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ScienceDirect

Energy Procedia 160 (2019) 246–252

Energy Procedia

www.elsevier.com/locate/procedia

2nd International Conference on Energy and Power, ICEP2018, 13–15 December 2018, Sydney, Australia

Investigation of Direct Contact Membrane Distillation coupling with a Concentrated Photovoltaic solar system

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Abstract

The scarcity of fresh water amongst a growing population is an impending global issue, which must be addressed by utilizing renewable energy sources. A Concentrated Photovoltaic (CPV) and Direct Contact Membrane Distillation (DCMD) hybrid system is a viable solution to address water shortage in arid and rural areas. The objective is to determine the feasibility of the combination of a DCMD and CPV system, demonstrate fresh water production utilizing the DCMD method and increase total CPV system efficiency. An experimental setup has been designed and built, and the results indicate a mass flux of 7.096 L/m2.h is achievable with a Polytetrafluoroethylene Membrane area of 0.0491 m2, salinity concentration of 1±0.1 % and a membrane temperature difference of 18.82 °C.

Keywords: Direct contact membrane distillation; concentrated photovoltaic solar system; heat and mass transfer

1. Introduction

The competitive nature of the renewable energy market is imposing barriers on companies forcing them to innovate, and better their products to compete on a global scale. Australia's abundant renewable energy sources and its pledge

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1876-6102
10.1016/j.egypro.2019.02.143

to reduce Green House Gas (GHG) emissions by 25% by 2020, it is inevitable, long-term investment will be in renewable energy sources such as solar; hydro; and aero power generation [1]. Efforts must be made with a growing population to ensure that power generation is efficient and sustainable for the foreseeable future. Because of exponential population growth, water scarcity is impending issue. Only 2.5% of the world's fresh water reserves can be used by humans [2]. Globally, one-seventh of the world's population is without sustainable sources of water and a further 2 billion people lack adequate water sanitation. With an expected increase in the global population to 9.5 billion by the year 2050, there is a growing concern the demand for water will surpass the supply. Furthermore, in recent years most of the countries in the world have experienced rapid increase in primary energy demand [3].

Residential and commercial PV systems are essential to cater for Australia's increasing energy demand, security of energy supply and reduction of emissions [1]. Solar energy promises large-scale development potential and is expected to become the most important form of renewable energy [4]. Concentrated Photovoltaic (CPV) system installations, for instance, have rapidly increased over the last 10 years with few MW per year installed in 2007 compared to over 60MW in 2014 [5]. The use of CPV systems in excess of 400 suns and multi-junction solar cell efficiencies larger than 40% are extremely efficient processes for harvesting the solar radiation available [5].

Generally, for desalination system to operate it needs access to saline water source, and energy source. With ever increasing energy demands and energy source plays an important role in water desalination. One of the thermal desalinations technologies is direct contact membrane distillation (DCMD) which can operate at low temperatures (50°C to 70°C) heat source temperatures [6]. These low temperatures are readily available from the CPV cooling system. Therefore, combining CPV and a thermal desalination system will provide an opportunity make both these technologies sustainable. However, further research needs to be conducted on coupling of CPV and DCMD. By utilizing low temperature wasted heat energy from CPV systems will increase the overall hybrid system efficiency.

2. Proposed CPV+DCMD system

The system proposed is based on a CPV system together with a DCMD. CPV systems use concentrated sunlight focused by either lenses or mirrors onto multi junction solar cells to produce electricity. CPV usually operates with a cooling system to increase its efficiency. The idea here presented is to use this heat removed from the solar cells to drive a DCMD.

