Enhancement of the air gap membrane distillation system performance by using the water gap module

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ABSTRACT

The negative effect of an air gap layer presented between the membrane and cooling plate on air gap membrane distillation (AGMD) performance was diminished largely by inserting a water gap membrane distillation (WGMD) module in series. The new design of air-gap–water-gap membrane distillation (AG-WGMD) was evaluated experimentally by comparing with an AGMD system under different operating conditions. In theory, mass and heat transfer in the new (AG-WG)MD and imitative AGMD systems were analyzed. Experimental outcomes showed that a new (AG-WG)MD design profoundly enhanced flux ($P_d$) and gained output ratio (GOR), and greatly decreased energy consumption (STEC) and heat input ($E_{H.I}$). At a concentration of 5,000 mg/L, coolant temperature of 20°C, and flow rate of 18 L/h, $P_d$ was promoted by 76.26%, 40.84%, 35.45%, 30.91%, and GOR by 46.38%, 33.46%, 31.27%, 26.65%, in addition to STEC being reduced about 55.63%, 46.81%, 43.66%, 38.30%, and $E_{H.I}$ around 31.31%, 25.84%, 23.53%, 20.55%, from the AGMD to (AG-WG)MD system at feed temperatures of 50°C, 60°C, 70°C, and 80°C, respectively. The outcomes proved that the AGMD performance could be significantly promoted by integrating with WGMD in a combined MD system. This combination increased the temperature difference across the membrane and decreased thermal-concentration boundary layers for the AGMD system.

Key words | air gap membrane distillation, energy consumption, gained output ratio, membrane module, water gap membrane distillation

HIGHLIGHTS

- Adding the WGMD in series with the AGMD in a combined MD system decreased the negative air gap effect.
- The new design (AG-WG)MD system increased water flux and gained output ratio deeply by about 76.26% and 46.38%, respectively.
- The system of (AG-WG) reduced significantly the specific thermal energy consumption and waste heat input by around 55.63% and 31.31%, respectively.

NOMENCLATURE

$A_{\text{iner}}$ Effective evaporation surface area based on the inner diameter of the hollow fiber membrane (m$^2$) $A_c$ Area of the heat exchange tube in the cold feed channel (m$^2$)

$A_h$ Area of the hollow fiber membrane in the hot feed channel (m$^2$) $A_{\text{surface}}$ Area of the cooling surface (m$^2$) $C_{pw}$ Specific heat of saline water (J/kg°C)

