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Renewable energy seawater desalination using combined flat plate collector (FPC) and direct contact membrane distillation (DCMD).

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***Abstract*— this paper presents a thermal collector simulation system powering a direct contact membrane distillation (DCMD) unit for freshwater production from seawater. The simulation is carried out using commercial software, Transient System Simulation (TRNSYS). A new model type has been inserted in TRNSYS in order to include the DCMD unit in the plant. The simulation of the solar distillation system consists of 10 h per day; day 21st was selected from four months (March, September, December, June) and meteorological conditions of Ain Témouchent (Algeria). The effect of the main parameters in desalinated water production capacity was appraised. The results from the simulation showed that the effect of flow rate on flux was less significant than the feed temperature, the average difference between the permeate fluxes provided by the present model and experiment in reference is 4.766 % for the Membrane effective length at 0.110 m.**

***Keywords*— Solar desalination, direct contact membrane distillation, flat plate solar collector, water treatment, TRNSYS.**

I. INTRODUCTION

This Rural and remote areas have specific needs that influence the choice of appropriate technologies. This includes technical requirements related to a small-scale application using renewable sources of easy operation and maintenance. Membrane distillation (MD) can be a great option especially in view of the possibility to utilize solar thermal and low-grade heat directly as the primary source of energy [1], [2].

Four common configurations, mainly air-gap membrane distillation (AGMD), vacuum membrane distillation (VMD), sweeping-gas membrane distillation (SGMD), and direct contact membrane distillation (DCMD) [3], [4].

Among the four configurations, DCMD is the most widely considered due to the straightforwardness to setup and the adequately high flux rate in examination with other MD configurations. To the authors' knowledge, there are many modeling and experimental papers of complex processes during DCMD operation including heat and mass transfer, operating parameters effects, pore size distribution and air flux, flow rate, flow velocities and feed temperature have been reported in the literature [5]-[7].

In this paper, the following technologies are at the same time incorporated into the system: SSH (Solar Seawater Heating) system with flat plate solar collector (FPC) and DCMD (Direct Contact Membrane Distillation) for SW (seawater) desalination.

II. THEORY AND MATHEMATICAL MODELLING

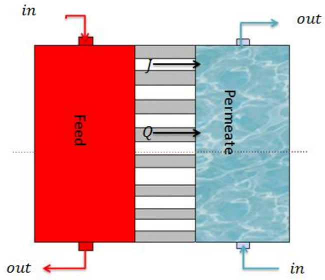
A. *Membrane Distillation (MD)*

Membrane Distillation (MD) is a half process that consolidates both thermal process and a membrane process. The membrane directly contacts a fluid on the feed side and a fluid or vaporous stage on the permeate side. Therefore can be characterized as a procedure for expelling water vapour from aqueous feed solution heated to a temperature of under 100 °C. The transfer force of the process is the difference in partial pressures between the two sides of the membrane, which causes evaporation on the feed side.

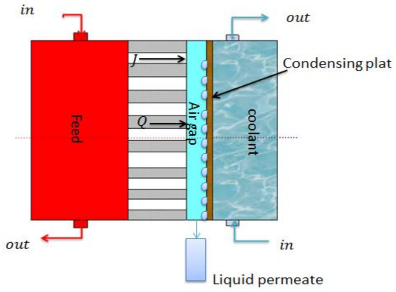
B. *Les configurations de la distillation membranaire (MD)*

Contingent upon the procedure arrangements, four different systems of MD have been distinguished [3,4]: Direct Contact Membrane Distillation (DCMD) where a cold liquid is in coordinate contact with the layer at the permeate side, Air Gap Membrane Distillation (AGMD) where a stagnant air gap is kept up between the membrane and condensing surface, Vacuum Membrane Distillation (VMD) where a pump is utilized to make the vacuum on the permeate side and subsequently the condensation happens outside the membrane module ,and Sweep Gas Membrane Distillation (SGMD) where inert gas is typically used to sweep the vapors at the permeate side and after that to condense these vapors outside the membrane module. As shown in Fig 1.

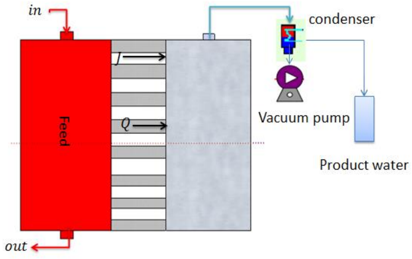
(A):DCMD



(B):AGMD



(C):VMD



(D):SGMD

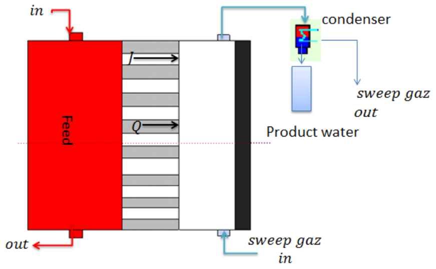


Fig. 1 Different configurations of membrane distillation technology: (A): DCMD, (B): AGMD, (C): VMD, (D): SGMD

C. DCMD model

The membrane distillation process is governed by different heat and mass transfer mechanisms that occur at both the feed side, the membrane and the permeate side. Mass transfer occurs through the pores of the membrane while heat is transferred through both the membrane and its pores.

