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Experimental Study for Water Desalination by Low-Pressure Membranes: Air Gap Membrane Distillation.

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Experimental Study for Water Desalination by Low- Pressure Membranes: Air Gap Membrane Distillation

دراسة عمليه لتحلية المياه باستخدام أغشية الضغط المنخفض التحلية بطريقة الثغرة الهوائية

Salwa .Abobeah, Kamal El-Nahhas, A.A.Hegazi and G.I.Sultan

KEYWORDS:
Membrane distillation, desalination, Air-gap, experimental testing

***الملخص العربي:*- تحلية المياه من الأبحاث التي تتوجه اليها معظم الدول في الوقت الحالي بسبب عدم كفاية مصادر المياه النظيفة مع ارتفاع أعداد السكان بها، هذا البحث يتناول دراسة عمليه لعملية تحلية المياه باستخدام أغشية الضغط المنخفض والفجوة الهوائية حيث تم دراسة العوامل المؤثرة علي معدل إنتاج ماء خالي من الملاح العالية وصالح للاستخدام الآدمي من محلول ملحي عالي التركيز. وتم تصنيع وحده عملية لتحلية المياه باستخدام أغشية الضغط المنخفض ، والفجوة الهوائية تتكون من غرفتين لاستقبال الماء المالح وغرفة تبريد مشتركة ، وتم تشغيل هذه الوحدة بطريقتين: الطريقة الأولي يتم فيها إدخال ماء مالح عند نفس درجة الحرارة الى كلتا الغرفتين ، الطريقة الثانية يتم فيها إدخال الخرج من الغرفة الأولي كتغذية للغرفة الثانية. العوامل التي تمت دراستها علي الوحدة هي تاثير كل من درجة حرارة الماء المالح المستخدم ودرجة حرارة الماء المستخدم للتبريد وكذلك سرعة دخول كل من الماء المالح والماء المستخدم في التبريد علي كمية الماء النقي الناتج من الوحدة . البحث العملي يبين أن انسب ظروف لتشغيل الوحدة هو ضبط درجة حرارة دخول الماء المالح على 70 ^{O}C ودرجة ماء التبريد على 10 ^{O}C وسرعة دخول الماء المالح على 0.8 m^2/s وسرعة دخول الماء البارد علي 0.65 m^2/s حيث زيادة درجة الحرارة والسرعة أعلي من هذه القيم يزيد التكلفة في استهلاك الطاقة ويصبح غيرإقتصادي. واستخدام هذه الظروف للتشغيل أدي إلى معدل إنتاج 110 L/m^2h عند تشغيل الوحدة بالنظام الأول عند نفس درجة الحرارة للغرفتين وذلك خلال 50 ساعة من التشغيل المتواصل بينما كان الإنتاج في نفس الوقت عند استخدام الطريقة الثانية للتشغيل 100L/m^2h**

***Abstract*— Water desalination became very important process because of the leakage in clean water sources and the increase of human demand. This paper introduces an experimental study for air gab membrane desalination process AGMD using low pressure membrane type. The experimental unit was designed and fabricated according to the data collected from the literature review. The unit used experimentally is a double feed desalination unit. The study consists of two categories: the first one studies desalination unit as a parallel feed unit, the two feed have the same temperature, the second one studies desalination unit as a forward feed unit, the feed to second stage is the recycled outlet of first stage.**

Experimental study shows that the most effecting parameters in AGMD are; inlet feed temperature, inlet feed velocity, inlet coolant temperature and inlet coolant velocity. The optimum operating conditions to get maximum permeate flux according to experimental results are; inlet feed temperature of 70 ^{0}C, inlet feed velocity of 0.8 m/s, inlet coolant temperature of 15 ^{0}C, inlet coolant velocity of 0.65 m/s. As increasing temperature and velocity lead to increase in cost compared with the amount of product. Using the previous operating conditions lead to permeate flux amount of 55.657 L/m^2h from each feed chamber, total permeate flux of 110 L/m^2h, when operating the unit as parallel feed. The operating time of the unit was 50 h. In the

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recycled feed method, the maximum permeate flux was found to be 100 L/m^2h from the two chambers together.

I. INTRODUCTION

Water desalination became an international industry because of the high need of valid water around the world and leakage in fresh water sources. The most used membrane desalination technology is reverse osmosis (RO). Where fresh water can be obtained using semi-permeable membranes under high pressure leaving behind brine solution with high salt concentration [19**],[20]**.. Because of high energy consumption and high cost, the method used in desalination should be economical to reduce cost. So mmembrane distillation will be used, it is a thermal separation process that can be used for the extraction of clean water. The mass transfer occurs through a porous membrane which is not ***wettable*** for the solvent. Two liquids with different temperatures get in contact with the membrane. The feed side contains the warm aqueous solution, e.g. sea water, on the distillate site contains the condensed steam, permeate, passed the pores of the membrane. Temperature gradients between the two sides of the membrane causes a steam pressure difference which is the driving force for the formation and transportation of steam molecules through the pores of the membrane. [1**].**

Many researches had been done on water desalination, some of them introduced only theoretical study, others were only experimental researches and others done both theoretical and experimental model to study.

