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Study of a Developed Model Describing a Vacuum Membrane Distillation Unit Coupled to Solar Energy

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***Abstract*—**Desalination using solar energy coupled with membrane techniques such as vacuum membrane distillation (VMD) is considered as an interesting alternative for the production of pure water. During this work, a developed model of a polytetrafluoroethylene (PTFE) hollow fiber membrane module of a VMD unit of seawater was carried out. This simulation leads to establishing a comparison between the effects of two different equations of the vaporization latent heat on the membrane surface temperature and on the unit productivity. Besides, in order to study the effect of putting membrane modules in series on the outlet fluid temperature and on the productivity of the process, a simulation was executed.

***Keywords*—**Vacuum membrane distillation, membrane module, membrane temperature, productivity.

I. INTRODUCTION

WATER scarcity in the world requires that many solutions must be taken to solve this problem. Membrane distillation (MD) is a promotive technology to act on this problem. MD is a thermal process which is based on the vapor/liquid separation in the interface of a selective membrane and which requires the heating of the supply feed solution [1]. The advantage of this thermal process is the ability to collect it with another energy source as solar energy or geothermal energy [2]. Wherefore, several MD units coupled to solar energy are planted in several countries [3], [4]. However, the MD has different configurations which are: direct contact membrane distillation (DCMD), VMD, air gap membrane distillation (AGMD), sweeping gas membrane distillation (SGMD) [5]. Each one of those configurations is characterized by its different method for condensing on the permeate side. Among these most used MD configurations, VMD allows obtaining a partial pressure gradient across the membrane upper than that achieved with other configurations [6] which allow obtaining upper distillate water. VMD coupled with solar energy is a hybrid technology for desalinating the seawater and brackish water for the production of great purity water. This process is based on a vapor pressure gradient created by the heating feed water and the vacuum inside the membrane [7]. Also, the favor of this process is its ability to operate at a temperature easily reached which is in the range of 60-90°C [8].

Industrial membranes are made according to different typical geometries, and the frequently used in the MD process are the plate and frame, tubular, spiral wound and hollow fiber membrane modules [9].

The MD used a selective membrane to ensure vapor penetration only into the pores. For VMD, the membrane must be hydrophobic and microporous. For this reason, several materials are used for the manufacture of those selective membranes. Nowadays, the most used hydrophobic membrane materials are PTFE, polyvinylidenefluoride (PVDF) and polypropylene (PP) [10].

In this work, a mathematical model of hollow fiber membrane module was developed. The membrane module is a part of a VMD unit coupled to a solar collector. The MATLAB software was used to achieve a numerical simulation program which allows studying different critical parameters as the surface membrane temperature Tm, the feed out temperature Tfout and the productivity of the hollow fiber membrane module.

II. DEVELOPED MODEL

A. Unit Description

Fig. 1 presents the schematic diagram of the VMD unit connected to solar energy. The objective of this unit is to heat the seawater entering the membrane module by a flat solar collector by means of a plate heat exchanger. After the passage of the vapor through the pores of the hydrophobic membrane, a base pressure force or depression is exerted on the permeate side. The obtained permeate is condensed outside the membrane module.

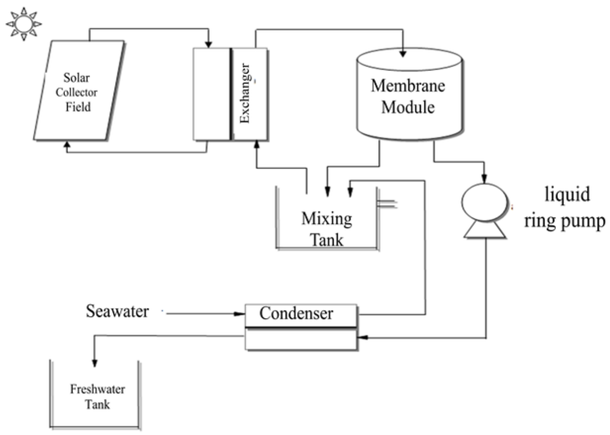

Fig. 1 VMD unit collected to solar energy

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B. Modeling

Based on several thermal equations, a mathematical model of the membrane module connected to a solar collector was carried out. However, several equations describing the total heat and mass transfer mechanism of VMD, taking into consideration the polarization of temperature, was represented as follows:

C. Mass Transfer of Membrane Module

The mass transfer for the VMD process and the vapor transfer through the hydrophobic membrane pores are controlled by the Knudsen number Kn which is defined as [11]:

$$K_n = \frac{\lambda}{d_p} \tag{1}$$

where dp is the pore size of the membrane and λ is the mean free path of the transported molecules (m) which is calculated by [12]:

$$\lambda = \frac{k_B T_f}{\sqrt{2}\pi \bar{P} \sigma^2} \tag{2}$$

where KB and σ are the Stefan-Boltzmann constant (W/m².K4) and the collision diameter of the water vapor (Å), respectively, and $\bar{P}$ is the pores mean pressure of the membrane (Pa).

According to the calculation of the Knudsen number Kn, the transfer of the water vapor across the membrane pores is governed by the Knudsen diffusion, the viscous flow or the combine of the both of them as explained in the following:

The Knudsen diffusion is dominated for Kn >10 and the diffusion coefficient (s/m) is calculated by [13]:

$$K_{Knudsen} = \frac{8}{3}\frac{r\varepsilon}{\tau\delta}\sqrt{\frac{1}{2\pi RMT_m}} \tag{3}$$

The viscous flow is dominated for Kn < 0.01 and the diffusion coefficient (s/m) is calculated by [13]:

$$K_{viscous} = \frac{1}{8\eta}\frac{r^2\varepsilon}{\tau\delta}\frac{\bar{P}}{RT_m} \tag{4}$$

The combination of viscous flow and Knudsen diffusion dominates if 0.01<Kn <10 and in this case the diffusion coefficient (s/m) is calculated by [13]:

$$K_m = K_{Knudsen} + K_{viscous} \tag{5}$$

r is the pore radius (m), ε is the porosity (%), δ is the thickness (m) and τ is the tortuosity (%), respectively. More, Mw is the molar mass of water (Kg/Kmol), R is the gas constant (J/Kmol.K) and T is the absolute temperature (K). Therefore, the mass flux of water (kg/m².h) for the VMD process is defined by [14]:

$$J = K_m (P_m - P_v) \tag{6}$$

where Pm refers to the saturated vapor pressure (Pa) at the membrane surface and Pv refers to downstream pressure on the permeate side (Pa).

D. Heat Transfer of Membrane Module

To quantify the heat transfer in the hollow fiber VMD process, the heat transfer stream of the feed between the bulk and the boundary layer [15] can be defined by:

$$Q_f = h.(T_f - T_m) \tag{7}$$

where Tf, Tm and h are the temperature of the bulk at feed side (°C), the temperature at the membrane surface (°C) and the heat transfer coefficient in the feed side (W/m².K), respectively. The heat conduction through the membrane can be neglected because the temperatures on the two sides of the membrane are the same.

The heat transfer by the movement of vapor across the membrane (Qm) [15] can be given by:

$$Q_m = J.\Delta H\nu \tag{8}$$

where J is the mass flux of water (kg/m².h) and $\Delta H\nu$ is the latent heat of vaporization (J/Kg) which is described in the literature by [10]:

$$\Delta H\nu = 1.7535\ T + 2024.3 \tag{9}$$

Montégut presented another method for the calculation of vaporization latent heat [16] as:

$$\Delta H\nu = 2501.6 - 2.363.T \tag{10}$$

The heat flow exchanger area is calculated from the heat balance of inlet and outlet temperatures of the module as [17]:

$$Q_{rec} = \dot{F}.Cp.(T_f - T_{fout}) \tag{11}$$

where $\dot{F}$ is flow rate (Kg/s), Cp is the calorific capacity (J/Kg.°C) and Tfin, Tfout are the inlet and outlet temperatures (°C) of the membrane module respectively.