$E_{H.I}$ Total heat transfer across the thermal feed side boundary layer by the convection mode (kJ/h)
\( E_{\text{gap,total}} \) Total heat transfer across the gap of AGMD and (AG-WG)MD (kJ/h) 
\( E_{\text{gap(AGMD)}} \) Heat transfer across the gap of AGMD by the conduction and evaporation modes (kJ/h) 
\( E_{\text{gap(AG-WG)MD}} \) Heat transfer across the gap of (AG-WG)MD by the natural convection and evaporation styles (kJ/h) 
\( E_{\text{surface,total}} \) Total heat transfer through the cooling surface via conduction mode (kJ/h) 
\( E_{\text{c,f,total}} \) Total heat transfer across the distilled water film by convection (kJ/h) 
\( E_{\text{c,total}} \) Total heat transfer across the thermal permeate side boundary layer via convection (kJ/h) 
\( E_{\text{H.I}} \) Specific waste heat input (MJ/kg) 
\( E_{\text{L.H}} \) Evaporation latent heat transfer (MJ/kg) 
\( g \) Gravitational acceleration (m/s^2) 
\( h_h \) Convection heat transfer coefficient of the hot feed (W/(m^2·C)) 
\( h_c \) Convection heat transfer coefficient in the cold permeate side (W/(m^2·C)) 
\( h_{\text{mem,material}} \) Heat transfer coefficient of the membrane (W/(m^2·C)) 
\( h_{\text{air gap}} \) Heat transfer coefficient of the air gap region (W/(m^2·C)) 
\( h_{\text{water gap}} \) Heat transfer coefficient of the water gap region (W/(m^2·C)) 
\( h_{C,f} \) Heat transfer coefficient for the condensation film on the vertical surface (W/(m^2·C)) 
\( h_{\text{global}} \) Global membrane coefficient (kg/(m^2·h·mbar)) or (m^3/m^2·Pa) 
\( h_d \) Diffusion coefficient through the membrane (kg/(m^2·h·mbar)) 
\( h_c \) Convection coefficient through the gap (kg/(m^2·h·mbar)) 
\( K_{\text{mem,material}} \) Thermal conductivity of the membrane material (W/(m·C)) 
\( K_{\text{air gap}} \) Thermal conductivity of the air gap (W/(m·C)) 
\( K_{\text{water gap}} \) Thermal conductivity of the water gap (W/(m·C)) 
\( K_{C,f} \) Thermal conductivity of the distilled water film (W/(m·C)) 
\( K_{\text{surface}} \) Thermal conductivity of the cooling surface material (W/(m·C)) 
\( L_{\text{mem}} \) Membrane length (m) 
\( M_w \) Water molar mass (≈18 g/mol) 
\( m_f \) Feed flow rate (L/h) 
\( P_{v,\text{feed}} \) Partial water vapor pressure at the hot feed side (MPa) 
\( P_{v,\text{air gap}} \) Partial water vapor pressure at the gap side (MPa) 
\( P_d \) Water flux volume (kg/(m^2·h)) 
\( P_{d(AGMD)} \) Water flux of the AGMD (kg/(m^2·h)) 
\( P_{d(AG-WG)MD} \) Water flux of the (AG-WG)MD (kg/(m^2·h)) 
\( R \) Ideal gas constant (≈8.3145 J/mol·K) 
\( S_d \) Salt concentration of distilled water (mg/L) 
\( S_f \) Salt concentration of feed saline water (mg/L) 
\( t \) Time (minute) 
\( T_h \) Temperature of the hot bulk feed (°C) 
\( T_{h,1} \) Temperature of the membrane surface at the hot feed side (°C) 
\( T_{h,2} \) Temperature of the membrane surface at the gap side (°C) 
\( T_c \) Temperature of the cold bulk feed (°C) 
\( T_{C,1} \) Temperature of cooling surface at the condensation film (°C) 
\( T_{C,2} \) Temperature of cooling surface at the water gap side (°C) 
\( T_{C,3} \) Temperature of cooling surface from the cold feed side (°C) 
\( T_{C,f} \) Temperature of cooling surface at the air gap side (°C) 
\( T_{d,AGMD} \) Temperature of the distilled water (°C) 
\( T_1 \) Inlet temperature of the hot feed stream (AGMD) 
\( T_2 \) Outlet temperature of the hot feed stream (AGMD) 
\( T_{2}^' \) Outlet temperature of the hot feed stream ((AG-WG)MD) 
\( T_3 \) Inlet temperature of the cold feed stream (AGMD) 
\( T_{3}^' \) Inlet temperature of the cold feed stream ((AG-WG)MD)
$T_4$ Outlet temperature of the cold feed stream (AGMD)
$\Delta T_{\text{cross}}$ Temperature difference across the membrane (°C)
$\Delta H_v$ Evaporative latent heat (≈2,326 kJ/kg)
$\rho_w$ Feed saline water density (kg/m$^3$)
$\delta_{\text{mem,material}}$ Thickness of the membrane (m)
$\delta_{\text{air gap}}$ Thickness of the air gap (m)
$\delta_{\text{water gap}}$ Thickness of the water gap (m)
$\delta_{\text{surface}}$ Thickness of the cooling surface (m)
$\mu_w$ Dynamic viscosity (kg/(m·s))
GOR Gained output ratio (dimensionless)
TIR Thermal insulation region (m)
AGMD Air gap membrane distillation
WGMD Water gap membrane distillation
(AG-WG)MD Air-gap–water-gap membrane distillation
STEC Specific thermal energy consumption (MWh/kg)
SRR Salt rejection rate (%)
$W_d$ Weight of water flux (kg)

INTRODUCTION

In recent decades, a fast increase in climate change, industrialization, and overpopulation as well as a horrible decrease in freshwater resources around the world have made water desalination technology occupy the first rank and receive more attention from investigators as an interesting and attractive solution for water scarcity (Baaqel & El-Halwagi 2018; Qasim et al. 2019; Yang et al. 2019). In comparison with thermal desalination processes (i.e., electrodialysis (ED), forward osmosis (FO), and reverse osmosis (RO)), the membrane separation process is more suitable due to less energy usage (Kesieme et al. 2013). A membrane is a functional element that separates salts and other impurities contained in the feed solution. Diverse materials are used in membrane fabrication and several applications. For example, enzymatic membrane bioreactors for wastewater treatment (Chakraborty et al. 2012), biocatalytic membrane reactors for environmental treatment, fine chemicals, and food (Chakraborty et al. 2014), polymeric membranes for drinkable water reuse, and membranes to support biorefineries (Saha et al. 2017). Membrane-based desalination processes split the inlet feed solution into permeated water and concentrated brine, such as biomimetic membranes (Giw et al. 2017), photothermal membrane distillation (Politano et al. 2017), polyethersulfone (PES) membranes used as ultrafiltration (UF) membrane and membrane distillation (MD) (Liu et al. 2015).

Membrane distillation (MD) is one of the most important water desalination technologies that has gathered between membrane separation and phase-change thermal distillation (Drioli et al. 2015). The membrane used in MD technology should be hydrophobic and porous in order to permit only the water vapor to pass through the dry membrane pores leaving the liquid beyond the membrane body at the hot feed side. MD is characterized by the possibility of coupling with a solar thermal collector to yield pure water squarely from seawater or brackish water at a low feed temperature ranging from 40°C to 80°C (Koschikowski et al. 2003), increase of water recovery after reverse osmosis (RO) (Sanmartino et al. 2017; Yan et al. 2017; Warsinger et al. 2018a, 2018b), and competitive energy efficiency (Tijing et al. 2014; Duong et al. 2015). Despite MD features, weak MD performance is still a challenge. Recently, Naidu et al. (2020) reviewed several hybrid MD systems which were installed specifically for performance improvement as well as resource recovery, such as hybrid MD-crystallizer, -adsorbent, -bioreactor (MDBR), -forward osmosis (MD-FO), -pressure retarded osmosis (MD-PRO), and -reverse electrodialysis (MD-RED). MD is divided into four main systems like vacuum (VMD), air gap (AGMD), sweeping gas (SGMD), and direct contact MD (DCMD) (Alkhudhiri et al. 2012; Warsinger et al. 2014).

