4ème Conférence Internationale des Energies Renouvelables (CIER-2016)
Proceedings of Engineering and Technology – PET
Vol.18, pp.67 - 72

Simulation of the operation of a VMD module coupled with a liquid ring pump

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Abstract— **In this work, a VMD plant coupled with solar energy using a liquid ring pump was studied. The operation of hollow fiber module and the liquid ring vacuum pump was simulated by programs developed in the MATLAB codes. These programs are based on mass and heat transfer within the hollow fiber module and the liquid ring vacuum pump. The global model developed allowed us to perform a parametric study that quantifies the influence of different parameters. This study was useful in selecting appropriate operating conditions. Among the studied parameters, we include the influence of vacuum pressure applied, the inlet feed flow rate, the inlet feed temperature and the auxiliary fluid flow rate.**

Keywords— **Membrane distillation, liquid ring pump, heat and mass transfer, parametric study, seawater.**

I. INTRODUCTION

In recent years, the lack of fresh water is considered as a serious problem that is constantly increasing, due to the population growth and changes in weather conditions [1]. Among the solutions presented to tackle such problem, the process of desalination has been in operation over 50 years among different technologies. Membrane distillation (MD) is a new technology that combines distillation and membrane separation. In comparison with other desalination methods, MD has several advantages. MD is characterized by a lower operating temperature than the typical distillation and lower operating hydrostatic pressures than the pressure-driving process. In addition, a high rejection factor is achieved when solution containing no-volatile components. Besides, the system efficiency and high product water quality are almost independent from the salinity of the feed water. Furthermore, the operating temperature of the MD process is in the range of 60-80°C, at which the thermal solar collectors perform well [2]. In membrane distillation a porous hydrophobic membrane, which serves as both a thermal insulator and a physical barrier, permits the free transport of water vapor through the membrane pores but prevents the liquid phase from passing through the membrane [3]. The driving force in MD is the vapor pressure difference across the membrane and may be applied by a variety of methods, giving rise to various MD configurations, namely direct contact MD (DCMD), air gap MD (AGMD),sweeping gas MD (SGMD) and vacuum MD (VMD) [4].

In this work, we are interested in VMD technology. Vacuum membrane distillation (VMD) is believed to be attractive and cost-competitive membrane separation technology. The vacuum pressure is applied to the permeate side of the membrane. Compared with the other MD configurations, VMD permits higher partial pressure gradients, and hence higher permeate flux can be achieved. In addition, it is better than DCMD in terms of energy consumption /permeate flow ratios, and thermal evaporation efficiency. In VMD, the choice of condensation and vacuum creation systems is an important issue. The conventional solution is to couple a condenser or a heat pump with a vacuum pump. But, the most modern solution is the vacuum liquid ring pump. This liquid ring pump has a dual functionality: condensation and vacuum creation.

In this work, the various equations describing heat and mass transfer within the hollow fiber module and the vacuum liquid ring pump "LRP" allow to develop a model describing the system operation. Also simulations of the operation of the hollow fiber module and liquid ring vacuum pump were done to study the effect of several parameters on the amount of distillate produced.

II. DESIGN OF THE PLANT

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Fig.1 gives a schematic presentation of the principle of vacuum membrane distillation unit using liquid ring pump. The main components of desalination plant are:

- ✓ A membrane module (UMP 3247 R) with 806 fibers (PVDF) with an internal diameter of 1.4mm. This module has a length of 1.129m and offers a total area of 4m2.
- ✓ Field of solar collector (seven rows and five collectors in series, total area: 70m2).
- ✓ Field of solar photovoltaic modules (16 modules, peak power: 2.1 kW).
- ✓ Plate heat exchanger with 27 titanium plates and offering an exchange area of 1.08m2 (maximal power of heat exchange: 26 kW).
- ✓ Liquid ring pump (ElmoRietschle L-BV2) ensuring the condensation and the vacuum on the permeate side of the membrane (Flow up to 0.20 l/h , power: 1.5 kW).
- ✓ Flow pump ensuring the supply of seawater (Flow up to 2,500 l/h, power: 1 kW).
- ✓ Circulator pump circulates the coolant in the collector field (power: 0.5 kW).

