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## Modeling and Experimental Study by Using Air Gap Membrane Distillation Process

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### ABSTRACT

The aim of this work is to design and manufacture AGMD module that enable us to complete experimental investigation on the system execution. The investigation has performed for laboratory prepared salty water solutions. The effect of operating parameters as well as module design parameters on the system execution has been studied. These parameters include hot water temperatures, warm water flow rates, hot water salinity, cold water temperatures, and cold water flow rates and PTFE pore sizes. The system execution has been assessed quantitatively by distillate flux and qualitatively by distillate salinity. The distillate flux has been dramatically increased with increasing of hot water temperatures and hot water flow rates. However, it was reduced by increasing of cold water temperature. The system execution is mostly affected by both hot water temperatures and hot water flow rates, but the cold water temperature has relatively considerable effect on distillate flux. It is noticed that increasing the hot water temperature from 40°C to 70°C is led to about 346 % increment in flux production. Further increasing in hot water temperature up to 80°C the permeate salinity was increased from 50 ppm to 450 ppm. Also, increasing the hot water flow rate from 2 to 6 L/min is led to about 173 % growth in distillate flux and the salt refusal factor is found to be a greater than 99.99 % throughout all experiments.

**Key words:** experimental study of AGMD: development of velum distillation: enhancement of Air Gap Membrane Distillation-Based Desalination Technologies: Modeling study.

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### Introduction

Desalting water is known as a process that separates salts of water. Desalting methods can be used in municipal, manufacturing or commercial uses. By means of developments in technology, desalination costs will be cheap with other methods of making process in order to reduce our rising needs of drinking water. While the request for clean water has been increasing in the social and financial areas and the land consists of approximately  $1.4 \times 10^9 \text{ km}^3$  of water, which can take up about 70 % of the earth's surface, the proportion of salt water in this large amount is 97.5%. The remaining 2.5% are fresh water with 80% of this amount frozen in the ice caps or combined as soil moisture. Both forms are not readily available for daily human use. The remaining amount, about 0.5 %, is considered sufficient to support all life on earth. Unluckily, this water does not barge evenly through the plant and is not presented in plenty amounts once or when it wants (Drioli and Criscuoli, 2000).

Global water consuming has been risen dramatically, twice as fast as population growth. The universal obtainability of clear water for manufacturing wants and human consumption is limited. Recently, several development activities have led to an increase in pollution and deterioration of water quality. The demand for water in the world has grown rapidly in the event of a progressive increase in water demand for irrigation, rapid industrialization, population growth and improvements in living standards (Alkhudhiri *et al.*, 2012). All types of water have different salt contents, which is often described by the total dissolved solids (TDS) concentration. Water is considered to be drinking water if

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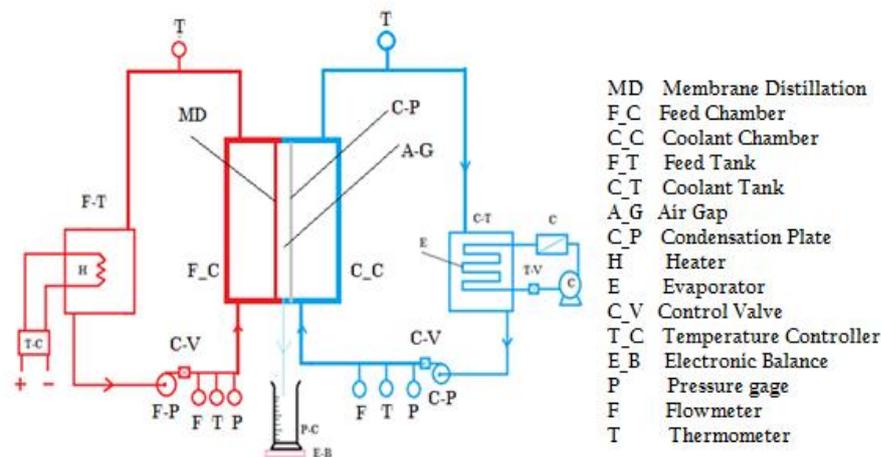
its TDS is lower than 500 ppm. Seawater has a TDS of about 35,000 ppm and brackish water has a TDS among drinking water and seawater. Wastewater is another species that contains dissolved salts mainly in the low brackish water limit. The repaired water from the sewage can be used for irrigation, cooling water and other industrial applications. However, the recycling and reuse of residual waste water should be treated for the future management of water (Zhang *et al.*, 2010; Khayet, 2010).

