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DESIGN AND OPERABILITY COMPARISON BETWEEN SOLAR DRIVEN DIRECT CONTACT AND VACUUM MEMBRANE DISTILLATION DESALINATION SYSTEMS

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The objective of this research is to combine renewable solar thermal energy and seawater membrane distillation desalination systems into green processes. The units of the systems include solar collectors, heat exchangers and membrane distillation modules. In order to assess the economic design point of the process, the Aspen Custom Molder (ACM) was used to build the mathematical model to describe each unit of solar membrane distillation desalination systems. Simulation results show that the optimal total annual costs (TAC) of direct contact (DCMD) and vacuum membrane distillation (VMD) modules for 2000 kg/hr water production are $844,200 and $576,359, respectively. The fundamental differences between DCMD and VMD are driven by temperature and pressure difference between either side of the membrane. A larger temperature difference between the hot and cold sides of the membrane will require an increased heat supply from the solar collector and the heat exchanger. This will cause a dramatic increase in cost of the solar collector and the heat exchanger for DCMD systems. The control structures of DCMD and VMD systems were built in order to maintain the water production rate. The operability analysis in the optimal design points were done for DCMD and VMD systems with a typical summer solar intensity curve. For a short-term one day operability analysis in Taiwan, the 1.2 times overdesign of heat storage tank will handle the processes well either in DCMD or VMD systems. Finally, the dynamic simulations of DCMD and VMD systems in summer are demonstrated to validate the operability analysis results. The water production amounts per day are 37.17 tons and 35.39 tons, respectively.

1. INTRODUCTION

Due to greenhouse effects, Earth's climate has changed and caused worldwide water resources re-distribution. In order to solve the lack of drinking water resources in some areas, combining renewable solar energy and membrane distillation desalination systems have being studied in recent years. The driving force of membrane distillation systems can be cataloged into two types: temperature difference and pressure difference. Temperature driven membrane distillation modules are known as direct contact (DCMD) and air gap membrane distillation (AGMD) [1,2]. The pressure driven type of membrane distillation is vacuum membrane distillation (VMD) [3]. El-Bourawi *et al.*, 2006 [4] summarized advantages and disadvantages of all types of MD systems in different application fields. In this work, design and operability analysis of solar driven DCMD and VMD desalination systems are discussed incorporating varying solar power intensities.

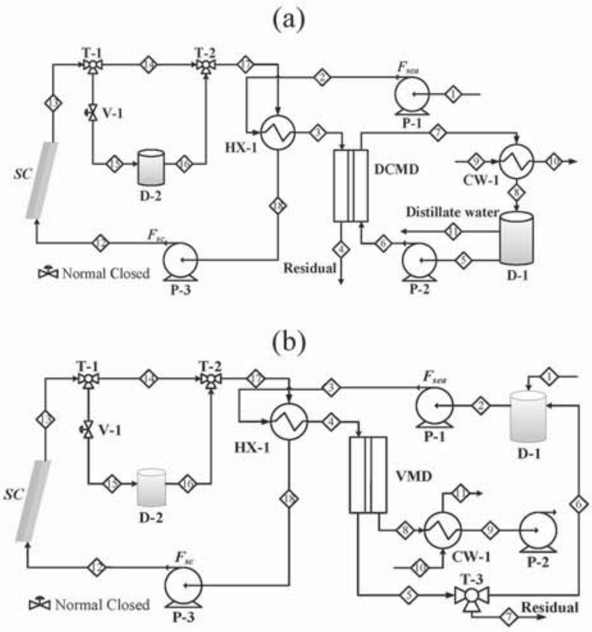

Fig. 1 Process flow diagrams of (a) DCMD, (b) VMD systems

2. MODELING

2.1 Unit Models

Solar driven direct contact and vacuum membrane distillation desalination systems include: solar collectors, heat exchangers, membrane distillation modules. Figure 1 shows the process flow diagram of DCMD and VMD desalination systems, respectively.

2.1.1 Solar Collector Model

Chen et al., 2012 [1] built mathematical models to describe solar collectors. Table 1 shows the modeling equation of each unit.

2.1.2 Heat Exchanger Model

The modeling equations of heat exchangers are shown in Table 1.

2.1.3 DCMD/VMD Model

Chang *et al*., 2009 [5] and Lawson and Lloyd, 1996 [3] established mathematical models of DCMD and VMD which are shown in Table 1.