Scheer et al. [2] experimentally studied and explained the effect of feed temperature and pore size of MD. They found that the pressure of the feed side has no effect. They studied the flow rate at two types of membrane and found that using membranes of PTFE was better than using membranes of PP. Also, they had been tested pressure loading capacity and recommended the flow of the feed solution should be turbulent along the membrane.

De Andres et al. [3] experimentally tested a combined MD module and a one stage multi-effect distiller. Results showed that permeate flux from the two systems was higher by about 7.5% and the gain output ration (GOR) of the system was increased by 10%. The temperature of about 85 °C was considered as the optimum operating condition for the feed at the evaporator inlet and a circulation flow of about 170kg/h.

Feng et al. [4] used Polyvinylidene fluoride Nano fibre membrane in AGMD to have pure water from feed saline water with NaCl concentration of 6 wt. %. They found that the membrane material was still unknown and the result was closed to commercial micro filtration membranes.

Pangarkar and Sanean. [5] Experimentally investigated the performance of (AGMD) for aqueous NaCl solution, natural ground water and seawater using a flat sheet PTFE membrane. They found that permeate flux increased with increasing the feed temperature and feed flow rate and decreased with increasing coolant temperature and air gap thickness. The optimum operating conditions of AGMD process was tested.

Alkhudhiri et al. [6] experimentally tested the impact of using a high concentration of NaCl, $MgCl_2$, Na_2CO_3, and Na2SO4 as feed solution in AGMD. Results showed that the permeate flux decreased with increasing feed concentration. It was also found that energy consumption at different membrane pore size, and feed solution type and concentration was independent of feed solution concentration, feed solution type and membrane pore sizes.

Tian et al. [7] made a new design of AGMD with advanced improvement method, high efficient and low cost. The new module was able to produce a maximum of 119kg/m^2h distil water when tap water was used as the feed solution. The maximum flux was obtained at the coolant and feed temperature of 12 °C and 77 °C respectively.

Khalifa et al. [8] studied experimentally and theoretically the performance of an (AGMD) system. The effects of main operating and design parameters on the permeate flux were tested. The design of the AGMD module and the experimental setup were presented in details. PTFE membranes of two different pore sizes were used and experimented. The performance of the system was highly affected by changes in both feed temperature and air gap width. Increasing the feed temperature from 40 °C to 80 °C, increased the flux by 550% to 750%, it was depended on the other operating variables. The theoretical model was validated by comparing the permeate flux with experimentally measured values where a maximum deviation of 15% was observed.

Gryta and Tomaszewska [9] experimentally studied membrane distillation (MD) with a laminar flow of the streams in the MD module. The model equations describing the heat transfer in MD modules were inserted and compared with an experimental result. The accuracy of the calculation of the interphase temperatures increases which cause the increase of MD model credibility. The Nusselt number correlation developed was said to be used for membrane distillation heat transfer in MD module.

Liu et al. [10] made experiments on AGMD using different aqueous solutions, namely: tap water, salted water, dyed solutions, alkali solutions and acid solutions. Simple relationships were obtained. Theoretical model of heat and mass transfer associated with Air gap membrane distillation was developed and the developed model was validated against the experimental result. The developed model was in good agreement with the experimental results.

Carrasco et al. [11] experimentally and theoretically worked on AGMD unit which was manufactured from an insulated material to minimized heat losses. The experiments were conducted for different values of feed temperatures and flow rates and one-dimensional heat and mass transfer model with no free parameters was proposed. Model prediction and the experimental data showed good agreement and the errors between measured and a predicted temperature was approximated to 5% different. However, the trends of the model and the experimental data differed so; the possible improvements to the model were discussed.

Alsaadi et al. [12] designed one-dimensional model using theoretical equations governing the mechanism for mass and heat transfer process in air gap membrane distillation. An experiment was done at different operating conditions. The model was validated against the experimental data. Comparison showed that the model flux predictions were related to the experimental data, with model predictions being within +10% of the experimentally determined values. After model validation, the model was used to be studied and analysed the thermal efficiency and the parameters that improved the AGMD unit.

Guijta et al. [13] experimentally designed counter flow AGMD and validated the results with the theoretical model calculations. It was found that decreasing the total air gap pressure to the saturated water vapor pressure of the feed flow temperature of 65 ^{0}C increased the permeate flux by three folds. The energy efficiency of the system was equally analysed experimentally and theoretically and it was found that the thermal efficiency of the experiment was slightly lower than that of the theoretical result as a result of heat loss.

