with lower salinities, but can affect slightly at very high salinity feeds. When the flow rate was increased from 1lpm to 3lpm, the flux was increased by 16%. Elhenawy et al. also showed that with feed flow rate the flux for an AGMD module without any spacer or corrugation in feed channel the flux increased by 25% for the same flow rate range (Elhenawy et al. 2020). As can be seen from this figure the maximum flux of 13.8 kg/m² hr is achieved at feed flow rate of 3 lpm and cold flow rate of 2 lpm for 75 °C FT.

Salinity

The effect of salinity (S) on the distillate production rate for the different feed flow rates is shown in Figure 10. In this figure, distillate output is plotted against different values of salinity for different values of feed flow rates. The FT was maintained constant at 75 °C and the cold fluid at 29 °C. It can be seen from the figure that an increase in the feed salinity decreases the distillate output. Increased salinity decreases the vapor pressure at given FT (Shahu & Thombre 2020) and thus, the driving force is reduced, as stated earlier. Higher feed flow rate causes higher turbulence that further washes away and reduces the effect of the saline layer present over the membrane surface, if any, yielding higher flux. Increase in a feed salinity from 5 gm/liters to 30 gm/liters by six times reduces

![Figure 9](image_url)  | Effect of feed flow rate on Flux at salinity – 20 gm/liter.

![Figure 10](image_url)  | Effect of salinity on Flux with different feed flow rate at FT – 75 °C.
the flux only by 1.4 times for all the low rates of 1–3 lpm. This shows that HAGMD can also be used for higher salinity solutions in similar to AGMD modules (Alsally et al. 2018).

Figure 11 shows the effect of salinity on flux for different feed temperatures. The cold fluid was maintained at 29 °C. Feed flow rate as well as cold flow rate is maintained at 2 lpm. It is observed that for any value of FT, distillate output decreases with an increase in salinity due to reduced vapor pressure and therefore the lower heat of evaporation available at membrane surface. However, the effect of FT variation is dominant on the vapor pressure and therefore the lower heat of evaporation availability has a little impact on vapor pressure (Geng et al. 2015). It is clear from the figure that the slope of flux change is different for different temperatures. For the variation of salinity from 5 gm/liters to 30 gm /liters, at FT of 45 °C the flux is reduced by 5.2 times whereas at 75 °C this reduction is only by 1.5 times. The reason for this is that at lower saturation temperatures the latent heat required is higher than that at higher saturation temperatures, and therefore the effect of reduced water activity due to increased salinity is prominent at lower temperatures.

**Cold flow rate**

An increase in cold flow rate increases the flux in the HAGMD module. Most studies in the literature show that the cold side flow rate only marginally affects the distillate flux (Banat & Simandl 1994; Elhenawy et al. 2020), while some researchers say that cold side flow rate also affects the flux to a considerable extent (Khalifa & Alawad 2018). In AGMD systems the domination resistance is offered through the air gap (Banat & Simandl 1994; Francis et al. 2013), but in the present study the air gap width is reduced by employing conductive fins and therefore the overall conductivity of the gap is increased and reduces the heat and mass transfer resistances and increases the flux. The condenser in the present study is made up of highly conductive copper material and also equipped with fins, and therefore the effect of cold conditions also plays a very important role in deciding the driving force. The higher cold flow rate helps in maintaining the temperature of the condenser at lower values and this result in overall higher driving force and thus the higher flux. The coolant temperature in our study was constant. In this experiment no chiller was used and therefore to keep the temperature of cold fluid constant, the increase in its flow rate helped to do so. It was observed that the cost of pumping for the coolant water was much less than the overall gain in the flux. The direction of cold water was counter to that of the permeate flow direction. This arrangement of fluid path will result in the best performance over other possible directions, as suggested by Swaminathan et al. (Shahu & Thombre 2019). Figure 12 shows the effect of coolant flow rate on the flux for different feed temperatures. The coolant temperature was maintained constant at 29 °C.

