Accepted Manuscript

A novel integrated thermal-/membrane-based solar energy-driven hybrid desalination system: Concept description and simulation results

Young-Deuk Kim, Kyaw Thu, Kim Choon Ng, Gary L. Amy, Noredine Ghaffour

PII: S0043-1354(16)30317-7

DOI: [10.1016/j.watres.2016.05.002](https://doi.org/10.1016/j.watres.2016.05.002)

Reference: WR 12031

To appear in: *Water Research*

Received Date: 8 January 2016

Revised Date: 29 March 2016

Accepted Date: 1 May 2016

Please cite this article as: Kim, Y.-D., Thu, K., Ng, K.C., Amy, G.L., Ghaffour, N., A novel integrated thermal-/membrane-based solar energy-driven hybrid desalination system: Concept description and simulation results, *Water Research* (2016), doi: 10.1016/j.watres.2016.05.002.

This is a PDF file of an unedited manuscript that has been accepted for publication. As a service to our customers we are providing this early version of the manuscript. The manuscript will undergo copyediting, typesetting, and review of the resulting proof before it is published in its final form. Please note that during the production process errors may be discovered which could affect the content, and all legal disclaimers that apply to the journal pertain.

A novel integrated thermal-/membrane-based solar energy-driven hybrid desalination system: Concept description and simulation results

Young-Deuk Kim^{a,b,*}, Kyaw Thu^{b,c}, Kim Choon Ng^{b,c}, Gary L. Amy^b, Noredine Ghaffour^{b,**}

^a*Department of Mechanical Engineering, Hanyang University, 55 Hanyangdaehak-ro, Sangnok-gu, Ansan, Gyeonggi-do 15588, Republic of Korea*

^b*King Abdullah University of Science and Technology (KAUST), Water Desalination and Reuse Center (WDRC), Biological and Environmental Science and Engineering Division (BESE), Thuwal 23955-6900, Saudi Arabia*

^c*Department of Mechanical Engineering, National University of Singapore (NUS), 10 Kent Ridge Crescent, Singapore 117576, Singapore*

* Corresponding author. Tel.: +82 31 400 5254; fax.: +82 31 436 8146.

E-mail address: youngdeuk@hanyang.ac.kr (Y.-D. Kim).

** Corresponding author. Tel.: +966 12 808 2180.

E-mail address: norednine.ghaffour@kaust.edu.sa (N. Ghaffour).

Abstract

In this paper, a hybrid desalination system consisting of vacuum membrane distillation (VMD) and adsorption desalination (AD) units, designated as VMD-AD cycle, is proposed. The synergetic integration of the VMD and AD is demonstrated where a useful effect of the AD cycle is channelled to boost the operation of the VMD process, namely the low vacuum environment to maintain the high pressure gradient across the microporous hydrophobic membrane. A solar-assisted multi-stage VMD-AD hybrid desalination system with temperature modulating unit is first designed, and its performance is then examined with a mathematical model of each component in the system and compared with the VMD-only system with temperature modulating and heat recovery units. The total water production and water recovery ratio of a solar-assisted 24-stage VMD-AD hybrid system are found to be about 21% and 23% higher, respectively, as compared to the VMD-only system. For the solar-assisted 24-stage VMD-AD desalination system having 150 m² of evacuated-tube collectors and 10 m³ seawater storage tanks, both annual collector efficiency and solar fraction are close to 60%.

Keywords: Solar energy; Membrane distillation (MD); Adsorption desalination (AD); Hybrid system; Emerging desalination technology

1. Introduction

Desalination capacity is rapidly increasing worldwide, particularly in the Middle East and North Africa (MENA) region. Despite tremendous technology improvements in the conventional thermal-based and membrane-based desalination processes, its wide use is still limited to energy-rich countries due to the high energy requirements since these technologies involve high throughput volumes (Ghaffour et al., 2013). Currently, these energy requirements are met with the burning of fossil fuels either at power or boiler plants which greatly contribute to global warming and the discharge of concentrated brine laden with chemicals causing much deterioration of the marine environment (Höpner and Lattemann, 2002; Lattemann and Höpner, 2008). Thus, it is essential for engineers and scientists to search for alternative processes that are either more energy efficient or utilize waste and low-grade heat sources to meet the growing demand for desalinated water (Ghaffour et al., 2014). Renewable energy such as solar, and to some extent geothermal, is the obvious choice in several regions, especially where there is a severe shortage of fresh water; for example, the Kingdom of Saudi Arabia has an abundant supply of such low grade energy where decentralized small-scale solar-driven impaired water quality treatment plants have been installed supplying potable water in remote (off grid) locations (Ghaffour et al., 2015). However, the question of reliability and maintenance has cast doubt on the operation of these conventional renewable energy-driven desalination systems, e.g., reverse osmosis (RO), which require connection to the grid (compensation) and skilled manpower to operate them efficiently (Ghaffour, 2009). In this respect, this paper presents a novel hybrid desalination system utilizing a low-temperature heat source derived from solar energy, consisting of integrating two emerging thermal-/membrane-based desalination technologies, namely vacuum membrane distillation (VMD) and adsorption desalination (AD).

It can be argued that the main advantages of these emerging technologies, compared to conventional processes, such as RO, multi-stage flash (MSF) and multi-effect distillation (MED), are that they are simple, compact, operate at low temperatures and low pressures, and can function with variable loads (intermittent energy supply) without additional operating modifications (Ghaffour et al., 2015). Detailed descriptions of the AD and MD processes have been widely reported elsewhere (Alkhudhiri et al., 2012; Alsaadi et al., 2015; Curcio and Drioli, 2005; Francis et al., 2014; Khayet, 2011; Kim et al., 2014; Lee et al., 2015; Ng et al., 2012; Thu et al., 2009, 2013a, 2013b). In this paper, a brief description of these processes is presented highlighting their potential integration in a hybrid system.

Over the past decade, AD has been reported as an emerging and yet efficient heat-driven adsorption/desorption cycle

for desalination. A detailed description and pros and cons of the AD process have been reported elsewhere (Ghaffour et al., 2015; Kim et al., 2014; Ng et al., 2012; Thu et al., 2009, 2013a, 2013b). In this novel process an adsorbent is used to adsorb the vapor generated from the evaporator at very low pressure and temperature, under low pressure environment, caused by the double-bond surface forces that exist between a mesoporous adsorbent (silica gel) and an adsorbate (water vapor). The pore diameters of the adsorbent range from 10 to 40 nm and the total pore surface area ranges from 600 to 800 m²/g. The main advantage of using an adsorbent like silica gel is its ability to be re-generated by a low temperature heat source (for desorption), typically from 55 to 85 °C, which is very suitable for solar energy use, and the high uptake rate of water vapor when exposed. In this process raw seawater is fed to the evaporator at its ambient temperature, which means there is no need to heat feed water as it is the case for other thermally-driven processes. When saturated, the adsorbent is heated to release the vapor (desorption process) and is then condensed inside an external condenser. Silica gel is available at low-cost and could be filled in beds of different geometries, such as in vertical silos reducing its footprint especially for large scale units.