At a steady state, for the VMD process, the global heat transfer flux across the membrane Q is given by [15]:

$$Q = Q_f = Q_m = Q_{rec} \tag{12}$$

Depending on the driving force applied on the both of the membrane systems, the polarization phenomenon could be also a temperature polarization [14]. The temperature polarization coefficient for the VMD process can be calculated by the ratio of the varied temperature across the membrane

[18]:

$$TPC = \frac{T_m}{T_f} \quad (13)$$

where Tm and Tf are the temperature of the membrane interface and the temperature of the feed bulk, respectively.

III. Studied Results

After modeling the VMD process that takes into account the temperature polarization, a system of different equations was established. It was solved with the Matlab software as a function of inlet temperature and considering water as feed. During each resolution of the equations, certain parameters have been modified. The main objective of these simulation studies was to study, firstly, the effect of the latent heat of vaporization on the fluid temperature at the membrane surface, the fluid temperature at the membrane module outlet and the productivity profile of permeate and secondly the effect of putting membrane modules in series on the productivity of the process.

The hollow fiber membrane module (PTFE) considered was equipped with 806 fibers, with 4 m² of the area and 1.129 m module length. The membrane properties used in the model were: pore size 0.1495 µm and porosity 47%.

A. Effect of the Latent Heat of Vaporization

The membrane module was divided into two parts in such a way that the outlet of the first part is the inlet of the second part; that means as if there are two membrane modules in series. In each run, the surface membrane temperature Tm and the productivity of the hollow fiber membrane module Qp are calculated. A comparison between the effect of the two equations of the latent heat of vaporization ΔHv mentioned above (9), (10) is carried out.

The seawater temperature, which is the feed supply to the membrane module and which is coming from the plate heat exchanger, was taken at Tf = 72 °C, and the feed inlet velocity was kept at V = 1 m/s. The overall curve of the feed temperature follows the same sinusoidal rate of the solar flux as shown in Fig. 2.

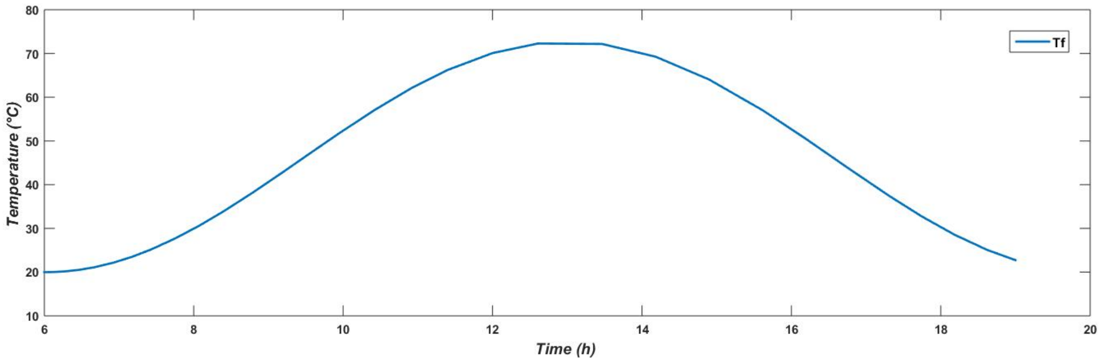

Fig. 2 Curve of feed temperature T_f (°C)

