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Experimental Investigation of Membrane Distillation Using Waste Heat for Sea Water Desalination

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Abstract: Membrane distillation is an unprecedented approach demonstrating admirable success in many water purification applications. Recently, many commercial-scale membrane distillation systems with production capacities ranging from 20 L/d to 50 m3/d were improved and assessed. The thermal efficiency and distillate flow of an air-gap membrane distillation (AGMD) system are affected by many factors. We are employing our compact, single-cassette AGMD unit to test these hypotheses. The distillate flow rate of (2,4,6) litter- min could be obtained under the following convenient parameters, cold feed inlet temperature (TC,in) between (25 to 10 oC), hot feed inlet temperature (Th,in) from (40 to 80 oC), feed flow rate (Vf) for both sides from 2 to 6 litter per minutes where distillate flux (Jd) and specific performance ratio (SPR) were considered as the performance indicators for the modelling. To achieve the best results, more than one type of membrane has been used, in addition to utilizing different pore sizes (0.2, 0.45), considering two types of polyvinylidene difluoride (PVDF) thicknesses (100, 200). Apart from this, graphene nanosheets (G) and zeolite nanoparticles (Z) have been added to improve the materials, which will accomplish the best results. All of those experiments are done using local materials obtained from a pilot scale setup located in Egypt.

Keywords: Membrane Distillation; Seawater; Desalination; Air gap.

Nomenclature

Vf	feed flow rate
Vd	distilled volumetric flow rate
Jd	distillate flux
Tc,in	cold feed inlet temperature
Th,in	hot feed inlet temperature
pr	performance index
Qmd	thermal energy supplied to the system calculated using the energy balance equation
t	Time, sec.
S	Effective membrane surface area of evaporation, m2
Md	The distillate water mass collected, kg
Cf	Concentration of the feed water
Cp	Concentrations of the permeate water
R %	Salt rejection percent

Subscript

a

Greek symbols

λ	water's latent heat for vaporization (2,326 kJ/kg),
ρw	water density as a function of the atmospheric pressure and distillate temperature

Abbreviations

AGMD	Air-gap membrane distillation
PVDF	Polyvinylidene difluoride
SPR	Specific performance ratio
Z	Zeolite nanoparticles
G	Graphene nanosheets
M D	Membrane distillation
DCMD	Direct contact membrane distillation
VMD	Vacuum membrane distillation
SGMD	Sweep gas membrane distillation
PTFE	Polytetrafluoroethylene

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1. Introduction

Water purification offers distinct benefits over traditional membrane-separating processes and improves separation efficiency by killing germs and eliminating all minerals. In addition, the volatile organic components are removed. Membrane distillation (MD) is a modern method that combines distillation with membrane separation; as a result, it might be used efficiently for a wide range of water purification applications. MD is a heat-dependent technique in which the difference in vapor pressure between the hot and cold sides has the upper hand. Water is frequently included in the feed solution, which vaporizes and flows through a microporous hydrophobic membrane. The usual working temperature is 80°C [1]. The desired liquid feed for MD treatment should be kept in direct contact with one side of the membrane without passing through its dry pores. The membrane materials include polyvinylidene fluoride, polytetrafluoroethylene, and polypropylene (pp), in addition to locally made PVDF, which is increased by the inclusion of polytetrafluoroethylene (PTFE) components.