Air gap membrane distillation (AGMD) is considered the most meaningful of MD systems in terms of attaining high thermal efficiency above 85% at intense concentration of salt due to a small heat loss by conduction across the membrane thanks to the air gap/thermal insulation region (TIR) placed between the membrane body and cooling surface (Alklaibi & Lior 2005; Swaminathan et al. 2016a, 2016b, 2018; Liu et al. 2017). An air gap/thermal insulation region (TIR) can affect positively or negatively the volume of AGMD water flux, as reported in several works (e.g., Francis et al. 2014; Tijing et al. 2014; Alsaadi et al. 2015;
Attia et al. (2017). Also, Asghari et al. (2013) announced an improvement in the water flux around 3.5-fold when the TIR width reduced from 25 to 5 mm. Similarly, as elaborated by Khalifa et al. (2015), AGMD water flux was increased deeply by 100% because of the corresponding decline in the resistance to vapor mass transport when the TIR width changed from 7 to 3 mm. On the other side, increasing the TIR width caused a further impediment to vapor mass transfer and then decreased the flux correspondingly as advertised in various studies (e.g., Jönsson et al. 1985; Kimura et al. 1987; Pangarkar et al. 2011; Alkhudhiri et al. 2012; Alsaadi et al. 2013; Khalifa 2015). To conclude, as above-mentioned, the enhancement of AGMD thermal efficiency has often taken place at the expense of water flux volume which makes getting a large water flux at the same time as a high thermal efficiency a great challenge to meet.

To mitigate the negative air gap/thermal insulation region (TIR) impact and improve the volume of AGMD water flux, several changes have been made on the AGMD system, for example vacuum-air gap membrane distillation (V-AGMD) (Abu-Zeid et al. 2016), material gap membrane distillation (MGMD) (Francis et al. 2013; Swaminathan et al. 2016a, 2016b), finned tube AGMD (Cheng et al. 2011), immediate assisted solar AGMD (Hengl et al. 2010; Summers & Lienhard 2013), spiral wound AGMD, and multi-stage AGMD (Raluy et al. 2012; Zaragoza et al. 2014; Abu-Zeid & ElMasry 2020).

Water gap membrane distillation (WGMD) is one of the most substantial changed AGMD systems indicated in the literature as liquid (LGMD) and permeate gap membrane distillation (PGMD) (Ugrozov et al. 2003; Singh & Sirkar 2012; Khalifa 2015). In WGMD as displayed in Figure 1, the permeate water filled the gap between the membrane body and cooling surface forming a water gap region (WGR) instead of an air gap region (AGR) (Mahmoudi et al. 2017). WGR assisted in achieving high internal heat recovery, small vapor mass transfer opposition, and minor heat loss across the permeate water.

In an experimental study executed by Francis et al. (2013), it was found that the system of WGMD deeply promoted water flux from 572% to 820% at a hot feed inlet temperature of 40°C when the water gap width changed from 9 to 13 mm. Likewise, approximately 90%–140% improvement in water flux was accomplished with varying the width of the water gap from 4 to 8 mm, as proclaimed by Khalifa (2015). Thus, it could be deduced here that the width of the water gap had no negative influence on the water flux volume contrasting to the air gap width when compared together as done formerly by some investigators (e.g., Kimura et al. 1987; Francis et al. 2013; Asghari et al. 2015; Im et al. 2018). As well, the findings of Essalhi & Khayat (2014) revealed that the water flux of a liquid gap membrane distillation (LGMD) system was nearly 2.2%–6.5% larger than that of the AGMD water flux under the same inlet operating conditions and experimental set-up. This was owing to the thermo-physical properties of water and the effective natural convection heat transfer inside the gap, which assisted in reducing vapor mass transfer opposition and improving heat and mass transfer characteristics. Also, Alawad & Khalifa (2019) mentioned that the influence of the water gap width on the evaporative efficiency (EE) and gained output ratio (GOR) could be omitted, where maximum values of 93% and 1.3 were reached, respectively at a feed temperature of 90°C. Recently, Khalifa (2020) mentioned that the forced convection heat transfer created inside the gap by the gap water circulation technique significantly enhanced the system flux by about 80% to 96% and GOR between 5% and 22% compared with that without gap circulation. Additionally, the effect of gap width could be ignored at higher circulation flow rates. In another study, numerical modeling developed by Swaminathan et al. (2016a, 2016b) revealed that the GOR obtained for a system of PGMD was higher by 20% than that for a system of AGMD. In work performed by Mahmoudi et al. (2017), the obtained theoretical results at different inlet operating conditions were largely identical to the experimental results of the PGMD module run with high internal energy recovery. Finally, in comparison with the AGMD system, the water flux and GOR obtained for PGMD developed about 7.9% and 59.82%, respectively (Cheng et al. 2018).

