EXPERIMENTAL INVESTIGATION OF A SYSTEM OF TWO AIR-GAP-MEMBRANE-DISTILLATION MODULES WITH HEAT RECOVERY

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ABSTRACT

The present paper is an experimental study to investigate the performance of a desalination system composed of two air gap membrane distillation (AGMD) Modules. A test rig was designed and constructed especially for this purpose. The two modules can be connected in different configurations. The base test case (BTC) is considered first by connecting the two modules in parallel. This means each module has the same operating condition of both feed and coolant flows. The coolant flow is used to condensate water vapour in the air gap then rejected with a relatively high temperature, which can be reused to increase the thermal efficiency and water productivity of the system. In order to make use of this rejected heat, two more configurations were selected and tested, namely; double and single heat recovery (DHR and SHR). In the DHR, the coolant flow leaving the two modules are used to heat the feed flow of the second module. Whereas, in the SHR, the coolant flow leaving the first module only (with relatively high temperature) is used to heat the feed flow of the second module. The water productivity as well as the Gain Output Ratio (GOR) were used to evaluate the performance of the system under different operating conditions of feed flow rates, and salinities. The results show that the DHR configuration increased the productivity of the system by 27% compared to the BTC, while the SHR increased the productivity by 41%.

Keywords: Membrane distillation, Air Gap, Heat recovery, Desalination
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1 INTRODUCTION

Our planet has a plenty of drinking water enough for all creatures living on it, however, this water is not equally distributed. As a result, many people suffer from lake of drinking water. Moreover, the Food and Agriculture Organization of the United Nations (FAO, 2007) predicted that the problem of water scarcity to be more sever in the future. Although our fresh water resources are limited and finite, there are abundant quantities of salt water. The desalination of salt water provide a source of drinking water for those who lake it.

Membrane distillation (MD) is a non-isothermal membrane separation in which porous hydrophobic membranes are used. The membrane from one side is exposed to hot saline water (feed water) with relatively high vapour pressure and from the other side to a cooler media. The liquid and salts are prevented from passing through the pores of the membrane due to liquid surface tension and the hydrophobicity of the membrane, while the water vapour is allowed to pass through. The difference in partial pressure at both sides of the membrane drives the transport of vapour through the membrane. The conditions on the other side of the membrane defines the type of membrane. If the other side of the membrane is a cold fresh water then this is called direct contact membrane distillation (DCMD). On the other hand, if the other side of the membrance is separated from the coolant by an air gap then it is called air gap mebrane distillation (AGMD). In this technique, water vapour is condensed on a cold plate. This plate is exposed to the coolant water from the other side, which may be fresh or salt water. Its simplicity, and the requirement for only small temperature differentials to operate the process, are the main merits of MD that make it very convenient for use by small communities in arid regions. (Khayet & Matsuura, 2011)

MD processes posses some favorable merits over conventional separation technologies such as: costs of energy are relatively low compared with distillation, reverse osmosis (RO), and pervaporation; membrane fouling is lower than that in microfiltration, ultrafiltration, and RO; lower operating pressure than RO and lower operating temperature as compared to conventional evaporation; high purity water with near 100% salt rejection. (Khayet & Matsuura, 2011) and (Onsekizoglu, 2012)

Accoding to Khayet & Matsuura (2011), MD technology is relatively new as its first appear, in the literature, was in the 60s of the last century. However, it was only in the 1980s when MD was first developed commercially on a small scale (Shatat, 2008). Martinez (2004) found that water flux through a DCMD decreases as feed concentration increases. Lawal (2014) arrived at the same conclusion with AGMD. The effect of feed temperature and feed flow rate were studied by Alkhudhiri et al. (2013), Khalifa (2015), and Lawal (2014).

Different researchers used different membrane materials: Khayet & Matsuura (2004) and Srisurichan et al. (2006) used polyvinylidenedifluoride (PVDF); Sudoh et al. (1997), EL-Abbassi et al. (2012) used polytetrafluoroethylene (PTFE); Criscuoli et al. (2008) tested polypropylene (PP); Gazagnes et al. (2007) and Cerneaux et al. (2009) used ceramic membrane of different nature. Moreover, Xu et al. (2016) compared the performance of PVDF, PTFE, and PP membranes, they found that membrane made of PP has a better performance than PVDF, and PTFE. The effect of module inclination angle on AGMD was studies by Warsinger et al. (2014).