Fig. 2 shows the schematic of DCMD heat and mass transfer, The mass flux J_w (L/(m^2.h)) of water can be written as a linear function of the vapor pressure difference across the membrane and the membrane mass transfer coefficient B_m (L/(m^{2}h.Pa)) [8]-[10], given by:

$$J_w = B_m\left(P_{mf} - P_{mp}\right) \tag{1}$$

Where P_{mf} and P_{mp} are the partial pressures in feed and permeate sides (Pa) as a function of the temperature on the feed (T_{mf}) and permeate (T_{mp}) at the membrane surface (C) can be calculated with Antoine equation:

$$P_{mf,p} = \exp\left(23.1964 - \frac{3816.44}{T_{mf,p}+227.04}\right) \tag{2}$$

The heat transfer involved in DCMD can be divided into three regions [4], [10]:

1) *Convective thermal transfer in the feed boundary layer* $Q_{f,conv}$ *(W/m^2) can be calculated as:*

$$Q_f = Q_{f,conv} = h_f\left(T_{bf} - T_{mf}\right) \tag{3}$$

2) *The combination of the conduction heat transfer across the membrane* $Q_{m,cond}$ *(W/m^2) and the heat transferred due to the migration of water vapor through the pores of the membrane* $Q_{m,MT}$ *(W/m^2), which can be calculated as:*

$$Q_m = Q_{m,cond} + Q_{m,MT} \cdot = h_m\left(T_{mf} - T_{mp}\right) + J_w \Delta H_v \tag{4}$$

3) *Convective thermal transfer in the permeate boundary layer* $Q_{p,conv}$ *(W/m^2) is described as:*

$$Q_p = Q_{p,conv} = h_p\left(T_{mp} - T_{bp}\right) \tag{5}$$

In the equations above, h_f is the feed boundary layer heat transfer coefficient (W/(m2K)), h_p is the permeate boundary layer heat transfer coefficient (W/(m^{2}K)), ΔH_v is the latent heat of vaporization(J/L) [11], h_m is the thermal transfer coefficient of the hydrophobic membrane (W/(m^{2}K)) which can be calculated from the membrane thermal conductivity k_m (W/(m.K)) [3] as follows:

$$k_m = \varepsilon k_g + (1-\varepsilon)k_p \tag{6}$$

$$h_m = \frac{\varepsilon k_g + (1-\varepsilon)k_p}{\delta_m} \tag{7}$$

Where δ_m and ε are respectively the thickness (m) and the porosity (-) of the hydrophobic membrane, k_g (W/(m.K)) and k_p (W/(m.K)) are the thermal conductivity of polymer and the air trapped inside the pores of the membrane respectively.

In the stationary state, the overall flow of heat transfer across the entire DCMD system Q (W/m^2) is given by [12]:

$$Q = Q_f = Q_m = Q_p \tag{8}$$

By combining equations (3) - (8), the heat flux can be written as follows [12]:

$$Q = \left(\frac{1}{h_f} + \frac{1}{h_m + \frac{J_w \Delta H_v}{T_{mf} - T_{mp}}} + \frac{1}{h_p}\right)^{-1} (T_{bf} - T_{bp}) \tag{9}$$

As a result, the overall heat transfer coefficient U (W/(m^2.K)) for the DCMD process can be written as follows [12]:

$$U = \left(\frac{1}{h_f} + \frac{1}{h_m + \frac{J_w \Delta H_v}{T_{mf} - T_{mp}}} + \frac{1}{h_p}\right)^{-1} \tag{10}$$

The temperatures T_{mf} and T_{mp} at the surfaces of the membrane can be estimated as [3, 11]:

$$T_{mf} = \frac{k_m\left(T_{bp} + \frac{h_f}{h_p} T_{bf}\right) + \delta_m (h_f T_{bf} - J_w \Delta H_v)}{k_m + h_f\left(\delta_m + \frac{k_m}{h_p}\right)} \tag{11}$$

$$T_{mp} = \frac{k_m\left(T_{bf} + \frac{h_p}{h_f} T_{bp}\right) + \delta_m (h_p T_{bp} + J_w \Delta H_v)}{k_m + h_p\left(\delta_m + \frac{k_m}{h_f}\right)} \tag{12}$$

