A HYBRID MULTI EFFECT DISTILLATION–AIR GAP MEMBRANE DISTILLATION SYSTEM

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ABSTRACT

In this study, a hybrid desalination system driven by an electric heater has been designed and constructed at the faculty of engineering, Port Said University, Egypt. This system combined two types of desalination processes: two units of Multi Effect Distillation (MED), and an Air Gap Membrane Distillation (AGMD) unit. The first MED unit is powered by steam, from an electrically heated boiler, and the rejected relatively hot brine is directed to the AGMD unit for further extraction of fresh water. The effect of varying brine mixing ratio and feed flow rate on the performance of the MED unit is studied experimentally. Also, the effect of using different feed temperature on the AGMD, is involved. The productivity and efficiency of the hybrid MED-AGMD system with zero mixing ratio remarkably enhanced by about 26\% and 25\%, respectively.

Keywords: Desalination, Hybrid, Membrane Distillation, MED, AGMD, MED-AGMD

1 INTRODUCTION

The availability of freshwater is mandatory for humankind to inhabit Earth. Although the amount of fresh water is adequate for all humanity, it is not evenly distributed. As a result, millions of people do not have access to fresh water (FAO, 2007). Therefore, seawater desalination is a global solution to provide freshwater. As known, there are many methods for seawater desalination. Such methods have been divided mainly into thermal and filtration methods (Elhenawy, 2016).

In the thermal processes, water is heated to be evaporated and the fresh water is obtained by condensing this vapor. Multi-Effect Distillation (MED), and multi stage flash (MSF) are typical examples of thermal methods. Although these methods can produce large quantities of water, they are energy-consuming methods. Renewable energies such as solar energy is used to alleviate this energy consumption issue. Several solar assisted desalination plants have been designed and implemented using the MED process (Moh’d et al., 2001), (Garcí, 2003), (Begrambekov, 2004), (Epp&Pappapetrou, 2004), (Eltawil et al., 2009), and (Joo&Kwak, 2013).

On the other hand, in the filtration methods, a membrane sheet is used to separate permeate from saline water. Reverse Osmosis (RO) and Membrane Distillation (MD) are typical examples. MD is a newly emerging technology that requires low grade energy consumption compared to other technologies such as multi stage flash (MSF) or reverse osmosis (RO) (El-Ghandour et al., 2017). It provides continuous separation, beside the fact of the ease of combining the membrane process with thermal separation processes (hybrid strategies). Also, MD process can be modular and flexible for scale up keeping the advantage that the separation occur under mild conditions. Many demonstration projects using solar
thermal MD have been built world wide (Banat et al., 2007), (Wang et al., 2009), (Chen & Ho, 2010), (Manna et al., 2010), (Guillén-Burrieza et al., 2011) & (Zhang et al., 2013).

The membrane in MD is made from hydrophobic material which allows water vapor to pass through and prevents liquid water then the vapor is condensed on the other side of the membrane which is lower in temperature. The vapor pressure difference is the driving force behind vapor motion. MD has several configurations, based on the way of vapor condensation, such as: direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweep gas membrane distillation (SGMD), and vacuum membrane distillation (VMD). The DCMD is the simplest, however it suffers from high heat loss by conduction that makes it of low efficiency. In AGMD, the air gap increases the resistance of heat to flow, thus minimizing heat conduction losses, but it suffers from low flux as the air gap represents an additional resistance for mass transfer. The DCMD is the most popular for MD laboratory research, with more than half of the published references (Alklaibi & Lior, 2005), (Curcio & Enrico, 2005), (Hanemaaijer et al., 2006). However, AGMD is the more popular in commercial applications because it has high efficiency and the capability of latent heat recovery (De Andres et al., 1998).

The idea of combining two systems of desalination is not new but has a continuous interest from many researchers. Andres et al. (1998) experimentally investigated a combined multi-effect distiller and a DCMD system. They achieved an increase in the production by about 7.5% and an improvement of efficiency of 10%. Farag et al. (2016) & Mabrouk et al. (2016) examined a hybrid system of MED and AGMD driven by solar energy in outdoor conditions.

In this study, the performance of a hybrid MED-AGMD desalination system, driven by electric heaters, is evaluated under different operating conditions. This system combined two types of desalination processes, namely, MED and AGMD. The MED is a two effects plant that is heated by steam. The brine leaving the two effects is combined then distributed as a feed to the AGMD. The AGMD is composed from one commercial module.

