Desalination 408 (2017) 70–80

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Experimental evaluation of the performance and energy efficiency of a Vacuum Multi-Effect Membrane Distillation system

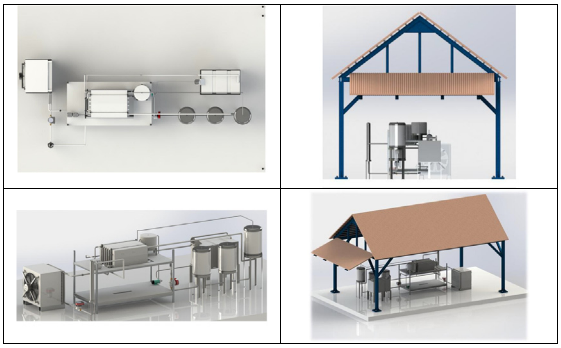
Essam Sh. Mohamed *, P. Boutikos, E. Mathioulakis, V. Belessiotis

National Center for Scientific Research, NCSR "DEMOKRITOS", Solar and Other Energy Systems Laboratory, 15310 Agia Paraskevi, Athens, Greece

HIGHLIGHTS

- A Vacuum Multi-Effect Membrane Distillation system (V-MEMD) was designed, installed and tested in outdoor conditions.
- Parameters affecting distillate production were studied.
- Two feed water types were used, namely tap water and artificial saline water 30 mS/cm.
- Energy efficiency indicators were calculated and presented.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 July 2016
Received in revised form 21 November 2016
Accepted 29 December 2016
Available online xxxx

Keywords:
Vacuum Multi-Effect Membrane Distillation
Experimental investigation
System design
Performance evaluation
Energy efficiency

ABSTRACT

The main goal of the current manuscript is the experimental outdoor testing of a Vacuum Multi-Effect Membrane Distillation (V-MEMD) System, the evaluation of the performance and energy efficiency under real operating conditions and the overall design of system components under local economic conditions. This system has a nominal capacity of 30–50 L/h and operating temperature range of 50–85 °C. The MD system utilizes the memsys V-MEMD modules with four effects. Supporting equipment and systems such as heating, cooling, feed, brine, distillate, recirculation and vacuum loops (cycles) were designed, purchased, installed and tested as an integrated system under outdoor environmental conditions. Experiments were conducted with tap and artificial saline water 30 mS/cm as feed streams. The system performance testing showed that the distillate production can reach 50 L/h at 80 °C of inlet heating water. The system distillate production was found to increase mainly with the increase of heating water temperature and flow rate. The energy efficiency indicators of the system was calculated based on the obtained experimental data, namely Specific Thermal Energy Consumption (STEC) ranged between 300–700 kWh/m^3, Gained Output Ratio (GOR) was recorded to vary between 1–2.2 and Performance Ratio (PR) was calculated to be 0.4–0.9 kg/Mj.

1. Introduction

The United Nations has achieved, five years ahead of schedule, the target to halve, by 2015, the proportion of the population without sustainable access to safe drinking water. This target is part of the Millennium Development Goal (MDG) to Ensure Environmental Sustainability

---

* Corresponding author.
E-mail address: esamsh@aua.gr (E.S. Mohamed).

http://dx.doi.org/10.1016/j.desal.2016.12.020
0011-9164/

[1]. However, there are still 663 million people in the world with lack access to safe drinkable water [2]. Moreover, the World Economic Forum has characterized water crisis as the number one global risk, based on impact to the society [3].

Brackish and seawater desalination have become a very important source of non-traditional drinkable water supply, especially for costal and isolated rural areas. Moreover, Water desalination covers >93% of the total water demand in some areas in the Middle East [4]. However, energy consumption and the associated environmental impact along with high water production cost, have hindered the application of desalination technologies in less developed rural and isolated regions [5].

Renewable Energy powered desalination systems have proved to be a sustainable solution for the mitigation of fresh water scarcity in areas where the lack of drinkable water happens to be with the existence of high Renewable Energy Sources (RES) potential, such as solar and wind potentials [6–10]. Seawater desalination technologies that are coupled with renewable energy have been identified to be Reverse Osmosis (RO), Multi-Effect Distillation (MED), Multi-Stage Flash Distillation (MSF), Vapor Compression (VC) and Membrane Distillation (MD) [11].

MD is a non-isothermal membrane separation process that involves the transport of water vapor molecules from a hot aqueous solution through a microporous hydrophobic membrane, due to the vapor pressure difference that is created by the temperature difference between the two sides of the membrane, especially in the case of DCMD configuration [12–14]. The main advantages of the process include the production of high quality distillate, the possibility of operation at low temperatures, perfect coupling with RE systems, the ability of operation with intermittent operation conditions, low pressure requirements, minimal electrical energy needs, the ability to handle high salinity feed, scalability and relatively high fouling resistance [15]. However, in comparison to RO, there are some disadvantages of MD, such as the low flux and high thermal energy consumption. In order to enhance the driving force of vapor transfer across the membrane (pressure gradient), four MD configurations are available: Direct Contact Membrane Distillation (DCMD), Air Gap Membrane Distillation (AGMD), Sweeping Gas Membrane Distillation (SGMD) and Vacuum Membrane Distillation (VMD) [16]. In DCMD, high fluxes can be achieved. However, heat losses are high, which makes the process to exhibit low efficiency. In AGMD there is a reduction in the conduction heat losses and there is the possibility to separate volatile substances before they mix with the permeate stream. However, this additional barrier (air gap) reduces the mass transfer through the membrane, which as a result reduces the flux compared to DCMD. In SGMD, the condensation of the vapor takes place outside of the MD module by forced movement of the vapor. The advantage of this configuration over AGMD is the further reduction of the mass transfer barrier and thus higher flux could be achieved. However, the gas flow could reduce the driving force (vapor gradient across the membrane) due to the heating of the gas itself. In VMD, the vapor in the permeate side is sucked with a vacuum pump and condensed outside of the MD module. One major advantage of this configuration is that the evaporation of seawater could be achieved at lower temperatures. This leads to lower thermal energy demand. However, the operation of the vacuum pump requires additional electrical energy. Moreover, the use of vacuum requires more complications in the system.