This figure shows that flux increases as the cold flow rate increases. Increasing the cold flow rate helps in faster heat removal because of increase in cold side heat transfer coefficient and thus maintains a higher driving force at any given inlet cold fluid temperature that increases the flux. From the figure it is clear that at higher feed temperatures the variation of flux with CFR is more than that at the lower values. The reason for this is that at lower feed temperatures the latent heat of condensation is higher than that at higher feed temperatures. For a given temperature difference the latent heat will be removed more effectively at higher cold flow rates. Additionally, provision of fins at the condenser surface presents more area for condensation and therefore more latent heat needs to be removed. Therefore, at higher cold flow rates the flux is higher as the heat is more effectively removed. Also, at higher feed temperatures the latent heat of vaporization required is less and therefore

![Figure 11](http://iwaponline.com/ws/article-pdf/21/4/1450/903864/ws021041450.pdf)
by employing higher cold flow rates renders higher driving force maintained and therefore more heat is utilized for evaporation at the membrane surface that results in higher flux. The distillate flux increases almost two-fold for increase in cold flow rate from 1 lpm to 3 lpm. Khalifa et al. also showed in their study that, for AGMD the coolant flow rate increases the flux by 14%, whereas for WGMD systems the flux was increased by almost 25% (Khalifa & Alawad 2018). This shows that, as the air gap conductivity is increased, the coolant flow rate plays an important role in positively affecting distillate flux.

Table 4 compares of the flux obtained by different studies that considered the modifications in air gap or the condenser side designs. The table shows operating parameters corresponding to the maximum flux obtained by different investigators.

The same comparison is shown in a bar graph using Figure 13. The values of parameters are different by different investigators but only the maximum flux obtained in each study is plotted here.

**CONCLUSIONS AND FUTURE SCOPE**

A novel design of the HAGMD system is developed and analyzed. The design of the module resembles to shell and tube heat exchanger. The feed flows through the outside shell and the cold water flows inside the hollow copper tube, which forms the condenser. The helical fins are provided over the outer surface of the condenser. The fins act as support for the membrane and also creates the air gap. The performance of the HAGMD system is experimentally investigated. The effect of FT, feed flow rate, cold flow rate, coolant temperature

| Module configuration | Module arrangement | Membrane material | Feed/cold flow rate (lpm) | Feed inlet temperature (°C) | Cold inlet temperature (°C) | Salinity | Maximum flux (kg/m².hr) | Reference |
|---------------------|--------------------|-------------------|---------------------------|-----------------------------|-----------------------------|---------|--------------------------|-----------|
| Hollow fiber AGMD   | Multiple cooling channels | Polypropylene (PP) | 0.4/0.3 | 75 | 20 | 3.5% w/v NaCl | 12.5 | Aryapratama et al. (2016) |
| Tubular AGMD        | Finned tube condenser | PTFE | 3/5 | 50 | 28 | – | 15 | Cheng et al. (2011) |
| Hollow fiber AGMD   | Double pipe module | PVDF | 12 | 90 | – | 530 µs/cm | 11.4 | Liu et al. (2016) |
| Plate and frame AGMD | Material gap | PTFE | 1.5 | 80 | 20 | 61,400 µs/cm | 20.45 | Francis et al. (2013) |
| Plate and frame AGMD | Conductive gap | – | 0.06 | 70 | 25 | – | 1.76 | Swaminathan et al. (2016b) |
| Cylindrical AGMD    | Helically finned copper condenser | PTFE | 3/3 | 75 | 29 | 5 gm/liter | 20 | This study |
and salinity of feed are analyzed on the system’s performance. Following conclusions can be drawn from the analysis:

- The fins on the copper condenser tube are helical in a design that starts from the top and continues to the bottom. The membrane is flat sheet and is wrapped and pasted over the condenser and forms a cylindrical shape that rests over the fins. The condensing vapors travel through the helically finned path from the top toward the exit at the bottom. The provision of fins facilitates the smaller air gap width with a very large condensation area, that is always favorable for the higher flux hence improving performance of HAGMD system.
- The maximum flux obtained from the system is 20 kg/m²·hr with feed of 5gm/liter salinity and with a driving force temperature difference of 45˚C, which is very high.
- The flux increases with an increase in FT feed flow rate, and cold flow rate, and reduces with an increase in salinity. The heat transfer resistance in air gap is reduced by employment of conductive fins and therefore the cold side flow rate helps to increase the heat and mass transfer coefficient that helps to increase the flux. It is suggested that to reduce the overall cost of the system, costly chilling units can be eliminated. The idea behind this is to result in higher average driving force by employing higher cold flow rates with normal room temperature cold water instead of that with lower cold flow rates and very low temperature cold water, as the advantage in flux overrides the cost of pumping in HAGMD systems.
- At lower permeate production rate, the module configuration is AGMD at the top half while conductive gap at the bottom half. This configuration is thus referred as a mixed HAGMD configuration. While at a higher distillate production rate, the HAGMD module behaves like a conductive HAGMD configuration.