**WGMD Module Used as an Internal Heat Recovery System**

The present research work suggested a new technique to develop the minor trans-membrane temperature difference...
and major temperature-concentration polarizations of the AGMD system by connecting it with a WGMD module consecutively. The natural convection heat transfer prevailing through the permeate water-filled gap in the case of WGMD is almost 24.17 times quicker than that of the conduction heat transfer dominating through the air-filled gap in the case of AGMD (i.e., the thermal conductivities of water and air are 0.58 W/(m·K) and 0.024 W/(m·K), respectively). This results in upgraded the heat and mass transfer coefficients and then the water flux. As represented schematically in Figure 2, the WGMD module connected consecutively with the AGMD module composed a new MD system called air-gap–water-gap membrane distillation (AG-WG)MD. The proposed connection was intended to make use of the advantage of the high internal heat recovery possessed by WGMD in increasing the inlet temperature of the cold feed stream $T_3$ before entering the AGMD module at the permeate side. After that, inside the AGMD module, the cold feed stream entering at temperature $T_3$ gained more heat from the hot feed stream to become $T_4$. Then, the high outlet temperature of the cold feed stream $T_4$ assisted in increasing the inlet temperature of the hot feed stream $T_1$ due to improved mixing in the feed tank. Consequently, the increase in temperatures $T_1$ and $T_4$ meant an increase in the temperature difference across the membrane ($\Delta T_{\text{cross}} = T_1 - T_4$) and a decrease in the temperature-concentration boundary layers (i.e., polarization) formed at the hot feed side of the AGMD module.

The effect of the new (AG-WG)MD system was evaluated by comparing it with an AGMD system operated without a connection with a WGMD module (Figure 3) at various inlet operating parameters involving feed inlet temperature ($T_{f}$), feed flow rate ($M_f$), and salt concentration ($C_f$).

From surveying several research works implemented on this topic, it was found that authors have been focused only in their studies on the AGMD (e.g., Liu et al. 2020; Shahu & Thombre 2020) and WGMD systems independently (e.g., Alawad & Khalifa 2019; Gao et al. 2019; Mahmoudi et al. 2020) or through a comparative study (e.g., Cheng et al. 2018; Amaya-Vías & López-Ramírez 2019). No work has been found that studies the combination impact between AGMD and WGMD systems together in series on MD performance, which reflects a deep literature gap regarding this point.

Thus, in the current work we focused on the combination effect between WGMD and AGMD in series on AGMD performance in terms of the flux reduction issue resulting from the air gap/thermal insulation region (TIR). So, a module of AGMD integrated with WGMD in series was promoted and examined practically to boost the transmembrane temperature difference and to decrease the negative impact of temperature-concentration boundary layers.
layers utilizing highly saline feed solution. The influence of a new integration air-gap–water-gap membrane distillation (AG-WG)MD system was evaluated by comparing it with AGMD operated alone without WGMD under different feed inlet temperatures, flow rates, and concentrations.

**MODEL OF MASS AND HEAT TRANSFER IN THE AGMD AND (AG-WG)MD SYSTEMS**

The processes of mass and heat transfer in the new suggested air-gap–water-gap membrane distillation (AG-WG)MD system occur simultaneously while the hot and cold feeds are circulating in a counter-current flow over the hot and cold feed channels of the AGMD and WGMD modules connected in series. As illustrated schematically in Figure 4, the two air gap and water gap regions between the membrane body and the cooling surface are combined together as the positive effect of the WGMD process was extended to make a significant change in the temperatures at the hot feed side, membrane surface, and gap region of the AGMD.

**Mass transfer**

**Membrane pore and gap region**

The total vapor mass transfer \( P_{d,\text{total}} \) across the membrane pores of the AGMD and (AG-WG)MD systems is predominantly by Knudsen and molecular diffusion, and across the gap region by the natural convection mode. The \( P_{d,\text{total}} \) could be formulated mathematically as (Cussler 1997; Bouguecha et al. 2002; Khayet & Matsuura 2011; Alkhudhiri et al. 2012; Cipollina et al. 2012):

\[
P_{d,\text{total}} = h_{\text{global}}(\Delta P_{v(\text{AGMD})} + \Delta P_{v(\text{AG-WG})MD})
\]

\[
\Delta P_v = P_{v,\text{feed}} - P_{v,\text{gap}}
\]

\[
P_{d,\text{total}} = M_w \times \left( \frac{h_{\text{global}}}{R} \right) \times (P_{v,\text{feed}} - P_{v,\text{gap}})
\]
where $P_{v,feed}$ and $P_{v,gap}$ are the partial water vapor pressure at the hot feed and the gap sides (MPa), $R$ is the ideal gas constant (≈8.3145 J/mol·K), $M_w$ is the water molar mass (≈18 g/mol), and $h_{global}$ is the global membrane coefficient, which can come from the following equation:

$$h_{global} = \left( \frac{1}{h_d^{-1} + h_c^{-1}} \right)$$

where $h_d$ is the diffusion coefficient through the membrane (kg/(m²·h·mbar)), and $h_c$ is the convection coefficient through the gap (kg/(m²·h·mbar). As revealed by García-Payo et al. (2000), $h_{global}$ typically varies either from $3 \times 10^{-10}$ m³/m²·s·Pa to $7 \times 10^{-10}$ m³/m²·s·Pa or from 0.10 kg/(m²·h·mbar) to 0.25 kg/(m²·h·mbar).