2.1. Concentrated Photovoltaic (CPV)

A cooling system is always necessary in CPV devices to increase their efficiency. Advancements have been made in micro-channel water cooling and jet impingement cooling systems. In particular A.Royne et al. [6] experimentally demonstrated the use of jet impingement method to increase the cooling capabilities of CPV solar cells using different channel geometries and nozzle types. From the experimental analysis it is deduced that the guidelines for developing an optimal device include the size of the cooling unit, a high number of nozzles, an optimal nozzle-to-plate to diameter ratio and optimizing nozzle diameter to reduce negative cross flow areas [6]. The downfalls of such a system is the pressure loss, therefore larger pumping pressures are required at the inlet and the issue involved with reducing the temperature non-uniformity. An alternative to impingement cooling is micro-channel cooling. A micro-channel cooling system is a combinatory model of an array of micro-channels enclosed in a wide parallel flow channel design. The micro-channel arrangement produces the best heat exchange when fluid flow is laminar, the Reynolds number is low and when the channels are straight which must be maintained to keep pressure losses to a minimum, approximately 8.8 kPa [7]. Besides, they reduce the complexity of the system and minimize the pressure losses throughout the heat sink when compared to other hybrid designs such us micro-channel-jet-impingement heat sinks.

2.2. Membrane Distillation (MD)

Desalination techniques can be divided into two categories: thermally driven and electrically driven. The electrically driven desalination method includes Reverse Osmosis (RO); Electro-dialysis (ED); and Mechanical Vapor Compression (MVC). As the scope of the work here presented uses the heat removed from a CPV, thermal desalination methods are the ones applicable. They use phase change to separate fresh water from contaminants. MD is a method where water vapour permeates through a hydrophobic membrane surfaces and condenses on the opposite side due to cooling fluid [8].

Li-Zhi Zhang has incorporated a membrane-based humidification and dehumidification system. Hollow membrane is employed as a humidifier to humidify air with solar energy heated saline water. Analysis of the test results signify that salt rejection using a hollow fibre membrane is around 99.9% and that thermal energy storage is beneficial for fluctuating solar radiation values [7]. The most prevalent DCMD and solar coupling analysis have been conducted by Wang Geun Shim [8] and Nakoa [6]. The first one modelled a DCMD system of seawater, mathematically predicting the permeate flux of an unsteady state. Maintaining a feed in temperature of 60°C, a permeate feed temperature of 20°C and a flow rate of 4.5 L/min yielded a fresh water production rate of 40.9 L/m^2.h [8]. This theoretical analysis provides a foundation for DCMD, however variations in practical applications such as fluctuating solar radiation values, will alter the fresh water production rate. Nakoa and team have demonstrated coupling of DCMD and salinity-gradient solar pond (SGSP) as the heat source providing the temperature difference across the DCMD membrane [9]. The results conclude that the higher the feed temperature, the higher the permeate flux.

As it can be seen in Fig. 1, the proposed system in this work has two loops. The first loop is to extract the heat from the solar collector (CPV) and the second loop is where the feed is then circulated through a DCMD system. The distillate is collected in a tank, and the concentrate is re-circulated into the feed of the second loop.

