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Experimental Analysis of Solar Thermal Integrated Membrane Distillation System for Co-generation of Drinking Water and Domestic Hot Water

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Abstract

Fresh water resources are very scant in Middle East and North Africa (MENA) region and people depend mostly upon the bottled water for drinking purpose. The bottling process right from treatment to delivery is highly unsustainable and hence we focus on the issue of providing drinking water in a sustainable way through solar domestic hot water (SDHW) systems. The shift towards sustainability in the oil rich region and recent growth of interest on Membrane Distillation (MD) technique at small scale application development by coupling with solar energy source has motivated the present work. An Air-gap Membrane Distillation (AGMD) module has been characterized experimentally than can produce 1.5 to 2 l/hr of distillate and a pilot design of the combination SDHW-MD system is described. Further experimental investigation will be carried on the combined system for co-generation of pure water of around 15-40 l/day along with enough hot water generation for an average family of five living in MENA region

Keywords: Air-GapMembrane Distillation; AGMD;Solar Water Distillation; SDHW; Sytem Integration;Bottled water

1. Introduction

Water is the most desirable and potentially combustible resource in MENA region. Fresh water scarcity is not a new concern in Middle East, but the growing demand with rising population and depletion of resources calls for the discovery of new sources of fresh water. Thus, desalination has strategic importance in the region as a main source of fresh water. The UAE has become leader in implementing

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alternative methods for creating fresh water resources through desalination and it has a capacity to produce 919 million imperial gallons per day through desalination. Majority proportion (43%) of it is consumed mostly as potable and household water. A recent survey in UAE reveals that only 6% of people drink tap water due to potential health and safety concerns over tap water. This brings in the big picture of reliance of bottled water by urban population and in fact, UAE stands top as a largest per capita bottled water consumer in the world. Desalination itself is high energy consuming process and researchers around the world striving to perfect the process of desalination, making it efficient and cost-effective. But purifying the desalinated water again for bottling adds more energy along the conversion chain and the potential environmental impact of plastic waste makes bottling process highly unsustainable.

The need for sustainable approach to tackle the issue of bottled water has motivated us to develop an in-house water purification unit based on Membrane Distillation (MD) technology. MD is a novel process that could be adapted effectively for many water purification applications. A difference in partial pressure serves as the driving force, and the presence of a hydrophobic membrane ensures high water quality regardless of feedstock parameters. Hot-side temperatures below 90ºC are suitable and this process has been proven ideal for exploiting waste heat or solar thermal resources for small scale applications.

In dry and arid regions like UAE, lack of fresh water resources corresponds to high solar insulation. Theoretically, the average solar insolation in the region of around 600 W/m^2h will be sufficient to run system at more than 95% solar fraction. A brief research on the design approach of local distributors or suppliers of solar heaters reveals the fact that the typical SDHW systems designed for 60-75% solar fraction. Out of the 175 standard installations approved by local governing authority, 60% are designed for less than 75% solar fraction [1]. In UAE, hot water is needed during the months from October to May and since the water gets heated to 35 to 45ºC in the mains during very sunny months, solar thermal systems are designed to be idle during the summer. Two potential problems arise due to this design approach

- Collectors have to cope with high stagnation temperatures
- Backup electrical heaters are used to kill Legionella by heating up to 60ºC

Since the building council in UAE promoting sustainable ways to regulate building energy consumption, this approach could be a setback in terms of overall efficiency of the solar collector system. Therefore, we propose suitable integration of MD unit into solar hot water system that can produce 1.5 – 2 l/hr of distillate along with fulfilling hot water demand of a single family dwelling of five in the region. The proposed co-generation system would be ideal for maximizing the solar fraction through production of pure water in summer and thus reducing backup heating requirement. Overall thermal performance of system could be increased and additionally acts as a source for pure distilled water. This study provides design and development of a pilot test prototype for technical evaluation of MD modules and solar thermal collectors suitable for the co-generation application.