Gil et al. [14] used AGMD to test the aqueous solutions of alcohol ethanol, methanol and isopropanol experimentally. The equivalent film heat transfer coefficient and the overall membrane mass as well as alcohol and water membrane transfer coefficients were resulted from the experimental data and were used to calculate the transmembrane composition and temperature. Subsequently, the temperature polarization model, and Seidler and Tate heat transfer correlation was used to the know the effect of Reynolds number on the amount of distillate produced.

Geng et al. [15] presented the new study of AGMD module with internal heat recovery for water desalination to investigate the impact of AGMD operating parameters. Experimental results yield a maximum permeates flux of 5.30 kg/m^2 h and a GOR of 5.70. The experimental result also yielded a minimum of 80% thermal efficiency.

Pavo et al. [16] presented the results obtained from theoretical model and experiment conducted with (AGMD). Sucrose aqueous solutions were used as the feed solution. The influence of important operating parameters such as feed temperature, flow rate, concentration, air gap thickness and membrane type were investigated. The theoretical models showed good agreement with the experimental data over the range of temperatures investigated.

From these literatures reviewed it was found that, there is no enough researches study the AGMD system as multi stage, forward and parallel feed experimentally, so this research focused on this point. This research introduces an experimental study for the performance of air gap membrane distillation (AGMD). The influences of system operating conditions such as feed temperature, feed velocity, coolant temperature, coolant velocity on permeate flux were studied. Hydrophobic PTFE membrane of pore sizes 0.45 µm was used and the air gab thickness was 3mm. Experimental setup is designed, fabricated and equipped with the required measuring devices to obtain the required experimental results. Validation for experimental results is included also

II. EXPERIMENTAL UNIT

A. *Experimental set up*

The experimental unit used in this research is a double stage desalination unit that used to remove salts from saline solutions using membrane distillation method MD by air gab distillation AGMD. This unit consists of two hot feed channels in which hot saline solution is flow to get in contact with low-pressure membrane, this membrane is a hydrophobic membrane that passes only water vapour through its pores, the water vapour passed membrane pores is collected in an air gab area behind the membrane. A common coolant channel is located in the middle of the desalination unit in which cold water flow to condensate the permeate flux collected in both two air gabs. The condensation occurs through the wall of two stainless steel plates located on the two sides of the coolant channel and closed to the two air gabs. Then the permeate flux is to be collected through a hall in the bottom of the two air gabs, each channel of the two-feed channel has separated permeate flux discharge. To prevent leakage through the unit gasket frames are used between unit parts. The inlet of the feed champers is connected to heater and the discharge is recycled back to hot feed tank. The inlet of the coolant chamber is connected to refrigerator and the discharge is recycled back to cold water tank.

The experimental test based on two operating methods, *first operating method* introduces direct hot feed to both hot feed champers, *parallel operating method*, at different variables, *velocity and temperature* are inputs values. *Second operating method* based on feed the outlet flow from chamber one to chamber two, *forward operating method*.

B. *Prototype design*

The prototype designed by SOLIDWORKS program, SOLIDWORKS program is 3D model design, figure (1) show lay out of the parallel feed categories of the experimental unit and idea of the prototype of desalination unit. The three chambers manufactured from ACRYLIC polymer of 2cm thickness and formed by laser machine to have inner thickness of 1 cm, condensers and air gab material is a St.37. Air gap and condenser also manufactured by laser machine.

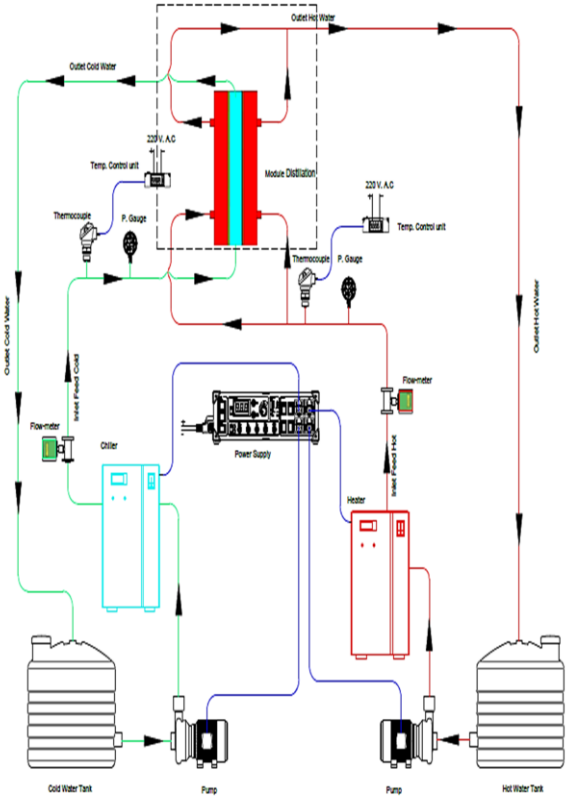

Fig. (1) layout diagram to parallel feed.