The overall analysis reveals that the helical air gap MD system is very suitable for producing high distillate flux. An economic analysis and energy efficiency studies can be performed in future to further analyze the system’s better feasibility.

**DATA AVAILABILITY STATEMENT**

Data cannot be made publicly available; readers should contact the corresponding author for details.

**REFERENCES**

Alsalhy, Q. F., Ibrahim, S. S. & Hashim, F. A. 2018 Experimental and theoretical investigation of air gap membrane distillation process for water desalination. *Chem. Eng. Res. Des.* 130, 95–108. https://doi.org/10.1016/j.cherd.2017.12.013.

Aryapratama, R., Koo, H., Jeong, S. & Lee, S. 2016 Performance evaluation of hollow fiber air gap membrane distillation module with multiple cooling channels. *Desalination* 385, 58–68. https://doi.org/10.1016/j.desal.2016.01.005.

Banat, F. A. & Simandl, J. 1994 Theoretical and experimental study in membrane distillation. *Desalination* 95, 39–52. https://doi.org/10.1016/0011-9164(94)00005-0.

Bouguecha, S., Chouikh, R. & Dhabhi, M. 2005 Numerical study of the coupled heat and mass transfer in membrane distillation. *Desalination* 152, 245–252. https://doi.org/10.1016/S0011-9164(02)01070-6.

Cheng, L.-H., Lin, Y.-H. & Chen, J. 2011 Enhanced air gap membrane desalination by novel finned tubular membrane modules. *J. Memb. Sci.* 378, 398–406. https://doi.org/10.1016/j.memsci.2011.05.030.

Chouikh, R., Bouguecha, S. & Dhabhi, M. 2005 Modelling of a modified air gap distillation membrane for the desalination of seawater. *Desalination* 181, 257–265. https://doi.org/http://dx.doi.org/10.1016/j.desal.2005.04.006.

Dietrich, A. M., Glindemann, D., Pizarro, F., Gidi, V., Olivares, M., Araya, M., Camper, A., Duncan, S., Dwyer, S., Whelton, A. J., Younos, T., Subramanian, S., Burlingame, G. A., Khiari, D. & Edwards, M. 2004 Health and aesthetic impacts of
copper corrosion on drinking water. Water Sci. Technol. 49, 55–62. https://doi.org/10.2166/wst.2004.0087.

El Amali, A., Bougueche, S. & Maalej, M. 2004 Experimental study of air gap and direct contact membrane distillation configurations: application to geothermal and seawater desalination. Desalination 168, 357. https://doi.org/http://dx.doi.org/10.1016/j.desal.2004.07.020.

Elhenawy, Y., Elminshawy, N. A. S., Bassyouni, M., Alhathal Alanezi, A. & Drioli, E. 2020 Experimental and theoretical investigation of a new air gap membrane distillation module with a corrugated feed channel. J. Memb. Sci. 594, 117461. https://doi.org/10.1016/j.memsci.2019.117461.

Eykens, L., Reyns, T., De Sitter, K., Dotremont, C., Pinoy, L. & Van der Bruggen, B. 2016 How to select a membrane distillation configuration? Process conditions and membrane influence unreviewed. Desalination 399, 105–115. https://doi.org/10.1016/j.desal.2016.08.019.

Francis, L., Ghaffour, N., Alsadi, A. A. & Amy, G. L. 2013 Material gap membrane distillation: a new design for water vapor flux enhancement. J. Memb. Sci. 448, 240–247. https://doi.org/10.1016/j.memsci.2013.08.013.

Geng, H., Lin, L., Li, P., Zhang, C. & Chang, H. 2015 Study on the heat and mass transfer in AGMD module with latent heat recovery. Desalin. Water Treat. 57, 15276–15284. https://doi.org/10.1080/19443994.2015.1074122.

Khalifa, A. E. & Alawad, S. M. 2018 Air gap and water gap multistage membrane distillation for water desalination. Desalination. 437, 175–183. https://doi.org/10.1016/j.desal.2018.03.012.

Khalifa, A. E. & Lawal, D. U. 2016 Application of response surface and Taguchi optimization techniques to air gap membrane distillation for water desalination – A comparative study. Desalin. Water Treat. 57, 28513–28530. https://doi.org/10.1080/19443994.2016.1189850.

Khalifa, A., Lawal, D., Antar, M. & Khayet, M. 2015 Experimental and theoretical investigation on water desalination using air gap membrane distillation. Desalination. 376, 94–108. https://doi.org/10.1016/j.desal.2015.08.016.