2. Membrane Distillation module

Membrane Distillation is a combined thermal driven membrane separation process that involves a micro porous hydrophobic membrane to separate pure vapor from the bulk feed. Basic configurations have hot and cold fluids flowing on either side of the membrane and due to the induced temperature difference vapor flows from hot side to cold side to get condensed into a pure liquid. The present work utilizes an Air-Gap Membrane Distillation unit developed by Scarab Development AB. A sketch of geometrical layout of the module is shown in Fig.1. It has a plate and frame configuration with following specifications

- Material: Hydrophobic PTFE membrane
- Pore size: 0.2 µm; Thickness: 280 µm; Membrane area: 0.2 m^2

The AGMD module consists of a 2.4 cm gap between two aluminum condensing plates, behind which are located the cooling channels in a serpentine shape covered with rigid aluminum end plates. Two membranes each of 0.1 m^2 surface area are thermally welded on to the cassette to be fitted into the module. The hot feed flow comes in from the bottom of the cassette, and flows out from the top. An air-gap of around 5mm is maintained on both sides. However, when the cassette is filled with water, the membranes bulge out onto the condensation plates and the gap reduces to as low as 1 mm. Some pictures of the cassette and module are shown in Fig. 2.

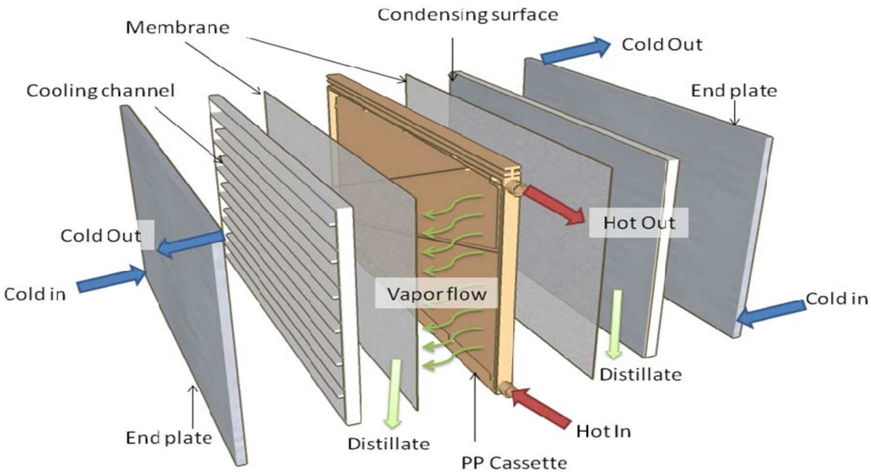
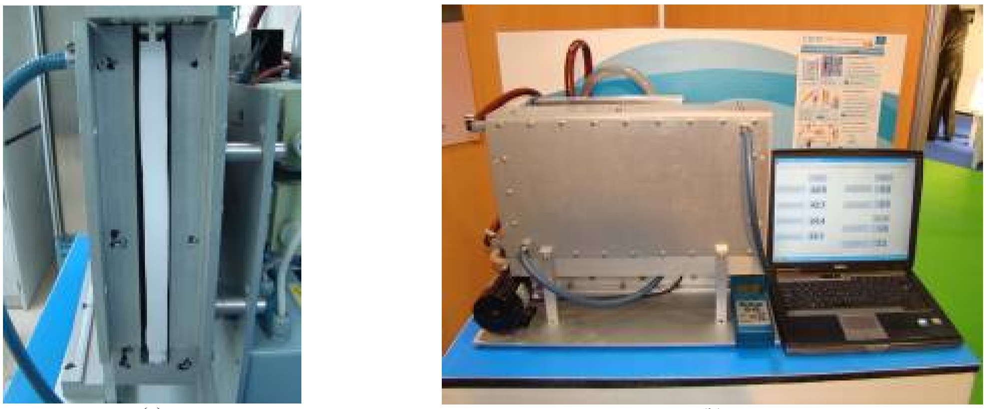


Fig. 1. Sketch of a Laboratory scale MD module

As shown in Fig. 1, the whole process can be summarized through description of flows in three channels