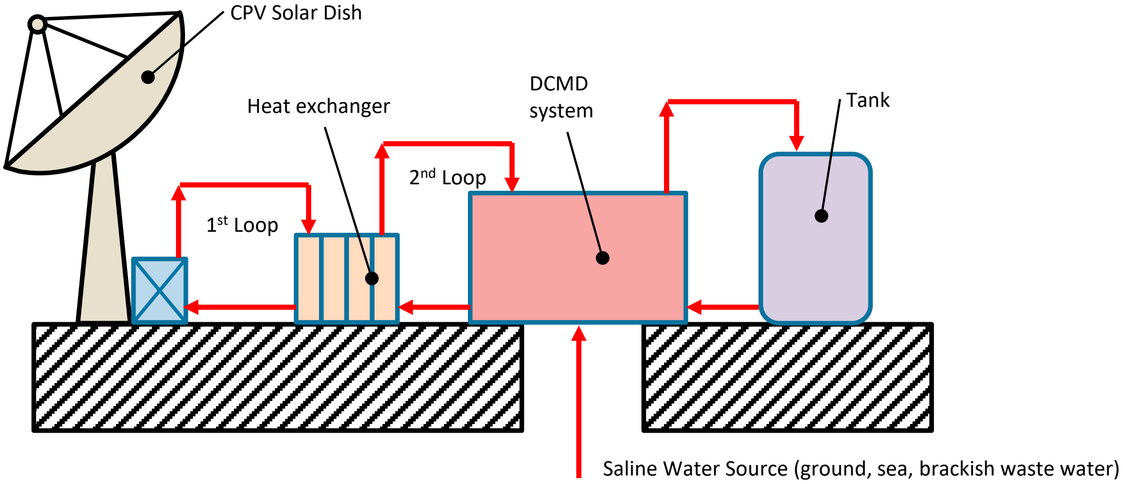


Fig. 1. Schematic if the proposed CPV and DCMD hybrid system, employing the use of a two-loop process

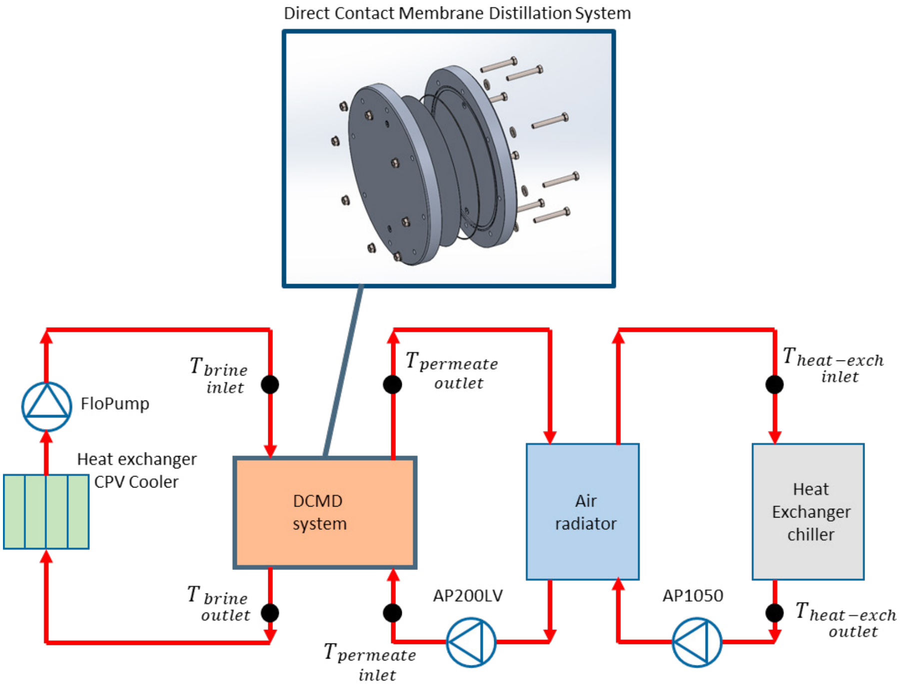
3. Experimental setup

The experimental setup consists of a hot permeate reservoir, a hot saline feed reservoir, a heating element, an air radiator heat exchanger and the DCMD system. The schematic shown in Fig. 2 and the actual experimental set-up in Fig. 3 outlines the interconnection of the main systems. Hot saline water and cool permeate water enter and exit the DCMD via inlet and outlet ports situated on either side.

The permeate reservoir stores the fresh water and is kept at a constant temperature with the use of a copper coil heat exchanger facilitating heat transfer from the permeate reservoir to the coolant. A 240 V Aquapro AP200LV pump is used to circulate the permeate fluid through the DCMD at a rate of 3.3 L/min and an 18 W 240 V Aquapro AP1050 pump is used to circulate the fluid through the coil heat exchanger. As mass transfer occurs through the membrane the mass of fluid in the permeate reservoir will increase over time. An overflow system attached to the top of the reservoir collects distillate produced by the system. The hot saline feed is heated using an electric heater (simulating CPV heat recovery) controlled by thermo-cut off switch. The saline feed reservoir is a modified stainless-steel container impervious to leaks and deterioration at experimental temperatures. The hot saline feed is circulated using a 12V DC FloPump with a flow rate of 2 L/min. All hot feed lines are insulated to restrict heat loss. Furthermore, K-Type

Thermocouples and a PicoLog recorder are used to monitor and record the inlet and outlet temperatures of the feed and permeate and the coil heat exchanger.

