Design and Operability Comparison between Solar Driven Direct Contact and Vacuum Membrane Distillation Desalination Systems

Chii-Dong Ho (何啟東)*、Yih-Hang Chen(陳逸航)、Hao-Chia Hung(洪浩嘉)
Energy and Opto-Electronic Materials Research Center, Department of Chemical and Materials Engineering, Tamkang University, Tamsui, New Taipei, Taiwan 251
(淡江大學化學工程與材料工程學系、能源與光電材料研究中心)

國科會計畫編號：NSC 101-2621-M-032-002

Abstract--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 are $857,990 and $576,359, respectively. The fundamental differences between DCMD and VMD are driven by temperature and pressure variation on 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 increase a dramatic in cost of the solar collector and the heat exchanger. Finally, the operability analyses in the optimal design points were done for DCMD and VMD systems. The VMD systems provided a wider operability range than DCMD.

Keywords: Solar energy, membrane distillation, design, operability.

*Corresponding author. Tel: 886-26215656 ext. 2724 Fax: 886-2-26209887;
E-mail: cdho@mail.tku.edu.tw

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]. The pressure driven type of membrane distillation is vacuum membrane distillation (VMD) [2]. 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.

2. Modeling

2.1 Unit models

Solar driven direct contact and vacuum membrane distillation desalination systems include: solar collectors, heat exchangers, membrane distillation modules. As shown in Fig.1 (a), (b) shows the process flow diagram of DCMD and VMD desalination systems.

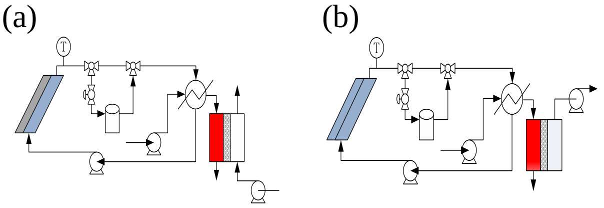


Fig. 1 (a) DCMD system, (b) VMD system

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. And the assumptions are listed as follows.

(1) The effluent stream from the solar collector does not exceed 95 ^{o}C to prevent water vaporization. (2) The velocity of the working

fluid in the absorbed tube is the same. (3)The system operates under adiabatic conditions.

Table 1 Modeling equations for solar collectors, heat exchangers, membrane distillation modules. [1-2, 5]

Solar collector (SC)

$$\frac{dTc}{dt}=\frac{SU'}{McCp,c}\left(\frac{BI(t)}{U'}+Ta(t)-Tc\right)-\frac{Shc}{McCp,c}(Tc-Tf) \tag{E-1}$$

$$\frac{\partial Tf}{\partial t}=-Lc\frac{m_{f,c}}{Mf}\frac{\partial Tf}{\partial z}+\frac{Shc}{MfCp,w}(Tc-Tf) \tag{E-2}$$

Heat exchanger (H-1)

$$\frac{\partial \mathrm{T_{hl}}}{\partial \mathrm{t}}=\mathrm{L}\frac{\mathrm{m_{hl}}}{\mathrm{M_{hl}}}\left(\frac{\partial \mathrm{T_{hl}}}{\partial \mathrm{x}}\right)-\frac{\mathrm{A_{HX-1}U}}{\mathrm{M_{hl}C_{phl}}}(\mathrm{T_{hl}}-\mathrm{T_{cl}}) \tag{E-5}$$

$$\frac{\partial \mathrm{T_{cl}}}{\partial \mathrm{t}}=\frac{\mathrm{m_{cl}}}{\mathrm{M_{cl}}}\left(\frac{\partial \mathrm{T_{cl}}}{\partial \mathrm{x}}\right)+\frac{\mathrm{A_{HX-1}U}}{\mathrm{M_{cl}C_{pcl}}}(\mathrm{T_{hl}}-\mathrm{T_{cl}}) \tag{E-6}$$

DCMD system

Mass and energy fluxes

$$N_{hl,w}=k_{hl}\rho_{hl}ln\frac{1-x_{gm1}}{1-x_{hl,w}} \tag{E-7}$$

$$N_{gm,w}=\frac{k_{gm,w}}{RT_{gm,avg}}(P_{gm1}-P_{gm2}) \tag{E-8}$$

$$N_{cl,w}=k_{cl}\rho_{cl}ln\frac{1-x_{cl,w}}{1-x_{gm2}} \tag{E-9}$$

$$Q_{hl}=h_{hl}(T_{hl}-T_{gm1}) \tag{E-10}$$

$$Q_{N,hl}=N_{hl,w}C_{p,hl}(T_{hl}-T_{gm1}) \tag{E-11}$$

$$h_{vap,gm1}=N_{hl,w}\Delta H_{vap,w} \tag{E-12}$$

$$Q_{gm}=[\varepsilon \mathrm{h}_{m}+(1-\varepsilon)h_{mem}](T_{hl}-T_{gm1}) \tag{E-13}$$