During a batch-operated operation, the reactor beds can be linked to the evaporator or the condenser during the half-cycle periods via a series of valves for the control of vapor and water flows. Consequently, an AD cycle comprises two half-cycles (intervals vary from 200 to 700 s) and a switching interval (from 20 to 40 s) in between which handles either the pre-heating or cooling of the exchangers (Kim et al., 2014; Ghaffour et al., 2014). Besides energy efficient, the AD cycle is inherently low in maintenance by design because it has almost no major moving components.

MD is a thermally driven process that utilizes a hydrophobic, microporous membrane as a contactor to achieve separation by liquid-vapor equilibrium. The driving force of MD is the partial vapor pressure difference maintained at the two interfaces of the membrane (hot feed and cold permeate). The hot feed solution is brought into contact with the membrane which allows only the vapor to pass through its dry pores so that it condenses on the coolant side (Alkhudhiri et al., 2012; Khayet, 2011).

As it is the case for the AD process some of the main advantages of MD are that the process performance is negligibly affected by high feed salinity (Adham et al., 2013; Alkhudhiri et al., 2012; Alsaadi et al., 2015; Curcio and Drioli, 2005; Francis et al., 2014; Lee et al., 2015), and it holds the potential of being efficient and cost effective separation process that can utilize low-grade waste heat or renewable energy such as low-enthalpy geothermal or solar energies (Alsaadi et al., 2014; Bundschuh et al., 2015; Goosen et al., 2014; Sarbatly and Chiam, 2013; Zaragoza et al., 2014).

Different MD module configurations have been proposed, mainly direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD) and VMD. More recently, other new

MD configurations aiming to enhance the flux have been developed, such as liquid-gap MD and material-gap MD (Alkhudhiri et al., 2012; Alsaadi et al., 2013; Francis et al., 2013; Khayet, 2011). VMD is considered to possess a great potential for scale-up as it offers the highest flux and efficient heat recovery compared to the other configurations (Khayet, 2011), though that AGMD may offer similar or better internal heat recovery as condensation takes place inside the module. However, in the VMD configuration the condensation of water vapor takes place outside the module using a vacuum pump, which is considered as the main disadvantage of this configuration compared to others, e.g. AGMD, due to the vacuum energy required. However, the vacuum pressure of the AD process naturally created by adsorbents is a perfect environment to run the VMD process in an integrated configuration (VMD-AD) without the need for a vacuum pump, which represents the novel hybrid process combining the AD vacuum environment to the permeate side of the VMD module as proposed in this paper. A detailed description of this hybrid cycle is presented in the next sections.

2. System description

A schematic of the solar-assisted multi-stage VMD-only and VMD-AD hybrid desalination systems is illustrated in Figs. 1 and 2, respectively. The system comprises mainly the solar-thermal system with temperature modulating (TM) scheme, the heat recovery unit (HRU), the shell-and-tube type VMD modules and the AD unit which consists of three heat exchangers: a condenser and a pair of adsorber/desorber heat exchangers (sorption elements). As shown in bottom of Fig. 2, a pair of adsorber beds of the AD cycle containing highly porous hydrophilic adsorbent, i.e. silica gel, is connected to the VMD modules (permeate side) at each stage for a low vacuum environment to maintain the high pressure gradient across the pores of the membrane surface. Therefore, the vacuum provided by the beds of the AD cycle is employed to create the partial vapor pressure difference to drive the VMD process. After saturation, the desorption cycle is applied to release the water vapor collected from VMD modules by the adsorbents (adsorption process) and flows into the condenser through desorption process, which then get collected as final water product.

The solar-thermal system consists mainly of two circuits, namely, the solar energy collection circuit (ECC) and the energy storage circuit (ESC) that supplies the hot seawater to the VMD modules through the four storage tanks and the TM unit. When the storage tank-4 temperature is greater than the desired feed temperature during the mid-day hours, the hot seawater supply to the VMD modules is regulated by TM unit, which results in energy savings for application in the late-afternoon and night-time hours. That is, the hot seawater drawn from storage tank-4 is mixed with the relatively cold makeup seawater to achieve the desired feed temperature by controlling valve (CV1, CV2 and CV3). More details on the flow rate control scheme of the system are described elsewhere (Kim et al., 2012, 2013, 2015). These ECC and

ESC are thermally connected via a plate heat exchanger (PHE), as shown in Figs. 1 and 2. The four storage tanks are built in a top-to-bottom configuration to attain thermal stratification yet fulfilling the load demand in terms of hot seawater supply. Whenever the storage tank-4 temperature drops below the desired feed temperature, the maximum possible portion of the thermal demand is supplied by keeping the discharge mass flow rate equal to the desired feed flow rate and the rest of the thermal demand is supplemented by the auxiliary heat.

As shown in Fig. 1(a), the makeup seawater via the HRUs that recovers latent heat from the permeate vapor is supplied to the mixing junction once the hot seawater is withdrawn from the storage tank-4. This arrangement ensures that the seawater storage tank is always full of seawater. The seawater drawn from storage tank-1 is mixed with makeup seawater at the mixing junction, and then a mixture flows into the PHE. The return hot seawater is dynamically supplied to the tanks based on the temperature, namely, it is supplied back to the tank with temperature that is closest to, but less than or equal to the return hot seawater. This operation scheme assures the storage tank-4 temperature to be the highest. And the operation of the pump in the ECC is controlled based on the inlet temperature of the PHE in the ESC and the outlet temperature of evacuated tubular collector. It is activated whenever the temperature of the latter is higher than that of the former or for heating up the heat transfer fluid (Syltherm 800, Dow Corning Co.) with a deactivation of pump in the ESC after sunrise. Here, the silicone-based fluid is implemented because of its features such as no corrosivity, low fouling potential ($1.5 \times 10^{-5} \text{ m}^2\text{C/W}$), high-temperature stability (400°C), low freeze point (-40°C), long life (10 years or more), low odor and acute oral toxicity (Kim et al., 2013, 2015).

3. Theoretical model

The mathematical models for the analysis of solar-assisted multi-stage VMD desalination system consist of the hollow fiber VMD, the meteorological data (i.e., ambient temperature and solar radiation), the evacuated-tube collector, the seawater storage tank, the HRU and the PHE. Here, it is assumed that system configuration and control are close to the ones considered in the development of the mathematical models and the system has well-insulated pipes.