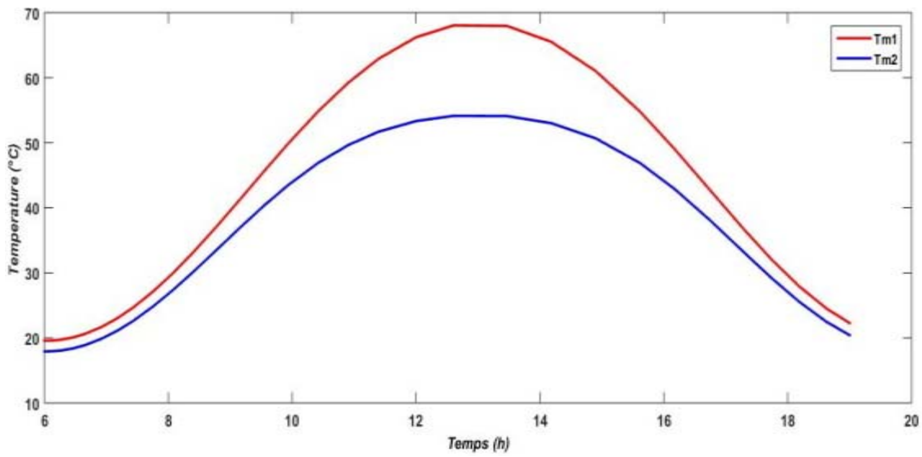

Fig. 3 Membrane surface temperature T_{m1} and T_{m2} (°C) for (9)

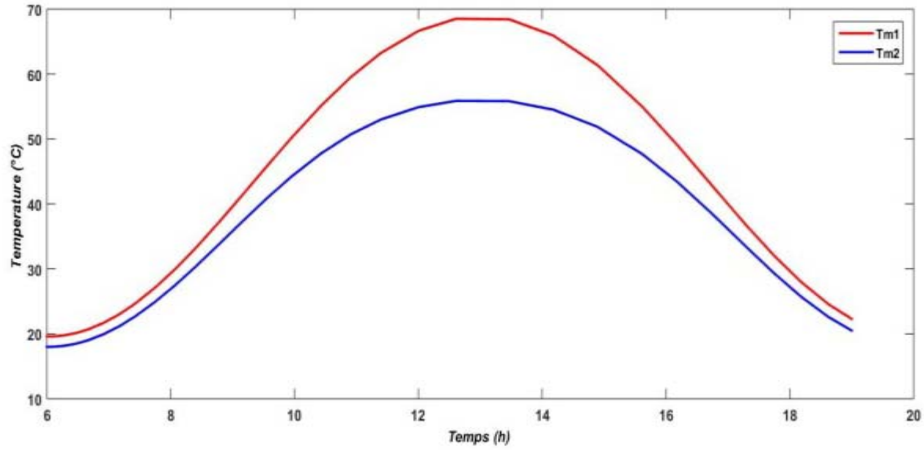

Fig. 4 Membrane surface temperature Tm1 and Tm2 (°C) for (10)

The temperatures of the membrane surface of both parts of the membrane module Tm1 and Tm2 are lower than the feed temperature Tf. It can be seen in Fig. 4 that both Tm1 and Tm2 are higher than those of Fig. 3 and the highest difference is obtained for Tm2. Therefore, it indicates the importance of choosing the appropriate expression for the latent heat of vaporization $\Delta H\nu$ calculation. If we compare the two expressions used for calculating $\Delta H\nu$, we can notice a different trend with the temperature: it increases with temperature with (9), while decreases with temperature with (10). The last trend is what expected and, therefore, even if both equations can be found in the literature, (10) should be preferred.

The productivity Qt of the entire membrane module, which is the sum of the productivities of each part of the module, is influenced by the temperatures of the membrane surface. Thus, it can be seen in Fig. 6 that the productivity of module calculated with (10) (36.8126 Kg/h) is higher than the productivity of module calculated with (9) (35.3749 Kg/h) as shown in Fig. 5.

B. Effect of Putting Modules in Series

In order to use the hot stream exiting from the module to produce more permeate, the model was run by considering an extra membrane module in series with the original one calculated above, as two membranes in series, so that there are three membrane modules in series with the same length. Equation (10) was used to calculate the latent heat of vaporization in this simulation. The feed temperature is taken as in Fig. 2.