**Heat transfer**

**Thermal feed side boundary layer (hot feed side)**

The total heat transfer ($E_{h,total}$) across the thermal feed side boundary layer of the AGMD and (AG-WG)MD modules by the convection mode in (kJ/h) can be expressed by (Martínez-Díez & Vázquez-González 1999; Srisurichan et al. 2006; Chen et al. 2009; Khayet 2011; Essalhi & Khayet 2013, 2014):

$$E_{h,total} = A_h \times h_{mem,material} \times \left( T_{h,1} - T_{h,2} \right)_{AGMD}$$

where $A_h$ is the area of the hollow fiber membrane in the hot feed channel (m²), $T_h$ is the temperature of the hot bulk feed (°C), $T_{h,1}$ is the temperature of the membrane surface at the hot feed side (°C), and $h_{mem}$ is the convection heat transfer coefficient of the hot feed (W/(m²·°C)).

**Membrane**

The total heat transfer ($E_{mem,total}$) through the membrane material ($E_{mem,material}$) by the conduction style and through the membrane pores ($E_{mem,pores}$) by the evaporation mode in (kJ/h) can be given by the following equations:

$$E_{mem,total} = E_{mem,material} + E_{mem,pores}$$

$$E_{mem,material} = A_h \times K_{mem,material} \times \left( T_{h,1} - T_{h,2} \right)_{AGMD} + (T_{h,1} - T_{h,2})_{AG-WG|MD}$$

$$E_{mem,pores} = \Delta H_v \times (P_{v,AGMD} + P_{v,AG-WG|MD})$$

where $K_{mem,material}$ is the thermal conductivity of the membrane material (W/(m·°C)), $\delta_{mem,material}$ is the thickness of the membrane (m), $T_{h,2}$ is the temperature of the membrane surface at the gap side (°C), $\Delta H_v$ is the evaporative latent
heat (∼2,326 kJ/kg), $h_{\text{mem,material}}$ is the heat transfer coefficient of the membrane (W/(m²·°C)), and $P_{d(AGMD)}$ and $P_{d(AG-WGMD)}$ are the water fluxes of the AGMD and (AG-WG)MD (kg/(m²·h)).

**Gap**

The total heat transfer ($E_{\text{gap,total}}$) across the gap of AGMD ($E_{\text{gap(AGMD)}}$) by the conduction and evaporation modes, and across the gap of the (AG-WG)MD ($E_{\text{gap(AG-WG)MD}}$) by the natural convection and evaporation styles in (kJ/h) are calculated by (Liu et al. 1998; Izquierdo-Gil et al. 1999; Alawad & Khalifa 2013):

$$E_{\text{gap,total}} = E_{\text{gap(AGMD)}} + E_{\text{gap(AG-WG)MD}}$$ (9)

$$E_{\text{gap(AGMD)}} = \left( A_{\text{air-gap}} \frac{K_{\text{air-gap}}}{\delta_{\text{air-gap}}} (T_{h,2} - T_{C,f}) \right) + (P_{d(AGMD)} \times \Delta H_v)$$ (10)

$$E_{\text{gap(AGMD)}} = \left( A_{\text{water-gap}} \frac{K_{\text{water-gap}}}{\delta_{\text{water-gap}}} (T_{h,2} - T_{C,f}) \right) + (P_{d(AGMD)} \times \Delta H_v)$$ (11)

$$E_{\text{gap(AG-WG)MD}} = \left( A_{\text{water-gap}} \frac{K_{\text{water-gap}}}{\delta_{\text{water-gap}}} (T_{h,2} - T_{C,2}) \right) + (P_{d(AG-WG)MD} \times \Delta H_v)$$ (12)

$$E_{\text{gap(AG-WG)MD}} = \left( A_{\text{water-gap}} \times h_{\text{water-gap}} (T_{h,2} - T_{C,2}) \right) + (P_{d(AG-WG)MD} \times \Delta H_v)$$ (13)

where $K_{\text{air gap}}, K_{\text{water gap}}$ are the thermal conductivity of the air gap and water gap (W/(m·°C)), $\delta_{\text{air gap}}, \delta_{\text{water gap}}$ are the thickness of the air gap and water gap (m), $h_{\text{air gap}}, h_{\text{water gap}}$ are the heat transfer coefficient of the air gap and water gap regions (W/(m²·°C)), and $T_{C,5}, T_{C,2}$ are the temperature of the cooling surface at the air gap and the water gap sides (°C).

**Distilled water film**

The total heat transfer across the distilled water film ($E_{\text{C,f,total}}$) by convection fashion in (kJ/h) is determined as:

$$E_{\text{C,f,total}} = h_{\text{C,f}} \left( (T_{C,f} - T_{C,1})_{\text{AGMD}} + (T_{C,f} - T_{C,2})_{\text{AG-WG)MD}} \right)$$ (14)
MATERIALS AND METHODS

AGMD and (AG-WG)MD experimental set-up

The schematic diagrams of the AGMD and (AG-WG)MD systems utilized in the investigation are displayed in Figure 5(a) and 5(b). The systems consist of feed tank, air gap and water gap membrane distillation modules, circulation pump (MP-55RZ, Shanghai Xinshishan Industrial Limited Company, China), flow meter (LZB-4, Huanming, Yugao Industrial Automation Instrument Company, Zhejiang, China), valves, thermostatic water bath (CS-501, Tongzhou Branch of Shanghai Jinping Instrument Limited Company, China), balance, and coolant (DLSB-10, Tianjin Xingke Instrument Limited Company, China).