The usage of membrance separation is not limited to extract water from salty solution but it found many applications in the literature: Sudoh et al. (1997) extracted water from aqueous lithium bromide solution; EL-Abbassi et al. (2012) handled water from olive mill wastewater; Khayet and Matsuura (2004) used a solution of chloroform-water mixture; Srisurichan et al. (2006) used water-humic acid solution; Criscuoli et al. (2008) used various dye solutions; Zhao et al. (2008) used aqueous Ginseng solution.

Fath et al. (2006) studied the performance of solar dervin MD. Mabrouk et al. (2016) and Elhenawy (2016) combined a solar driven MD unit with a conventional thermal desalination unit (multi effect distillation, MED) which proved the capability of MD syetem to integrate with other conventional systems. A comprehensive review of solar-power membrane distillation (SP-MD) is provided by Saffarini et al. (2012).

In this paper, two AGMD modules are used. A special test trig is designed and constructed for testing the performance of this system. These modules could be connected in various configurations. Three cofigurations are used in this work. The base test case is considered first by connecting the two module in parallel without heat recovery. In order to make use of the rejected heat with coolant flow, two other configurations were selected and tested, namely; double and single heat recovery (DHR and SHR). The water productivity as well as the Gain Output Ratio (GOR) are used to evaluate the performance of the system under different operating conditions of feed flow rates and feed salinities.

2 EXPERIMENTAL TEST RIG

The experimental apparatus is installed, as shown in Fig.1. It consists of three main loops: the feed loop, the coolant loop and the heat source loop, besides, the distillate water which is to be collected and measured in a distillate tank.

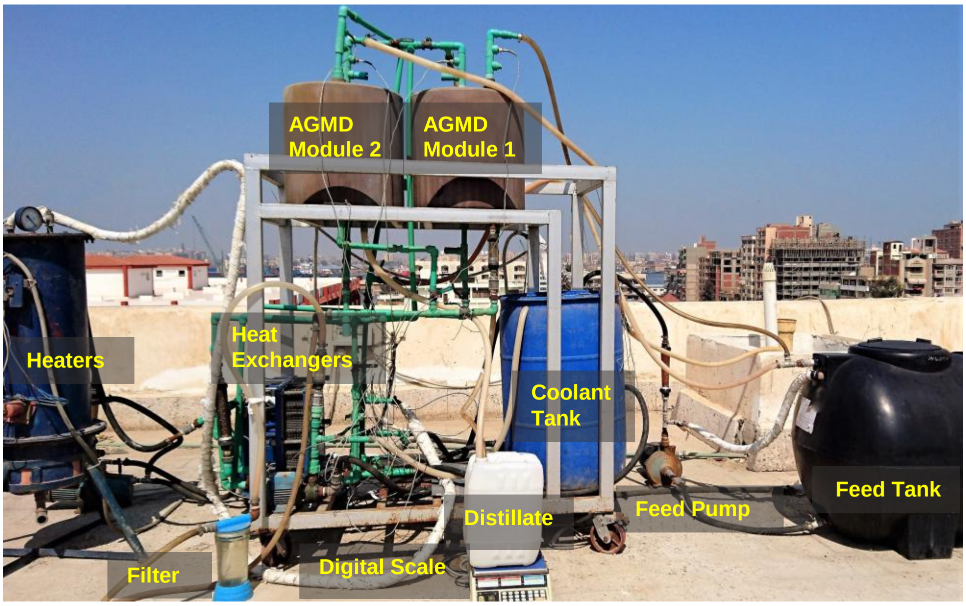


Figure 1. The experimental apparatus.

Two Aquastill® (AS14A3.0L) multi-envelope spiral wound AGMD modules were used in this system with the main specifications demonstrated in table.1. A schematic diagram of the AGMD module is shown in Fig.2. The red envelopes are the hot feed channels while the blue envelopes are the coolant channels. Both sides of the coolant channel work as condenser foils (gray) while, an air gap with a spacer lies between each coolant and feed channels in which the permeate is collected and expelled from the module. The six membrane envelopes are spiral wound into a cylindrical shape. The feed and coolant flows are countercurrent. To achieve that, the hot feed is supplied at the center of the base and discharged peripherally from the top. On the other side, the coolant is supplied at the outside of the module and leaves at the core.

Table 1. Membrane module characteristics.