Khayet, M. & Matsuura, T. 2011 Chapter 1 – Introduction to membrane distillation. Membrane Distillation (Khayet M & Matsuura T, eds.), pp. 1–16. Elsevier. https://doi.org/10.1016/b978-0-444-53126-1.10001-6.

Khayet, M. & Matsuura, T. 2012 Chapter 13 – Air gap membrane distillation. Membrane Distillation (Khayet M & Matsuura T, eds.), pp. 361–398. Elsevier. https://doi.org/10.1016/b978-0-444-53126-1.10013-2.

Koschikowski, J., Wieghaus, M. & Rommel, M. 2003 Solar thermal driven desalination plants based on membrane distillation. Water Sci. Technol. Water Supply. 3, 49–55. https://doi.org/10.2166/ws.2003.0149.

Lee, J., Alsadi, A. S. & Ghaffour, N. 2019 Multi-stage air gap membrane distillation reversal for hot impaired quality water treatment: concept and simulation study. Desalination. 450, 1–11. https://doi.org/10.1016/J.DESAL.2018.10.020.

Liu, Z., Gao, Q., Lu, X., Zhao, L., Wu, S., Ma, Z. & Zhang, H. 2016 Study on the performance of double-pipe air gap membrane distillation module. Desalination 396, 48–56. https://doi.org/10.1016/j.desal.2016.04.025.

Mahmoudi, F., Moazami Goodarzi, G., Dehghani, S. & Akbarzadeh, A. 2017A Experimental and theoretical study of a lab scale permeate gap membrane distillation setup for desalination. Desalination 419, 197–210. https://doi.org/http://dx.doi.org/10.1016/j.desal.2017.06.013.

Mahmoudi, F., Siddiqui, H., Pishbin, M., Goodarzi, G., Dehghani, S., Date, A. & Akbarzadeh, A. 2017b Sustainable seawater desalination by permeate gap membrane distillation technology. Energy Procedia. 110, 346–351.

Shahu, V. T. & Thombre, S. B. 2013 Air gap membrane distillation: a review. J. Renew. Sustain. Energy. 11, 45901. https://doi.org/10.1063/1.5063766.

Shahu, V. T. & Thombre, S. B. 2020 Analysis and optimization of a new cylindrical air gap membrane distillation system. Water Supply 20, 361–371. https://doi.org/10.2166/ws.2019.164.

Singh, D. & Sirkar, K. K. 2012 Desalination by air gap membrane distillation using a two hollow-fiber-set membrane module. J. Memb. Sci. 421–422, 172–179. https://doi.org/10.1016/j.memsci.2012.07.007.

Summers, E. K. & Lienhard V, J. H. 2015 A novel solar-driven air gap membrane distillation system. Desalin. Water Treat. 51, 1344–1351. https://doi.org/10.1080/19443994.2012.705096.

Swaminathan, J., Nayar, K. G. & Lienhard V, J. H. 2016a Mechanical vapor compression – membrane distillation hybrids for reduced specific energy consumption. Desalin. Water Treat. 57, 26507–26517. https://doi.org/10.1080/19443994.2016.1168579.

Swaminathan, J., Chung, H. W., Warsinger, D. M., AlMarzooqi, F. A., Arafat, H. A. & Lienhard V, J. H. 2016b Energy efficiency of permeate gap and novel conductive gap membrane distillation. J. Memb. Sci. 502, 171–178. https://doi.org/10.1016/j.memsci.2015.12.017.

Swaminathan, J., Chung, H. W., Warsinger, D. M. & Lienhard V, J. H. 2018 Energy efficiency of membrane distillation up to high salinity: evaluating critical system size and optimal membrane thickness. Appl. Energy. 211, 715–734. https://doi.org/10.1016/j.apenergy.2017.11.043.

Teoh, M. M., Bonyadi, S. & Chung, T. S. 2008 Investigation of different hollow fiber module designs for flux enhancement in the membrane distillation process. J. Memb. Sci. 311, 371–379. https://doi.org/10.1016/j.memsci.2007.12.054.

Wu, H. Y., Tay, M. & Field, R. W. 2016 Novel method for the design and assessment of direct contact membrane distillation modules. J. Memb. Sci. 513, 260–269. https://doi.org/10.1016/j.memsci.2016.04.009.

Yang, X., Yu, H., Wang, R. & Fane, A. G. 2012 Analysis of the effect of turbulence promoters in hollow fiber membrane distillation modules by computational fluid dynamic (CFD) simulations. J. Memb. Sci. 415–416, 758–769. https://doi.org/10.1016/j.memsci.2012.05.067.

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