3.1. Vacuum membrane distillation (VMD)

A schematic of a shell-and-tube type VMD module is shown in top of Fig. 3. The hollow fiber VMD module comprises an array of porous hydrophobic membranes, assembled together in a shell-and-tube module. The heat and mass transfer through the membrane is established by exposing the shell side of the fiber to seawater and vacuuming the lumen side of the fiber (out-in configuration), as shown in bottom right of Fig. 3. The VMD process entails mass transfer of water vapor across a microporous membrane, coupled with heat transfer through the feed boundary layer

adjacent to the membrane surface and across the membrane, as shown in bottom left of Fig. 3. The heat transfer process comprises the heat transferred through the boundary layer of feed side (Q_f) and across the membrane (Q_m). In the VMD process the heat transfer through the boundary layer of permeate side and by conduction across the membrane can be assumed to be negligible (Lawson and Lloyd, 1996, 1997). The convective heat transfer through the membrane pores is also assumed to be negligible as the heat transfer by convection constitutes only 0.6% of the total heat transferred across the membrane and at most 6% of the total heat loss by dissipation in the membrane (Gostoli et al., 1987).

The convective heat transfer across the feed boundary layer is given as:

$$Q_f = \pi N_f d_o h_f (T_f - T_{f,m}) \quad (1)$$

where N_f is the number of hollow fibers, d_o is the outer diameter of the fiber, h_f is the convective heat transfer coefficient, T_f is the bulk feed temperature and $T_{f,m}$ is the liquid/vapor interface temperature on the feed side of the membrane, respectively. The convective heat transfer coefficient at the shell side can be determined by Groehn's correlation (Groehn, 1982):

$$Nu_f = \frac{h_f d_h}{k_f} = 0.206 (\text{Re} \cos \alpha)^{0.63} \text{Pr}^{0.36} \quad (2)$$

where k_f is the thermal conductivity of the bulk feed and α is the yaw angle, which is between 0° for cross flow and 90° for parallel flow. The characteristic length of heat transfer at the shell side refers to the hydraulic diameter of shell d_h , $d_h = d_o (1 - \phi) / \phi$, that is a function of the packing density of the hollow fibers in the module ϕ , $\phi = N_f (d_o / d_s)^2$, where d_s is the shell inner diameter (Thanedgunbaworn et al., 2007).

The latent heat transfer across the hollow fiber membrane can be written as:

$$Q_m = \pi N_f d_{lm} J \Delta H \quad (3)$$

with $d_{lm} = (d_o / d_i) / \ln(d_o / d_i)$. ΔH is the enthalpy of evaporation at the mean temperature through the membrane T_m .

The overall heat transfer across the membrane at steady state is given by:

$$Q_f = Q_m \quad (4)$$

The mass flux of the water (J_z) is linearly proportional to its partial pressure gradient (ΔP) as follows:

$$J_z = C (P_{f,m} - P_r) \quad (5)$$

where C is the membrane distillation coefficient (MDC), $P_{f,m}$ is the water vapor pressures at the liquid/vapor interface on the feed side of the membrane and P_r is the pressure in the permeate side. Due to the existence of dissolved species with molar concentration x_f at the feed side (i.e., seawater), the decrease in the vapor pressure can be estimated with Raoult's law by assuming seawater as an ideal solution for simplicity:

$$P_{f,m} = (1 - x_{f,s}) P_{w,m} \quad (6)$$

where $P_{w,m}$ is the water vapor pressure (in Pa) without dissolved species in the water, which can be calculated using the Antoine equation (Felder and Rousseau, 2000):

$$\log_{10}(133.3 P_{w,m}) = 8.07131 - \frac{1730.63}{T + 233.426} \quad (7)$$

where T is the temperature (in °C).

In the VMD configuration with a membrane having small pores, the mean free path of water vapor molecules (λ) may have a relatively high value due to the dependence of λ on $1/P$. For the considered operating conditions, i.e., temperatures from 30 °C to 80 °C at 4 kPa pressure, the mean free path of water vapor molecules varies from 3.1 μm to 3.6 μm . On the contrary, the pore size of the hollow fiber membrane used in the present work is 0.2 μm . This indicates that the Knudsen number, defined as the ratio of the mean free path to the pore size, varies from 15.5 to 18. Therefore, the molecule-molecule collisions are negligible compared to the molecule-pore wall collisions. Thus, the Knudsen diffusion mechanism is dominant in the mass transfer across the membrane pores (Bandini et al., 1997; Lawson and Lloyd, 1997; Mengual et al., 2004; Schofield et al., 1987) and the MDC can be determined as:

$$C = \frac{8}{3} \frac{\varepsilon d_p}{\tau \delta} \left(\frac{M}{2\pi RT} \right)^{1/2} \quad (8)$$

where ε is the fractional void volume of the membrane, d_p is the pore size, τ is the pore tortuosity, δ is the membrane thickness, M is the molecular weight of water and R is the universal gas constant.

In order to describe the transport behavior in the hollow fiber module, a mathematical model is established by formulating mass, momentum and energy balances for the feed side. The transport equations are derived with the following assumptions: (i) incompressible steady flow under given operating conditions, (ii) unidirectional Newtonian fluid flow for feed in the shell side, (iii) negligible axial diffusion compared to convection, (iv) negligible heat generation due to viscous dissipation, (v) the fibers distributed uniformly in the shell side, (vi) negligible heat loss to the ambient and (vii) constant pressure in the permeate side (Kim et al., 2013, 2015).

The mass, momentum and energy balances for the feed flow in the shell side on simplification yield the following equations, Eqs. (9)–(12), in terms of velocity (v_f), concentration (x_f), pressure (P_f) and temperature (T_f) (Kim et al., 2013, 2015). The overall molar balance and the molar species balance for the salt species on the feed side are respectively simplified as:

$$\frac{1}{X_f} \frac{dv_f}{dz} - \frac{v_f}{X_f^2} \left(\frac{M_s}{\rho_s} - \frac{M_w}{\rho_w} \right) \frac{dx_f}{dz} = - \frac{2N_f r_o J_z}{M_f (r_s^2 - N_f r_o^2)} \quad (9)$$

$$\frac{x_f}{X_f} \frac{dv_f}{dz} + \frac{v_f M_w}{X_f^2 \rho_w} \frac{dx_f}{dz} = 0 \quad (10)$$

Under the unidirectional (lubrication) flow assumption, the feed-side pressure equation can be obtained by solving the z-component Navier-Stokes equation. The solution of the z-component of the Navier-Stokes equation by assuming pressure gradient independent of radial variation gives the axial velocity which is averaged in the radial direction to obtain the following equation:

$$\frac{dP_f}{dz} = -\frac{8\mu_f v_f}{r_h^2} \quad (11)$$

The energy balance on the feed side yields the following equation on simplification:

$$\frac{d\rho_f v_f c_{p,f} T_f}{dz} = -\frac{Q_f}{\pi(r_s^2 - N_f r_o^2)} \quad (12)$$

where X is the molar volume, z is the local axial coordinate, M is the molecular weight, ρ is the density, N_f is the number of hollow fibers, r_o is the radius of hollow fiber, r_s is the inside radius of shell, μ is the dynamic viscosity, c_p is the specific heat capacity and subscripts s , w and f are the salt, water and feed phases, respectively.