Material	Polyethylene	Air gap thickness	1 mm
Total membrane area	14.4 m^2	Porosity of membrane	0.85
Diameter	0.4 m	Membrane sheet tortuosity	1.56
Height	0.4 m	Membrane sheet thickness	0.3 μm
Length of envelope	3 m	Feed/coolant channels	6
Channel thickness	2 mm	Distillate channels	12
Spacer porosity	0.781325	Maximum allowable pressure	0.75 bar

In this system, Fig. 3, the saline water was prepared in different salt concentrations to resemble seawater or brackish water in the feed tank. The feed flows by a pump through a filter, then into the two flat-plate heat exchangers (each of capacity 11 kW) where it heats-up by hot water from an electrically heated water tank (heat source), then divided to the AGMD modules using a system of control valves and flowmeters. Pressure sensors were used to ascertain that feed pressure is lower than the maximum allowable pressure. Thermocouples are used to measure the inlet and outlet temperatures of the two modules. The brine rejected is directed back to the feed tank, which increases the salinity. To overcome this problem, distilled water is periodically returned to the feed tank after being measured, causing salinity stabilization. In practical large-scale desalination plants, the reject brine is returned to the sea with no such salinity problem. The amount of distillate is determined using digital balance. The brine and distillate concentrations are measured by the TDS meter. The measuring data is recorded using a data logger (Graphtec, Model: GL220_820APS).

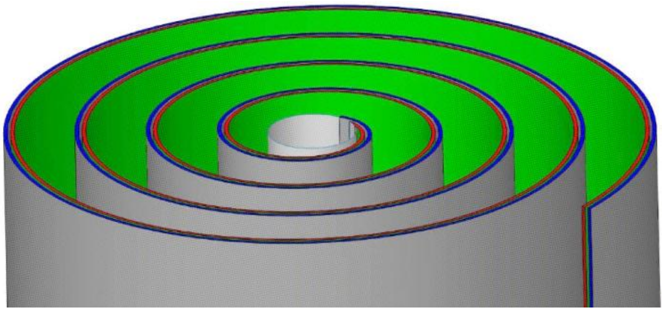
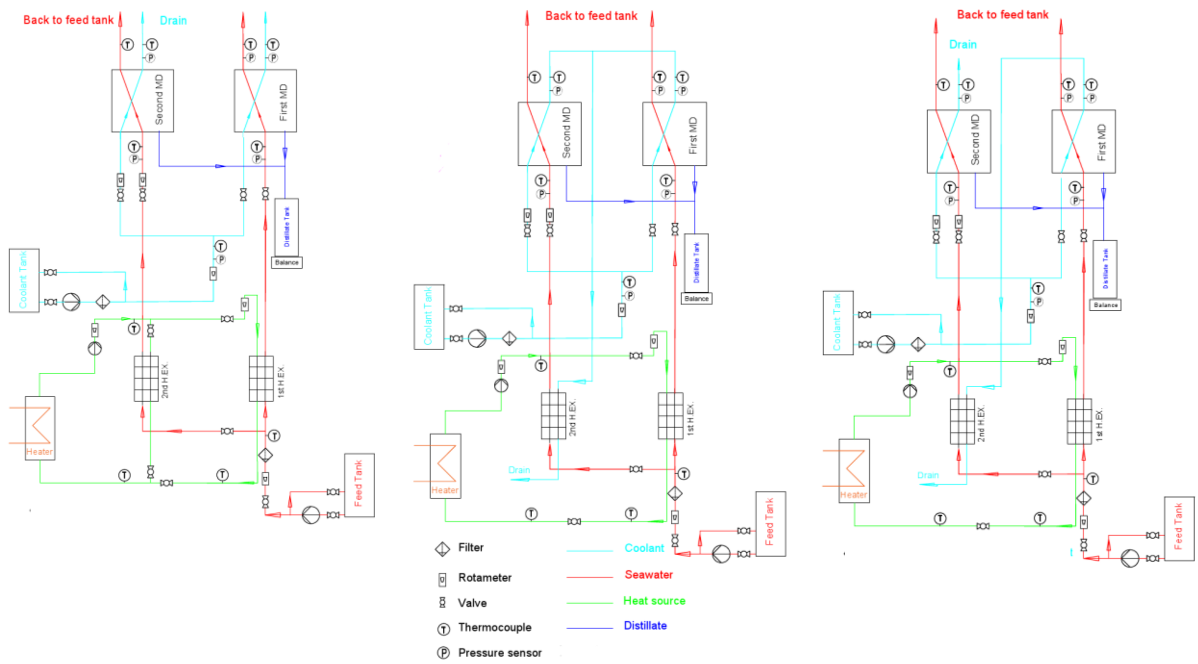


Figure 2. The AGMD module.



