

Performance of a Solar Vacuum Membrane Distillation Pilot Plant, for Seawater Desalination in Mahares, Tunisia

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Abstract: The main objective is to improve the overall performance of membrane-based water desalination processes by applying innovative technologies to reduce energy consumption by using renewable energy and save energy of condensation. We design and develop an autonomous solar desalination system (PV – thermal collector). The pilot plant was installed in the village of orphaned children (S.O.S MAHARES). Experimental tests were carried to determine the permeate water production.

Key words: Solar energy • Desalination • Vacuum membrane distillation • Pilot plant • Performance

INTRODUCTION

Tunisia is located on the southern rim of the Mediterranean basin; it is confronted by a problem of fresh water shortage. In fact, it has very limited water resources and has a high degree of salinity, aggravated by a large spatial and temporal disparity between southern and northern parts and fluctuations from year to another.

The desalination of brackish water or the seawater by the solar energy coupled with the membrane technique is regarded as an alternative very interesting and effective for the production of drinking water in particular in the rural and arid areas being given the availability of this source of inexhaustible and free energy in the majority of the regions.

The possibility of designing innovative processes based on the coupling of this technology with the solar energy is becoming an attractive way to reduce the production costs and for increasing the performance of the processes.

Despite the advantages of solar membrane distillation (MD) systems, very few experimental systems have been developed

compared with the reverse osmosis and solar distillation [1-14].

This paper deals with the MEDINA (MEMbrane-based Desalination: an INtegrated Approach) project supported by the European Commission.

Principle of a Solar Membrane Desalination Technique: Vacuum membrane distillation (VMD) for seawater desalination is based on the evaporation of seawater through hydrophobic porous membranes improved by applying a vacuum or a low pressure on the permeate side. Permeate condensation takes place outside the module inside a condenser.

Design of the Pilot Plant: The design and the optimization of a vacuum membrane distillation process require the implementation of a step associating a structured analysis, the phenomena comprehension and the identification of the relevant parameters, the physical phenomena modelling, the capitalization and the integration of knowledge then the results validation. The complexity of this system comes from that the various technological components strongly interact between them. In particular, the operation is particularly sensitive to the variations of pressure.

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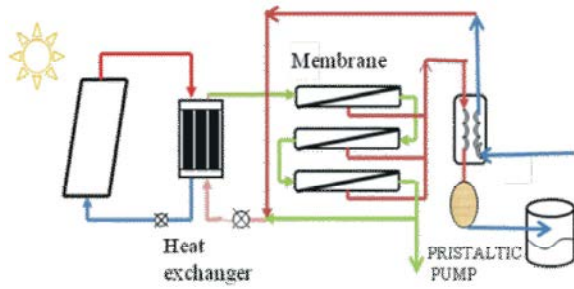


Fig. 1: Flowsheet of VMD

The main components of desalination plant are a:

- Membrane module
- Field of solar collector (7 rows and 5 collectors in series)
- Field of solar photovoltaic cell (16 modules)
- Flow pumps and circulator,
- Peristaltic pump,
- Plate heat exchanger,
- Tank of fresh water production.

Solar Collector Design: The design of the solar collector field will depend on:

- The temperature of exit of retentate that will depend on the membrane characteristics, the crossing through the membrane number,
- The energy recovery system from the distillate,
- The heat exchanger efficiency,
- The season choice : summer, winter.

For the design of a solar-powered desalination system, the question of energy efficiency is very important since the investment costs mainly depend on the area of solar collectors to be installed.

The heat quantity required by the collector is defined by the specific consumption of the process C_{sp} i.e. the number of kWh necessary to produce one m^3 of distillate water.

This consumption is a function:

- Energy needs for water evaporation through the membrane,
- Heat recovery efficiency, the condenser position ...,
- Thermal losses at the various elements of the pilot plant

$$C_{sp} = L_v + losses - \phi_{recovery}$$

L_v is latent heat of vaporization

The heat quantity recovered by vapour condensation $\phi_{recovery}$ represents the fraction of the condensation heat recovered.