$$Q_{cl}=h_{cl}(T_{gm2}-T_{cl}) \tag{E-14}$$

$$Q_{N,cl}=N_{cl,w}C_{p,cl}(T_{gm2}-T_{cl}) \tag{E-15}$$

$$h_{vap,gm2}=N_{cl,w}\Delta H_{vap,w} \tag{E-16}$$

Mass and energy balances

$$N_{hl,w}=N_{gm,w} \tag{E-17}$$

$$N_{cl,w}=N_{gm,w} \tag{E-18}$$

$$Q_{gm}=Q_{hl}+Q_{N,hl}-h_{vap,gm1} \tag{E-19}$$

$$Q_{gm}=Q_{cl}+Q_{N,cl}+h_{vap,gm2} \tag{E-20}$$

VMD system

Mass and energy flux

$$N_{hl,w}=k_{hl}c_{hl}\ln\frac{x_{fm}-x_{p}}{x_{f}-x_{p}} \tag{E-21}$$

$$N_{gm,w}=\frac{1}{\delta_{m}RT_{gm,avg}}\left[K_{0}\left(\frac{8RT_{vp}}{\pi M_{vp}}\right)^{0.5}\Delta p_{gm}+B_{0}\frac{p_{gm}}{\mu}\Delta P\right] \tag{E-22}$$

$$Q_{hl}=h_{hl}(T_{hl}-T_{gm1}) \tag{E-23}$$

$$Q_{N,hl}=N_{hl,w}C_{p,hl}(T_{hl}-T_{gm1}) \tag{E-24}$$

$$h_{vap,gm1}=N_{hl,w}\Delta H_{vap,w} \tag{E-25}$$

$$Q_{gm}=[\varepsilon h_{m}+(1-\varepsilon)h_{mem}](T_{gm1}-T_{gm2}) \tag{E-26}$$

Mass and energy balances

$$N_{hl,w}=N_{gm,w} \tag{E-27}$$

$$Q_{gm}=Q_{hl}+Q_{N,hl}-h_{vap,gm1} \tag{E-28}$$

2.1.2 Heat exchanger model

The modeling equations of heat exchangers are shown in Table 1 and the modeling assumptions are listed as follows：

(1) The heat capacities of both flows are constant.
(2) No phase change and adiabatic operation in the heat exchanger.

2.1.3 DCMD/VMD model

Chang *et al.*, 2009 [5] and Lawson and Lloyd, 1996 [2] established mathematical models of DCMD and VMD which are shown in Table 1. The modeling assumptions are:

(1) The pores of the membrane are filled with air and water vapor. (2) Film theory is used to describe the correlation formula of the mass and heat transfer coefficient. (3) Pressure drop in the membrane is negligible.

2.2 Membrane distillation model validation

Experimental data of membrane distillation modules were taken from Lawson and Lloyd, 1996 [2,3] Simulation result fits well with experimental data.

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:

$$N_{D}=N_{\mathrm{variables}}-N_{equations} \tag{1}$$

After calculation, we found the number of design DOFs of VMD and DCMD systems to both be five. These design variables are F_{sea}, F_{R}, F_{R1}, A_{SC}, A_{M} and F_{sea}, F_{R}, P, A_{SC}, A_{M}, respectively.

3.2 Objective function

The cost functions of all equipment are taken from Seider *et al.*, 2010 [7]. The objective of the work is to minimize the total annual cost (TAC) of the system. The distilled 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°C which can prevent water vaporization. (2) The concentration of the outlet sea water from heat-integrated VMD is limited to 0.45*wt%* and the outlet pressure of VMD vacuum side is set at 9320 Pa. The optimization of DCMD and VMD were formulated as:

DCMD

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

$$\Omega=\{F_{sea},F_R,F_{R1},A_{SC},A_{MD}\} \tag{2}$$

Subject to

$$T_{sc,out} < 95\ ^{o}C$$

$$D = 2000\ kg/hr$$

VMD

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

$$\Omega=\{F_{sea},F_{sc},P_v,A_{SC},A_{MD}\} \tag{3}$$

Subject to

$$T_{sc,out} < 95\ ^{o}C$$

$$C_{NaCl} < 0.45wt\%$$

$$T_{vac,out} < 45^{o}C$$

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

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 \$857,990 and \$576,359 at 500 W/m^2.