In this section, review of previous work concerning the research studies carried out for the development of Velum-Based Desalination Technologies. Chouikh *et al.* (2005) studied numerically and experimentally the execution of the air hole velum distillation (AGMD) which has been combined the low conductive heat loss of an air hole velum for distillation with the reduced mass transfer resistance of a direct contact velum. The result was shown a slight enhancement of distillate flux. An experimental laboratory apparatus was built, and different operating parameters have been investigated such as hot water flow rate, hot water temperature and air hole width. The results have been in a good agreement with those found in the numerical study. Francis *et al.* (2013) experimentally investigated the effect of material width and characteristics have been investigated. An increase in the water gap width from 9 mm to 13 mm was led to increase of permeability of membrane. An investigation on an AGMD and MGMD execution comparison, carried out using two diverse of viable membranes provided by different companies. Adham *et al.* (2013) evaluated that, the feasibility of using MD technology to desalinate brines from thermal desalination plants. A state-of-the-art MD bench scale unit was assembled and the execution of different MD membrane was compared under changeable of operating conditions using synthetic saline solutions. Camacho *et al.* (2013) [8] considered that, the fundamental heat and mass transfer procedures in velum distillation. As a result, large pore size PTFE flat sheet was showed higher permeability than laboratory fabricated velum when tested under similar conditions. Warsinger *et al.* (2015) studied the hydrophobicity of the support mesh for the velum was found to have minimal effect on the distillate flow rate, but high conductivity for the mesh was showed notable improvement in distillate flux. Also super hydrophobic condensing surfaces have shown very significant distillate flux increases for AGMD, with more than a 100% improvement in some cases Khayet and Cojocaru, (2012). This paper is an overview for modeling and optimization of air hole membrane distillation process used in desalination. Regression models have been developed to predict the execution index and the specific execution index that took into consideration the energy consuming as function in differ of changeable parameters. The developed models have been statistically validated by analysis of variance. The salt refusal factors were found to be greater than 99.9%. Alsaadi *et al.* (2013) theoretical model was validated by using AGMD experimental data obtained at diverse of operating conditions and parameters. The predicted distillate flux was compared by five different hot water temperatures, two different hot water salinities, three different air hole widths and two MD with differ of pore sizes. This comparison showed that the model flux predictions are strongly linked with the experimental data, with model predictions being within +10% of the experimentally determined values. Guijt *et al.* (2004) studied and compered amongst air hole membrane distillation that calls (AGMD) and predictive model designs. The experimental results shown that, the previous developed predictive model, with velum parameters determined from gas permeability experiments, describes correctly the dependence of water vapour flux on hot water temperature, air hole width, hot water flow and membrane type. Khan and Martin (2014) examined one approach by investigating the application in terms of suitable membrane technologies, specifically air hole membrane distillation that calls (AGMD). Results shown that the tested AGMD prototype was capable of achieving high salt refusal factor. Francis *et al.* (2013) investigated the experimental effects of material thickness and properties studied. An increase of 9 mm to 13 mm width of the water gap increased the steam throughput. A study was also reported comparing the performance of AGMD and MGMD using two different commercial membranes supplied by different manufacturers. However, it has been observed that the water vapor stream is significantly enhanced using suitable materials amongst the film and the condensation plate in an air cavity membrane distillation unit (AGMD). Meindersma *et al.* (2006) analyzed hydrophobic MD membranes that vapor was allowed to pass into pores. The vapor pressure was created by the different among feed and cool temperature which led to increase the vapor pressure. It was projected that the full fee of clear water that created by film distillation could be lesser than \$ 0.5/m<sup>3</sup>, however, depending on supplier of thermal energy that wanted for the evaporation of water membrane could be reduced almost to \$ 0.26/m<sup>3</sup>. Pangarkar *et al.* (2011) used an air-space membrane distillation process (AGMD) to purify natural groundwater with membrane modification. The commercial hydrophobic