(a) BTC **(b) DHR** **(c) SHR**

Figure 3. Flow diagram of the three configurations.

Tap water at atmospheric temperature was used as the coolant which was stored in a coolant tank. Then, it is pumped to the two modules to be used and finally to drain or heat recovery utilization depending on the operation configuration used. In practical large-scale desalination plants, seawater itself serves as the coolant, so no freshwater is wasted in a large quantity as in the lab-scale test rig. An electric heater (18 kW) is installed in a water storage tank (300 L capacity) to be used as a heat source to supply sufficient energy to the desalination system.

During this study, three different configurations were tested to investigate the effect of heat recovery on the distillate productivity of the system. The first one is the BTC, Fig. 3a, which is the reference configuration with no heat recovery, the feed was equally divided and heated by the heat source water in the two plate type heat exchangers. The coolant flow, coming from the coalant tank, is also divided equally and passes through the two AGMD modules. Finally, the distillate is collected from both membrane modules and measured before returning back to the feed tank.

In the two other configurations (DHR and SHR), Figs. 3a & b, the heat recovery system was used to obtain energy from coolant which was heated during the distillation process. In the DHR configuration, shown in Fig. 3b, only one branch of feed flow was heated by the heat source in the 1st

heat exchanger and passes through the first MD module. The other feed branch is heated in the 2nd heat exchanger (heat recovery heat exchanger) by the relatively hot coolant, exiting from both modules of membrane mixed together, before entering to the second MD module. Here, the temperature of hot coolant coming from the first MD module is higher than that of the coolant exiting the second module which after mixing result in a third temperature value in between the two mentioned with the total coolant flow rate.

This is why the SHR configuration was installed, as shown in Fig. 3c, which uses only the coolant from the first MD module with the higher temperature as a heat recovery source to heat the second feed branch. However in this case, the flow rate of the coolant, used in heat recovery, is only half the total coolant flow rate.

3 RESULTS AND DISCUSSIONS

The performance of the BTC is presented in terms of water productivity (productivity for short) and the GOR at different operating parameters of feed and coolant flow rates and feed salt concentrations. The feed flow rate of 6, 7, 8, 10 L/min were used, and the coolant flow rate were 6, 7, 8, 10, 13 L/min. In addition, two feed salinities of 10000 and 20000 ppm were used.

The GOR of the system, which is an indication of the overall efficiency of the desalination system, is calculated from (Kayvani et al., 2015):

$$GOR = \frac{\dot{m}_d LH_v}{\dot{m}_s cp_s (t_{si} - t_{so})} \quad (1)$$

where $\dot{m}_d$ (kg/s) is the distilled product mass flow rate, $\dot{m}_s$ (kg/s) is the heat source mass flow and both are determined from the experiment. LH_v (J/kg) is the latent heat of evaporation at the distillate temperature, cp_s (J/kg K) is the specific heat of the average heat source temperature and t_{si}, t_{so} are the inlet and outlet temperatures of the heat source fluid, respectively.

3.1 The effect of feed flow rate on water productivity and GOR

For the BTC (without heat recovery), the influence of changing the feed flow rate on water productivity and GOR is illustrated in Figs. 4 and 5, respectively. In these figures, the coolant flow rate, mc, was kept equal to the feed flow rate, mh. As can be seen, the water productivity increases by increasing the feed flow rate. This fact is shown in Fig. 4, where different flow rates are tested and water productivity of each one is measured at the same feed salinity of 20000 ppm. This is because increasing the feed flow rate, increases the heat transfer coefficient in the boundary layer. The temperature and concentration at the membrane surface approach the bulk ones. This reduces the boundary layer resistance when Reynolds number increases resulting in an increase of the driving force and higher AGMD permeate flux. From Fig. 5, it is also found that, although the distillate product flow rate increases with the increase of feed flow rate, the GOR decreases. This can be attributed to the relatively low feed temperature at higher feed flow rates with the same heat source capacity.