- Hot channel; where hot feed enters the cassette in contact with the membrane, vapor is generated and passes through membrane
- Air-Gap; a stagnant air gap between outer membrane surface and condensation plates allow the vapor to condense and collected in a distillate channel at the bottom
- Cold channel; where a cold fluid flows in contact with other side of condensation plate absorbs the latent heat of condensed vapors



(a) (b)

Fig. 2. Laboratory scale MD unit; (a) MD cassette between cooling channels (b) Front view of MD unit

3. Experimental characterization of MD module

3.1. Experimental setup and plan

Experimental setup as shown in Fig.3 consists of a single cassette MD module connected with hot and cold water storage tanks. Feed water is taken from the municipal water supply and a circulation pump is used to pump hot feed water from a storage tank fitted with thermostat controlled electric heating elements. In order to perform experiments with high cold water temperatures, a thermostatic mixing valve is used to control temperatures on cold side. The temperatures are monitored using four Pt-100 sensors and flow rates are measured by visual flow meters. On site conductivity measurements of feed and product are taken using a conductivity probe. Through experimental campaign has been carried at different hot and cold side temperatures as per the specifications in Table 1.

Table 1. Operational conditions of tested MD Module

Operational parameter	Specification
Feed flow rate	4 l/min
Coolant flow rate	2.5 l/min
Hot water operation temperature	45 – 85°C
Cold water operation temperature	20 – 75°C
Tap water conductivity	550 – 700 µS/cm

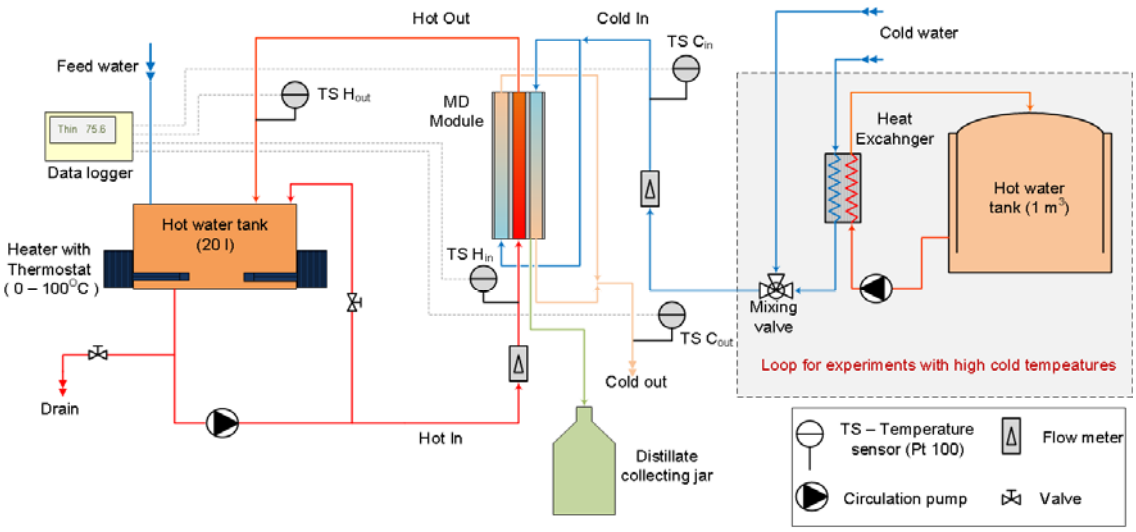


Fig. 3. Sketch of laboratory scale experimental setup

3.2. Test results and discussion

In order to integrate MD into solar hot water system, it is critical to know the effect of temperature variations on distillate flow rate. A set of preliminary experiments have been performed with municipal tap water as feed and pure distillate is obtained at conductivities less than 10 µS/cm. Fig. 4 (a) shows the permeate flux obtained as a function of hot and cold feed temperature differences. Flux increases linearly with increase in feed temperature differences and hence it's desirable to keep hot and cold sides at maximum and minimum temperatures respectively. Flux varies from 1.5 l/m^{2}h to 13 l/m^{2}h, with increase at higher temperature differences. The values are in agreement with the reported values in literature [2] [3]. Form the results, it is also evident that flux could be obtained with the unit with ΔT of as low as 5ºC.