Additionally, zeolite nanoparticles (Z) and graphene nanosheets (G) [2] are frequently used in medical procedures. They have several exceptional advantages over conventional distillation methods, including low operating temperatures and pressures and tolerance to varying salt concentrations. Utilizing low-grade or waste heat is a unique benefit of being a doctor [3]. MD is classified into four types: direct contact membrane distillation (DCMD), air-gap membrane distillation (AGMD), vacuum membrane distillation (VMD), and sweep gas membrane distillation (SGMD). DCMD is the most investigated MD formulation due to its naturalness and simplicity of usage. DCMD, on the other hand, has poor energy efficiency owing to conduction heat loss. To improve the AGMD's thermal energy efficiency, a stagnant air gap is placed between the membrane and a condensation surface [4]. Researchers, including conductive gap MD, have developed several AGMD topologies, permeate gap MD, liquid gap MD, and material gap MD [5-7]. Scarab Development presently manufactures the original flat plate AGMD technology, developed in 1988 by the Swedish business Svenska Utvecklings AB [8]. Each module comprises ten planar cassettes with a 2.3 m2 membrane surface area and a global distillate water capacity of 1-2 m3/d. The single stage consists of two condensing walls, two warm water supply and exit tubes, and two injection-moulded plastic frames with two parallel membranes [9]. [10] modified the Scarab AGMD modules to improve thermal efficiency. [11] developed a multistage AGMD system with hollow fiber and plate-and-frame designs. Memstill [12] is the name of two pilot plants with design capacities of 50 and 80 m3/d, respectively. Fraunhofer ISE developed spiral wound MD modules with a production capacity of 100 L/d that could be raised to 500 L/d to 10 m3/d by combining several modules [13,14,15]. The current study employs the AGMD module, which has been proven for low-capacity manufacturing aimed at residential applications [16]. However, many of these modules were designed for desalination at capacities larger than 100 L/d. Khan et al. performed experimental investigations to remove arsenic using a single cassette AGMD with an effective membrane area of 0.2 m2 and observed fluxes of 20 L/m2 h at a temperature difference of 50°C between the hot and cold intake temperatures [17]. [18] performed an experimental study on the performance of RO using thin film composite (tfc) membrane. The results revealed that as feed water increased the permeate flow rate decreased.

The literature review showed that a modified AGMD module should be developed through a laboratory scale of experimental test rig. The goal of the present work is to use a prepared MD membranes for desalination of saline water and to apply a modified AGMD module with different pore sizes to improve the productivity flux of distillate. The present work presented AGMD module that is characterized experimentally to show the process parameters effects (inlet temperature through the hot and cold channels of MD module and feed flow rate) on the productivity flux of distillate.

2. EXPERIMENTAL SETUP AND METHODOLOGY

2.1 Flat Sheet AGMD Module

The experimental setup was designed to fulfill the theoretical circuit presented in figure1. The experimental test rig used in the present work is shown in figure2. It has been built on previous experiments, considering current conditions, and adjusting the experiment settings to prevent any previous errors and produce the best results. The device design proceeded through many phases, the first of which was the temperature procedure. Because this is a heat-sensitive technique, a cold stainless tank is well-sealed save for the exits and entrances and comes with a cooling unit.

Nonetheless, the hot tank is linked to a thermal heater, which raises the water temperature to 90 oC. Maintaining this temperature is important for managing the target heat exchange and evaporation rates throughout the experiment. The heat differential between the cold and hot tanks should be maintained between 10 and 75 oC, which the thermal sensor linked to the controlling unit can readily do. The primary water supply provides both cold and hot tanks; a large flow metering system regulates the volume of water entering the experiment, which is one of the most critical characteristics. Following the flow measurement device, an elastic heat-resistant connection allows the device to be moved and the membrane to be changed several times throughout the trials. The filtering process is the device's second component. The flow-measuring equipment measures the required quantity of water and sends it to the desalination unit through appropriate connectors. The device is made up of several pieces. The first is appropriate for cold water from the cold tank. Except for an upper entry aperture at the side of the line and a lower departure opening, it is sealed from both sides. The device's inner layer is made of a thin layer of stainless steel with a thickness of 0.8 mm. The more the thinness, the greater the heat transmission. The next layer is a 0.9 mm space known as an air gap; the thinner this space is, the greater the heat exchange.

To preserve the membrane from damage or leakage, it is placed between two thermal elastic and non-flexible gowns after the air gap. All of the previous parts are connected to the shape of a cassette in the right order by fastening and loosening screws for the ease of changing the membrane and maintenance.

PVDF is one of the most important membranes for its notable characteristics. First is a hydrophobic membrane with premium thermal, mechanical, and chemical characteristics. Moreover, it is thermally suitable with other polymers, allowing it to be modified to promote tailor-made functions. On top of that, PVDF has a high dissolution capacity in many organic solutes. Accommodation of the membrane goes through many steps: the choice of the solvent, the effect of the coagulation path, the air gap distance, and the post-casting heat handling. All of these factors restrain the whole process; improving one by another gives us the privilege of reaching more appropriate AGMD procedures. AGMD is combined with inorganic Nanoparticles without much effort than the hydrophobic coating; alternately, we have the advantage of controlling the pore size for higher salt rejection.