2 PROCESS DESCRIPTION AND EXPERIMENTAL SET UP

Figure 1 shows the flow diagram of the proposed hybrid MED-AGMD system driven by electric heaters. It is composed of two different subsystems of desalination based on different technologies, namely, the MED and the AGMD. Each system is surrounded by a closed dashed line as shown in the figure. In this system, an electrically heated boiler is used to generate steam which is used as the heating source. The generated steam is introduced into the evaporator tubes of the first effect where it condenses then returns to the boiler. The evaporator tubes are cooled externally by the sprayed saline water. As a result, part of the sprayed seawater is evaporated, and the other part is collected as brine with increased salt concentration. The produced vapor is at lower temperature than the heating steam; however, it can still be used as a heating media for the second effect where the process is repeated. The decreased pressure from one cell to the next allows the brine and distillate to be drawn to the next cell. This generated vapor is directed to the second effect where it is condensed and collected as fresh water; therefore, more vapor is generated in the second effect. This vapor is condensed, externally, in the water condenser. The brine of the second effect of MED is mixed with that from the first effect to feed the AGMD module. In the AGMD, water vapor crosses the membrane and condensed in the air gap side. Seawater feed, lines colored in blue, is directed to the condenser to condense the vapor of the second effect (cell2) MED; consequently, the seawater gets warm due to the latent heat release. Part of this cooling seawater is directed to the MED cells to be sprayed on the top of the evaporator tubes. Another part of the seawater is used as a coolant fluid in AGMD modules to condense the permeated vapor. The remaining part of the seawater feed is rejected, as shown in the Fig. 1. A photo of the actual system test rig is shown in Fig. 2.
The flow rates of the feed and permeate are measured using rotameters. The temperature and the pressure are measured using thermocouples of type T and pressure transducers, respectively. The water flux is determined by the weight of the distillate using weighing balance and a stop watch. Brine and
permeate concentrations are measured by the TDS meter model. The data is recorded using DATAQ Instruments (Graphtec Model: GL220_820APS, Graphtec).

3 RESULTS AND DISCUSSION

In this section, the results and discussions of the collected data are presented. The performance of the MED system is solely presented first, then that of the AGMD. Finally, the performance of the combined system is then shown.

3.1 The MED unit

In the experimental investigations, almost all the experimental runs were conducted with seawater feed of average salinity of 35,000 ppm. The steam condition introduced into the system was kept constant at a mass flow rate of 23 kg/h and a temperature of 102 °C. The effect of the brine ratio and the seawater feed flow rate on the MED performance was tested. The performance was measured by the productivity of produced water and by the performance ratio. The thermal performance PR of the MED plant, defined as the mass of distillate water produced per unit mass of the heating steam (Ding et al., 2005), is given by:

\[
PR = \frac{m_d}{m_s}
\]  

where \(m_d\) is the total mass of distillate formed by the boiling and flashing in all effects, and \(m_s\) is the amount of steam supply to the first effect from the boiler, respectively.

Although, the brine of the MED system is of high salinity, it has a large heat content due to its relatively high temperature. Therefore, some brine is circulated back to the MED system after mixing with the fresh seawater of low temperature. The brine ratio is defined as the mass flow rate of the recirculated brine to the mass flow rate of total brine leaving the MED.

Three brine mixing ratios of 60%, 70%, and 80% were tested, and their influence on the performance ratio (PR) of system is illustrated in Fig. 3. It shows that, for the test range, the performance ratio increases as the brine mixing ratio increases. This is attributed to the gain of energy supplied to the system from the recirculated relatively hot brine instead of rejecting it. This could be concluded from examining equation 1. In the case of fixed amount of heat supplied, more vapor is produced by the MED system as can be seen from Fig. 4. The maximum value of PR is 1.75 which occurred at a brine mixing ratio of 80%. On the other hand, increasing the brine mixing ratio increases the salt concentration in the brine leaving the MED which increases the scaling problems.