Since the temperatures of tap water in UAE vary from average of 14ºC in winter to 40ºC in summer, a study with high cold side temperatures is carried out to determine optimum process conditions for desired production of 1.5 – 2 l of distillate per hour throughout the year. As shown in Fig. 4(b), hot feed temperature between 60 – 80ºC and cold feed temperatures at 20 – 40ºC would be ideal for SDHW-MD system to obtain desired yield. The recovery ratio (RR) calculated as the percentage of distillate yield to total feed is around 1% which is half that of the value reported in literature for larger MD modules [4].

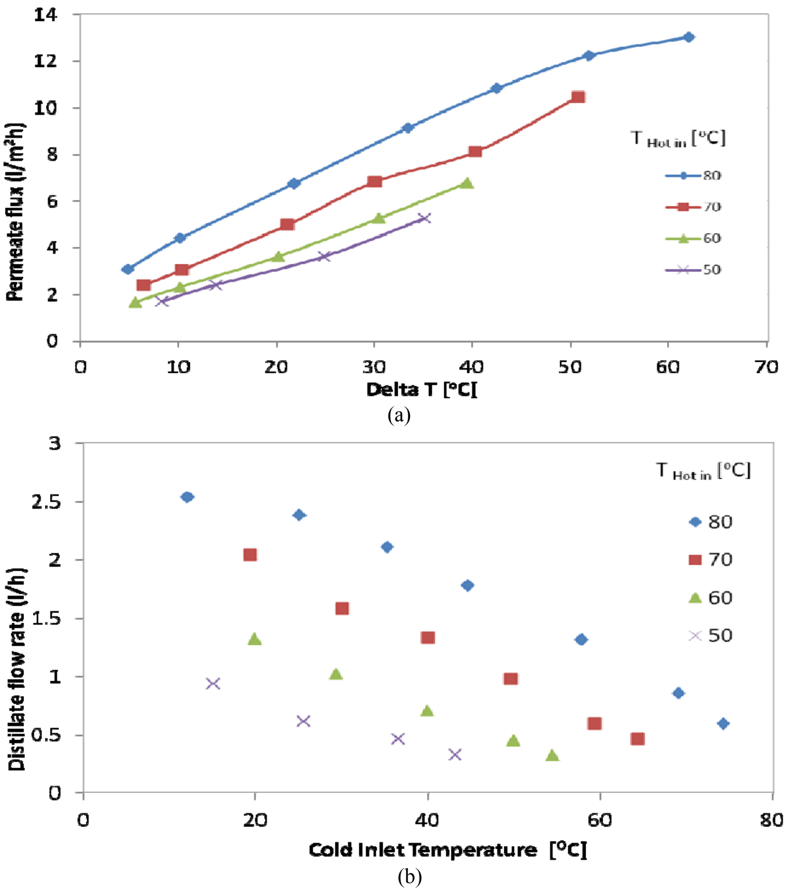


Fig. 4. (a) Permeate flux as a function of feed water temperature differences ($\Delta T = T_{Hin} - T_{Cin}$)
(b) Distillate flow rate at different cold water inlet temperatures

4. Design of Solar thermal integrated co-generation system

Form the laboratory scale results, optimum conditions needed to ascertain desired distillated flow has been determined. But, in order to realize optimum operating conditions for co-generation system, a pilot test facility has been designed and installed at CSEM uae, Ral Al Khaimah. A sketch of the installation is shown in Fig. 5 consisting of 8 flat plate solar thermal collectors each with absorber area of 2.55 m2. Three different arrays are connected in parallel consisting of 2, 3 and 3 collectors in each array. Thermal energy is charged to a stratified storage tank from which energy is distributed to meet demand of both DHW and MD. MD module has been integrated directly to storage tank and it purifies the storage medium i.e. grey water filled in the tank. Hot water at higher temperature zone of storage tank is pumped into MD unit and returned back to lower temperature zone. Ideally, this mode of integration would decrease thermal energy demand of MD system and better performance could be achieved. Through this integration, the issue of low recovery ratio could be neglected as the percentage of loss would not have much effect on the large thermal buffer during refilling of lost volume.