polytetrafluoroethylene (PTFE) membrane having a pore size of 0.22  $\mu\text{m}$  and a porosity of 70% was used. The modification of the surface of the membrane was carried out by treating the membrane with alcohol. The effect of the hot water flow rate, hot water temperature, cold water temperature, air space depth, and operating time in the permeate flow were examined for the treated and untreated membrane. Within the range tested, the MD flux was significantly increased by 69% at 40.48  $\text{kg}/\text{m}^2 \text{ h}$ , as it increased to 42% of the membrane mass transfer coefficient due to membrane surface modification. Xu *et al.* (2016) showed ten different PTFE, PP and high membrane distillation desalination air gap brine commercially available PVDF velum (AGMD). Performance temperature methods were searched for the various operating parameters, feed and salt concentration of the membrane material flow rates, thickness, pore size, hot water solution concentration 120  $\text{g}/\text{l}$ , and the membrane has achieved different properties and local design and manufactured AGMD module, The results showed that the infiltration flux increased with increasing of hot water temperature regardless of the hot water solution concentration. However, the cold water flow rate has not significantly affected the distillate flux. On the other hand, PP membrane performed was better than PVDF and PTFE membranes.

### Experimental set-up

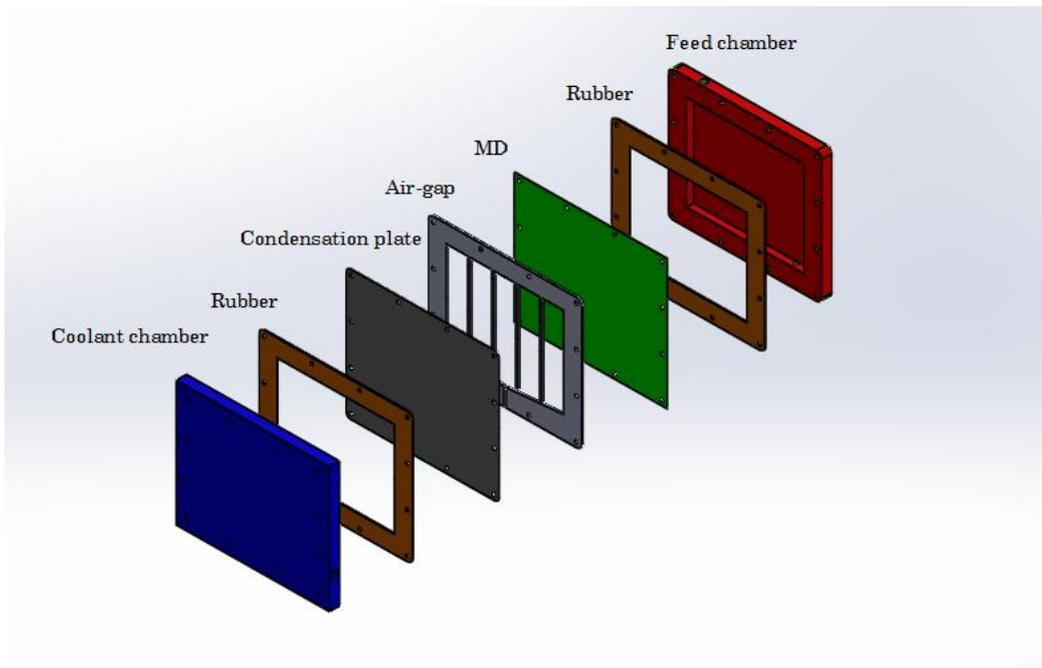
The air hole film distillation that calls (AGMD) set up layout is illustrated in figure 4-1. A one stage only is utilized in this study. The structure is consisted of two water locked rotations, hot and cold cycles, which linked to the AGMD unit. The main components of the experimental setup involves of 0.5 hp centrifugal pumps, which are responsible for driving hot saline water from feed bath to the module at particular of flow rates and the cold bath to the module at differ of flow rate. A digital thermostat controller is connected with an electric heater in order to control the feed water temperature bath to make sure that, the hot water temperature is stable during the test time. Heater (2 kW) is responsible for supplying the hot water solution, manual valves, hot water tank, cold water tank and water flow rates are measured by acrylic flow-meters (accuracy of 4%) and controlled by control valves and temperature was measured by J-type thermocouple with temperature range of (-200 to 800  $^{\circ}\text{C}$ ). Also, the cooling water unite is linked with cooling tank circulating bath (chiller) for providing cooling water recovery. However, the MD unit is a core of the system where a salty water is separated.