2.2 Model Validation

Experimental data of membrane distillation modules were taken from Lawson and Lloyd, 1996 [2,3]. Simulation results fit well with experimental data. The DCMD and VMD used different of Polypropylene(PP) membranes. The mass fluxes were obtained by varying feed temperature which was operated form 30 ℃ to 85 ℃. The permeate temperature of DCMD was operated at 20℃. The vacuum pressure of VMD was operated at 3000 Pa.

3. OPTIMIZATION

3.1 Design Variables

Design variables are used to identify the equipment sizes of solar driven DCMD and VMD desalination systems. In order to determine the number of design variables, the design degree of freedom (DOF) analysis method was used which was proposed by Luyben,(1996) [6]. The definition of Design DOF is shown as follows:

$$N_D = N_v - N_e \tag{1}$$

After calculation, we found the number of design DOFs of VMD and DCMD systems to both be eleven. The aspect ratio (L_{SC}/W_{SC}) of the solar collector is set at 14 due to its optimal efficiency [7]. The water flow channel thickness in the solar collector (δsc) is set at 1 cm [8], the aspect ratio (L_{MD}/W_{MD}) of the DCMD/VMD is set at 24.44 [2,3] and the flow channel thickness (δ_{MD}) of the DCMD/VMD unit is set at 0.63 cm [2,3] due to the manufacturing limitation. Ambient temperature (T_a)and feed temperature of the seawater (T_{sea}) is set at 25℃. These design variables are reduced to five which are F_{sea}, F_{sc}, F_{MD}, A_{sc}, A_{MD} and F_{sea}, F_{sc}, P_v, A_{sc}, A_{MD}, respectively.

Table 1 Modeling equations for solar collectors, heat exchangers, membrane distillation modules [1-3, 5]

Solar collector (SC)

$$\frac{dT_c}{dt} = \frac{A_{SC}U'}{M_c C_{p,c}}\left(\frac{BI(t)}{U'} + T_a(t) - T_c\right) - \frac{A_{SC}h_c}{M_c C_{p,c}}(T_c - T_f) \tag{E-1}$$

$$\frac{\partial T_f}{\partial t} = -L_c\frac{m_{f,c}}{M_f}\frac{\partial T_f}{\partial z} + \frac{A_{SC}h_c}{M_f C_{p,w}}(T_c - T_f) \tag{E-2}$$

Heat exchanger (HX-1)

$$\frac{\partial T_{hl}}{\partial t} = L\frac{m_{hl}}{M_{hl}}\left(\frac{\partial T_{hl}}{\partial x}\right) - \frac{A_{HX-1}U}{M_{hl}C_{phl}}(T_{hl} - T_{cl}) \tag{E-3}$$

$$\frac{\partial T_{cl}}{\partial t} = \frac{m_{cl}}{M_{cl}}\left(\frac{\partial T_{cl}}{\partial x}\right) + \frac{A_{HX-1}U}{M_{cl}C_{pcl}}(T_{hl} - T_{cl}) \tag{E-4}$$

DCMD system

Mass and energy fluxes

$$N_{hl,w} = k_{hl}\rho_{hl} ln\frac{1 - x_{gm1}}{1 - x_{hl,w}} \tag{E-5}$$

$$N_{gm,w} = \frac{k_{gm,w}}{RT_{gm,avg}}(P_{gm1} - P_{gm2}) \tag{E-6}$$

$$N_{cl,w} = k_{cl}\rho_{cl} ln\frac{1 - x_{cl,w}}{1 - x_{gm2}} \tag{E-7}$$

$$Q_{hl} = h_{hl}(T_{hl} - T_{gm1}) \tag{E-8}$$

$$Q_{N,hl} = N_{hl,w}C_{p,hl}(T_{hl} - T_{gm1}) \tag{E-9}$$

$$h_{vap,gm1} = N_{hl,w}\Delta H_{vap,w} \tag{E-10}$$

$$Q_{gm} = [\varepsilon h_m + (1-\varepsilon)h_{mem}](T_{hl} - T_{gm1}) \tag{E-11}$$