![Figure 5](https://example.com/figure5.png)

**Figure 5** The schematic diagram of the (a) AGMD and (b) (AG-WG)MD experimental set-up.
Membrane materials and dimensions

The plexiglas membrane module and the system of feed circulation are enveloped with thermal insulation cotton to prohibit heat losses to the surroundings. The hollow fiber membrane and the corresponding heat exchange tube are fabricated from polyvinylidene difluoride (PVDF) and polypropylene (PP), respectively. The total effective area of the hollow fiber membrane is 0.36 m² for each of the AGMD and WGMD modules with a thickness of 150 μm, average pore size of 0.20 μm, and average porosity of 85%. Each module has 120 PVDF hollow fibers (0.18 m² interior membrane surface area) and 240 PP (0.18 m² interior membrane surface area). Inner/outer diameters (m x 10⁻³) of the hollow fiber membranes and heat exchange tubes are 0.80/1.10 and 0.40/0.50 respectively. The effective length of the hollow fiber membrane and the heat exchange tube is 0.59 m. The gap width employed is ≈5 mm.

The (AG-WG)MD experiments

In the (AG-WG)MD, the hot feed was pumped from the feed tank into the hollow fiber membranes of the AGMD and WGMD top (solid line) respectively in the downward direction where the water vapor diffuses across the membrane pores. After the hot feed left the WGMD module bottom it entered the coolant device. Then, after the cold feed departed the coolant device it came into the heat exchange tubes of the WGMD and AGMD bottom (dashed line) respectively in the opposite direction. After the cold feed left the AGMD top it returned to the feed tank for starting a new desalination process. To keep the feed volume and salt concentration constant inside the tank throughout the experiment, the collected pure distilled water was returned to the feed tank.

The system performance was examined at different hot feed temperatures of 50 °C, 60 °C, 70 °C, and 80 °C, feed salt concentrations of 5,000 mg/L, 12,500 mg/L, 22,500 mg/L, and 30,000 mg/L, and feed flow rates of 14 L/h, 18 L/h, 22 L/h, and 26 L/h (flow velocities of 0.065 m/s, 0.083 m/s, 0.101 m/s, and 0.112 m/s and Reynolds numbers of 51.90, 66.27, 80.64, and 89.42), respectively. The temperature on the cold permeate side was kept stable at 20 °C. To make the obtained data more accurate and credible, each experiment was implemented three times under the same inlet operating conditions for one hour operation time and average values are announced. Prior to initiating the experiment, each system was left running for one hour to guarantee no dissolved gases in the feed stream, the gap region filled with permeate water, and reached equilibrium.

In view of the difficulty of measuring the interface temperature at the membrane surface, four temperature sensors were fixed at the inlets and outlets of the hollow fiber membrane and the heat exchange tube and mean temperature differences were reported. The temperature controller XMTD-3001 (Easey Commercial Building, Hennessy Road, Wanchai, Hong Kong, China) was used to control the hot inlet feed temperature. The vapor pressures of P_v,feed and P_v,air gap at the feed and air-gap sides were viewed continually using a manometer.

The obtained distilled water was weighed by electronic balance every ten minutes to note the variation of water flux. The electrical conductivity of distilled water and saline feed were checked continually using conductivity meter DDS-11A (Shanghai Leici Xinjing Instrument Company, China) to ensure the safety of the PVDF hollow fiber membrane and the quality of the pure distilled water.

The performance parameters of the AGMD and (AG-WG)MD systems

The performances of the AGMD and (AG-WG)MD systems are appraised by calculating gained output ratio (GOR), specific waste heat input (E_w,H), and specific thermal energy consumption (STEC). The different values of the saline water specific heat (C_p_w) and saline water density (ρ_w) are obtained at an ambient air temperature of 25 °C and listed in Table 1. The different measurements including inlet temperature of the hot feed stream (T_i), outlet temperature of the hot feed stream (T_2), inlet temperature of the cold feed stream (T_3), outlet temperature of the cold feed stream (T_4), and water flux P_d (kg/(m².h)) are recorded every ten minutes for one hour operation time and listed in Tables 2–4 at different feed temperatures (T_i), feed flow rates (M_i), and feed salt concentrations (C_i), respectively. It should be mentioned here, the measurements and calculations have been conducted just on the AGMD module,
not on the connected WGMD module in the case of the (AG-WG)MD system, except only for measuring the temperatures at the inlets and outlets of the WGMD module as shown in Figure 2 and then comparing with the inlet and outlet temperatures of the AGMD module working alone to know how much the temperature increased by virtue of the WGMD module.