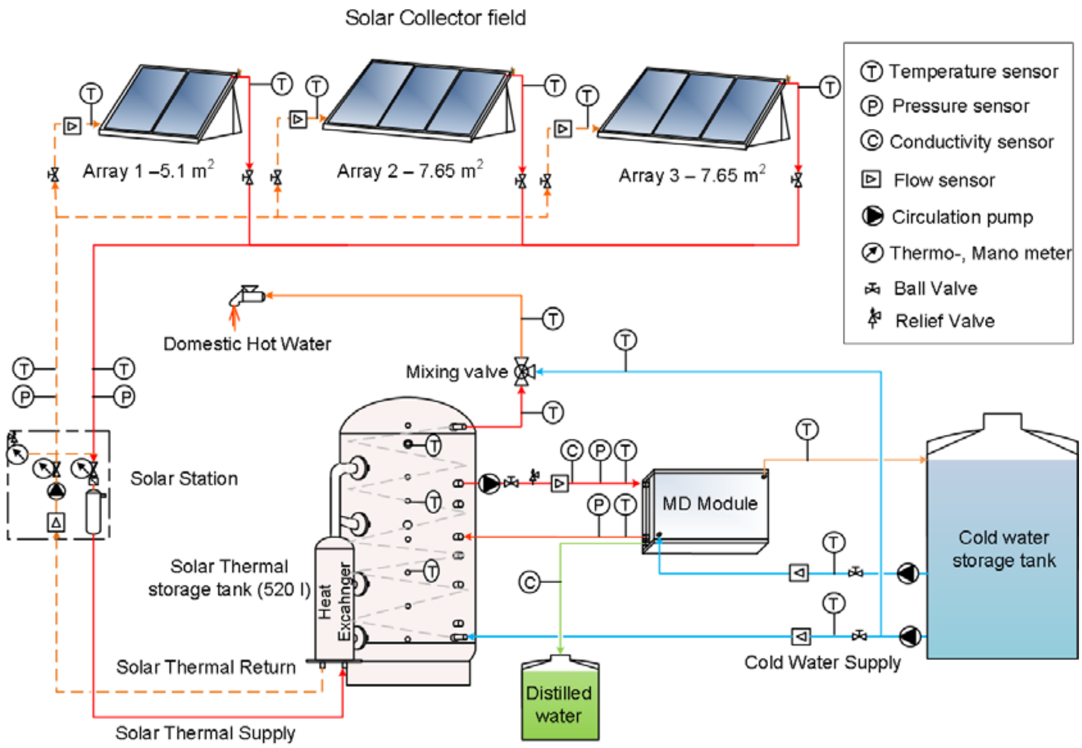


Fig. 5. Sketch of pilot experimental setup of SDHW-MD system

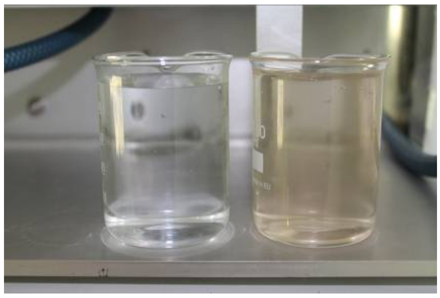
All circuits in the test facility are equipped with different measurement and control devices to monitor and control the process. Temperatures are measured using Pt-100's (Wika, TR 10, 3-wire) in solar circuit, storage tank and DHW circuit. Pressures are also monitored using Wika S-10 pressure transmitters. MD circuit is equipped with Burkert instruments for measuring conductivity, temperature and pressures (Type 8225, 8400 and 8311 respectively). High efficient, low energy consuming pumps from Grundfos (Alpha 2) are used along with Grundfos direct flow sensors to monitor flow rates in each circuit. Control strategies are adopted for drawing off hot water according to DHW profile using auto control valves. The data is continuously logged using Advantech Adam modules. Some pictures of the pilot installation are shown in Fig. 6.