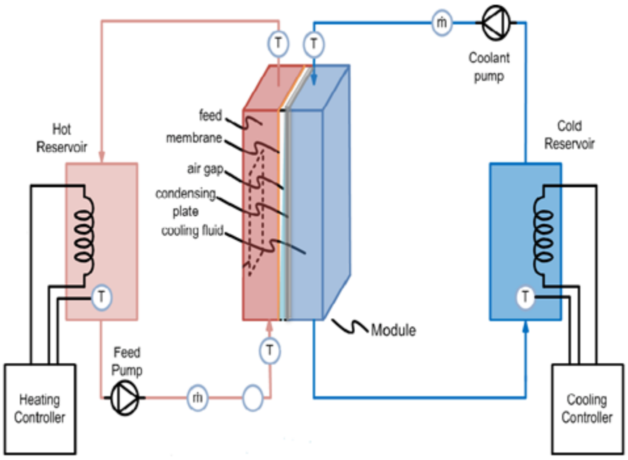

Fig 1: Schematic representation of the Flat sheet AGMD module.

Fig 2: Real photo of the AGMD experimental setup

2.2 Material: hydrophobic PVDF membrane

graphene nanosheets (G), zeolite nanoparticles (Z), In addition to other modified materials

- **Pore size: 0.2 µm, 0.45 µm; thickness: 100 µm, 200 µm**

From all of that, we can summarize the whole process into three paths

- Hot path: where the liquid feed turns into vapor under the pressure effect
- Air-gap: it's the gap that permits the vapor to condense into water drops that are then collected by the gravity effect from the bottom opening
- Cold channel: this is where the concealed heat is absorbed from the condensed vapors.

3. THEORETICAL WORK

The performance of AGMD is calculated through the performance index (pr) and plotted as a function of temperature differences in the cold and hot paths. We can calculate the (pr) by the following equation (1):

$$pr = \frac{\lambda \rho_{w,(Ta,Pa)}\, V_d}{Q_{md}}$$ rλρ_w, (Ta, Pa) V_d/Q_md (1)

Where: Q = V′.[ρw(Thin, Phin).hw(Thin, Phin)- ρw(Tho, Pho). hw(Tho, Pho)]

Where: (V = V′f - Vd) and Vf is the feed rate of the MD module.

From all previously mentioned parameters, the feed flow rate (Vf), the cooling inlet temperature (Tc, in), which is the condensation temperature, and the feed inlet temperature (Th, in) are the most remarkable ones affecting the procedure. On the other hand, the AGMD implementation indicators are:

Distillate flux (Jd) and specific performance ratio (SPR) are calculated according to equations (2) and (3) as follows:

$$J_d = \frac{M_d}{S * t} \qquad (2)$$

$$SPR = \frac{M_d}{Q_{md}} \qquad (3)$$

PR=M_d/Q_md (3)

Where: Qmd (kWh) is the thermal energy supplied to the AGMD module.

Using the TDS device, the salt rejection percent (R%) is measured after each experiment in addition to measuring the amount of the undissolved substances by chemical materials and calculated by equation (4) as follows:

$$R\,\% = \frac{(C_f - C_p)}{C_f} * 100 \qquad (4)$$

%= (C_f-C_p)/C_f*100 (4)

4. RESULTS AND DISCUSSION

The MD permeate flow is very sensitive to feed temperature, making it a crucial operational parameter. Because of the temperature difference between the two sides of the membrane, the vapor partial pressure difference acts as the driving force in MD, making MD a thermal separation process. Water vapor pressure rises as input temperature rises, which increases the driving power. Increases in feed temperature may result in more flux but optimizing the MD process's operating temperature and other parameters requires thought about energy use and thermal efficiency. Fig. 3 shows the combined effect of the inlet temperature through the MD module's hot and cold channels on the distillate productivity flux. The hot feed saline water is in contact with the membrane, where vapor is generated and passes through the membrane to the cold feed side temperature. It is found that both hot and cold side temperatures have significant effects on distillate flux, especially at high hot feed temperatures. The figure illustrates that, for constant feed water temperature as the hot feed temperature increases the distillate productivity flux increases. While, as the cold feed water increases, the distillate productivity flux decreases. Moreover, the results revealed that, at a feed flow rate of 2 L/min, a maximum productivity flux of 9.2 L/m2h was obtained at 80 oC and 10 oC of hot and cold temperature, respectively. So that, the hot feed temperature has a further significant effect on the productivity flux than the cold feed temperature.