The thermal energy in MWh/kg needed for outputting 1 kg of water flux is given by Equation (18):

\[
STE\text{C} = \frac{M_f \times \rho_w \times C_{Pw} \times \Delta T_{cross}}{3.6 \times 10^6 \times 10^3 \times P_d}
\]

where \(STE\text{C}\) is the specific thermal energy consumption, \(M_f\) is the feed flow rate (L/h), \(\rho_w\) is the feed saline water density (kg/m³), \(C_{Pw}\) is the specific heat of saline water (J/kg·°C), \(\Delta T_{cross}\) is the temperature difference across the membrane (°C), and \(P_d\) is the water flux volume (kg/(m²·h)), which is calculated as:

\[
P_d = \frac{W_d}{A_{inner} \times t}
\]

where \(W_d\) is the weight of water flux within time \(t\) (kg), and \(A_{inner}\) is the effective hollow fiber membrane surface area based on inner diameter (m²).

The specific waste heat input \((E_{H1})\) in MJ/kg can be determined by the following expression:

\[
E_{H1} = M_f \times C_{Pw} \times \Delta T_{cross}
\]

\[
E_{H1} = M_f \times C_{Pw} \times (T_1 - T_4)
\]
The gained output ratio (GOR) is estimated by (Yao et al. 2013; Geng et al. 2014):

\[
\text{GOR} = \frac{E_{L,H}}{E_{H,I}} \quad (21)
\]

\[
E_{L,H} = P_d \times \Delta H_v \quad (22)
\]

where \( E_{L,H} \) refers to the evaporation latent heat transfer (MJ/h).

The salt rejection rate (SRR) in % can be determined by:

\[
\text{SRR} = \left( 1 - \frac{S_d}{S_f} \right) \times 100 \quad (23)
\]

where \( S_f \) is the feed salt concentration (mg/L) and \( S_d \) is the distilled water concentration (mg/L).

**RESULTS AND DISCUSSION**

**The performance of the (AG-WG)MD system at various hot feed bulk temperatures \( (T_f) \)**

Figure (6) shows the influence of the water gap membrane distillation (WGMD) module on improving the performance of the air gap membrane distillation (AGMD) system. The investigation proceeded as a function of hot feed bulk temperature at a stable cooling temperature of 20 °C, feed flow rate of 18 L/h, and concentration of 5,000 mg/L. Figure 6(a)–6(e) demonstrates that the WGMD deeply affected the AGMD system performance. In comparison with the system of the AGMD as elucidated in Figure 6(a), increases of around 76.26%, 40.84%, 35.45%, and 30.91% in water flux \( (P_d) \) of the (AG-WG)MD system were achieved at feed temperatures of 50 °C, 60 °C, 70 °C, and 80 °C, respectively. The advanced water flux \( (P_d) \) was associated with the considerable rise in the vapor pressure difference through the membrane as well as the reduction in the negative temperature polarization (TP) effect at the membrane surface of the hot feed side thanks to the WGMD module contrasting with the AGMD system in which the air gap region obliges further vapor mass transfer resistance and temperature decrease leading to flux decrease. The fabricated micro-porous PVDF membrane used in saline water desalination offered high salt separation efficiency of about 99.7%.

In connection with the gained output ratio (GOR), it is evident from Figure 6(b) that the GOR of the system of (AG-WG)MD was incremented by about 46.58%, 33.46%, 31.27%, and 26.65% compared with the system of AGMD. The main reason for the enhanced GOR of the (AG-WG) MD system is better heat recovery into the cold feed stream achieved within the WGMD module which improved the trans-membrane temperature difference \( (\Delta T_{\text{cross}} = T_1 - T_4) \) by about 5.88%, 5.48%, 3.49%, and 3.61% from the AGMD system to the (AG-WG)MD system as shown in Figure 6(c) and listed in Table 2. Also, the evaporation latent heat transfer \( (E_{L,H}) \) in the case of the (AG-WG)MD system was greater (6.95 MJ/h, 8.58 MJ/h, 10.40 MJ/h, and 13 MJ/h) compared with the AGMD system (4.49 MJ/h, 6.09 MJ/h, 7.68 MJ/h, and 9.95 MJ/h).

Likewise, compared with the system of the AGMD, the (AG-WG)MD system profoundly minimized the thermal energy consumption (STEC) by nearly 55.63%, 46.81%, 43.66%, and 38.50%, as illustrated in Figure 6(d). Also, the (AG-WG)MD system reduced the specific waste heat input \( (E_{H,I}) \) by approximately 31.51%, 25.84%, 23.53%, and 20.55% (Figure 6(e)).

**The performance of the (AG-WG)MD system at various feed flow rates \( (M_f) \)**

The effect of the WGMD module on the AGMD performance as a function of feed flow rate is elucidated in Figure 7(a)–7(e). The results were obtained at a constant hot feed temperature of 70 °C, cooling water temperature of 20 °C, and feed concentration of 5,000 mg/L. The WGMD module enhanced significantly the performance of the AGMD system. Figure 7(a) shows the promotion of (AG-WG)MD water flux \( (P_d) \) deeply by 27.78%, 35.45%, 29.37%, and 21.11% at feed flow rates of 14 L/h, 18 L/h, 22 L/h, and 26 L/h, respectively. The hydrophobic PVDF hollow fiber membrane used in the test gave a high salt rejection rate (SRR) at 99.7%.