The Effect of brine mixing ratio on the water productivity is shown in Fig. 4. The same trend is also evident as shown in Fig. 3. Higher mixing ratio gives more vapor and consequently more fresh water production. The maximum value of productivity occurs at the mixing ratio of 80% is about 40.5 kg/h.
Figures 5 and 6 show the effect of varying the feed seawater flow rate on the performance ratio and water productivity of the MED system. The feed seawater flow rates of 660, 720, and 900 L/h were used while the mixing brine ratio was kept constant at 80%. It is found that, both the performance ratio and water productivity decrease with the increase of seawater mass flow rate. This result could be referred to the reduction of brine temperature due to the increase of the feed flow rate which reduces the system ability to evaporate steam.
3.2 The AGMD unit

The performance of the AGMD module is measured under varying operating parameters of feed temperature, flow rate, and concentration. During these experiments, the coolant temperature and salinity were kept constant at 35 °C and 35000 ppm, respectively. The coolant flow rate was equal to the feed flow rate. The performance is evaluated by the water productivity and the energy efficiency. The energy efficiency of the system is calculated from (Mabrouk et al., 2017):
where \( m_f (kg/s) \) is the mass flow rate of the feed side determined from the experiment, \( J_m (kg/s) \) is the water productivity, \( LH_v (J/kg) \) is the latent heat of evaporation of water at the average temperature, \( CP_f (J/kg K) \) is the heat capacity of water at the average temperature, and \( t_{fi}, t_{fo} \) are the temperatures of the feed flow rate at inlet and outlet, respectively.

Figure 7 shows the effect of varying the feed temperature from 45 to 65 °C on the water productivity at feed flow rate of 600 L/h and salinity of 38500 ppm. The figure shows that, the relation between the feed temperature and the water productivity is almost linear. This is attributed to the fact that the driving force behind the vapor transport through the membrane is the vapor pressure difference which is a function of the temperature difference. Also, it shows that, at the maximum temperature tested of 65 °C, the unit gave a maximum productivity of 18 L/h.

![Figure 7. Effect of feed temperature on water productivity of the AGMD unit.](image)

The effect of feed temperature on the energy efficiency of the AGMD module is illustrated in Fig. 8. For the AGMD module, it is found that the energy efficiency increases with the increase in the feed temperature. This relation is nonlinear as the change in the energy efficiency with respect to the change in the feed temperature is high at low temperatures and vice versa. The non-linear behavior is reported also by other authors (Al-Obaidani et al., 2008) & (Mabrouk et al., 2016). This is attributed to the increase in the feed temperature difference between inlet and outlet, \( (t_{fi} - t_{fo}) \), which increases at higher feed inlet temperature. Hence, this reduces the rate of increase in efficiency, as it is reversely proportional to it.
3.3 The hybrid MED-AGMD system

Figure 9 shows the productivity of the MED, AGMD, and the MED-AGMD systems at seawater feed flow rate of 660 L/h without brine mixing. In this hybrid system, the output brine of the MED system is the input feed to the AGMD system. While the salinity at the feed of the MED system was 35000, it was 38500 at the inlet to the AGMD system. The MED system gave a productivity of 20 L/h while the AGMD system gave 40 L/h. The productivity of the hybrid system is 60 L/h which is simply the algebraic sum of the productivity of the system components. The advantage of this proposed hybrid system is to increase the productivity at the same heat source. Consequently, the price of one cubic meter of distillate water is remarkably decreased.

The effect of brine mixing ratio on the hybrid system is also investigated. The productivity of the hybrid system with 60% brine mixing ratio and without mixing is depicted in Fig. 10. The figure shows clearly that the productivity of the hybrid system is reduced from 60 L/h to 40 L/h for the brine mixing ratios of 0% and 60%, respectively. This reduction is attributed to the decrease in the feed flow rate of the AGMD system. This is due to the extraction of brine for recycling.
CONCLUSION

Two different desalination processes, namely, Multi Effect Distillation (MED), and Air Gap Membrane Distillation (AGMD), were investigated experimentally. A hybrid system is also proposed. This hybrid system consists of two units of the MED and an AGMD commercial unit. The first MED unit is powered by steam, from an electrically heated boiler, and then the rejected relatively hot brine is directed to the AGMD unit for further extraction of fresh water. The effect of brine mixing ratio and the feed flow rate, on the performance of the MED unit, is studied. Also, the effect of feed temperature on the AGMD is taken into account. The following conclusions are obtained:

- Regarding the MED system, increasing the brine mixing ratio increases the system productivity and the performance ratio.
- Regarding the AGMD system, increasing the feed temperature increases the productivity of the system.
- Regarding the hybrid MED-AGMD system, the productivity and efficiency of the hybrid MED-AGMD system with zero mixing ratio remarkably enhanced by about 26% and 25%, respectively.

REFERENCES