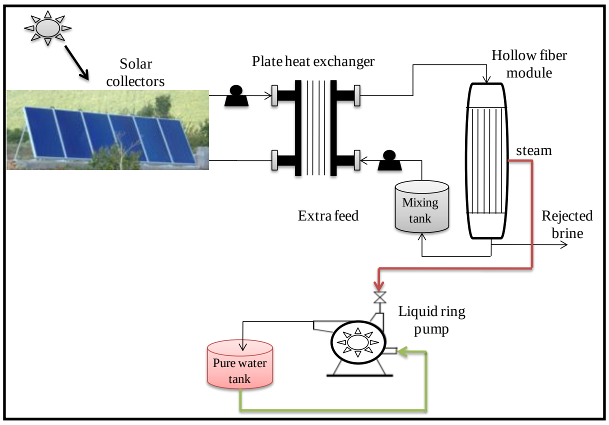

Fig. 1 VMD plant using liquid ring pump

In the proposed flow sheet (Fig. 1), the coolant fluid out of the field of solar collectors is routed to the heat exchanger to provide heat to the seawater at the inlet of membrane module. The heat transferred inside the module is coupled with a mass transfer through the membrane, which is due to the difference in pressure on both sides of the membrane. The vapor is withdrawn by applying a vacuum on the permeate side. The diffusion of the vapor through the membrane pores is made according to a Knudsen mechanism [2]. Permeate condensation takes place outside the module in the liquid ring pump. Liquid ring vacuum pumps operate with only one moving part, the impeller shaft assembly. The impeller is mounted eccentrically relative to its casing. The liquid ring is formed by the service liquid (normally water) rotating concentrically in its casing. Process gas enters through the suction port. It then travels between the impeller blades and is compressed prior to exhausting through the discharge port, along with a quantity of service liquid. By contacting the liquid ring, the steam will be condensed.

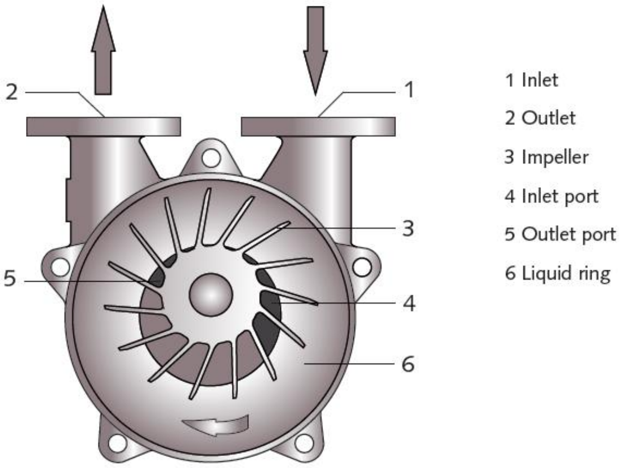

Fig. 2 Inside the liquid ring vacuum pump

III. MODELIZATION

A. *Modeling of hollow fiber membrane*

To establish a model that determinates the temperature of the retentate and the vapor produced and the flow of permeate and retentate, we propose to perform a heat and matter balance on an elementary volume dV. For a given fiber, when the feed liquid flows through the elementary volume dV, a quantity of water evaporates and thus the flow of water to be treated decreases and the water temperature varies. So, there is a simultaneous transfer of mass and heat. The module configuration studied is internal–external: the feed fluid flows inside the fibers. Depression is applied to the outside of the fibers and the permeate flow is directed from inside the fibers out [2] [5].

For the calculation of energy balance, the following assumptions were taken into account:

- The radial propagation of heat is negligible and, therefore, all fibers will be at the same temperature for the same side z.