**Fig. 1:** Experimental set up.

However, figure 2 shows a CAD drawing of the new AGMD module. A PTFE membrane specimen of 30 cm width and 25 cm height was tested in an AGMD flat sheet module made of polycarbonate meth-acrylate as shown in figure 3, it is locally designed. It consists of two chambers which are the hot water chamber and the cold water chamber. Also consist of the condensation plate of 30 cm width, 25 cm length and 1 mm thickness which providing necessary surface area for the condensation of vaporized water and situated at the cooling side. Amongst every components within the module, there is a rubber gasket to prevent leakage and in some case to control the air hole width.

The hot chamber and cooling chamber are dimensioned of the hot chamber are 30 cm width, 1.2 cm depth, and 25 cm length. Cooling channel dimensions are 30 cm width, 1.2 cm depth, and 25 cm length. The effective velum area at the hot chamber is  $0.04 \text{ m}^2$ . The condensation surface is made of stainless steel material of 1mm thickness, 30 cm width and 25 cm length.



**Fig. 2:** CAD design of the new MD cell.



**Fig. 3:** AGMD flat sheet module design.

### **Distillate flux (estimation)**

Distillate flux ( $J$ ) for a given MD unit is known as the total volume of product water obtained per unit area per unit time at a specified conditions (hot water flow rate and hot water temperature, cold water flow rate and cold water temperature, membrane area, etc).

The distillate flux unit is (L/m<sup>2</sup>.h) by using the volume of permeating collected by sampling time from the module's effective velum area as written:

$$\dot{m}_p = \frac{v\rho}{t} \dots\dots\dots (1)$$

$$J = \frac{\dot{m}_p}{A} \dots\dots\dots (2)$$

Where t and A mention time in h and the effective velum area in m<sup>2</sup> separately. The productivity of the system has been obtained from manual measurements by collecting a liter of permeate and recording the time during the test and then returned it to the system.

Moreover, the salt refusal factor (R<sub>f</sub>) is calculated by following relation:

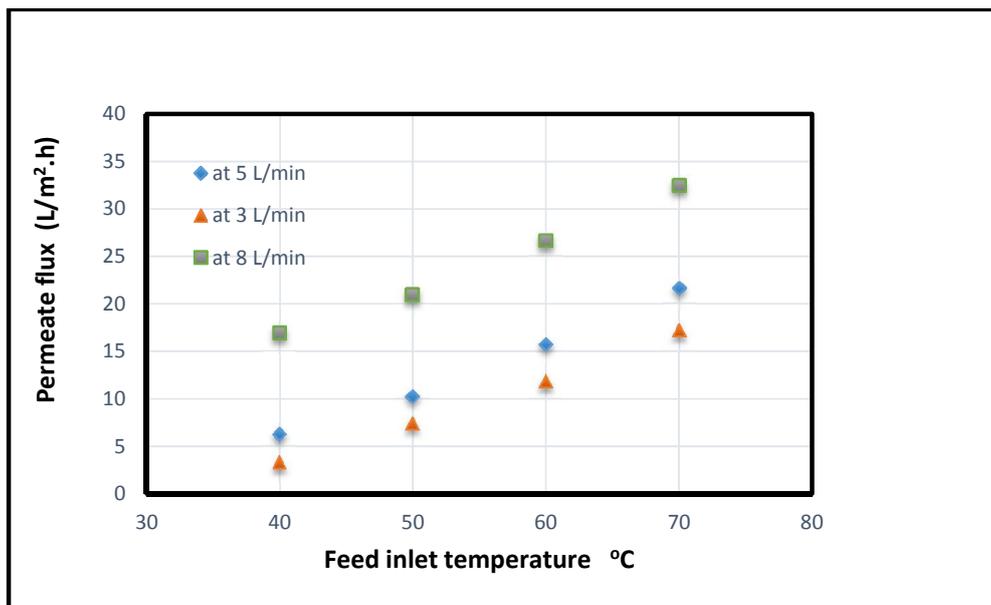
$$R_f = \left( \frac{C_H - C_D}{C_H} \right) * 100 \% \dots\dots\dots (3)$$