Fig. 2. Experimental schematic showing main system components and direction of flows. Exploded view of DCMD system.



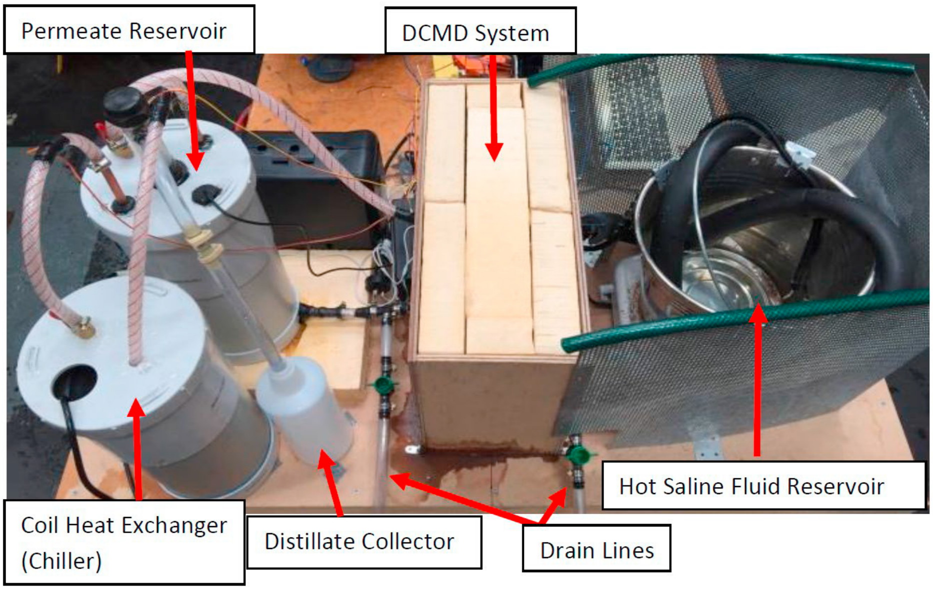


Fig. 3 Experimental set-up showing main system components

The experimental aim was to measure the distillate produced by the system at a given permeate temperature and hot saline temperature with salinity concentration likely to be expected in the field. The permeate system is filled with fresh-water and the salinity recorded with the aid of a salinity meter. A similar process is carried out for the hot saline feed. Salt is added to the hot feed saline reservoir to create a saline solution. For experimental purposes 50 grams of

NaCl is dissolved into 5 liters of water. The hot water heating element is turned on and the hot water reservoir saline solution heated until it reaches a temperature of approximately 60°C. Once the temperature has come to a steady state, pumps are activated, and the distillate collection bottle is placed under the overflow collection tube. The salinity levels of the saline solution are measured every five minutes for the duration of the experiment. The PicoLog recorder is set to continuously record thermocouple temperatures every 10 seconds for the total experimental time. On completion of the experiment the distillate bottle is weighted on a measuring scale and the weight is recorded. The experiments have been performed 3 times to check repeatability.

4. Results and discussion

The DCMD laboratory experiments simulate the realistic conditions of a fully operating DCMD hybrid system. The bulk permeate temperature was held at 28 ± 4°C and the bulk hot feed temperature was held at 58 ± 4°C.

The measured outputs of the system are the mass flux, using the overflow technique to gauge distillate production, bulk temperature difference across the membrane, quantified by the difference between the bulk hot feed and permeate temperatures measured at the respective thermocouples and the salinity level across the duration of the experiment, 60 minutes.