$$Q_{cl} = h_{cl}(T_{gm2} - T_{cl}) \tag{E-12}$$

$$Q_{N,cl} = N_{cl,w}C_{p,cl}(T_{gm2} - T_{cl}) \tag{E-13}$$

$$h_{vap,gm2} = N_{cl,w}\Delta H_{vap,w} \tag{E-14}$$

Mass and energy balances

$$N_{hl,w} = N_{gm,w} \tag{E-15}$$

$$N_{cl,w} = N_{gm,w} \tag{E-16}$$

$$Q_{gm} = Q_{hl} + Q_{N,hl} - h_{vap\,gm1} \tag{E-17}$$

$$Q_{gm} = Q_{cl} + Q_{N,cl} + h_{vap\,gm2} \tag{E-18}$$

VMD system

Mass and energy flux

$$N_{hl,w} = k_{hl}c_{hl}\ln\frac{x_{fm} - x_p}{x_f - x_p} \tag{E-19}$$

$$N_{gm,w} = \frac{1}{\delta_m RT_{gm,avg}}\left[K_0\left(\frac{8RT_{vp}}{\pi M_{vp}}\right)^{0.5} + B_0\frac{P_{gm}}{\mu}\right]\Delta P_{gm} \tag{E-20}$$

$$Q_{hl} = h_{hl}(T_{hl} - T_{gm1}) \tag{E-21}$$

$$Q_{N,hl} = N_{hl,w}C_{p,hl}(T_{hl} - T_{gm1}) \tag{E-22}$$

$$h_{vap,gm1} = N_{hl,w}\Delta H_{vap,w} \tag{E-23}$$

$$Q_{gm} = [\varepsilon h_m + (1-\varepsilon)h_{mem}](T_{gm1} - T_{gm2}) \tag{E-24}$$

Mass and energy balances

$$N_{hl,w} = N_{gm,w} \tag{E-25}$$

$$Q_{gm} = Q_{hl} + Q_{N,hl} - h_{vap\,gm1} \tag{E-26}$$

3.2 Objective Function

The cost functions of all equipment are taken from Seider et al., 2010 [9]. The objective of the work is to minimize the total annual cost (TAC) of the system. The distillated water production rate is 2000 kg/hr. The process constrains are: (1) the maximum temperature of the effluent stream of solar collectors is restricted to 95 ℃ which can prevent water vaporization. (2) The concentration of the outlet sea water from heat-integrated VMD is limited to 0.45wt% and the outlet temperature of VMD vacuum side is larger than 45℃. The optimization of DCMD and VMD were formulated as:

DCMD

$$\underset{x\in\Omega}{\text{Minimize}}(\text{TAC})$$

$$\Omega=\{F_{sea},F_R,F_{MD},A_{SC},A_{MD}\}$$

Subject to

$$T_{sc,out}\le 95\ °C$$

$$D=2000\ \text{kg/hr}$$

VMD

$$\underset{x\in\Omega}{\text{Minimize}}\ (\text{TAC})$$

$$\Omega=\{F_{sea},F_{sc},P_v,A_{SC},A_{MD}\}$$

Subject to

$$T_{sc,out}\le 95\ °C\quad T_{vac,out}\ge 45^{o}C$$

$$C_{NaCl}\le 0.45\text{wt\%}\quad D=2000\ \text{kg/hr}$$

3.3 Optimal Results

Aspen Custom Modeler simulator was used to model and simulate the systems and the optimization problem was solved by using FEASOPT. After varying solar power intensities from 100 to 1000 W/m^2, the optimal TACs of DCMD and VMD systems were found to be \$844,200 and \$576,359 at 500 W/m^2.

3.4 Summary

Optimal design main equipment cost comparison between DCMD and VMD systems are shown in Fig. 2. TAC of VMD is lower than DCMD because a smaller solar collector, heat exchanger and membrane are needed. The reason for this is that the driving force of DCMD is temperature difference, which requires larger units (Solar collector and heat exchanger). Additionally, VMD is driven by pressure difference which requires less energy. The capital and electricity cost of vacuum pumps are relatively lower compared to the heat units.