Where, C<sub>H</sub> and C<sub>D</sub> are the salt concentrations of the hot water and distillate flux, separately.

## Results and Discussion

### Hot water temperature impact on permeability of membrane

Firstly, the experimental results of the effectiveness of hot water temperature on distillate flux in differ of warm water flow rates is presented in figure 4. It can be seen that, the productivity is risen by increasing of warm water flow rates and hot water temperatures. The distillate flux is dramatically improved from 3.3 to 33 L/m<sup>2</sup>.h without any sensible growth of the salinity pure water while the hot water temperature is risen from 40°C to 70°C, although the warm water flow rate is changed from 3 to 8 L/min. But, when the hot water temperature was bigger than 80 °C the salinity of product water is risen from 50 ppm to 400 ppm while the salt refusal factor is found to be a greater than 99.99 % throughout all experiments.



**Fig. 4:** Hot water temperature impact on distillate flux in differ of warm water flow rates.

Parameters: C<sub>T</sub> = 30 °C, Q<sub>c</sub> = 5 L/min, FC = 30000 ppm, air gap = 2 mm, P = 1 bar and using pore size of 0.22µm PTFE velum material.

Moreover, growing the hot water flow rate also reduces the water resistance time in hot canals and causes the temperature of the hot mass in the hot canal to be closer to the hot water temperature. The normal rise of permeate flux when the hot water flow rate changed from 3 to 5 L/min is approximately 133 %, but the typical distillate flux is risen of approximately 170 % by changing of

warm water flow rate from 5 to 8 L/min. As it can be seen in this figure that rising of hot water temperature consequences in an exponential growth in permeability of membrane.

Secondly, hot water temperature impact on distillate flux in differ of cold water temperatures as shown in figure 5, the changeable conditions are hot water temperature is ranged 40-70 °C and the cold water temperature is changed from 10 to 30 °C. Stable parameters are hot water flow rate 5 L/min, cold water flow rate 5 L/min, hot water solution concentration 30,000 ppm and air hole width 2 mm. It has been observed that the distillate flux is risen by increasing of hot water temperature and declined with increasing of cold water temperature. Also, Increasing of hot water inlet temperature is led to be as a fundamental growth in the distillate flux.

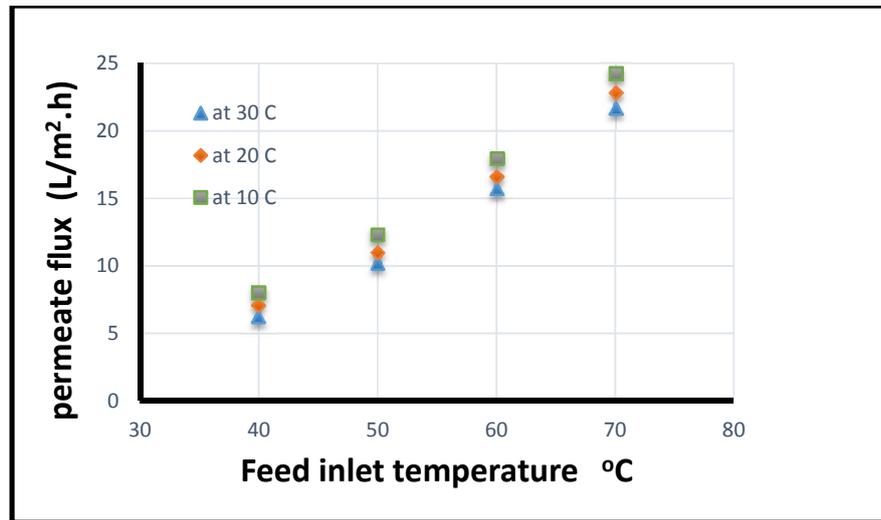


Fig. 5: Hot water temperature effect on distillate flux in differ of cold water temperatures.