- The transfer of water molecules in the gas phase through the pores of the membrane by the Knudsen diffusion mechanism.
- The coefficient of permeability of the membrane km (Knudsen permeability) is a function of temperature at the interface of the membrane (Ti) and can be expressed as follows:

$$k_m = \alpha T_i^{-0.5}$$

- The saturated vapor pressure Ps can be expressed using the equation of Antoine. Ps is in Pa and the temperature Tz is in Kelvin.

$$P_s = B_1 \exp\left(A_1 - \frac{A_2}{T_z - A_3}\right)$$

With A1 = 18.036, A2= 3816.44, $A_3 = 46.13$, $B_1 = 133.32$

The flux density of water vapor through the internal interface membrane-water (kg/s/m²) is described by the following equation:

$$J_v = k_m \left[P_s - P_{vide}\right]$$

The balance under transient conditions applied to a fiber in a volume element dV can be written as follows:

By performing a mass balance, the distillate flow rate produced between z and z + dz is:

$$\dot{m}_z\, cp_l \left(T_z - T_{ref}\right) = \dot{m}_{z+dz}\, cp_l \left(T_{z+dz} - T_{ref}\right) + \left(\dot{m}_z - \dot{m}_{z+dz}\right) L_v + \rho_l dV\, cp_l \frac{d(T - T_{ref})}{dt}$$

$$\frac{d\dot{m}_z}{dz} = -\frac{d\dot{m}_d}{dz} = n_{fib}\pi d_{fib} J_v = n_{fib}\pi d_{fib} k_{m0}\left[\exp\left(A_1 - \frac{A_2}{T_z - A_3}\right) - P_{vide}\right]$$

With nfib is the number of fibers, dfib is the diameter of a fiber, dz is the element of length, and dS is the elementary surface of the membrane relative to the volume dV. By combining the two balance equations, the final equation describing the evolution of the temperature of the retentate over time and space is obtained:

$$\frac{dT}{dt} = \frac{-4\dot{m}_z}{(\rho_l n_{fib}\pi d_{fib}^2)}\frac{dT}{dz} - \frac{4k_{m0}T_z^{-0.5}}{\rho_l d_{fib} cp_l}\left[\exp\left(A_1 - \frac{A_2}{T_z - A_3}\right) - P_{vide}\right]\left(-T\, cp_l + cp_l T_{ref} + L_v\right)$$

Solving the differential equation will determine the amount of distillate produced and the temperature of the liquid to each element of fiber length and thus the temperature at the exit of the membrane module.

$$\dot{m}_d = \int_0^L n_{fib}\pi d_{fib} k_{m0} T_z^{-0.5}\left[\exp\left(A_1 - \frac{A_2}{T_z - A_3}\right) - P_{vide}\right] dz$$

B. *Modeling of liquid ring pump*

The balance describing heat and mass transfer within the liquid ring pump is:

$$\dot{m}_V c_{pv}(T_V - T_{ref}) + \dot{m}_f c_{pf}(T_f - T_{ref}) + \dot{m}_v L_v = (\dot{m}_V + \dot{m}_f)\, c_{ps}(T_s - T_{ref})$$

Consequently the outlet temperature of the liquid mixture (pure water produced + liquid ring):

$$T_s = \frac{\dot{m}_v c_{pv}(T_v - T_{ref}) + \dot{m}_f c_{pf}(T_f - T_{ref}) + \dot{m}_v L_v}{(\dot{m}_v + \dot{m}_f) c_{ps}} + T_{ref}$$

IV. SIMULATION, PARAMETRIC STUDY AND DISCUSSION

The global model developed allowed us to perform a parametric study that quantifies the influence of different parameters. This study was useful in selecting appropriate operating conditions. Among the studied parameters, we include the influence of level of vacuum applied, the inlet flow rate, the temperature of inlet flow and the auxiliary fluid flow.