C. *Measuring instruments*

The instrumentation includes, applied pressure measurement using pressure gauge, velocity measurement using flow meter, Temperature measurement using thermocouple and concentration measurement using TDS instrument.

D. Experimental Calculations

The distillate flux (*J*) of MD unit is known as the overall production of pure water that has been obtained per unit of effective membrane area on time at an itemized condition such as feed flow rate and feed temperature, cooling flow rate and cooling temperature, effective film area, etc. The distillate flux unit is (kg/m^2.h) by utilizing the volume of collected distillate during the sampling time from the module's active membrane area as follows:

$$\dot{m}_p = \frac{V\,\rho}{t} \tag{1}$$

$$j = \frac{\dot{m}_p}{A} \tag{2}$$

where *V* is the volume of water in m^3, *t* is the time in h and A is the active membrane area in m^2. Distillate productivity data are achieved from the measurements by collecting a liter of distillate water and recording the time throughout the experiment.

The concentration balance is used to obtain the required feed water concentration as:

$$\dot{m}_f X_f = \dot{m}_p X_p + \dot{m}_b X_b \tag{3}$$

where $\dot{m}_f$ is the feed flow rate, (kg/s), X_f the feed salinity, (kg/m^3), $\dot{m}_p$ the permeate flow rate, (kg/s), X_p the permeate salinity, (kg/m^3), $\dot{m}_b$ the brine flow rate, (kg/s), and X_b the brine salinity, (kg/m^3).

E- Data Uncertainty

The uncertainty associated with each measuring device is shown in Table (2)

TABLE 2
THE ACCURACY AND PERCENTAGE ERROR FOR DIFFERENT DEVICES.

Instrument	**MEASURED VARIABLE**	**ACCURACY**	**ERROR**
Thermometer	T	± 1°C	± 3.3 %
Thermocouples	T	± 0.1°C	± 0.3 %
Measuring Jar	V	± 1 ml	± 4.8 %
Length	M	±1 mm	± 0.1 %
Stop Watch	τ	±1 %	±1 %
Instrument			
Thermometer			
Thermocouples			
Measuring Jar			
Length			

The relative error is obtained according to Holman [18] as:

$$\frac{\Delta \boldsymbol{j}}{\mathbf{j}} = \sqrt{\left(\frac{\Delta\mathbf{V}}{\mathbf{V}}\right)^2 + \left(\frac{\Delta\mathbf{T}}{\mathbf{T}}\right)^2 + \left(\frac{\Delta\boldsymbol{\tau}}{\boldsymbol{\tau}}\right)^2 + \left(\frac{\Delta\mathbf{A}}{\mathbf{A}}\right)^2} \tag{4}$$

Based on the accuracy of each measuring instrument illustrated in table (2), It has been found that the maximum uncertainty in calculating permeate flux was about 5.1%

III. RESULTS AND DISCUSSION

A. *Effect of inlet feed temperature*

Figure (2) shows experimental results for effect of feed temperature on permeate flux at different coolant temperatures, feed temperature ranges 40 ^{O}C-70 ^{O}C, feed velocity 0.8 m/s, coolant temperature ranges 15 ^{O}C-30 ^{O}C, coolant velocity 0.65 m/s, air gap 3mm thickness and 0.45μm PTFE membrane material, Parallel feed."

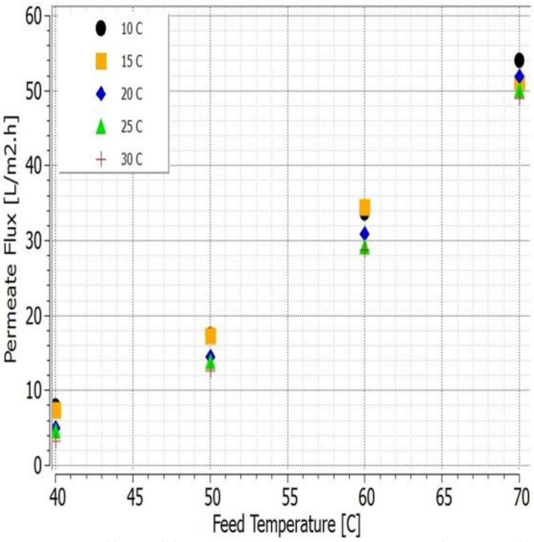

Fig. (2) Effect of feed temperature on permeates flux at different coolant temperatures, parallel feed.

Presented in figure (2), increasing feed temperature increasing permeate flux. The maximum amount of permeate flux is about 55 L/m^2.h can be obtained from each chamber, total permeate flux 110 L/m^2.h at feed temperature of 70 ^{O}C and coolant temperature of 10 ^{O}C.

Figure (3) shows experimental results for effect of feed temperature on permeate flux in the forward feed operating method.