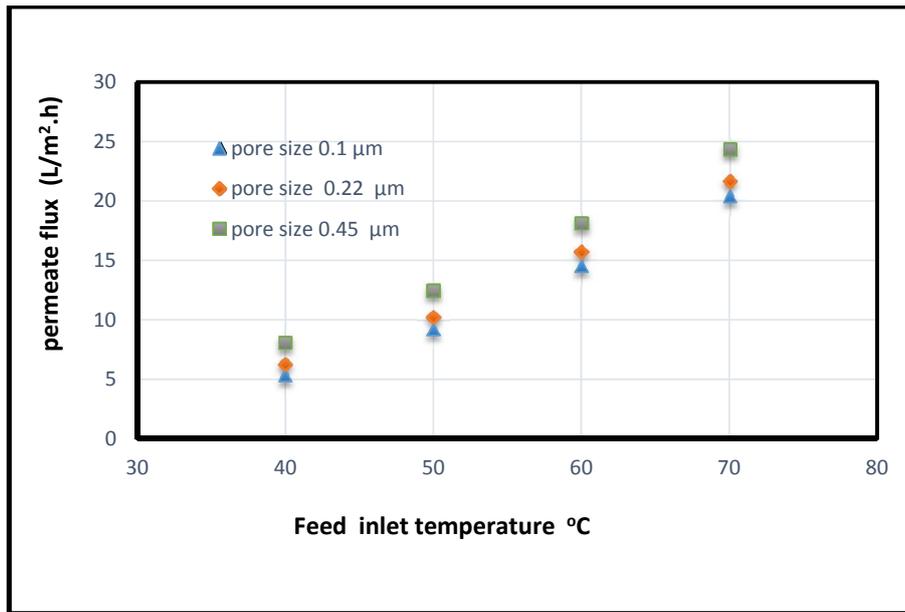
Parameters:  $Q_f = 5$  L/min,  $Q_c = 5$  L/min, FC = 30000 ppm, air gap = 2 mm, P = 1 bar and using pore size of 0.22 $\mu$ m PTFE velum material.

However, the observed increase in distillate flux therefore the decline in cold water temperature from 30 to 10 °C recognized as driving force responsible of transmembrane diffusion. Careful observation of figure 5 revealed that the high growth of distillate flux has been registered is about 346 % when the hot water temperature was changed from 40 to 70 °C. A normal calculation decrease in distillate flux of 6 % when the cold water temperature is changed from 10 °C to 20 °C, at same hot water temperature. It has also been dropped of 5 % once the cold water temperature was risen from 20 °C to 30 °C.

#### Pore size impact on distillate flux in differ of hot water inlet temperature

Pore size impact on distillate flux in differ of hot water temperature is illustrated in figure 6. The changeable conditions are hot water temperature which was ranged from 40 to 70 °C and the PTFE pore size is changed from 0.1 to 0.22 to 0.45 $\mu$ m. The stable test parameters are warm water flow rate 5 L/min, cold water flow rate 5 L/min, hot water solution concentration 30000 ppm and air cavity width 2 mm. It could be clearly noted that, distillate flux is increased by increasing of hot water temperature and increased by rising of PTFE film pore size as well.

It can be seen that the execution of the system is effected by the PTFE pore size which PTFE 0.1  $\mu$ m is given a lower permeability of the membrane by comparing to PTFE 0.22 and 0.45  $\mu$ m. But, 0.45  $\mu$ m of PTFE pours has a higher increase of distillate flux around of 120% than 0.1  $\mu$ m PTFE when the use of hot water temperature is risen from 40 to 70 °C. In addition, the distillate flux is increased by almost 105% once the pore size is changed from 0.1 to 0.22  $\mu$ m.