A. *Effect of vacuum pressure applied on the distillate flow rate:*

The vacuum pressure is the most influential parameter on the operation of the membrane desalination plant coupled to solar energy. The curves representing the variation of flow of distillate according to vacuum pressure are plotted. Fig.3 and Fig.4 show the distillate flow rate values for different vacuum pressure along hollow fiber module and for various pressure values (inlet flow=1500kg/h, inlet temperature=50°C, liquid ring flow=150kg/h and salinity=35g/l)

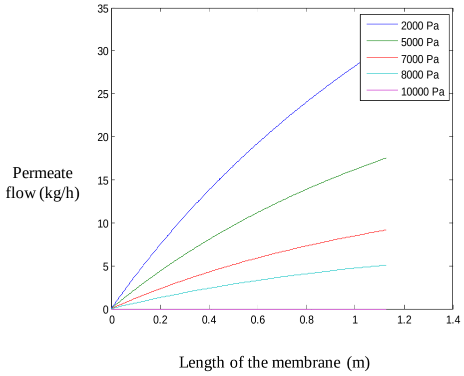

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Fig.3 Effect of vacuum pressure on distillate flow along module

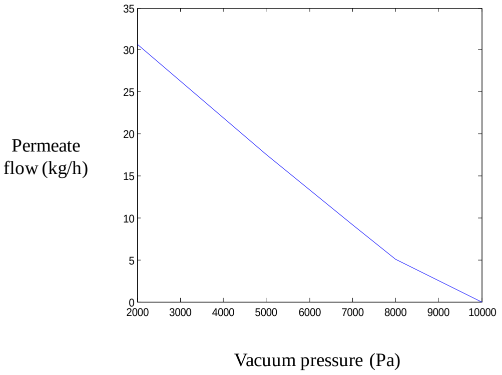

Fig.4. Effect of vacuum pressure on the flow of distillate

From both figures Fig.3 and Fig.4, the effect of vacuum pressure on distillate flow collected is clear. We note that the distillate flow is more important for low vacuum pressure and less important for large values of vacuum pressure. So the permeate flow rate increases with the increase of the pressure gradient which is the driving force of the transfer. Work with reduced vacuum pressures allows the evaporation of seawater for relatively low temperature. As a result reduced vacuum pressure is necessary to have an important flow of distillate.

B. *Effect of inlet flow of the distillate flow rate*

The rate of inlet flow does not lack importance on the operation of the desalination plant coupled with solar energy. For this we have plotted the evolution of distillate flow rate according to the input rate. The following figures Fig.5 and Fig.6 show the variations of the distillate flow along hollow fiber module and the variations of the distillate flow rate according to the inlet flow of the module (inlet temperature=50°C, liquid ring flow=150kg/h, salinity=35g/l and vacuum pressure =7000Pa)