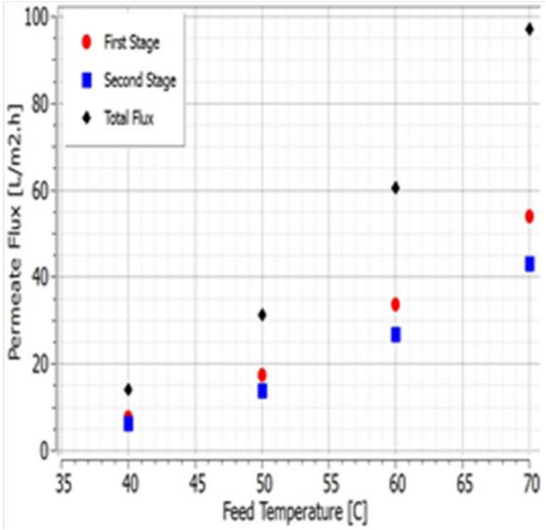

Fig. (3) Effect of feed temperature on permeate flux, forward feed.

Shown in figure (3), increasing feed temperature increasing permeate flux. The maximum total amount of permeate flux is about 100 L/m^{2}h can be obtained at feed inlet temperature of 70 ^{O}C and coolant inlet temperature of 10 ^{O}C in forward feed. The decrease in permeate amount in forward case than parallel case is due to heat losses through conduction with membrane and condensation.

B. *Effect of inlet coolant temperature*

Figure (4) shows experimental results for effect of coolant temperature on permeate flux at different feed temperature ranges 40 ^{O}C - 70 ^{O}C, feed velocity 0.8 m/s, coolant temperature ranges 15 ^{O}C - 30 ^{O}C, coolant velocity 0.65 m/s, air gab 3mm thickness and 0.45µm PTFE membrane material, Parallel feed.

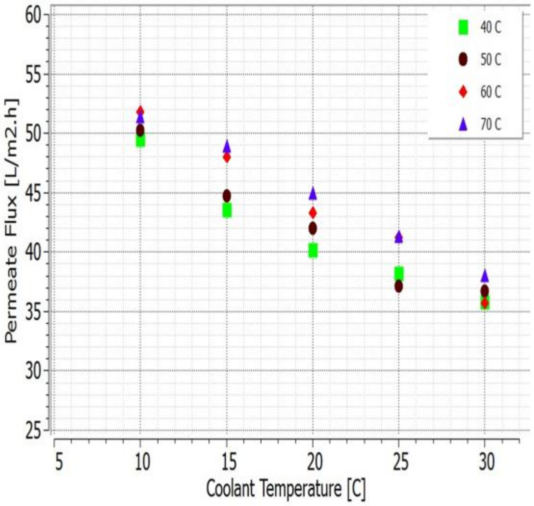

Fig. (4) Effect of coolant temperature on permeate flux at different feed temperatures, parallel feed.

Indicated in figure (4), decreasing coolant temperature increasing permeate flux. The maximum amount of permeate flux is about 55 L/m^{2}h from each chamber, 110 L/m^{2}h total flux, can be obtained at feed temperature of 70 ^{O}C and coolant temperature of 10 ^{O}C.

Figure (5) shows experimental results for effect of coolant temperature on permeate flux, forward feed.

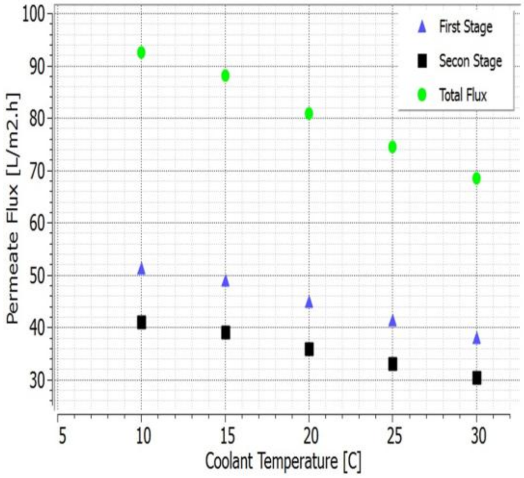

Fig. (5) Effect of coolant temperature on permeate flux, forward feed.

Presented in figure (5), decreasing coolant temperature increasing permeate. The maximum amount of permeate flux is about 95 L/m^{2}h can be obtained at feed temperature of 70 ^{O}C and coolant temperature of 10 ^{O}C.

C. *Effect of feed velocity*

Figure (6) shows experimental results for effect of feed inlet velocity on permeate flux at different coolant velocity, feed temperature 70 ^{O}C, feed velocity 0.2 m/s- 0.8 m/s, coolant temperature15 ^{O}C, coolant velocity 0.15 m/s - 0.65 m/s, air gab 3mm thickness and using 0.45 µm PTFE membrane material, parallel feed.