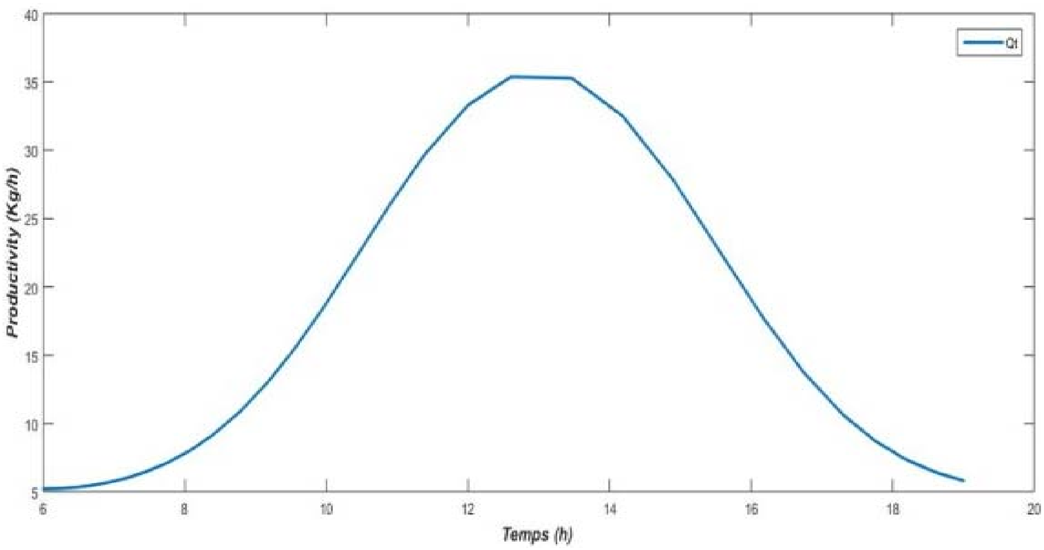

Fig. 5 Productivity Qt (kg/h) of the entire membrane module for (9)

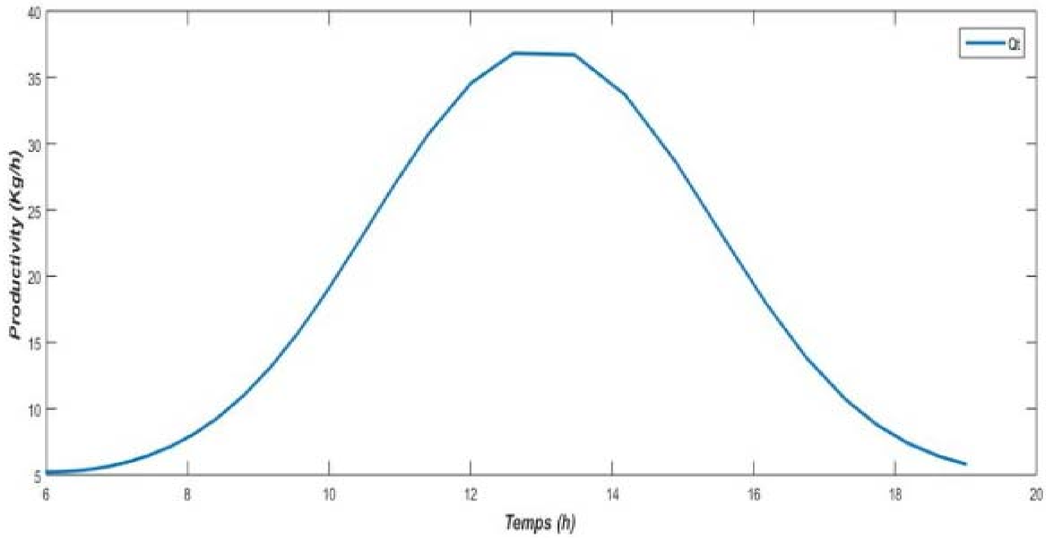

Fig. 6 Productivity Qt (kg/h) of the entire membrane module for (10)