It depends on the vapour temperature level and on the membranes modules configuration (a number of compartments per module, a passes number ...).

If we defines F_{eff} as being a factor condensation efficiency we can write:

$$\phi_{recovery} = F_{eff} L_v$$

If we neglect the losses by an effective heat insulation of the various installation elements, the installation specific consumption can be expressed as:

$$C_{sp} = (1 - F_{eff}) \cdot L_v$$

The solar collector area A_{cap} is a function of the energy use for the process ϕ_{utile} , of the collector efficiency η and solar irradiation G .

$$A_{cap} = \frac{\phi_{utile}}{\eta \cdot G} = \frac{P C_{sp}}{\eta \cdot G}$$

The collector choice will be related to its cost which is the sum of the real cost (purchase price) and of exploitation taking account of the maintenance and maintenance costs. Economic study is necessary.

The solar collector is a selective flat plate collector with an efficiency of 0.73 and 51 m^2 area.

Membrane

Characteristics of Membrane Module: The choice of the module of membrane depends on:

- Physical and chemical membrane characteristics (natural of material, ...)
- Hydrodynamic : nature and flow rate,
- Pass number in the module,
- Thermal stress,
- The costs,
- The fouling of the membranes,
- The cleaning frequency,...

The modules are the supports of the membranes, 4 modules types are marketed: tubular modules, hollow fibers modules, plane modules, spirals modules. We have chosen tubular modules.

Module of Membrane Design: The number of membranes is:

$$Nb_{\text{memb}} = \frac{Q_p}{j_v * I * L}$$

I : membrane height, L : membrane length

The number of modules is: $Nb_{\text{mod}} = Nb_{\text{memb}}/2$

The permeate flow of the membrane j_v is expressed by :

$$J_v = k_m \cdot (P_s - P_v)$$

With: $k_m = 4.37 \cdot 10^{-7}$ s/m, the permeability of the membrane and P_v the vacuum pressure.

The saturated vapor pressure P_s is :

$$P_s = \exp \left(23.1964 - \frac{3816.44}{T - 46.13} \right)$$

The chosen membrane module is a hollow fiber microfiltration module, provided by PALL Company.

The membrane system consists of 806 fibers in PVDF with an internal diameter of 1,4 m, the length of the module is 1,129 m and offering a total membrane surface of 4 m².

Design of the Flat Plate Heat Exchanger: The plate heat exchanger is composed of a set of corrugated metal plates. The number of plates is determined by the flow, fluid properties, pressure and temperature. The specific corrugation plates promote fluid turbulence and therefore heat exchange.

The coolant from thermal solar collector enter the heat exchanger at 77°C to heat the seawater from 55°C to 65°C. The coolant lives collectors at 60°C.

The power exchanger calculated in terms of desired temperatures and an average solar radiation of 700 W.m⁻² is about 26 kW. The heat exchanger coefficient is 3036 W.m⁻²K⁻¹. The plates are in titanium. The over sizing is about 13.4%.

Design of the Condenser: Seawater at 25°C ensures the condensation of vapor from the membrane module at 70°C. The temperature output desired is about 39.5°C.

Similarly, the chosen material is titanium. The overall condenser power is 60 kW. The tubes number is 41 of internal diameter equal to 7 mm and thickness 1 mm. The over sizing of the condenser is 30%.

Circulation Pumps: The coolant circulating in the solar system is provided by a circulation pump. The temperature range operation of the pump is -20 to 130 °C.

Peristaltic Pump: This pump is able to carrying the steam produced in the membrane to the condenser and then it ensures the flow of steam condensed to reservoir production. The vacuum level created is between 5000 and 7000 Pa.