The velocity, concentration, pressure and temperature on the feed side are subject to the boundary conditions as follows:

$$v_f(0) = v_{f,in}, x_f(0) = x_{f,in}, P_f(L_f) = P_0, T_f(0) = T_{f,in} \quad (13)$$

where P_0 is the ambient atmospheric pressure at the feed outlet and the subscript *in* is the inlet of the module.

In order to examine the performance of a VMD module, the mean permeate flux (J_m) and the total distillate production (TDP) of a VMD module are expressed as:

$$J_m = \frac{1}{L_f} \int_0^{L_f} J_z dz \quad (14)$$

$$TDP = J_m N_f \pi d_o L_f \quad (15)$$

where J_z is the local permeate flux as shown in Eq. (5).

The heat transfer through the boundary layer in the feed side is identified as the limiting factor of the transport efficiency in the VMD process. Therefore, as an index to evaluate the magnitude of the boundary layer resistance over the total heat transfer resistance, the temperature polarization coefficient (TPC) is used as follows:

$$TPC = \frac{T_{f,m}}{T_f} \quad (16)$$

In this study, thermophysical properties of seawater and water are used from Sharqawy et al. (2010). The set of coupled ordinary differential equations (ODEs), i.e., Eqs. (9)–(12), are discretized based on the finite volume method

(FVM) and solved with the boundary conditions, i.e., Eq. (13), and the membrane characterizations, i.e., Eqs. (1), (3) and (4) for heat transfer and Eqs. (5)–(8) for mass transfer. In order to solve the set of ODEs with splitting boundary values, Broyden's method (Broyden, 1965), which is a quasi-Newton method for finding solutions of nonlinear equations, has been implemented. It is noted that the unknown feed side pressure $P_f(0)$ at $z = 0$ is guessed, which converts the boundary-value problem to an initial-value problem in the spatial direction. The permeate flux and the corresponding concentration, velocity, pressure and temperature distributions for each control volume are iteratively computed using a successive substitution method until the relative error between two consecutive iterations is smaller than 10^{-10} . The solution is marched forward until $z = L_f$, and then the presumed value of $P_f(0)$ is updated. Thus, this procedure is repeated until the boundary conditions in Eq. (13) are satisfied with an absolute error below 10^{-6} . A uniform partition of the physical domain is implemented with a step size of 5.05×10^{-3} m. The solution obtained is proved to be independent of finer discretization. All of the governing equations are numerically solved by developing a source code written in Microsoft Fortran PowerStation 4.0.

3.2. Solar-thermal system

The detailed mathematical models for the meteorological data such as beam and diffuse irradiances and ambient temperatures, the evacuated-tube collector, the seawater storage tanks and the PHE in the solar-thermal system have been explained elsewhere (Kim et al., 2012, 2013). Fig. 4 shows the monthly average hourly global irradiance on the tilted surface and ambient temperature in Jeddah, Saudi Arabia (Kim et al., 2013), location of the solar-driven AD pilot plant, determined by using Hay-Davies-Klucher-Reindl (HDKR) anisotropic diffuse radiation model.

In order to examine the annual thermal performance of solar-assisted multi-stage desalination system, the annual solar fraction (SF), defined as the ratio of the annual thermal energy met by the solar thermal system to the annual thermal demand, and collector efficiency (SE), defined as the ratio of the annual thermal energy collected by the working fluid to the annual solar energy incident on the collector aperture, have been introduced and defined as (Kim et al, 2012, 2013, 2015):

$$SF = \frac{\sum_{i=1}^{365 \text{ days}} \int_0^{24 \text{ hrs}} Q_s dt}{\sum_{i=1}^{365 \text{ days}} \int_0^{24 \text{ hrs}} Q_s dt + \sum_{i=1}^{365 \text{ days}} \int_0^{24 \text{ hrs}} Q_a dt} \quad (17)$$

$$SE = \frac{\sum_{i=1}^{365 \text{ days}} \int_0^{t=24 \text{ hr}} Q_u dt}{N_c A_a \sum_{i=1}^{365 \text{ days}} \int_0^{t=24 \text{ hr}} G_T dt} \quad (18)$$

where

$$Q_s = \begin{cases} \dot{m}_f [h_f(T_{f,in}) - h_f(T_{s,1})], & \text{if } T_{t,4,1} > T_{f,in} \\ \dot{m}_f [h_f(T_{t,4,1}) - h_f(T_{s,1})], & \text{if } T_{t,4,1} \leq T_{f,in} \end{cases} \quad (19)$$

$$Q_a = \begin{cases} 0, & \text{if } T_{t,4,1} > T_{f,in} \\ \dot{m}_f [h_f(T_{f,in}) - h_f(T_{t,4,1})], & \text{if } T_{t,4,1} \leq T_{f,in} \end{cases} \quad (20)$$

$$Q_u = \dot{m}_c [h_f(T_{c,o}) - h_f(T_{c,i})] \quad (21)$$

where Q_s is the thermal demand met by solar energy, Q_a is the auxiliary energy required, Q_u is solar useful heat gain rate, N_c is the number of collectors, A_a is the aperture area per collector, G_T is the monthly average hourly global irradiance on a titled collector surface, $\dot{m}_f$ is the desired feed flow rate to the VMD module, $T_{f,in}$ is the desired feed seawater temperature to the VMD module, $T_{s,1}$ is the makeup seawater temperature from the HRU 1, $T_{t,4,1}$ is the seawater temperature at the top of the storage tank 4, $\dot{m}_c$ is the mass flow rate in primary circuit and T_c is the working fluid in primary circuit.

3.3. Heat recovery unit (HRU)

The water vapor produced from the lumen side of the hollow fiber in the VMD module travels to the shell side of the heat recovery unit (HRU) where the latent heat of condensation is recovered to heat up the feed seawater supplied to the solar-thermal system. The HRU is the shell-and-tube heat exchanger for vapor-to-liquid heat transfer with horizontal tube arrangement. With the assumption of complete vapor condensation, the energy balance of the HRU in communication with the VMD modules is written as:

$$\sum_{i=1+k}^{M \times j} TDP_i [h_v(T_{p,i}) - h_w(T_{r,j})] + \dot{m}_s c_{p,j} (T_{s,in,j} - T_{s,out,j}) = 0 \quad (22)$$

with $k = M(j-1)$ and $M = N_s / N_r$, where i and j are the number of module stages and HRUs, respectively, h_v is the enthalpy of permeate vapor from the VMD module, h_w is the enthalpy of distillate from the HRU, $\dot{m}_s$ is the mass flow rate of supply seawater, T_p , T_r and T_s are the temperatures of permeate vapor, HRU and seawater, respectively, and N_s and N_r are the total number of module stages and HRUs, respectively.