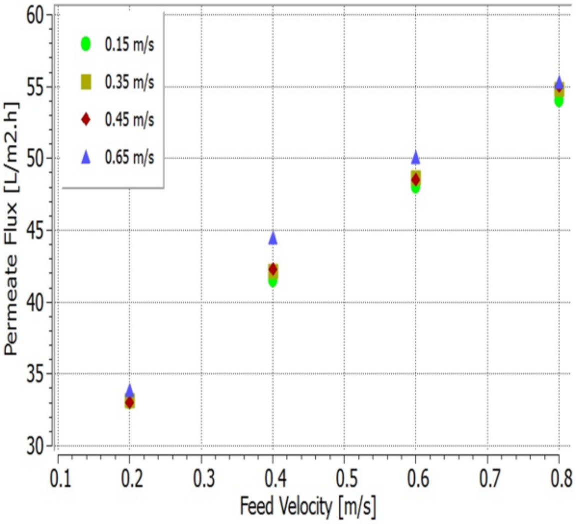

Fig. (6) Effect of feed inlet velocity at different coolant velocities on permeate flux, parallel feed.

Presented in figure (6), increasing inlet feed velocity increasing permeate flux. The maximum amount of permeate flux is about 55 L/m^{2}h from each chamber, 110 L/m^{2}h total flux, can be obtained at feed inlet velocity of 0.8 m/s and coolant velocity of 0.65 m/s.

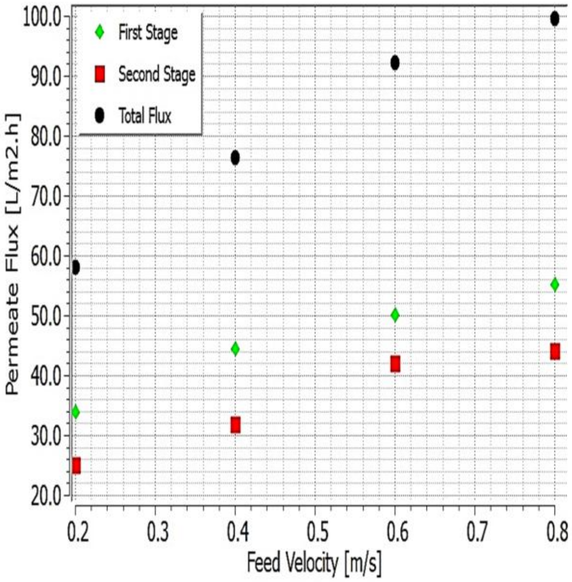

Fig. (7) Effect of feed inlet velocity on permeate flux at different feed velocities, forward feed.

Figure (7) shows experimental results for effect of inlet feed velocity on permeate flux, forward feed.

Shown in figure (7), increasing inlet feed velocity increasing permeate flux. The maximum amount of permeate flux is about 100 L/m^{2}h can be obtained at feed inlet velocity of 0.8 m/s and coolant velocity of 0.65 m/s.

D. *Effect of inlet coolant velocity*

Figure (8) shows experimental results for effect of coolant inlet velocity on permeate flux at different feed velocity, feed temperature 70 ^{O}C, feed velocity 0.2 m/s- 0.8 m/s, coolant temperature 15 ^{O}C, coolant velocity 0.15 m/s- 0.65 m/s, air gab 3mm thickness and using 0.45µm PTFE membrane material, parallel feed.

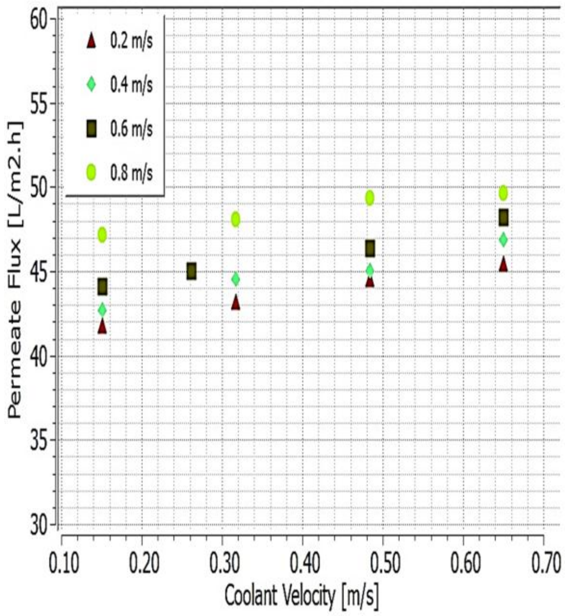

Fig. (8) Effect of coolant inlet velocity on permeate flux at different feed velocities, parallel feed.

As explained in figure (8), increasing coolant velocity increasing permeate flux. The maximum amount of permeate flux is about 50 L/m^2.h from each chamber, 100 L/m^2.h total flux, can be obtained at feed inlet velocity of 0.8 m/s and coolant velocity of 0.65 m/s.

Figure (9) shows experimental results for effect of inlet coolant velocity on permeate flux, forward feed.