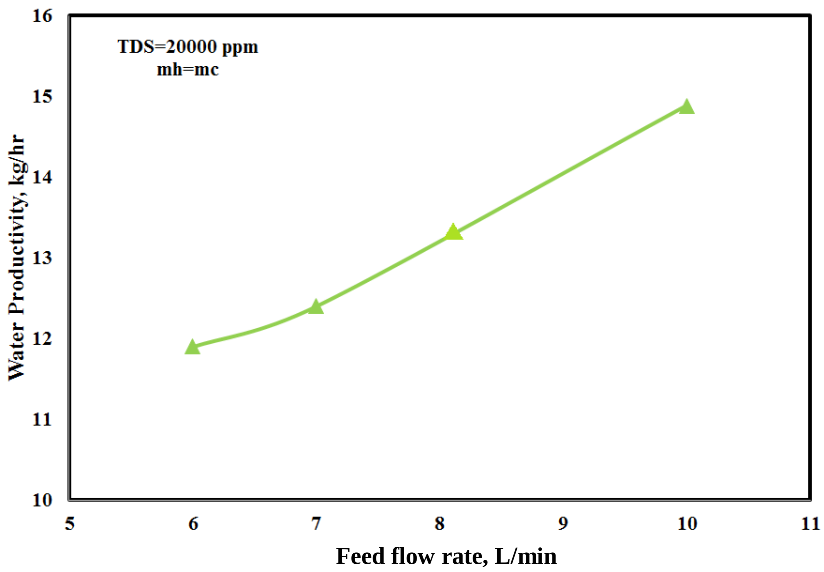


Figure 4. The effect of feed flow rate on the productivity

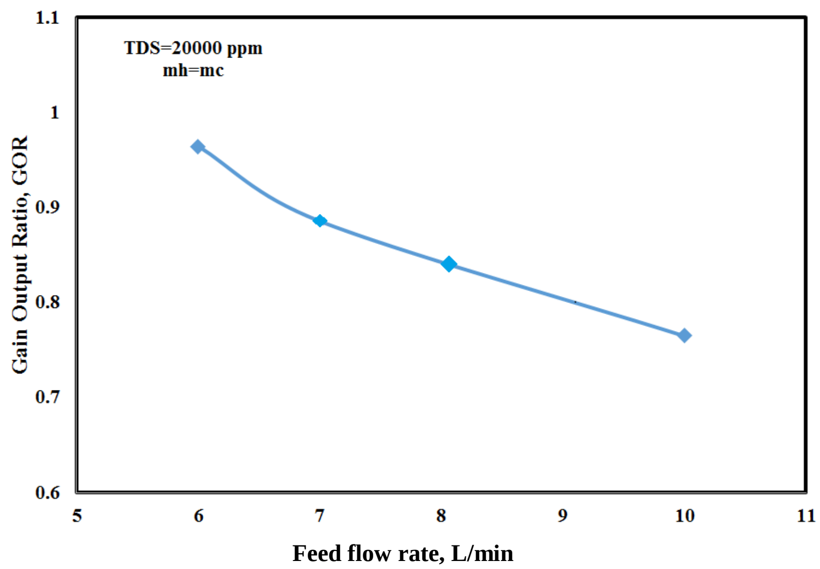


Figure 5. The effect of feed flow rate on the GOR

3.2 The effect of feed salinity on the productivity

AGMD can operate at very high salinities. This is a valuable advantage over RO whose performance is significantly affected at high feed salinities. Generally, increasing the feed salinity decreases the water productivity. This decrease can be explained in several ways: vapour pressure reduction at these concentrations, increasing concentration polarization at the membrane surface and temperature polarization phenomena. It is seen from Fig. 6 that doubling the feed concentration from 10000 to 20000 ppm (at constant feed and coolant flow rates of 8 L/min and 13 L/min, respectively), decreases the productivity by 1.25 %, for the BTC. Also, the productivity decreases by 1.55 % and 2.5 % for the SHR and the DHR, respectively.