The outlet temperature $T_{s,out}$ of the seawater from each HRU can be estimated using the log-mean temperature difference (LMTD) method:

$$T_{s,out,j} = T_{r,j} + (T_{s,in,j} - T_{r,j}) \exp \left(\frac{-U_{HRU,j} A_{HRU,j}}{\dot{m}_s c_{p,j} (T_{r,j})} \right) \quad (23)$$

where A_{HRU} is the surface area of the tubes and U_{HRU} is the overall heat transfer coefficient, determined as:

$$U_{HRU,j} = \left(\frac{r_o}{r_i} \frac{1}{h_{i,j}} + \frac{r_o}{k} \ln \frac{r_o}{r_i} + \frac{1}{h_{o,j}} \right)^{-1} \quad (24)$$

where r is the tube radius, h is the convective heat transfer coefficient, k is the thermal conductivity of the tube and subscripts i and o represent the inner and outer tube surfaces, respectively.

For a vertical tier of N horizontal tubes, the laminar film condensation correlation is used to estimate the heat transfer coefficient for the condensation of the water vapor on the outer surface of horizontal tubes (Incropera and DeWitt, 1996):

$$h_o = 0.729 \left[\frac{g \rho_l (\rho_l - \rho_v) k_l^3 h'_{fg}}{2 N_t \mu_l r_o (T_r - T_w)} \right]^{1/4} \quad (25)$$

where g is the acceleration due to gravity, k is the thermal conductivity, N_t is the number of tubes, T_w is the tube wall temperature and $h'_{fg} = h_{fg} + 0.68 c_{p,l} (T_r - T_w)$ with h_{fg} representing the latent heat of condensation. Subscripts l and v are the saturated liquid and vapor phases, respectively. The liquid properties are calculated at the film temperature and h_{fg} is calculated at T_r .

The heat transfer coefficient for the seawater inside the tubes is determined as (Gnielinski, 1976):

$$h_i = \frac{(f/8)(\text{Re}-1000)\text{Pr}}{1+12.7(f/8)^{1/2}(\text{Pr}^{2/3}-1)} \frac{k_f}{2r_i} \quad (26)$$

where k_f is the thermal conductivity of the seawater and the friction factor, $f = (0.79 \ln \text{Re} - 1.64)^{-2}$.

In the solar-assisted multi-stage VMD-only desalination system, therefore, the saturation pressure for the HRU temperature obtained from Eq. (22) is applied to the permeate-side pressure in Eq. (5).

4. Results and discussion

Prior to the performance investigation of solar-assisted multi-stage VMD-only and VMD-AD hybrid desalination systems, in order to verify the currently developed in-house computational code, the performance characteristics of shell-and-tube VMD module, as previously reported (Mengual et al., 2004), have been examined with respect to the feed velocity and the feed temperature at the inlet of the membrane module. The principal characteristics of a polypropylene hollow fiber membrane module used are as follows (Mengual et al., 2004): shell diameter: 0.025 m, number of fibers: 40; mean pore size: 0.2 μm ; inner fiber diameter: 1.8 mm; outer fiber diameter: 2.6 mm; effective membrane area: 0.1 m^2 ; LEP: 140 kPa, porosity: 70%; fiber length: 0.47 m. The permeate-side pressure (vacuum) is kept constant at 4 kPa and the pure water is employed in the experiments (Mengual et al., 2004).

As illustrated in Fig. 5, the predicted permeate flux as a function of the feed velocity and temperature are compared to

the measured data (Mengual et al., 2004), exhibiting good agreement. It is shown that the permeate flux increases with increasing feed velocity in the range of 0.2 m/s – 1.0 m/s and feed temperature in the range of 35 °C – 65 °C. The relative effect of the feed velocity on the permeate flux increases with the temperature, which can be attributed to the combine effects of exponential relationship between temperature and vapor pressure shown in Eq. (7) and higher heat transfer through the feed boundary layer at higher feed circulation velocity (i.e., higher Reynolds number in Eq. (2)), which results in lower temperature polarization (Eq. (16)) leading to greater transmembrane temperature difference (Kim et al., 2013; Mengual et al., 2004). On the other hand, the feed velocity at lower feed temperatures below 50 °C, i.e., decrease in the vapor-pressure driving force, can be assumed to have negligible effects on the permeate flux. Higher feed flow velocities have also a beneficial effect on permeation flux due to the decrease of the feed residence time leading to higher driving force throughout the module, especially at high feed temperatures. A detailed investigation on the effect of feed velocity and residence time on permeation flux and thermal efficiency have been reported elsewhere (Alsaadi et al., 2013). Thus, flow velocity has several useful effects on the MD process, such as fouling, polarization and heat and mass transfer which significantly influences the permeate flux, especially at high feed inlet temperatures as shown in Fig. 5. The higher the flow velocity, the lower the polarization and the higher heat and mass transfer, consequently the higher the driving force, hence higher permeate fluxes can be obtained. However, increasing the flow velocity can lead to the membrane pore wetting due to the hydrostatic pressure build-up and the higher pressure drop along the membrane module as well as higher pumping power (Kim et al., 2013). Hence, a range of flow velocities should be investigated in order to get an economic optimum value. Additionally, the flow condition adjacent to the membrane interface can play a vital role in controlling heat/mass transfer and polarization mechanisms across the membrane. Thus, the spacer can be also crucial to deter the formation of polarization layer while maintaining certain degree of pressure drop.

For the operating conditions ($T_{f,in} = 65$ °C, $v_{f,in} = 1.0$ m/s) in Fig. 5, the axial variations of temperature, i.e., bulk feed (T_f) and liquid-vapor interface at the feed side ($T_{f,m}$), permeate flux (J), water vapor pressure at the liquid-vapor interface on the feed side of the membrane ($P_{f,m}$) and bulk feed velocity (v_f) along the fiber length are depicted in Fig. 6. The transmembrane flux decreases slightly from 26.09 kg/m²h to 25.33 kg/m²h corresponding to the transmembrane vapor pressure difference (i.e., $P_{f,m} - P_r$) of 15.25 kPa and 14.79 kPa at the feed inlet and outlet of the module, respectively. This gradual decline along the fiber length is also reflected in the temperature and velocity fields, which is attributed to the latent heat loss by vaporization and permeate flux, respectively. It is also found that the axial hydrostatic pressure drop along the feed side of VMD module is about 562 Pa.