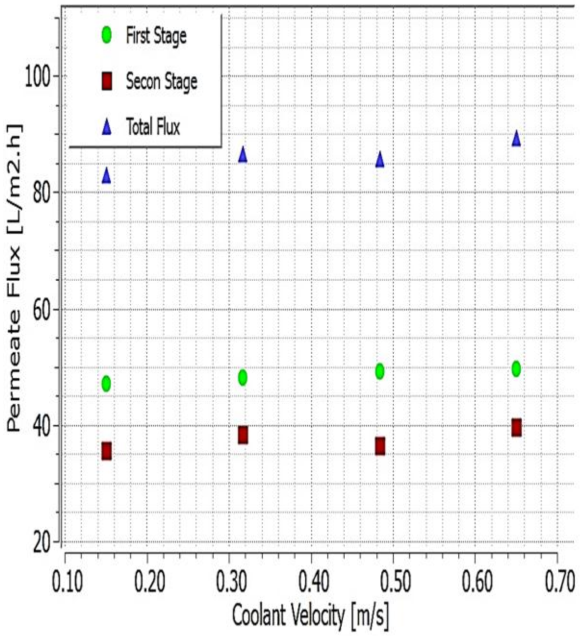

Fig. (9) Effect of coolant inlet velocity on permeate flux at different feed velocities, forward feed.

Figure (9) explains that increasing coolant velocity increasing permeate flux. The maximum amount of permeate flux is about 90 L/m^2.h total flux can be obtained at feed inlet velocity of 0.8 m/s and coolant velocity of 0.65 m/s.

IV. VALIDATION OF WORK

To make sure that the work done is accurate we make validation with a research of the same conditions. In order to confirm the validity of research, additional comparison between experimental data for Dahiru Lawal [17] and experimental data for recent research are discussed. It was found that Predicted responses show good agreement with actual results. Experimental test time was 50 h in the recent research, when the compared research time was 36 h. The operating conditions in present research were; inlet feed temperature range 40 ^{0}C-70^{0}C, inlet feed velocity range 0.2-0.8 m/s, coolant temperature range 10 ^{0}C -30^{0}C, inlet coolant velocity range 0.15-0.65 m/s. where the operating conditions of Dahiru Lawal [17] were; inlet feed temperature range 40 ^{0}C-80^{0}C, inlet feed flow rate range 1-5 L/min, coolant temperature range 15 ^{0}C -30^{0}C, inlet coolant flow rate range 1-3.5 L/min. The dimensions of the feed chamber in the valid research are 66 cm width, 4cm depth and length of 66 cm, and in present work about 25 cm length, 20 cm width and 1 cm depth. The comparison is in parallel feed results.

Figure (10) shows effect of feed temperature on permeate flux.

From figure (10) it can be noticed that present work is higher in permeate flux, this is due to working times is higher than Dahiru. Dahiru worked at 80 ^{o}C, but we didn't work at this temperature because of rising salt concentration in permeate flux.

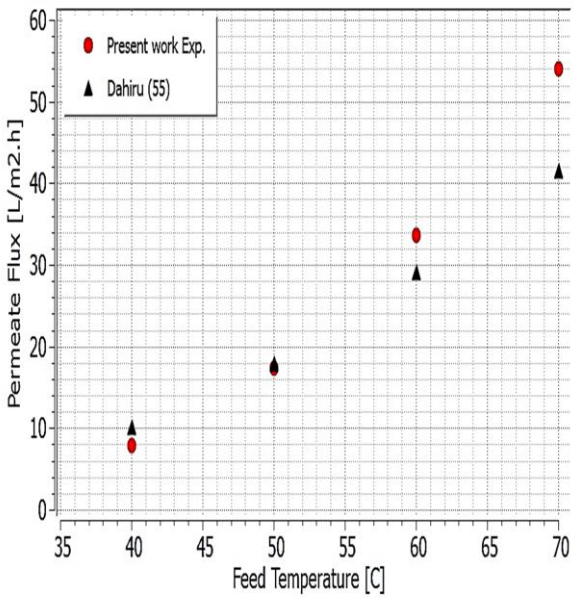

Figure (10) Effect of feed temperature on permeate flux

Figure (11) shows effect of coolant temperature on permeate flux.

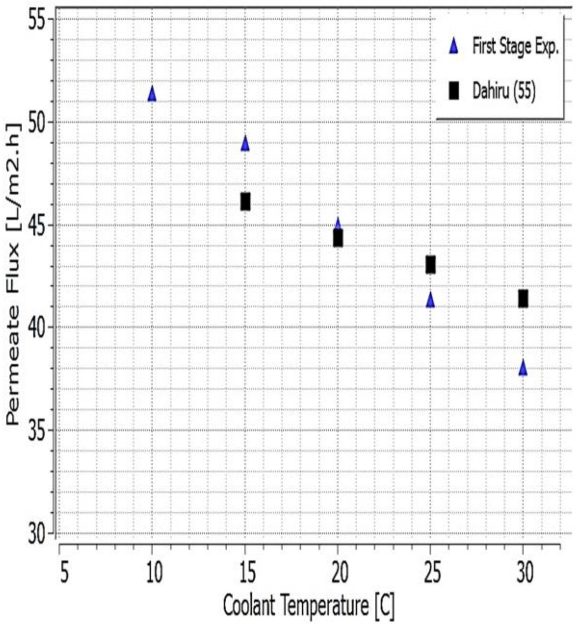

Figure (11) Effect of coolant temperature on permeate flux.