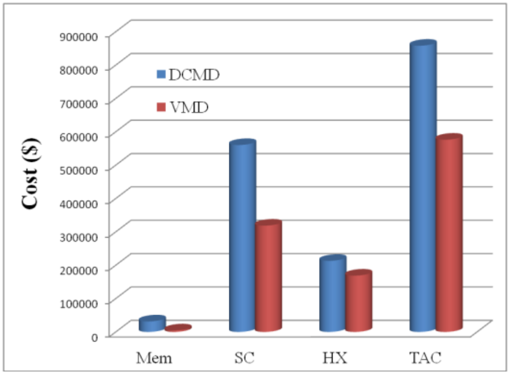


Fig. 2 Optimal design main equipment cost comparison between DCMD and VMD systems.

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.

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. From sensitivity analysis, 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), (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.

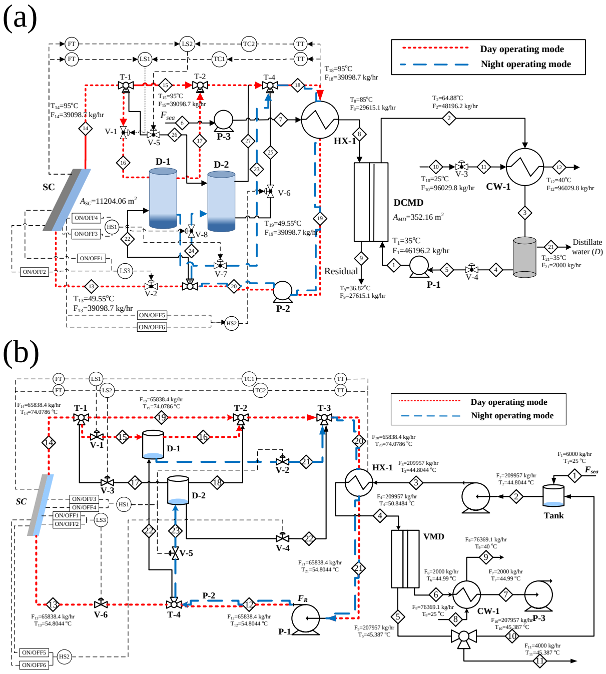


Fig. 3 Control structure design for (a) DCMD, (b) VMD desalination systems.

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 (K_u) and ultimate period (P_u). 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 constrain temperature from the solar collector was reduced with a slowly increased in TAC. The percentage increased in TAC was set at 2 % for both systems. The constrain temperature of DCMD and VMD systems are 76 ℃ and 66 ℃, respectively. From dynamic simulation, the maximum effluent temperatures of the solar collector are 84°C and 79°C. The difference between maximum effluent temperature and water vaporized temperature defined as operability range and shown in Fig.4 (Shadow areas are operability areas). The areas of the VMD are larger than the DCMD. The DCMD is temperature driven which requires higher energy demand. When the solar power intensity gets larger, the effluent temperature of the solar collector will close to 95 ℃ more closer to VMD systems.

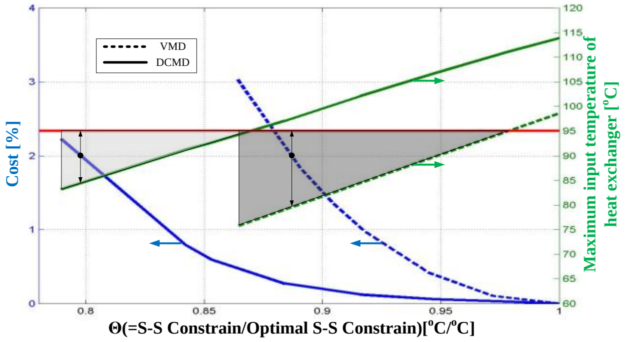
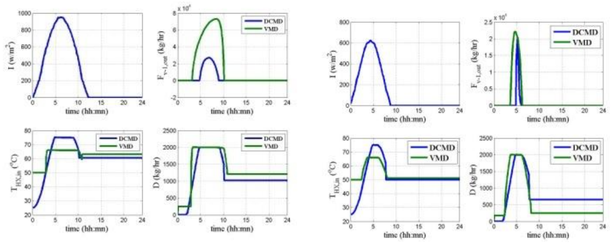


Fig. 4 Operability analysis for DCMD and VMD desalination systems.



(a) (b)

Fig. 5 Simulation result of the DCMD and VMD desalination system, (a) Summer, (b) Winter

4.4 Dynamic results and discussion

Chang [8] provided the solar intensity distribution of summer and winter in Taiwan. With a typical summer solar power intensity in Taiwan, the DCMD system can produce 28.02 tons; 19.01 tons in winter for whole day operation. The VMD system can produce 32.14 tons in summer; 13.72 tons in winter. When the solar energy is sufficient, the driving force of distillated water production of VMD is temperature plus pressure difference, which will make more water than DCMD.

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 \$857,990, \$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. DCMD system can produce 28.02 tons in summer and 19.01 tons in winter. The VMD can produce 32.14 tons in summer and 13.72 tons in winter.

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