As shown in top of Fig. 3, the shell-and-tube type VMD module may result in setting up of both axial and radial

pressure maldistributions in the fiber and module header, which in turn influence flow fields. Especially, in case of out-in configuration adopted in the present work, the axial pressure maldistribution along the lumen side of the fiber will be more significant than that of radial direction in the header, which is strongly dependent on the header angle. It is a well-known fact that the higher angle of the header could lead to a higher radial pressure maldistribution. Hence, it should be recognized as a crucial factor in the practical design for the scale-up of shell-and-tube type VMD module, as well as fiber length. In the present work, however, in order to fulfill the assumption employed for the process modeling and simulation (i.e., constant pressure in the permeate side), the VMD module design for the solar-assisted multi-stage desalination system has been achieved with a slight scale-up of VMD module (Mengual et al., 2004). For the performance evaluation of solar-assisted multi-stage VMD-only and VMD-AD hybrid desalination systems, therefore, the module configuration with the shell diameter of 0.03 m, fiber length of 0.5 m and 100 hollow fibers has been used for the 24-stage desalination system having a module at each stage and 10 HRUs (Kim et al., 2015). It was observed that the installation of the HRU at each VMD stage does not necessarily improve the water production rate (Kim et al., 2015). For the system simulation, the inlet feed temperature and velocity are 80 °C and 1.0 m/s, respectively, the feed seawater salinity is set to be 4.5 wt% as the salinities of the Red Sea and the Persian Gulf are about 4.0 wt% – 4.5 wt%. In the case of the hybrid VMD-AD desalination system, the permeate-side pressure in Eq. (5) is assumed to be kept constant at 2 kPa by communicating with an AD cycle, as discussed in the previous sections (Kim et al., 2014; Ng et al., 2012; Thu et al., 2009, 2013a, 2013b).

Fig. 7(a) shows the bulk feed temperature (T_f), liquid-vapor interface temperature at the feed side ($T_{f,m}$), HRU temperature (T_r) and temperature polarization coefficient (TPC) profiles along the module stages of 24-stage VMD-only and VMD-AD hybrid systems, i.e., the dimensionless axial distance, defined as $[L_f(i-1) + z] / L_f$. With the inlet feed temperature of 80 °C, the retentate temperature from the last stage is found to be about 43 °C for the VMD-only system, while the outlet temperature is about 32 °C with the VMD-AD system. These qualitative trends are also observed in the liquid-vapor interface temperature at the feed side, due to the latent heat loss by vaporization. For the VMD-only system, meanwhile, the HRU temperature increases from 33 °C at 10th HRU to 60 °C at the first HRU by recovering the latent heat of condensation of the permeate vapor at each HRU. In the case of VMD-only system, however, the TPC increases asymptotically along the fiber length of stages communicated with a HRU, followed by an abrupt drop and gradual increase in the stages connected with a next HRU. The trend with these characteristics recurs, but the magnitude of the sudden drop decreases gradually along the module stages, and finally its value approaches 0.997. This phenomenon is due to the exponential decline in the saturation pressure of the water vapor with decreasing temperature, resulting in the substantial decrease in the permeate flux. The reduced permeate flux involves the heat flux through the feed phase,

decreasing the temperature gradient in the feed boundary layer and thus the temperature polarization (Kim et al., 2013; Martínez-Díez and Vázquez-González, 1999; Mericq et al., 2011). The values of TPC for both systems are above 0.98 over the stages, indicating that about 2% of the temperature difference applied is dissipated in the feed boundary layer.

The profiles of water vapor pressure at the liquid-vapor interface on the feed side of the membrane ($P_{f,m}$), HRU pressure (P_r) and feed velocity (v_f) along the stages for both desalination systems are shown in Fig. 7(b). The transmembrane pressure with the VMD-only system, i.e., the driving force of VMD process ($P_{f,m} - P_r$), decreases from the inlet 20.2 kPa to the outlet 3.2 kPa, while for the VMD-AD system its value decreases from 34.2 kPa to 2.6 kPa. With the feed inlet velocity of 1 m/s at the first module stage of both systems, the brine velocities at the outlet of the last stage are approximately 0.783 m/s and 0.739 m/s for the VMD-only and VMD-AD hybrid systems, respectively. For both systems, the retentate flows in the shell side of the VMD module are in the laminar and transitional flow regimes. It is shown that the velocity gradient is rather steep near the inlet end of the module due to the larger transmembrane mass flux, which is attributed to a higher transmembrane pressure difference.

The permeate flux and seawater salinity profiles along the module stages of the 24-stage VMD-only and VMD-AD hybrid systems are shown in Fig. 8(a). It is shown that along the module stages the mean permeate flux of the VMD-only system decreases from 31 kg/m²h to 6 kg/m²h, while that of the VMD-AD system decreases from 53 kg/m²h to 5 kg/m²h, which is attributed to an asymptotic decrease of the driving force along the stages, yielding the lower permeate flux. The feed seawater concentration in the VMD-only system increases from 4.50 wt% to 5.75 wt%, whereas its value for the VMD-AD system increases from 4.50 wt% to 6.09 wt%. Fig. 8(b) presents the profiles of cumulative total distillate production (TDP) and water recovery ratio (WR), defined as the ratio of distillate production to feed flow, along the stages of 24-stage VMD-only and VMD-AD desalination systems. It is shown that both values increase asymptotically along the stages, due to an asymptotic decline of the permeate flux along the stages as shown in Fig. 8(a). The cumulative total distillate production and water recovery ratio of VMD-AD desalination system are found to be 4.05 m³/day and 30%, respectively, and these are about 21% and 23% higher, respectively, as compared to the VMD-only system. Salt rejection of both MD and AD products as previously reported is above 99.99%.

The annual thermal and performance analyses of both solar-assisted 24-stage desalination systems are carried out with respect to collector area (A_c) in the range of 126 m² – 150 m² and seawater storage volume (V_t) in the range of 8 m³ – 36 m³ at the ASHRAE standard flow rate. The results shown in Fig. 9(a) indicate that the maximum value of SF for the VMD-only system is about 98% with $A_c = 150$ m² and $V_t = 16$ m³, while the SE corresponding to the maximum solar fraction is about 53%. It is noted that as the storage tank volume increases, the solar fraction increases significantly, followed by a gradual decrease after achieving the maximum solar fractions at $V_t = 16$ m³ ($A_c = 126$ m²) and $V_t = 16$ m³

($A_c = 150 \text{ m}^2$), respectively, whereas the collector efficiency increases asymptotically with an increase in the storage tank volume due to a decrease in the storage tank temperature, resulting in an improvement of the collector efficiency (Kim et al., 2012). Beyond the maximum solar fractions, its gradual decrease is because the rate of the energy removed from the storage tank to supply the feed seawater decreases due to a higher heating load and an increase in the heat losses from the storage tanks to the ambient. As shown in Fig. 9(b), on the other hand, the maximum value of SF for the VMD-AD hybrid system is about 60% with $A_c = 150 \text{ m}^2$ and $V_t = 10 \text{ m}^3$ and the SE corresponding to the maximum SF is also about 60%.

5. Conclusions

A novel solar-assisted multi-stage VMD-AD hybrid desalination system with temperature modulating unit is designed and its performance is examined with a rigorous mathematical model of each component in the system and compared with a VMD-only system with temperature modulating and heat recovery units. The cumulative total water production and water recovery ratio of a solar-assisted 24-stage VMD-AD hybrid desalination system are found to be $4.1 \text{ m}^3/\text{day}$ and 30%, respectively, and these are about 21% and 23% higher, respectively, as compared to the VMD-only system which makes the proposed hybrid process an attractive and energy-efficient concept for water desalination application. For the solar-assisted 24-stage VMD-AD desalination system having 150 m^2 of evacuated-tube collectors and 10 m^3 seawater storage tanks, both annual collector efficiency and solar fraction are found to be 60%.