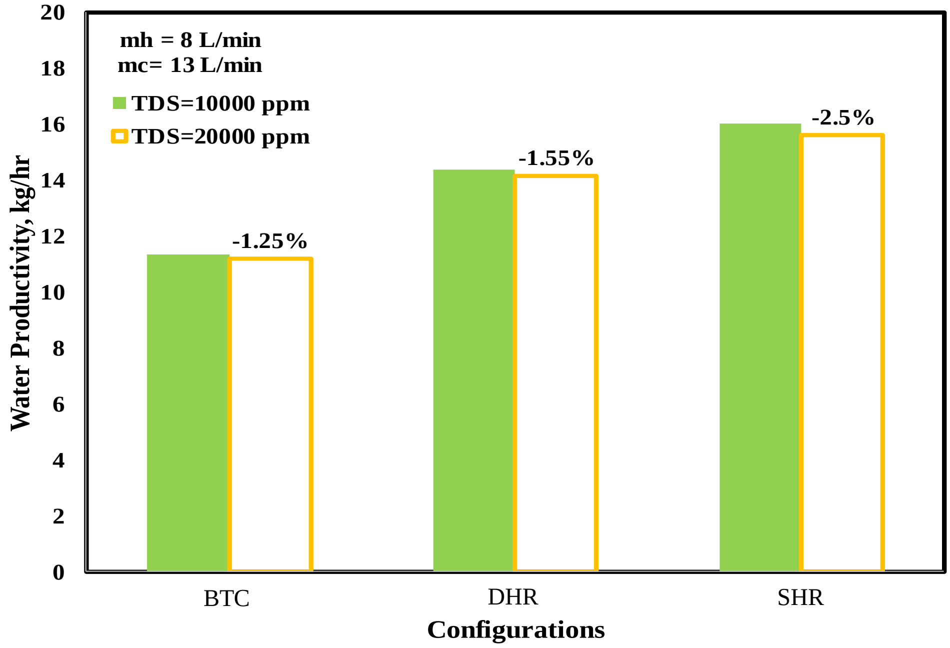


Figure 6. The effect of feed salinity on the productivity

3.3 The effect of heat recovery on the GOR

Figure 7 illustrates the GOR enhancement due to the heat recovery, keeping the feed and coolant flow rates constant at 8 and 13 L/min, respectively with feed salinity of 10,000 ppm. From the figure, it is found that the DHR leads to an enhancement in the average GOR by 37 % when compared with the BTC. Whereas, the GOR increases with the SHR by 42 %. This difference in increament of the GOR in SHR and DHR is attributed to the temperature of the coolant flow. The temperature of the coolant flow leaving the first module is higher than that at the second module. Mixing the two coolant streams as in DHR results in a reduction of combined coolant temperature. Consquentaly, the temperature of the feed flow to the second module is lower in the DHR than in SHR. The GOR values follow the same trend at water salinity of 20,000 ppm but with a minor negligible reduction that varies from 1 to 2 %.

3.4 The effect of heat recovery on the productivity

Figure 8 depicts the water productivity due to the heat recovery, keeping the feed and coolant flow rates constant at 8 and 13 L/min, respectively at feed salinities of 10,000 and 20,000 ppm. The figure shows that the DHR leads to an enhancement in the productivity by 37 % when compared with the BTC. Whereas, the GOR increases with the SHR by 27 % and 21% at salinity of 10,000 and 20,000 ppm respectively. On the other hand, the SHR gave an increase in the productivity of 41% and 28% at salinities of 10,000 and 20,000 ppm respectively. Moreover, the supority of SHR over DHR is more clear at higher salinities.