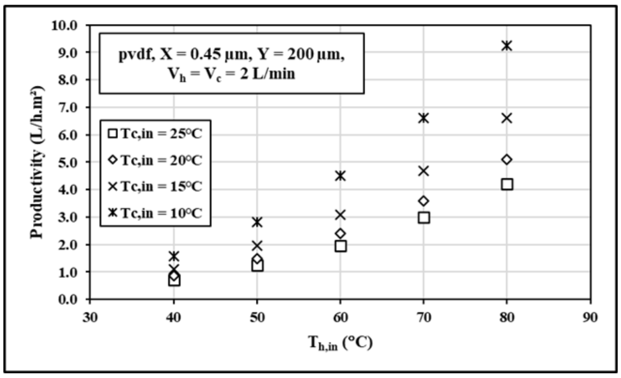

Fig. 3 Effect of feed hot and cold inlet temperatures on the productivity flux

The membrane characteristics (membrane pore size and thickness) generally affect the membrane distillation process. Figure 4 represents the effect of flow rate on the productivity flux for different membrane materials. It was found that there is a linear increase in productivity flux with all membrane materials. A small significant increase in the productivity of the PVDF membrane compared with modified membranes. Generally, a significant increase in the productivity flux was observed for the membrane that has a respectable hydrophobic membrane with modified thermal, mechanical, and chemical features for the AGDM process, as shown in Fig. 4. The flow rate of the hot inlet fluid influences the productivity flux of distillate at different membranes for a constant cold fluid inlet temperature and flow rate at 10 oC and 4 L/min. Figure 4 shows the effect of feed flow rate on distillate flux for different membranes for a constant hot inlet temperature and cold inlet temperature of 80 oC and 10 °C, respectively. A slight increase in the productivity flux with the feed flow rate for different membranes is observed. A high productivity flux of 13.95 L/m2.h and 12.2 L/m2.h are obtained at a high feed flow rate for graphene and zeolite, respectively, compared to neat PVDF membranes. The presence of graphene nanomaterial in the polymer matrix enhances the diffusion of vapor flux through the membrane due to the capacity increase through the sorption/desorption process.

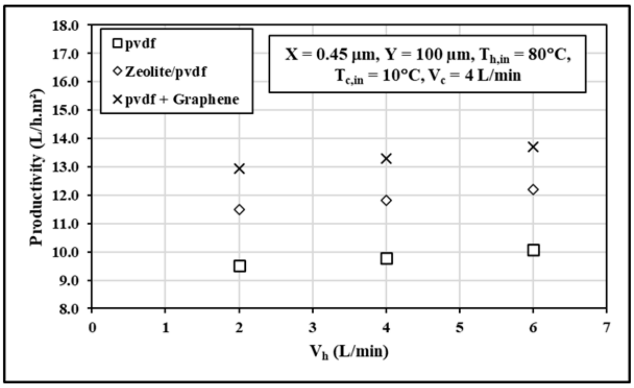

Fig. 4 Effect of feed flow rate on the productivity flux for different membranes

The impact of membrane pore size productivity flux for different inlet hot feed water temperature and cold feed water temperature of 20°C is illustrated in figure 5. It could be concluded that, at high feed hot inlet temperature, a high thermal driving force is produced, which permits the vapor to diffuse through the membrane. Better fluid mixing could be obtained especially at high feed flow rate; hence, a more significant increase is obtained in the productivity flux. The figure shows that, the highest productivity flux and salt rejection were obtained at high feed hot inlet temperature. Moreover, the membrane with a pore size of 0.45 µm provides a slightly higher productivity flux than 0.20 µm. The membrane prevents the liquid water from entering the pores, which is maintained by a microporous hydrophobic membrane.