Where T_{bf} and T_{bp} are the bulk temperature on the feed and permeate sides (K). On the other hand, polarization coefficient of TPC temperature [3], [13] is defined as follows:

$$TPC = \frac{T_{mf} - T_{mp}}{T_{bf} - T_{bp}} \tag{13}$$

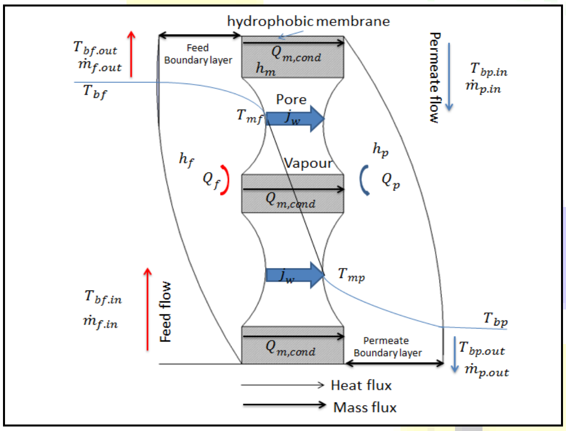


Fig. 2 Heat and mass transfer through a DCMD membrane.

III. SYSTEM SIMULATION USING TRNSYS

A. *TRNSYS model*

Transient Systems Simulation (TRNSYS) is a transient system simulation software that uses a modular structure. It is one of the most used in the execution of thermal or electrical energy simulations. TRNSYS is very useful for modelling systems using renewable energy sources such as solar, wind or geothermal energy (University of Wisconsin, 2000). [trnsys]

Once all the components of the system have been identified and a mathematical description of each component is available, the main components of this model are described and then schematically shown in Fig. 3

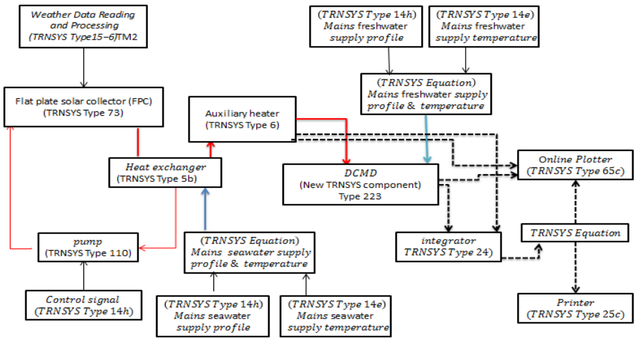


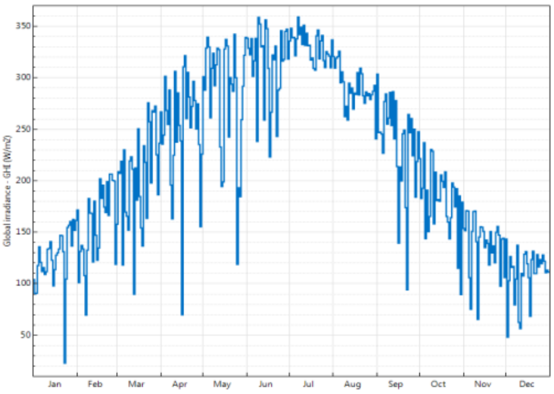
Fig. 3 TRNSYS17 diagram relative to the SSH-DCMD systems.

IV. SIMULATION RESULTS AND DISCUSSION

A. *Solar irradiations*

In order to run a simulation for one year and to predict the performance of the SSH system, a typical Meteorological Year of Ain Témouchent (TMY) is used at GMT1 time zone, latitude 35.306 ^{0}N and longitude -1.147^{0}E were used. Figure 4. (a) Shows the solar radiation, (b) wind speed and dry bulb temperature. The peak Total horizontal radiation is approximately 360 W.m^{-2} and occurs in the period from June to Jul. This period is characterized by high ambient temperature with the peak 37 °C and maximum wind speed is 15 m/s.

(a)



(b)

Fig. 4 (a) Total horizontal radiation, (b) ambient temperature and wind speed over one year.

B. Validation of the model with different membrane lengths

In order to validate our simulation based on the new TRNSYS component (DCMD unit); we studied the system designed by Jianhua Zhang et al. [15] .from co-current configurations for a speed of 0.4 m/s. The cold inlet temperature was kept constant at 20 °C and the hot inlet temperature at 60 °C, the Perspex module with membranes different lengths were used. Fig. 5 shows the comparison between the given experimental data set and the proposed model data. It can be noticed that the permeate flux predicted by the present model is in a good agreement with the experimental data.