**Fig. 6:** Pore size impact on distillate flux in differ of hot water temperatures.

Parameters:  $Q_f = 5$  L/min,  $Q_c = 5$  L/min, FC = 30000 ppm, air gap = 2 mm and  $p = 1$  bar.

#### **Cold water flow rate impact on distillate flux in differ of cold water flow rates**

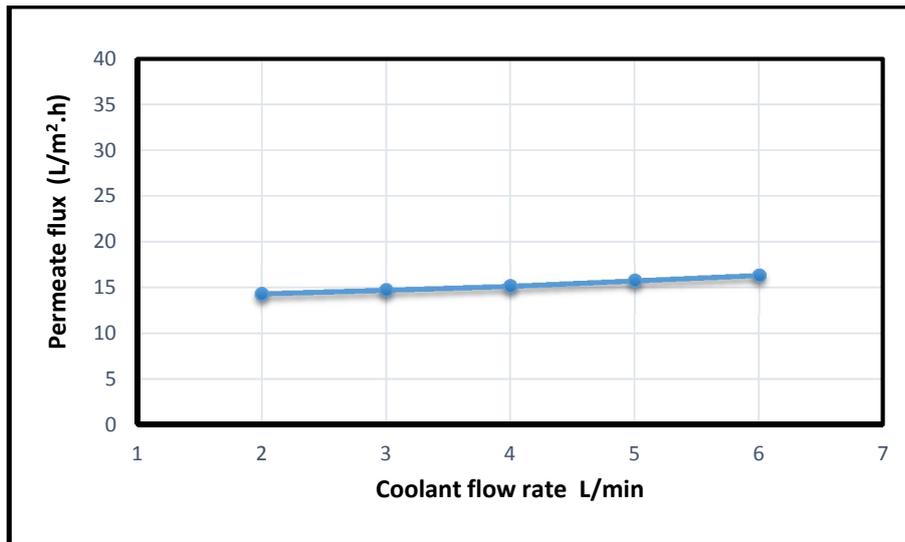
The effectiveness of cold water flow rate on distillate flux is illustrated in figure 7. The changeable condition is the cool water flow rate that is changed from 2 to 6 L/min. The stable conditions are hot water temperature 60°C, cold water temperature 30 °C and the hot water flow rate 3 L/min and air hole width 2 mm. There is no significant difference while the cold water flow rate was changed from 2 to 6 L/min, the percentage of distillate flux is slightly improved about 114 % as a result that obtained from the test.

However, it can be clearly seen that, the role of cool water flow rate is slightly effected on distillate flux as clearly observed from the figure and could be ignored it, when comparing with anther parameters.

#### **Hot water solution concentration effect on distillate flux**

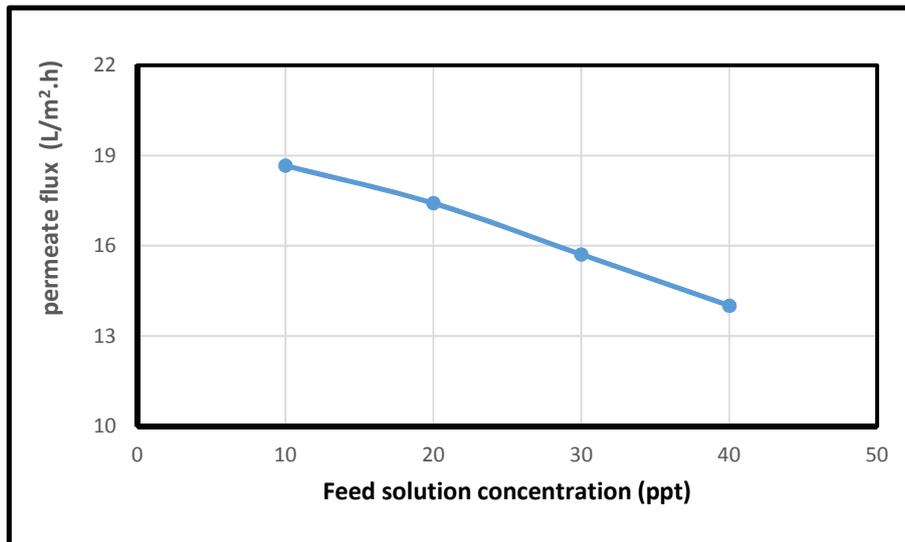
Figure 8 is explained the impact of hot water solution concentration on distillate flux, the hot water solution was changed from 10000 to 40000 ppm. But the stable parameters were hot water temperature 60°C, cold water temperature 30°C, hot water flow rate 5 L/min, cold water flow rate 5 L/min, air hole width 2 mm and PTFE pore size 0.22 µm.