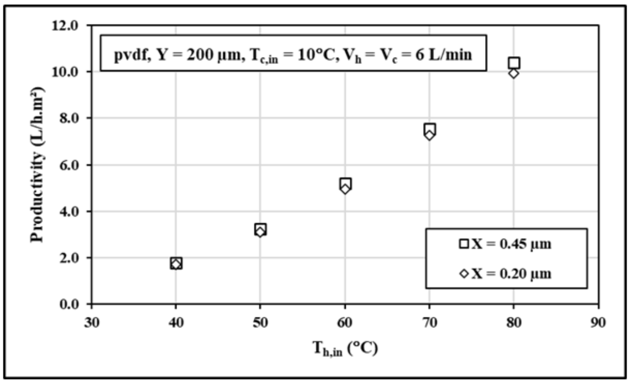

Fig. 5 Effect of pore size on the productivity flux

For feed and coolant temperatures of 80°C and 10°C, respectively, the effect of membrane material on productivity flux was studied. The rate of flow of the hot and cold fluid was carefully monitored and maintained steady at 6 L/min. The three types of membranes, PVDF membrane and the other two modified membranes was compared by using the AGMD module as shown in figure 6. The findings show that various membrane materials result in varying productivity flux. As represents in Fig. 6, the modified membrane with graphene has maximum pure water productivity of 13.95 L/h.m2, while the PVDF produces minimum productivity of 10.38 L/h.m2. This is related to the presence of graphene or zeolite in the PVDF membrane which improves the connectivity of the distillate production. The membrane's pore size must be as small as possible to diffuse the vapor and provide a low permeability of feed water into the pores.

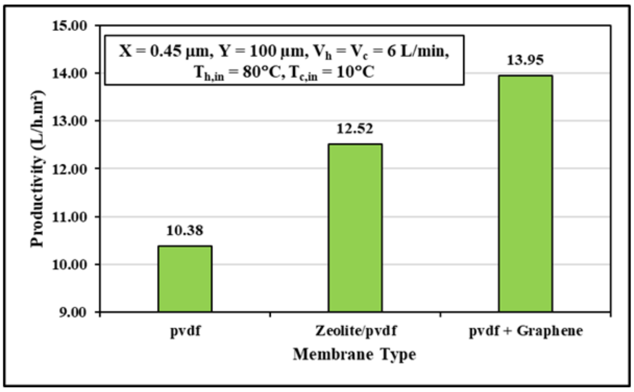

Fig. 6 Productivity flux of distillate for different membranes (Th,in= 80 oC, Vh = 6 L/min).

Figure 7 illustrates how the difference in temperatures (Th,in – Tc,in) affects the performance ratio (PR) of the MD system for various pore sizes. It has been discovered that the performance ratio improves if there is a greater temperature disparity between the hot and the cold input temperatures. At a feed flow rate of 6 L/min, the PR ranges from 0.4 to 0.8, and the membrane with pore size 0.45 µm produces a greater PR than the membrane with pore size 0.2 µm. This is because the larger pore size allows more water to pass through.

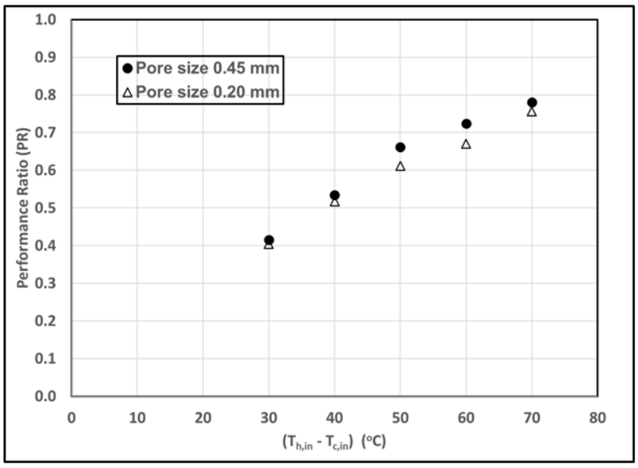

Fig. 7 Performance ratio variation against the temperature difference for different pore sizes

5. Conclusions

The results of the experiments demonstrate a new AGMD module that has membranes that have been altered. The AMGD approach looked at these membranes through the lens of three distinct membranes. The following findings and conclusions were reached because of the experimental module with modified membranes:

- The productivity flux increases for AGMD to 13.95, 12.52, and 10.38 for PVDF with Graphene, PVDF with zeolite, and PVDF, respectively.
- Controlling the pore size gives us the advantage of higher salt rejection and makes the membrane more convenient for AGMD implementations.
- The modified membranes with fine morphology and appropriate pore size of asymmetric PVDF membranes make it more convenient for AGMD procedures.
- A modified version of PVDF membranes with zeolite and graphene has good mechanical stability and connectivity characteristic.
- The presence of zeolite and graphene in the PVDF membrane increases the productivity flux by 21 % and 33 %, respectively.
- Higher values of productivity flux were achieved with high hot feed temperature and flow rates and low cold feed temperature.

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