The system of the (AG-WG)MD upgraded the gained output ratio (GOR) by roughly 23.68%, 29.70%, 24.70%, and 24.15% (Figure 7(b)). The reason for the enhanced GOR
related to better heat recovery into the cold feed stream inside the WGMD module (efficient internal heat recovery system) which caused an increase in the temperature $T_4$ and the corresponding temperature $T_1$ through a good mixing in the feed tank, leading to improvement of $\Delta T_{cross} = T_1 - T_4$ by about 3.44%, 4.42%, 3.94%, and 5.61% from the AGMD system to the (AG-WG)MD system as seen in Figure 7(c) and listed in Table 3. Also, the heat transfer by evaporation ($E_{LH}$) increased to 8.56 MJ/h, 10.40 MJ/h, 11.89 MJ/h, and 13.72 MJ/h in the case of (AG-WG)MD while the corresponding values in the
case of the AGMD system were approximately 6.70 MJ/h, 7.68 MJ/h, 9.19 MJ/h, and 10.47 MJ/h.

With respect to the thermal energy consumption (STEC) in the case of the system of (AG-WG)MD there was an appreciable decrease of around 36.49%, 42.47%, 37.88%, and 39.34% compared with the AGMD system as given in Figure 7(d). Similarly, the (AG-WG)MD system largely reduced the specific waste heat input ($E_{\text{WH}}$) by approximately 18.42%, 22.99%, 19.15%, and 20.20% as announced in Figure 7(e).
The performance of the (AG-WG)MD system at various feed salt concentrations ($C_f$)

Figure 8(a)–8(e) illustrates the relevant impact of the WGMD module on the AGMD system performance at different feed salt concentrations. The experiment was done at a stable cooling water temperature of 20 °C, feed temperature of 70 °C, and feed flow rate of 26 L/h. As revealed in Figure 8(a), augments of 31.11%, 26.83%, 45.94%, and 74.32% were obtained in the water flux ($P_d$)
for the (AG-WG)MD system compared with the AGMD system at different feed salt concentrations of 5,000 mg/L, 12,500 mg/L, 22,500 mg/L, and 30,000 mg/L, respectively. The improved $P_d$ was due to enlargement of the pressure difference across the membrane and dropping of the negative concentration polarization (CP) impact at the hot feed side. Concerning the salt rejection rate (SRR), the two AGMD and (AG-WG)MD systems demonstrated high salt rejection ranging from 99.70% to 99.51% when the salt concentration of the inlet feed increased from 5,000 mg/L to 30,000 mg/L.

Figure 8(b) shows increases of 21.14%, 19.39%, 36.02%, and 63.70% in GOR values associated with the rise in $\Delta T_{cross}$ by 8.31%, 6.19%, 7.19%, and 6.82% from AGMD to (AG-WG)MD (Figure 8(c)). Also, the evaporation latent heat transfer ($H_{LH}$) incremented to 13.72 MJ/h, 12.10 MJ/h, 10.86 MJ/h, and 9 MJ/h in the case of (AG-WG)MD while the corresponding values in AGMD were 10.47 MJ/h, 9.54 MJ/h, 7.44 MJ/h, and 5.16 MJ/h.

With regard to the thermal energy consumption (STEC), the system of (AG-WG)MD appreciably decreased the STEC by almost 37.50%, 33.33%, 49.48%, and 65.02% compared with the AGMD system as given in Figure 8(d). In like manner, the specific waste heat input ($E_{H.I}$) for the (AG-WG)MD system was reduced by approximately 16.67%, 16.85%, 26.79%, and 38.89% as announced in Figure 8(e). The calculated standard deviation values for the (AG-WG)MD and AGMD systems under different inlet operating conditions are too modest to read and therefore not shown clearly in Figures 6–8 which indicates a high precision in conducting the experiments and the results obtained.

CONCLUSIONS

The problems of low trans-membrane temperature difference and high temperature-concentration boundary layers affecting negatively the performance of the air gap membrane distillation (AGMD) system were solved experimentally through an effective combination with a water gap membrane distillation (WGMD) module in series. The WGMD deeply enhanced the AGMD water flux ($P_d$) and gained output ratio (GOR), and largely minimized the energy consumption (STEC) and waste heat input ($E_{H.I}$). Under optimal operating conditions of salt concentration of 5,000 mg/L, coolant temperature of 20 °C, and flow rate of 18 L/h, the $P_d$ was enhanced by 76.26%, 40.84%, 35.45%, 30.91%, and GOR by 46.38%, 33.46%, 31.27%, 26.65% as well as the STEC being minimized by about 55.63%, 46.81%, 43.66%, 38.50%, and $E_{H.I}$ by around 31.31%, 25.84%, 23.53%, 20.55%, from the AGMD to (AG-WG)MD systems at feed temperatures of 50 °C, 60 °C, 70 °C, and 80 °C, respectively. Based on outcomes, the new membrane design has potential for application in water distillation. As well, it will be very advantageous in multistage AGMD system performance enhancement whereas the distilled water quantity from each stage is inversely proportional to the number of incorporated stages because of a significant temperature drop and feed salinity increase which profoundly affects the temperature difference across the membrane and heat and mass transport, especially when a highly saline water solution is used as feed. So, adding a WGMD module into the multistage AGMD system will keep a high temperature difference across the membrane in upcoming stages and then increase the flux.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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