It can be obviously observed that, the distillate flux tends to gradually decrease with increasing of the hot water solution concentration. The high percentage reduction in distillate flux once hot water solution concentration was reformed from 10000 to 40000 ppm of around 25 %. The gradual reduction in the system execution with growing of hot water solution concentration is impacted of concentration polarization, which is resulted in reduction of water vapour pressure. In general, increasing of hot water solution concentration has a bad impact on the permeability of membrane that can be observed to be in significant when compared to other desalination technology like reverse osmosis where higher hot water inlet solution concentration seriously impacts on execution of the system. The measured salty water repudiation factor was found to be almost of 99.99 % in all situations of the examined.



**Fig. 7:** Cold water flow rate impact on distillate flux in differ of cold water flow rates.

Parameters:  $Q_f = 5$  L/min,  $f_T = 60$  °C,  $c_T = 30$  °C, FC = 30000 ppm, air gap = 2 mm, P = 1 bar and using pore size of 0.22 $\mu$ m PTFE velum material.



**Fig. 8:** Hot water solution concentration influence on distillate flux.

Parameters:  $Q_f = 5$  L/min,  $f_T = 60$  °C,  $c_T = 30$  °C,  $Q_c = 5$  L/min, air gap = 2 mm, P = 1 bar and using pore size of 0.22 $\mu$ m PTFE velum material.

## Conclusion

Water desalination employing air gap membrane distillation has been investigated. The effect of AGMD operating parameters like hot water temperature, hot water flow rate, cold water temperature, and cold water flow rate on the distillate production have been investigated experimentally. The effectiveness of pore size on distillate flux was also considered. Also, the impact of hot water solution concentration on distillate flux as well as salt refusal factor were studied and presented.

Generally, the system execution is mostly affected by both hot water temperature and hot water flow rate, but the cold water temperature has relatively considerable effect on permeability of the

membrane. It is noticed that increasing hot water temperature from 40°C to 70°C is led to about 346 % growth in distillate flux production. Further increasing in hot water inlet temperature up to 80°C the permeate salinity was increased from 50 ppm to 450 ppm. Also, increasing the hot water flow rate from 2 to 6 L/min is led to about 173 % growth in distillate flux. However, the permeability of membrane is improved by increasing of pore size from 0.1 to 0.22 to 0.45 separately. While increasing of hot water solution concentration has a bad impact on the permeability of membrane and the role of cold water flow rate is slightly effected on distillate flux in which could be ignored it, when comparing with another parameters.

#### **Acknowledgment:**

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#### **Abbreviation:**

AGMD	Air Gap Membrane Distillation
DCMD	Direct Contact Membrane Distillation
VMD	Vacuum Membrane Distillation
SGMD	Sweeping Gas Membrane Distillation
CFD	Computational Fluid Dynamics
TDS	Total Dissolved Solids
PTFE	Polytetrafluoroethylene
PP	Polypropylene
A	Air
W	Water
F	Feed
M	Membrane
D	Distillation

#### **Greek Letters:**

$\delta$	Membrane thickness; film thickness [ $\mu\text{m}$ ]
$\varepsilon$	Porosity [%]
$\mu$	Viscosity [Pa. s]
$\rho$	Density [ $\text{kg}/\text{m}^3$ ]

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