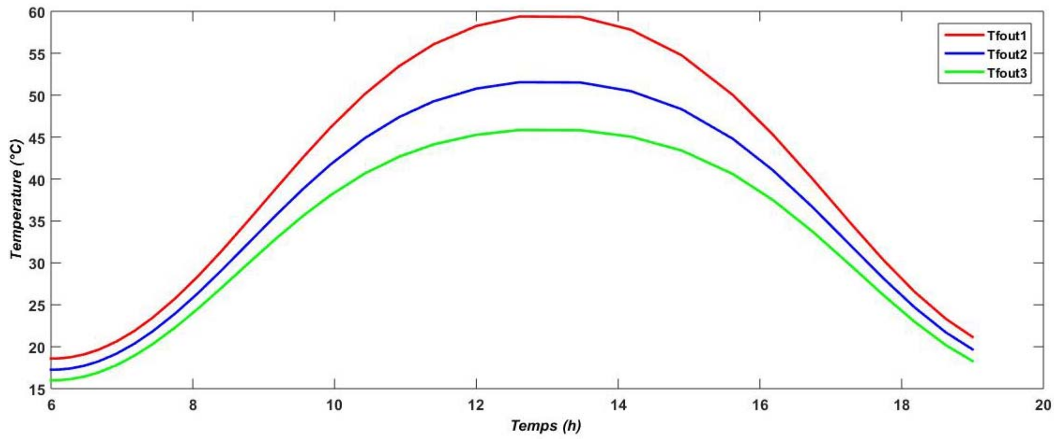

Fig. 7 The outlet temperature Tfout (°C) of the three modules in series

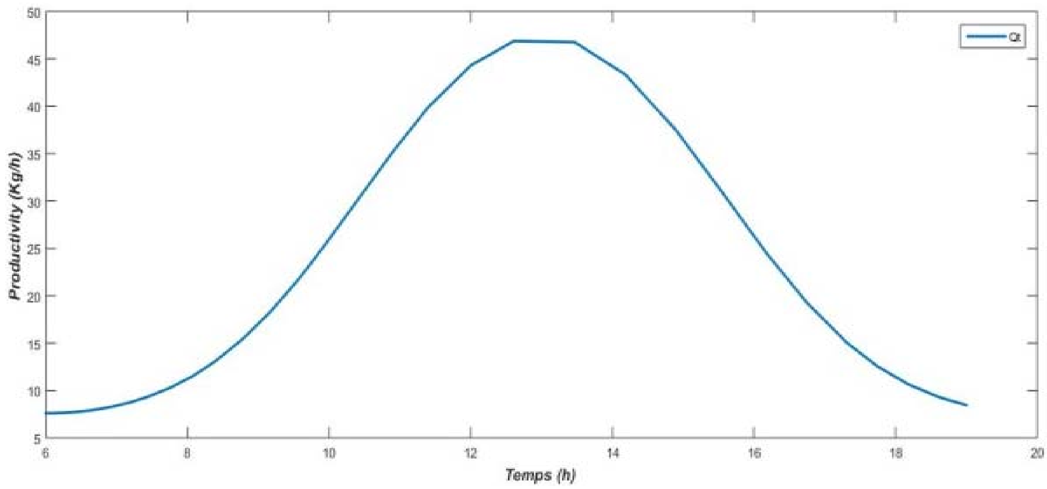

Fig. 8 Productivity Qt (kg/h) of the three modules in series

The outlet temperature Tfout1 represents the feed temperature for the second part of the module and Tfout2 represents the feed temperature for the third part. It can be seen in Fig. 7 that the last outlet temperature Tfout3 is still high, allowing to add another module in series, to further increase the permeate production.

The productivity Qt of the three modules in series is the sum of the productivity of each module. It can be seen in Fig. 8 that the addition of a third module improved the overall permeate production from 36.8126 Kg/h to 46.8778 Kg/h.

IV. Conclusion

In this work, a study of a simulation of a developed model describing the operation of a VMD unit coupled to solar energy was carried out. A comparison between two equations of the latent heat of vaporization was done. Thus, an addition of another module in series proves the improvement of the productivity of the unit.

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