Acknowledgments

This research reported in this paper was supported by a grant (code 13IFIP-B065893-03) from Industrial Facilities & Infrastructure Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government, and King Abdullah University of Science and Technology (KAUST), Saudi Arabia.

Nomenclature

A	area [m^2]
c_p	specific heat capacity [$\text{kJ/kg}^\circ\text{C}$]
C	membrane distillation coefficient [$\text{kg/m}^2\text{sPa}$]
d	diameter [m]
d_s	shell inner diameter [m]
f	friction factor [-]

431	G_T	monthly average hourly global irradiance on a tilted surface [W/m^2]
432	h	heat transfer coefficient [$\text{W/m}^2\text{°C}$]
433	ΔH	latent heat of vaporization [J/kg]
434	J	permeate flux [$\text{kg/m}^2\text{h}$]
435	k	thermal conductivity [$\text{W/m}^2\text{°C}$]
436	L	length [m]
437	M	molecular weight [kg/kmol]
438	N_c	number of collectors [-]
439	N_f	number of fibers [-]
440	N_r	number of heat recovery units [-]
441	N_s	number of module stages [-]
442	N_t	number of tubes [-]
443	P	pressure [Pa]
444	Q	heat transfer [W]
445	Q_a	auxiliary energy required [W]
446	Q_s	load met by solar energy [W]
447	Q_u	solar useful heat gain rate [W]
448	r	radius [m]
449	R	gas constant [$\text{J/kmol}^{\circ}\text{C}$]
450	SE	collector efficiency [-]
451	SF	solar fraction [-]
452	T	temperature [$^{\circ}\text{C}$]
453	TDP	total distillate production [kg/h]
454	TPC	temperature polarization coefficient [-]
455	U	overall heat transfer coefficient [$\text{W/m}^2\text{°C}$]
456	v	velocity [m/s]
457	V	volume [m^3]
458	x	molar fraction in liquid phase [-]
459	X	molar volume [m^3/mol]
460	z	axial coordinate [m]

461

462 *Dimensionless numbers*463 *Nu* Nusselt number, hd/k [-]464 *Pr* Prandtl number, $\mu c_p/k$ [-]465 *Re* Reynolds number, $\rho v d/\mu$ [-]

466

467 *Greek letters*468 α yaw angle [°]469 δ membrane thickness [m]470 ε membrane porosity [-]471 μ dynamic viscosity [kg/ms]472 ρ liquid density [kg/m³]473 τ pore tortuosity [-]474 ϕ packing density [-]

475

476 *Subscripts*477 *a* aperture478 *c* collector479 *f* feed, fiber480 *h* hydraulic481 *i* inner482 *in* inlet483 *l* liquid484 *m* membrane, mean485 *o* outer486 *out* outlet487 *p* pore488 *r* heat recovery unit489 *s* seawater, salt490 *t* tank, tube

v vapor
 w water, wall

References

- Adham, S., Hussain, A., Matar, J.M., Does, R., Janson, A., 2013. Application of membrane distillation for desalting brines from thermal desalination plants. *Desalination* 314, 101–108.
- Alkudhiri, A., Darwish, N., Hilal, N., 2012. Membrane distillation: a comprehensive review. *Desalination* 287, 2–18.
- Alsaadi, A.S., Francis, L., Maab, H., Amy, G.L., Ghaffour, N., 2014. Experimental and theoretical analyses of temperature polarization effect in vacuum membrane distillation. *J. Membr. Sci.* 471, 138–148.
- Alsaadi, A.S., Francis, L., Maab, H., Amy, G.L., Ghaffour, N., 2015. Evaluation of air gap membrane distillation process running under sub-atmospheric conditions: experimental and simulation studies. *J. Membr. Sci.* 489, 73–80.
- Alsaadi, A.S., Ghaffour, N., Li, J.-D., Gray, S., Francis, L., Maab, H., Amy, G.L., 2013. Modeling of air-gap membrane distillation process: a theoretical and experimental study. *J. Membr. Sci.* 445, 53–65.
- Bandini, S., Saavedra, A., Sarti, G.S., 1997. Vacuum membrane distillation: experimental and modeling. *AIChE J.* 43, 398–408.
- Broyden, C.G., 1965. A class of methods for solving nonlinear simultaneous equations. *Math. Comput.* 19, 577–593.
- Bundschuh, J., Ghaffour, N., Mahmoudi, H., Goosen, M., Mushtaq, S., Hoinkis, J., 2015. Low-cost low-enthalpy geothermal heat for freshwater production: innovative applications using thermal desalination processes. *Renew. Sust. Energ. Rev.* 43, 196–206.
- Curcio, E., Drioli, E., 2005. Membrane distillation and related operations - a review. *Sep. Purif. Rev.* 34, 35–86.
- Felder, R.M., Rousseau, R.W., 2000. *Elementary Principles of Chemical Processes*. John Wiley & Sons, New York.
- Francis, L., Ghaffour, N., Alsaadi, A.A., Amy, G.L., 2013. Material gap membrane distillation: A new design for water vapor flux enhancement. *J. Membr. Sci.* 448, 240–247.
- Francis, L., Ghaffour, N., Alsaadi, A.S., Nunes, S.P., Amy, G.L., 2014. Performance evaluation of the DCMD desalination process under bench scale and large scale module operating conditions. *J. Membr. Sci.* 455, 103–112.
- Ghaffour, N., 2009. The challenge of capacity-building strategies and perspectives for desalination for sustainable water use in MENA. *Desalin. Water Treat.* 5, 48–53.
- Ghaffour, N., Bundschuh, J., Mahmoudi, H., Goosen, M.F.A., Renewable energy-driven desalination technologies: A comprehensive review on challenges and potential applications of integrated systems. *Desalination* 356, 94–114.
- Ghaffour, N., Lattemann, S., Missimer, T.M., Ng, K.C., Sinha, S., Amy, G., 2014. Renewable energy-driven innovative