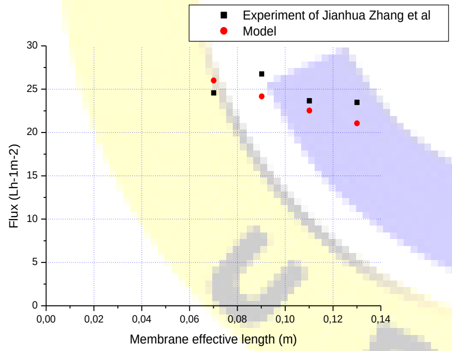


Fig. 5 Comparison between Jianhua Zhang et al experimental data and the model data.

C. Thermal performance evaluation

In the feed circulation velocity effect (Fig. 6.a) The flux diminishes marginally and in a straight way on the flow direction however the permeation flux increased with increasing circulating velocity of the feed fluid from 0.20 m/s to 0.40 m/s, fixed feed inlet temperatures of 60˚C and it appears to achieve the most extreme esteems asymptotically 32.5 L/h.m^2 for high velocity 0.40m/s. Indeed, the increase of the speed causes a superior disturbance of the supply which along these lines increases the mass transfer coefficients on the feed side. However, the flow velocity must be varied with cautiously in order to avoid membrane pore wetting and, at the same time, to assure working under turbulent flow regime in order to obtain high productivity.

The feed inlet temperature influence (Fig. 6.b) the DCMD permeates flux increases with increasing the feed temperature due to dependence of partial vapor pressure at the membrane surface on the feed temperature (Antoine equation). With an increase in the inlet feed temperature from 40 °C to 80 °C for PTFE membrane module, the modeling predictions permeate flux increases in the range of 10 L/h.m^2 to 80 L/h.m^2. The fluxes display higher esteems when operated at higher feed inlet temperature.

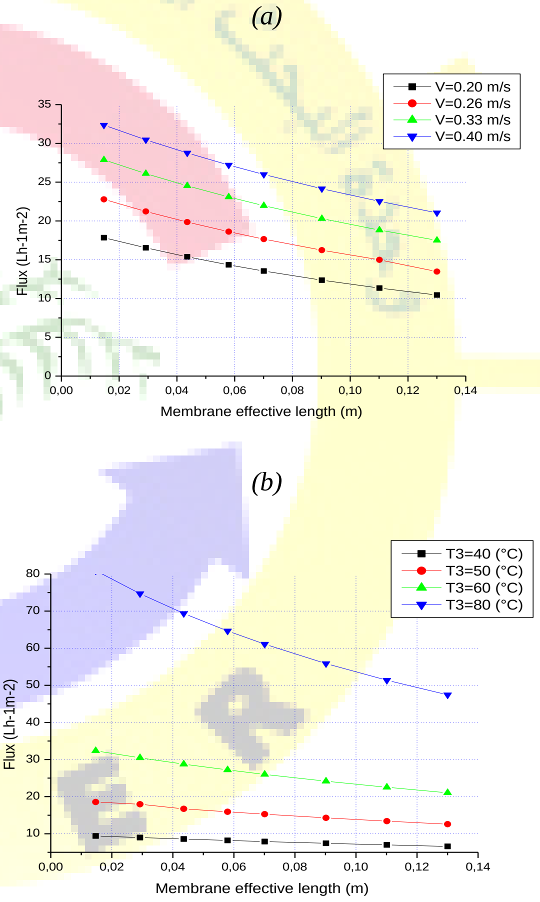


Fig. 6 (a) Effect of the feed fluid velocity on the permeate flux (Tc0=20°C, L=0.136m, Th0=60c), (b) Effect of the feed inlet temperature on the permeate flux (Tc0=20°C, L=0.136m, V=0.4m/s).

V. CONCLUSIONS

In this study, a new type of solar-energy-integrated DCMD system for seawater desalination was tested under actual environmental conditions in Ain Témouchent, Algeria. In the parametric studies, several parameters were investigated such as the feed water mass flow rate and the hot feed temperature. Finally, the system was simulated using TRNSYS program. The considered system is basically composed of: a flat plat collector, auxiliary heater, heat exchanger, pump and DCMD module. The main conclusions can be summarized as:

- ✓ The increase of inlet feed temperature from 40 °C to 80 °C for PTFE membrane module; the modelling predictions permeate flux increases in the range of 10 L/h.m^2 to 80 L/h.m^2.
- ✓ The permeation flux increased with increasing circulating velocity of the feed fluid from 0.20 m/s to 0.40 m/s, fixed feed inlet temperatures of 60˚C and it appears to achieve the most extreme esteems asymptotically 32.5 L/h.m^2 for high velocity 0.40m/s.
- ✓ The highest ambient temperature was 30 C; the maximum value of the average solar intensity was 834.7 W/m^2. The system was able to generated 2783,25 kJ.hr^{-1} of heat.

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