Experimental Study: The unit was installed in the village of orphaned children (SOS MAHRES). Power supply of the plant with photovoltaic cells to aggregate power of 1.5 kilowatts, with the possibility of storage electrical energy produced. When the electric charge accumulated in the batteries exceeds the power requirements needed to aliment the pumps, an electrical resistance can heat the contents of the tank. We have realized a system of data acquisition and control unit.

Figure 2 shows the photo of the pilot plant solar VMD

Experiences: The experimental study involves measuring the following parameters:

- The global solar radiation using a pyranometer.
- The coolant and seawater flow using flow-meters.
- The different temperatures at the condenser and heat exchanger using a temperature sensor Pt100.



Fig. 2: Photo of the pilot plant solar VMD

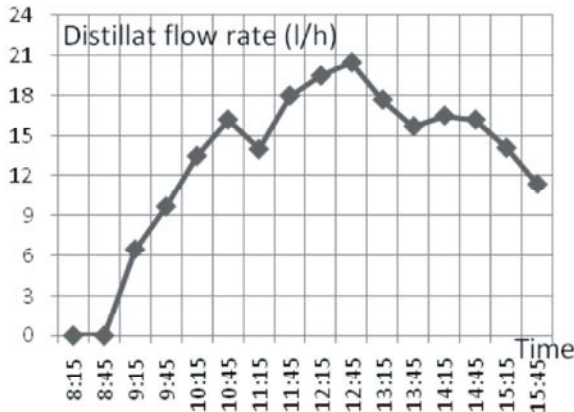


Fig. 3: Permeate water production versus time on a shiny day-March 17 2011-Pressure = 7000 Pa; Feed flow rate = 2130 kg/h, Re <670

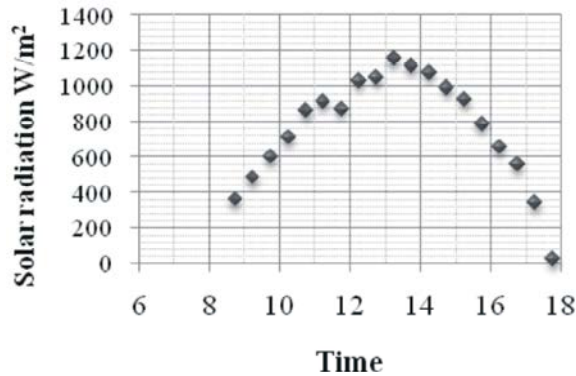


Fig. 4: Variation of solar flux simulated and experimental function of time

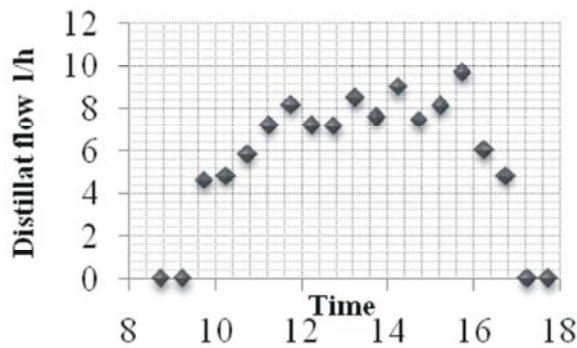


Fig. 5: Permeate water production versus time on a shiny day- 24 February 2011- Pressure = 7000 Pa; Feed flow rate = 785 kg/h, Re <250

Determination of Production of Desalinated Water:
We present the results collected March 17, 2011. This day is characterized by clear skies throughout the day with a maximum ambient temperature of 28.5 °C.

The evolution of the distillate flow versus time is given in Figure 3.

The curve increases gradually at the beginning of the day and reached a maximum between 12 and 13h and then it decreases gradually. This result is due to the incident solar energy is the most parameter affecting the production of a solar desalination unit. The daily production is about 210 kg.

Figures 4 & 5 shows the variations of a solar radiation and distillate flow to a cloudy day. Distillate flows are low compared to estimates. This is mainly due to the commercial membrane chosen is not dedicated for membrane distillation.