- energy-efficient desalination technologies. *Appl. Energy* 136, 1155–1165.
- Ghaffour, N., Missimer, T.M., Amy, G.L., 2013. Technical review and evaluation of the economics of water desalination: current and future challenges for better water supply sustainability. *Desalination* 309, 197–207.
- Gnielinski, V., 1976. New equations for heat mass transfer in turbulent pipe and channel flow. *Int. Chem. Eng.* 16, 359–368.
- Goosen, M., Mahmoudi, H., Ghaffour, N., 2014. Today's and future challenges in applications of renewable energy technologies for desalination. *Crit. Rev. Environ. Sci. Technol.* 44, 929–999.
- Gostoli, C., Sarti, G.C., Matulli, S., 1987. Low temperature distillation through hydrophobic membranes. *Sep. Sci. Technol.* 22, 855–872.
- Groehn, H.G., 1982. Influence of the yaw angle on heat transfer and pressure drop of tube bundle heat exchangers. *Heat Transf.* 6, 203–209.
- Höpner, T., Lattemann, S., 2002. Chemical impacts from desalination plants – a case study of the northern Red Sea. *Desalination* 152, 133–140.
- Incropera, F.P., DeWitt, D.P., 1996. *Introduction to Heat Transfer*. John Wiley & Sons, New York.
- Khayet, M., 2011. Membranes and theoretical modeling of membrane distillation: a review. *Adv. Colloid Interface Sci.* 164, 56–88.
- Kim, Y.-D., Thu, K., Bhatia, H.K., Bhatia, C.S., Ng, K.C., 2012. Thermal analysis and performance optimization of a solar hot water plant with economic evaluation. *Sol. Energy* 86, 1378–1395.
- Kim, Y.-D., Thu, K., Choi, S.-H., 2015. Solar-assisted multi-stage vacuum membrane distillation system with heat recovery unit. *Desalination* 367, 161–171.
- Kim, Y.-D., Thu, K., Ghaffour, N., Ng, K.C., 2013. Performance investigation of a solar-assisted direct contact membrane distillation system. *J. Membr. Sci.* 427, 354–364.
- Kim, Y.-D., Thu, K., Masry, M.E., Ng, K.C., 2014. Water quality assessment of solar-assisted adsorption desalination cycle. *Desalination* 344, 144–151.
- Lattemann, S., Höpner, T., 2008. Environmental impact and impact assessment of seawater desalination. *Desalination* 220, 1–15.
- Lawson, K.W., Lloyd, D.R., 1996. Membrane distillation: I module design and performance evaluation using vacuum membrane distillation. *J. Membr. Sci.* 120, 111–121.
- Lawson, K.W., Lloyd, D.R., 1997. Membrane distillation. *J. Membr. Sci.* 124, 1–25.
- Lee, J.-G., Kim, Y.-D., Kim, W.-S., Francis, L., Amy, G., Ghaffour, N., 2015. Performance modeling of direct contact

membrane distillation (DCMD) seawater desalination process using a commercial composite membrane. *J. Membr. Sci.* 478, 85–95.

Martínez-Díez, L., Vázquez-González, M.I., 1999. Temperature and concentration polarization in membrane distillation of aqueous salt solutions. *J. Membr. Sci.* 156, 265–273.

Mengual, J.I., Khayet, M., Godino, M.P., 2004. Heat and mass transfer in vacuum membrane distillation. *Int. J. Heat Mass Transfer* 47, 865–875.

Mericq, J.-P., Laborie, S., Cabassud, C., 2011. Evaluation of systems coupling vacuum membrane distillation and solar energy for seawater desalination. *Chem. Eng. J.* 166, 596–606.

Ng, K.C., Thu, K., Saha, B.B., Chakraborty, A., 2012. Study on a waste heat-driven adsorption cooling cum desalination cycle. *Int. J. Refrig.* 35, 685–693.

Sarbatly, R., Chiam, C.K., 2013. Evaluation of geothermal energy in desalination by vacuum membrane distillation, *Appl. Energy* 112, 737–746.

Schofield, R.W.A., Fane, A.G., Fell, C.J.D., 1987. Heat and mass transfer in membrane distillation. *J. Membr. Sci.* 33, 299–313.

Sharqawy, M.H., Lienhard V, J.H., Zubair, S.M., 2010. Thermophysical properties of seawater: a review of existing correlations and data. *Desalin. Water Treat.* 16, 354–380.

Thanedgunbaworn, R., Jiratananon, R., Nguyen, M.H., 2007. Shell-side mass transfer of hollow fibre modules in osmotic distillation process. *J. Membr. Sci.* 290, 105–113.

Thu, K., Kim, Y.-D., Amy, G., Chun, W.G., Ng, K.C., 2013. A hybrid multi-effect distillation and adsorption cycle. *Appl. Energy* 104, 810–821.

Thu, K., Ng, K.C., Saha, B.B., Chakraborty, A., Koyama, S., 2009. Operational strategy of adsorption desalination systems. *Int. J. Heat Mass Transf.* 52, 1811–1816.

Thu, K., Yanagi, H., Saha, B.B., Ng, K.C., 2013. Performance analysis of a low-temperature waste heat-driven adsorption desalination prototype. *Int. J. Heat Mass Transf.* 56, 662–669.

Zaragoza, G., Ruiz-Aguirre, A., Guillén-Burrieza, E., 2014. Efficiency in the use of solar thermal energy of small membrane desalination systems for decentralized water production. *Appl. Energy* 130, 491–499.

Figure captions

Fig. 1. Schematics of solar-assisted multi-stage VMD-only desalination system with the HRUs and temperature modulating (TM) scheme (Kim et al., 2015).

Fig. 2. Schematics of solar-assisted multi-stage VMD-AD hybrid desalination system.

Fig. 3. Schematic of shell-and-tube type VMD module (top) and heat and mass transfer through hollow fiber in the VMD process (bottom left). The feed seawater flows on the outer side of the hollow fiber membranes and the vacuum is applied at the lumen side of the fibers (bottom right).

Fig. 4. Monthly average hourly (a) global irradiance on the tilted surface and (b) ambient temperature in Jeddah, Saudi Arabia (Kim et al., 2013).

Fig. 5. Permeate flux as a function of (a) feed velocity for the different feed temperatures and (b) feed temperature for the different feed velocities. The measured data (symbol) (Mengual et al., 2004) are shown and compared to the computed data (dashed line).

Fig. 6. (a) Temperature and permeate flux and (b) pressure and velocity as a function of fiber length axial position.

Fig. 7. Comparison of (a) the temperature and temperature polarization and (b) the pressure and velocity profiles along the module stages of solar-assisted 24-stage VMD-only and hybrid VMD-AD desalination systems.

Fig. 8. Comparison of (a) the mass flux and seawater concentration and (b) the cumulative TDP and water recovery (WR) profiles along the module stages of solar-assisted 24-stage VMD-only and hybrid VMD-AD desalination systems.

Fig. 9. Effect of collector area ($A_c = 125 \text{ m}^2, 150 \text{ m}^2$) and storage volume ($8 \text{ m}^3 \leq V_t \leq 36 \text{ m}^3$) on the annual SF and SE of solar-assisted 24-stage (a) VMD-only and (b) hybrid VMD-AD desalination systems.

Highlights

- ▶ A hybrid desalination system consisting of VMD and AD units is proposed
- ▶ A solar-assisted multi-stage VMD-AD hybrid system with TM unit is designed
- ▶ Performance comparison between VMD-only and VMD-AD systems is performed
- ▶ VMD-AD hybrid system achieves a 21% improvement in cumulative water production