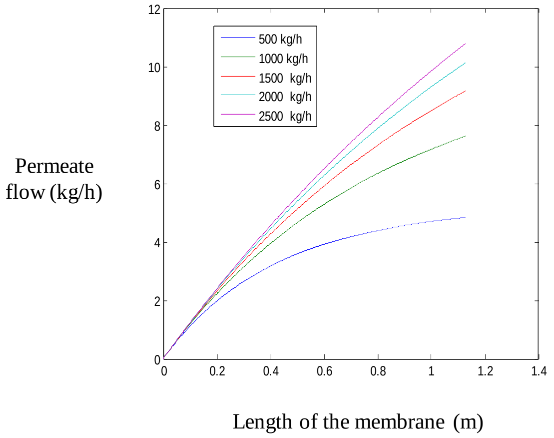

Fig.5 Effect of inlet flow on distillate flow along module

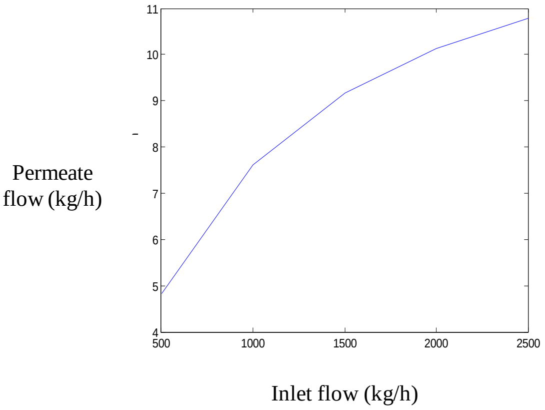

Fig.6. Effect of inlet flow on the flow of distillate

Fig.5 and Fig.6 show that the flow of distillate increases as the flow at the inlet of the hollow fiber module increase. But this variation is low for high flow rates. Based on the shapes of the previous curves, we note that it is preferable to increase the flow to the module entry to get more production.

C. *Effect of intet temperature on the flow of distillate*

The following figure Fig.7 shows the variation of the flow of distillate, depending on inlet temperature (inlet flow =1500 kg/h, liquid ring flow=150kg/h, salinity=35g/l and vacuum pressure =7000Pa).

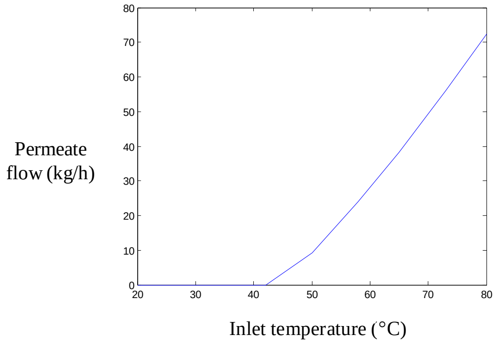

Fig.7. Effect of inlet temperature on the flow of distillate

From Fig.7, it is noted that for inlet temperature lower than 42°C the flow of distillate is zero kg/h, then at input temperature values above 42°C the flow of distillate increase. It can be concluded that more the inlet temperature is high more the distillate flow is important.

D. *Effect of the auxiliary fluid flow on permeate temperature at the output of the PAL*

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Fig.7 shows the impact of auxiliary fluid flow on outlet temperature of liquid ring vacuum pump (inlet temperature=50°C, inlet flow=1500kg/h, salinity=35g/l and vacuum pressure =7000Pa).

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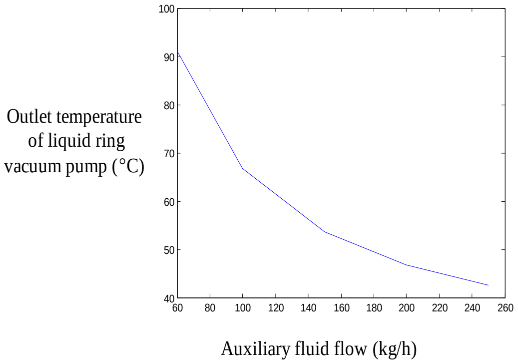

Fig.8. Effect of auxiliary fluid flow on the outlet temperature of liquid ring pump

It is noted that, when the auxiliary fluid flow increases, the temperature of distillate (the outlet temperature of liquid ring pump) decreases, because the auxiliary fluid is a cooling fluid. For auxiliary fluid flow rates between 60kg/h and 150kg/h there is a significant decrease in distillate temperature indeed going from 90°C up to almost 51°C. Beyond 150kg/h it is noted that the decrease in temperature becomes lower. In the case of the liquid ring vacuum pump selected (L-type BV2 2BV2 060-8NH02-80) and which works with an auxiliary fluid flow 200kg/h, the output temperature will be close to 47°C.

V. CONCLUSION

In this work, we have simulated the operation of hollow fibres module and the liquid ring vacuum pump by programs developed in the MATLAB codes. These programs are based on mathematical models developed in the third part. Then the effects of parameters characterizing the performance of the components of the installation (vacuum pressure applied, inlet feed flow rate, inlet feed flow temperature and auxiliary fluid flow) were studied.

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