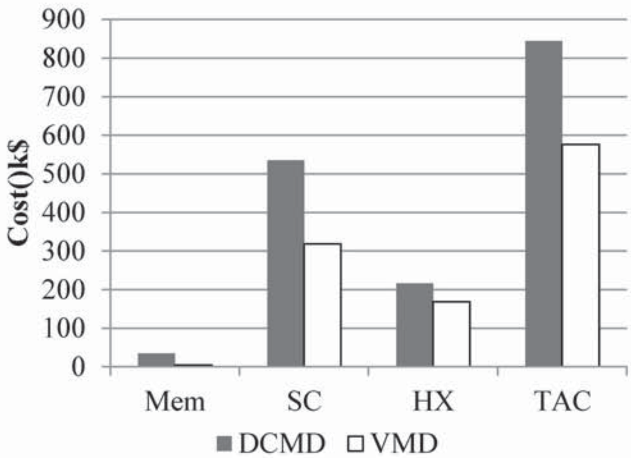

Fig. 2 Optimal design main equipment cost comparison between DCMD and VMD systems

4. CONTROL STRUCTURE

4.1 Control Structure Design

Chen, et al., 2012 [1] proposed a control structure design for maintaining the distillated water production rate of solar driven AGMD systems with an unpredictable solar energy intensity. After the sensitivity analysis is made, the inlet flowrate to the hot storage tank is used to manipulate the temperature of hot inlet stream of the heat exchanger. In this work, the same control structure was used in solar driven DCMD and VMD systems. Fig. 3 (a), and (b) show the control structures for both systems during day time operation. During night time operation, the heat storage tank which stores the energy in the day time is used to provide energy source to the hot side of the membrane.

4.2 Tuning of Controller Parameters

The dynamic response of hot and cold water streams mixed process is very fast. The measurement dynamic becomes more important. Three first-order temperature sensor dynamics are used and the time constants are all 30 sec. Auto-tuning variation method is used to evaluate the ultimate gain (Ku) and ultimate period (Pu). And these values can be substituted into T-L tuning rules to calculate the controller gain (K_C) and integral time (τ_I) for the temperature PI controller. The controller gains of DCMD and VMD systems are 7.22(%/%) and 24.8(%/%); the integral times are 246.84(sec) and 225.93(sec), respectively.

4.3 Operability Analysis

Optimal design points of DCMD and VMD desalination systems can't be work using existing control structure during summer day time operation. This was caused by the maximum effluent temperature from the solar collector higher than 95 ℃. In order to solve this problem, the constrained temperature from the solar collector was reduced with a slowly increased in TAC. The systems were operable when TAC of DCMD and VMD desalination system were increased a value of 6.7% and 0.1%, respectively. The constrain temperature($T_{HX,in}$) of DCMD and VMD systems were both around 72℃. From dynamic simulation, the maximum effluent temperatures of the solar collector are both 95℃. The difference between maximum effluent temperature of solar collectors and water vaporized temperature, which defined as the operability range for the systems, is shown in Fig. 4 (Shadow areas are operability areas). The operability area of the DCMD was smaller than the VMD because DCMD was temperature driven which required higher solar energy demand.