The parametric study has focused on the effect:

- Feed rate of the membrane,
- Water temperature supply,
- Coolant flow,
- Coolant temperature,
- Solar radiation

According to tests, it appears that the most sensitive parameter is the feed rate of the membrane. In the current state, an increase in feed rate of the membrane causes a decrease in exchange area. We must search a position of the membrane that allows a high flow rate without losing the exchange area.

CONCLUSION

Design calculations of system were performed with Matlab, taking into consideration mass and heat transfer equations in the membrane module and considering heat power due to the solar collector, along the year. Based on these calculations, pilot plant will be able to provide average permeate flow ranging from 35 l/h to 21 December to 70 l/h to 21 June with a temperature not exceeding 75°C in order to avoid membrane damage. The prospects are essentially looking for the optimal operating conditions to study the technical energy unit. While the current productivity is lower than desired, but several improvements can be conducted (increasing seawater flow rate, thermal insulation of the membrane and the tank ...). The objective is essentially to determine the optimal operating conditions and to carry an energetic study of the pilot plant.

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REFERENCES

1. Lagana, F., G. Barbieri and E. Drioli, 2000. Direct contact membrane distillation: modelling and concentration experiments, *Journal of Membrane Science*, 166: 1-11.
2. Alklaibi, A.M. and N. Lior, 2004. Membrane-distillation desalination: status and potential, *Desalination*, 171: 111-131.
3. Wirth, D. and C. Cabassud, 2002. Water desalination using membrane distillation: comparison between inside/out and outside/in permeation, *Desalination*, 147: 139-145.
4. Chaouchi, B., A. Zrelli and S. Gabsi, 2007. Desalination of brackish water by means of a parabolic solar concentrator, *Desalination*, 217: 118-126.
5. Jemni, H., N. Frikha and S. Gabsi, 2009. Simulation d'une unité de distillation membranaire de l'eau de mer couplée avec l'énergie solaire, *Récents Progrès en Génie des Procédés*, Numéro 98 - 20092-910239-72-1, Ed. SFGP, Paris, France (2009)
6. Teoh, M. and T.S. Chung, 2009. Membrane distillation with hydrophobic macrovoid-free PVDF-PTFE hollow fiber membranes, *Separation and Purification Technology*, 66: 229-236.
7. Yanga,b, X., R. Wanga,b, L. Shia, A.G. Fanea,b and M. Debowski, 2011. Performance improvement of PVDF hollow fiber-based membrane distillation process, *Journal of Membrane Science*, 369: 437-447.
8. Charcosset, C., 2009. A review of membrane processes and renewable energies for desalination, *Desalination*, 245: 214-231.
9. Qiblawey, H.M., 2008. Fawzi Banat, Solar thermal desalination technologies, *Desalination*, 220: 633-644.
10. Banat, F. and N. Jwaied, 2008. Economic evaluation of desalination by small scale autonomous solar powered membrane distillation units, *Desalination*, 220: 566-573.
11. Fatha, H.E.S., S.M. Elsherbiny, A.A. Hassana, M. Rommelb, M. Wiegshausb, J. Koschikowskib and M. Vatanseverc, 2008. PV and thermally driven small-scale, stand-alone solar desalination systems with very low maintenance needs, *Desalination*, 225: 58-69.
12. Khawajia, A.D., I.K. Kutubkhanaha and J.M. Wieb, 2008. Advances in seawater desalination technologies, *Desalination*, 221: 47-69.
13. Mericq, J.P., S. Laborie and C. Cabassud, 2011. Evaluation of systems coupling vacuum membrane distillation and solar energy for seawater desalination, *Chemical Engineering Journal*, 166(2): 596-606.
14. Mericq, J.P., S. Laborie and C. Cabassud, 2010. Vacuum membrane distillation of seawater reverse osmosis, *Water Research*, 44(18): 5260-5273.