In figure (11), the higher amount of permeate flux can be obtained at temperature of 10 ^{O}C. Dahiru didn't work at temperature of 10 ^{O}C.

Figure (12) shows effect of feed velocity on permeate flux.

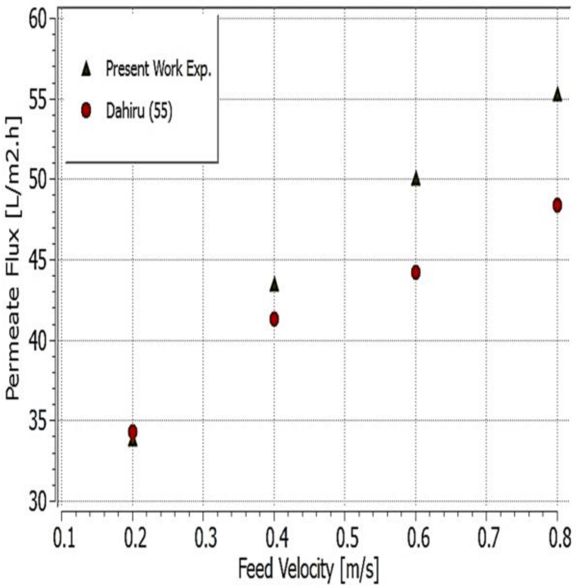

Figure (12) Effect of feed velocity on permeate flux.

Figure (13) shows effect of coolant velocity on permeate flux.

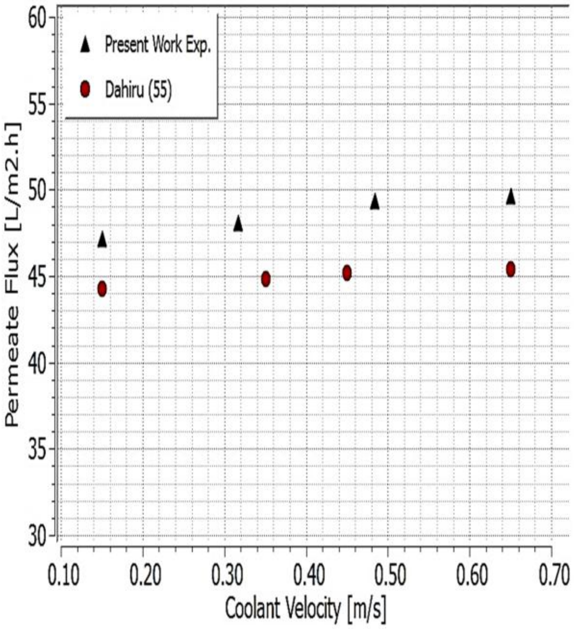

Figure (13) Effect of coolant velocity on permeate flux.

The permeate flux is higher in present work in figure (13) because of increasing operating time.

V- Conclusions

This work introduces an experimental study for AGMD consists of two categories, the first one introduced two fresh hot feed streams to both feed chambers, parallel flow, and the second one used the outlet of first chamber as the inlet of second chamber, forward flow. The influence of different operating parameters had been studied.

The conclusions can be summarized as follows:

The best operating parameters are feed temperature of 70°C, coolant temperature of 10°C, feed velocity of 0.8 m/s, coolant velocity of 0.65 m/s, membrane of thickness 0.175 μm and 0.45 μm pore size and air gap thickness of 3 mm. This combination gave a maximum flux of 55 L/m^{2}h from each feed chamber, total permeate of 110 L/m^{2}h, when operating the unit as parallel feed streams. In the forward flow feed method, the maximum permeate flux was found to be 100 L/m^{2}h at the same operating factors combinations.

The permeate flux recorded at these conditions was achieved through operating time of 50 h.

NOMENCLATURE AND ABBREVIATIONS

NOMENCLATURE

A	Effective membrane area	m^2
$\dot{m}$	Mass flow rate	kg/s
V	Volume of distilled water	m^3
ρ	Water density	kg/m^3
T	Temperature	^{o}C
J	Permeate flux	Kg/m^2.h
X	Concentration	ppm
Subscripts		
B	Brine	-
F	Feed	-
P	Permeate	-

ABBREVIATIONS

MD	Membrane Distillation
AGMD	Air Gap Membrane Distillation
RO	Reverse Osmosis

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