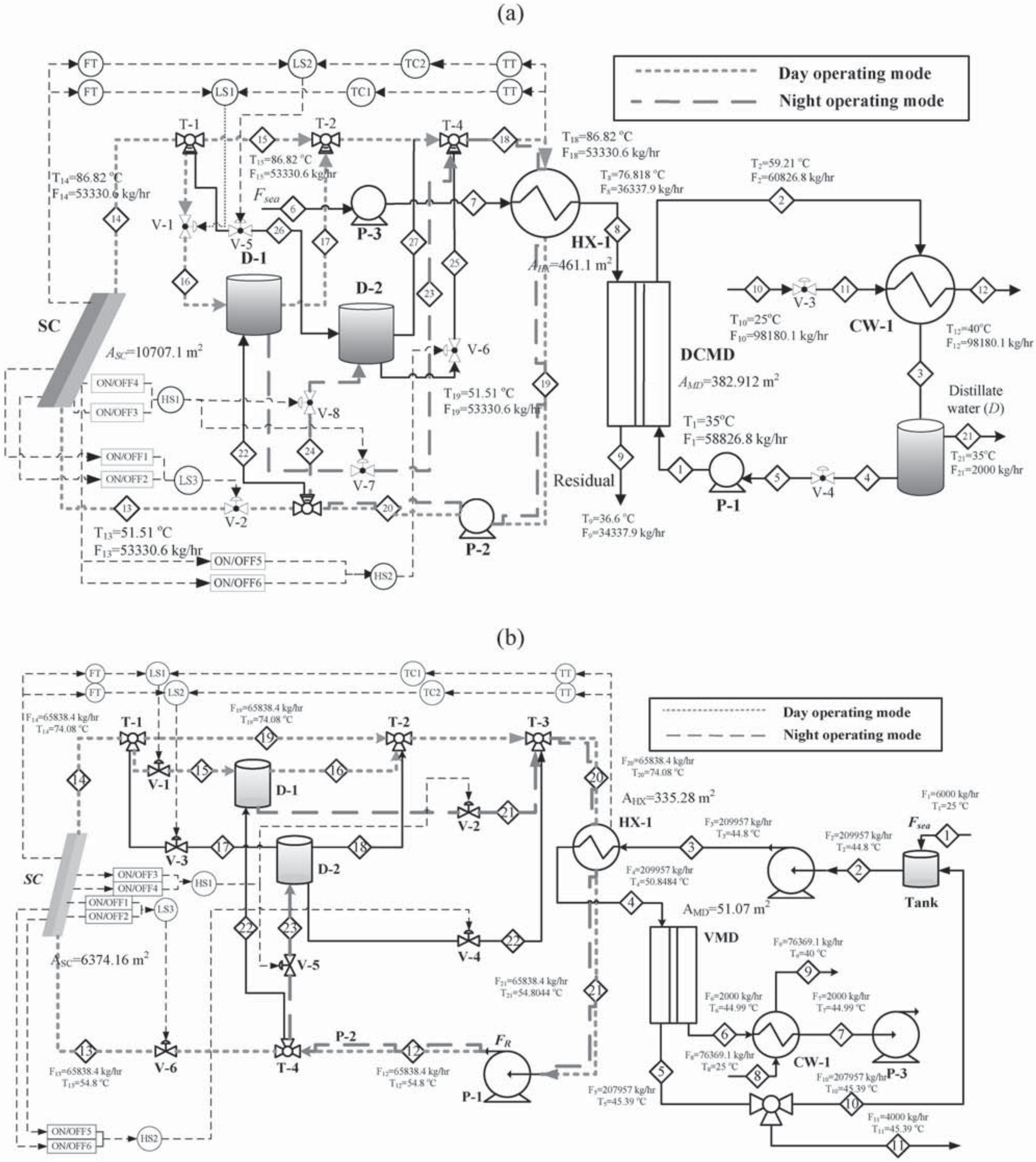

Fig. 3 Control structure design for (a) DCMD, (b) VMD desalination systems

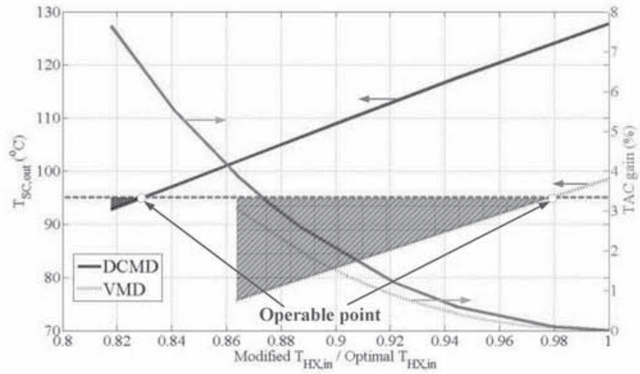

Fig. 4 Operability analysis for DCMD and VMD desalination systems

4.4 Dynamic Results and Discussion

Chang [10] provided the solar intensity distribution of summer and winter in Taiwan. The result is shown in Fig. 5. With a typical summer solar power intensity in Taiwan, the DCMD system can produce 37.15 tons water; 21.38 tons water in winter for whole day operation. The VMD system can produce 35.39 tons water in summer; 13.53 tons water in winter.

5. CONCLUSION

In this work, ACM simulator was used to build and simulate solar driven DCMD and VMD desalination systems. The optimal TAC of the DCMD and VMD systems are $844,200, $576,359 at 500W/m^2. The control structure design was installed in order to maintain the distillated water production rate. From operability analysis, we found the lower the solar collector effluent temperature; the higher the operability range for the systems. The dynamic simulation shows the operating range of VMD is larger than DCMD. The DCMD system can produce 37.15 tons in summer and 21.38 tons in winter. The VMD can produce 35.39 tons in summer and 13.53 tons in winter.