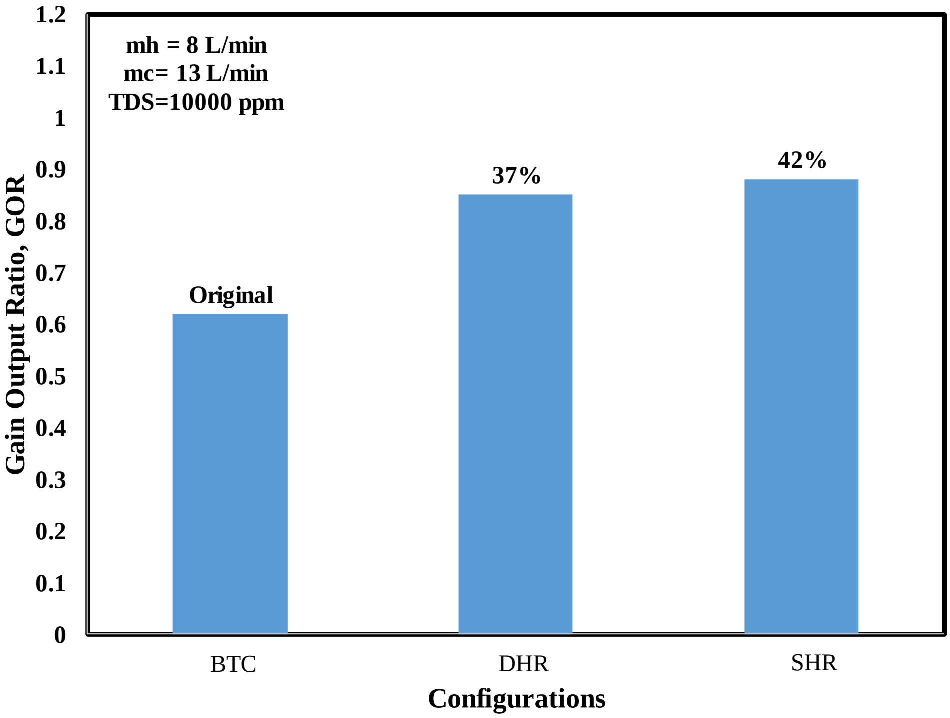


Figure 7. The effect of heat recovery on the GOR

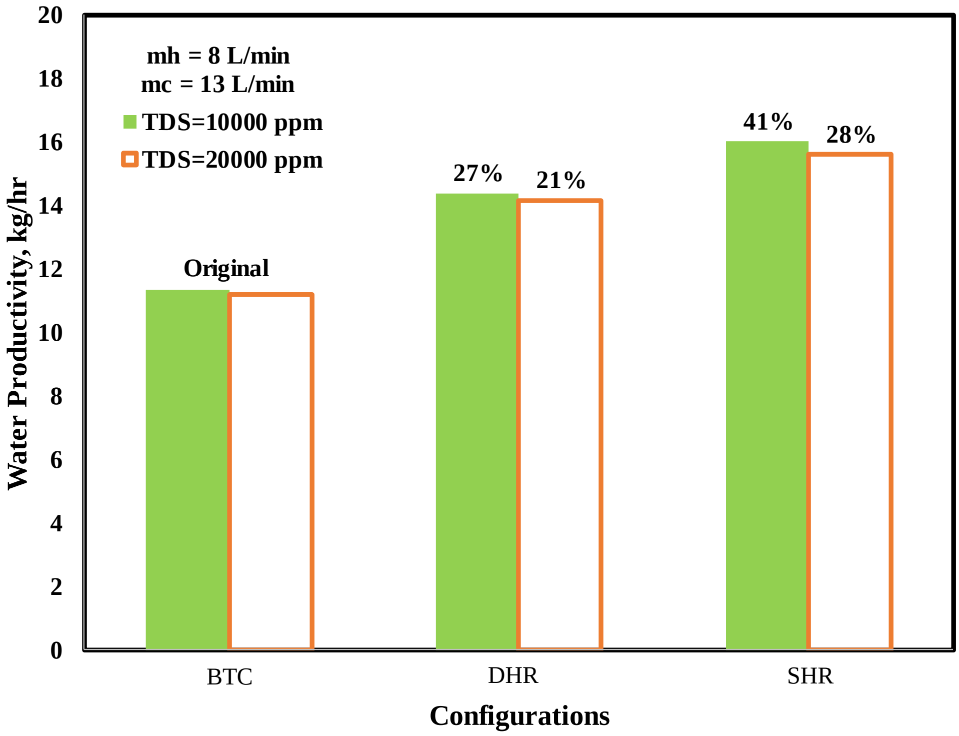


Figure 8. The effect of heat recovery on the productivity

4 CONCLUSIONS

A special test trig is designed and constructed to investigate the performance of two AGMD modules. Three cofigurations were used in this work. The base test case is when the two modules are connecting in parallel. Two other configurations were selected and tested, namely; single and double heat recovery (SHR and DHR). The water productivity as well as the Gain Output Ratio (GOR) were used to evaluate the performance of the system under different operating conditions of feed flow rates and feed salinity. From the results of this work, at the forementioned operating conditions, the followings could be concluded:

1- Increasing the feed flow rate increases the water productivity but reduced the GOR.

2- Increasing the feed salinity from 10,000 ppm to 20,000 ppm decreases the water productivity.

3- The DHR leads to an enhancement in the average GOR by 37 % when compared with the BTC. Whereas, the GOR increases with the SHR by 42 %.

4- The DHR leads to an enhancement in the productivity by 27 % and 21 %, when compared with the BTC, at salinities of 10,000 and 20,000 ppm respectively. On the other hand, the SHR gives an increase in the productivity by 41% and 28% at salinities of 10,000 and 20,000 ppm respectively.

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