There are many research efforts in the field of experimental MD application in desalination. However, most of them are laboratory scale experiments mainly performed to study several parameters affecting membrane operation and flux enhancement and to validate a theoretical models [17–31]. Full scale and outdoor MD systems testing and operation has gained less attention from researchers. A limited number of publications have tested full scale MD systems outdoor and elaborated the results for flux and energy efficiency.

Guillén-Burrieza et al. [32] have experimentally tested a pilot AGMD plant manufactured by the Swedish company Scrarab AB. The main goal of this study was to examine the effect of feed water salinity on the flux and Performance Ratio (PR). Some problems with leakage were recorded which resulted in distillate salinity increase, mainly due to gaskets and O-rings misshaping and membrane hydrophobicity damage. Those modules showed specific distillate flux values up to a maximum of 6.5 L/h·m^2 (ΔT of 65 °C and 1 g/L salt solution as feed). A percentage of 14% decrease in flux was observed with the increase of feed salinity from 1 to 35 g/L. The results showed also thermal efficiency value (Performance Ration – PR) of 0.79 which corresponds to specific energy consumption of 810 kWh$_t$/m^3. A range of decrease between 8 and 16% in RR (extra energy required of 100–400 kWh$_t$/m^3) was also observed when increasing feed water salinity from 1 to 35 g/L. Schwantes et al. [33] presented complete system designs of two solar powered and one waste heat driven MD plants in three different places (Namibia, Gran Canary and Pantelleria respectively). They focused on the two-loop system design, which is typically adopted for larger capacities. Defective collectors, and higher than expected heat losses in the collector array, were the main problems faced in the operation. Waste heat from combustion engines proved to be a promising alternative energy source and GOR was recorded to be between 2.4 and 4.4 and distillate production ranged from 1.4 to 3.69 m^3/d. Two recommendations were concluded from these tests, 1) carful design for the heat storage tanks should be taken into consideration and 2) minimizing heat losses by insulations in the system should be considered beforehand. Zaragoza et al. [34] evaluated different MD prototypes using solar thermal energy coupling, namely four prototypes were evaluated: 1) Scarab modules, 2) Keppel Seghers M33 and PT5 modules, 3) Solar Spring Oryx 150 unit and 4) Aquaver WTS-40A module. The main outcomes of these tests and evaluation was that the Aquaver WTS-40A modules had the highest water recovery ratio (58–59%) while all modules were the same regarding distillate flux (in the range of 1–5 L/h·m^2). The Solar Spring module had the lowest Spesific Thermal Energy Consumption (STEC) values (210 kWh/m^3), followed by the Aquaver WTS-40A with STEC lower that 400 kWh/m^3. Zhao et al. [35] have tested the memsys Vacuum Multi-Effect-Membrane-Distillation (V-MEMD). They concluded that the conditions (temperature and flow rate) of heating, cooling and feed are the main operating parameters affecting module performance and energy efficiency, with emphasis on the heating and cooling temperatures. While the number of stages and the size of each stage are the key parameters in optimizing module design and system scale-up. In this work, only the V-MEMD module was examined and not the design of the other supporting loops (heating, cooling, feed, vacuum etc.). Results showed a flux ranging from 3.9 to 8.7 L/h·m^2 and GOR ranging from 1.6 to 1.66 according to the number of frames from 17 to 7 respectively. Chafidz et al. [36] developed an integrated autonomous solar-driven desalination system using the memsys V-MEMD. This system includes heat pump and thermal storage. They concluded that the usage of the heat pump doubles the amount of distillate production with reference to that without heat pump (11.24 and 5.98 L/h respectively). However, the extra electrical energy required for the heat pump and the overall energy efficiency of the system was not elaborated. Chin Lee Ong et al. [37] investigated another memsys V-MEMD with 6 effects that utilizing thermal energy from high concentration photovoltaic system. The main goal of the investigation was to validate a steady state model of the system and to perform a parametric investigation for the influence of the feed salinity and flow rate. Nominal GOR value was recorded to be 3.85, STEC 157–188 kWh/m^3 and a recovery ratio between 39–47% and fluxes in the range of 3.88–5.79 L/h.m^2. Other parameters affecting the system operation such as the heating and cooling water flow rate and the influence of the vacuum were not discussed.

The current work focuses on the design and experimental testing of a full scale V-MEMD in outdoor real operating conditions. The main goal was to design all supporting loops, such as heating, cooling, feed water, distillate, brine and vacuum to achieve custom-made design and lower investment and operating costs. A 3D design of the system was performed in order to accurately determine the optimum sizes and allocation of components of the loops. A four effects memsys V-MEMD was