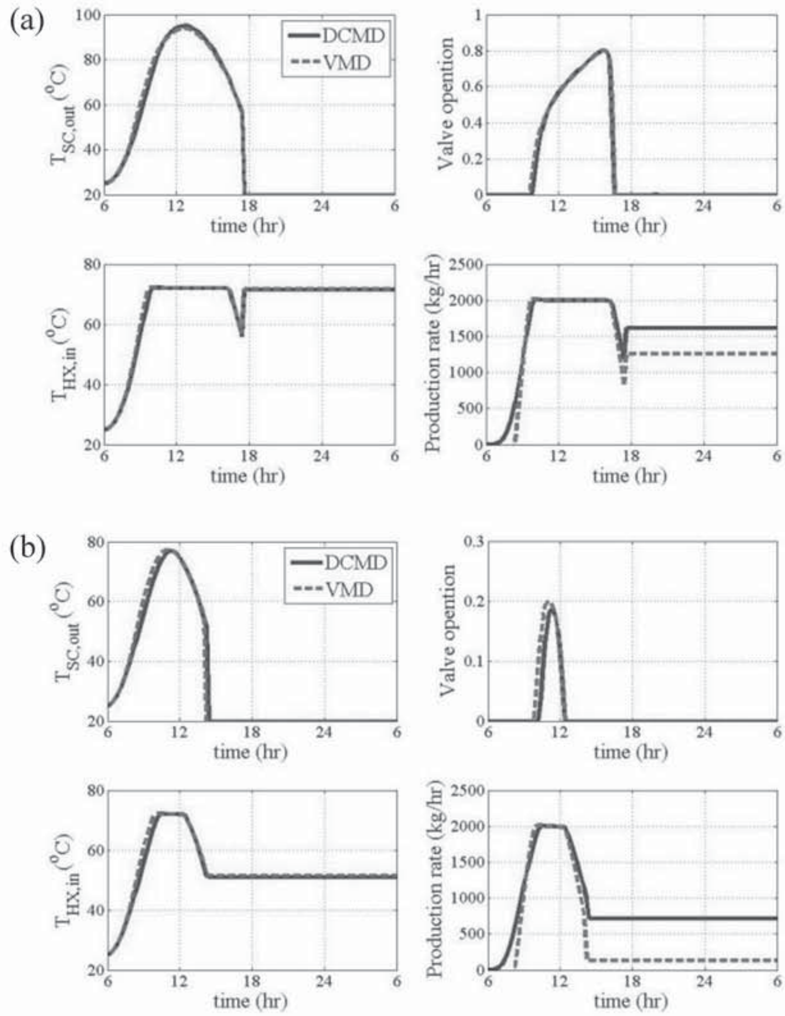

Fig. 5 Dynamic simulation of DCMD and VMD desalination systems in (a) Summer, (b) Winter

NOMENCLATURE

A_{HX}	= area of heat exchanger	[m^2]
A_{MD}	= area of membrane	[m^2]
A_{SC}	= area of solar collector	[m^2]
B	= Collector efficiency factor	[-]
$C_{p,c}$	= specific heat capacity of collector	[J/kg-K]
$C_{p,w}$	= specific heat capacity of water	[J/kg-K]
F_{MD}	= MD cold mass flowrate	[kg/hr]
F_{sc}	= SC mass flowrate	[kg/hr]
F_{sea}	= seawater mass flowrate	[kg/hr]
h	= heat transfer coefficient	[W/m^2-K]
I	= solar power intensities	[W/m^2]
Kc	= controller gain	[-]
Ku	= ultimate gain	[-]
k_{gm}	= mass transfer coefficient	[m/s]
L	= length	[m]
M_c	= mass of collector	[kg]
N	= molar flux	[kmol/m^2-s]
N_D	= degree of freedom	[-]
N_v	= number of variable	[-]
N_e	= number of equation	[-]
P_v	= vacuum pressure	[Pa]
ΔP_{gm}	= membrane surface pressure difference	[Pa]
Pu	= ultimate period	[sec]
Q	= heat flux	[kJ/m^2-s]
T_a	= ambient temperature	[℃]
ΔT_{gm}	= membrane surface temperature difference	[℃]
T_{sea}	= seawater temperature	[℃]
U	= overall heat transfer coefficient	[W/m^2-K]
τ_I	= integral time	[sec]
δ_{MD}	= MD flow channel high	[cm]
δsc	= SC flow channel high	[cm]

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