A preliminary test has been performed in June by charging the storage tank with top layer temperature of 70^{o}C and both MD, DHW circuits are run for 8 hours. DHW has been withdrawn at a rate of 25l/hr with an average temperature of 50^{o}C. MD unit is connected to thermal storage tank as shown in Fig.5 and 6(c) to purify the grey water with conductivity 1600 µS/cm. Average hot side temperature is around 60^{o}C and cold water is circulated at 35^{o}C with flow rates of 5 l/min and 3 l/min respectively. Distillate is obtained at a rate of 1 l/hr and with conductivity less than 2µS/cm. Fig. 6 (d) shows the comparison of feed water quality to that of distilled water.

(a)

(b)

(c)



(d)

Fig. 6 Pilot system installed at CSEM uae, Ras al Khaimah ; (a) Flat plate solar thermal collector arrays (b) Stratified thermal storage tank (c) MD Module, Solar station along with all instrumentation (d) Comparison between clear distillate and grey water

For the present application, it is evident that constant temperatures could not be maintained with solar heaters due to split in demand for both hot water and pure water production. Therefore, a detailed on-field experimental campaign will be conducted in the coming months to analyze dynamic behavior of the system and its technical feasibility will be assessed for the co-generation application. Operational parameters for the experimental analysis are listed in Table. 2. Although, theoretical demand of hot water for single family of five is 250 l/day, some studies in UAE reveals that each person consumes 100l/day of hot water. The plant has been overdesigned to have the flexibility of experimenting at higher hot water and pure water demands. Also, as described by several authors [4], recovery of heat on cold side would enhance the thermal efficiency of MD system; with a cold side ΔT of 7 -10^{O}C observed from laboratory experiments, significant amount of heat could be recovered that can meet the hot water demand of a single family. A backup fresh water storage tank would be used for this purpose and heat recovery rate would be determined.

Table 2. Operational conditions to be tested on SDHW-MD system

Operational parameter	Specification	Units	Notes
MD Hot feed flow rate	5, 7.5 and 10	l/min	Optimum flow rate will be determined
MD feed water conductivities	500, 1000, and 2000	µS/cm	Grey water from thermal storage tank will be treated
MD cold side flow rates	2.5, 3.75, and 5	l/min	Optimum flow rate will be determined
MD operational hours	10	h/day	For 15 – 20 l distillate
	20	h/day	For 30 – 40 l distillate
Solar thermal collector area (Flat plate)	5.1, 7.65, 12.75, 15.3 and 20.4	m^2	Optimum area required for single family dwelling would be determined for both cases (i) 250 l/day and (ii) 500 l/day
Primary storage tank volume	520	l	Refilling rate of lost volume should be determined
Secondary storage tank volume	300	l	Rate of heat recovery on cold side would be determined
Domestic hot water	250	l/day	50 l/person/day
	500	l/day	100l/person/day
Domestic hot water temperature	55	^{O}C	
Sunny hours	8-10	h/day	During summer months
	6-8	h/day	During winter months

5. Conclusions

Optimum operating conditions of a laboratory scale Air-gap Membrane Distillation unit are determined. Distillate flux is varied from 1.5 to 13 l/m^{2}h, with higher values achieved at higher hot and cold side temperature difference. Experiments at high cold temperatures carried to observe distillate flow rate and distillate has been collected at temperature differences of as low as 5^{o}C. To realize integration of MD unit into solar hot water system and for technical evaluation of co-generation application, a pilot system has been designed and installed in UAE. Various operation parameters have been identified and a through experimental research will be carried to identify optimum operating conditions for the co-generation application.

Acknowledgements

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