4.1. Salinity

The salinity concentration of the hot feed reservoir increased almost linearly with time as illustrated in Fig 4. The initial salt concentration of the experiments was set at 9000 ppm NaCl. The hot feed salinity increased linearly by an average of 92 ppm/min. The salinity levels of the distillate were recorded at beginning and end of the experiment and remained almost constant at 90 ppm of NaCl throughout experimental testing.

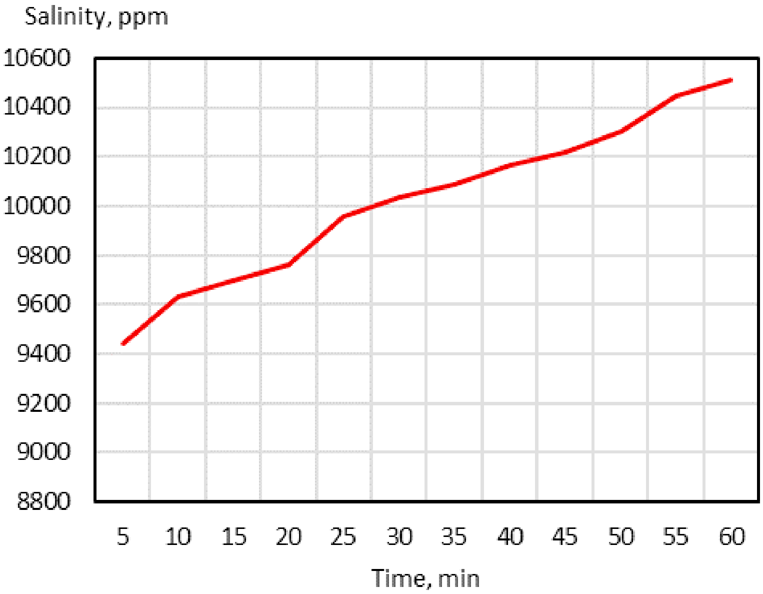


Fig. 4 Average NaCl concentration of hot feed reservoir.

4.2. DCMD Temperatures

The average bulk temperatures of the hot feed, the cold permeate, and the inlet temperature of the heat exchanger of the membrane are illustrated in Fig. 5. The bulk hot feed and permeate temperatures remain relatively steady at 50.36 ± 1.8°C and 25.88 ± 0.5°C. This is to maintain a constant membrane temperature difference. The temperature fluctuations are a result of thermal cut-off switch on the electric heating element. A heat exchanger coil is used to maintain a constant permeate feed temperature and a heating element used to maintain the hot feed temperature. The bulk membrane temperature difference is derived from the temperature difference between the bulk hot feed temperatures and permeates feed temperatures. The mean temperature difference among the experiments is 18.82 °C.

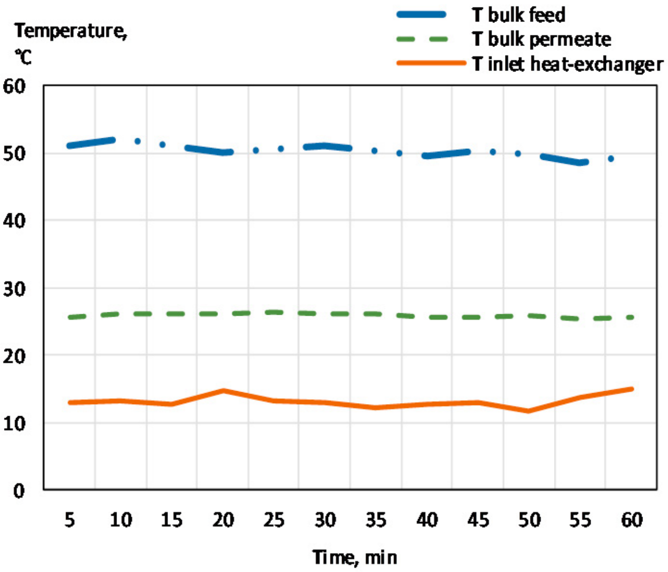


Fig. 5 Average bulk feed and permeate temperatures, and inlet temeprature of the coil heat exchanger.

4.3. Distillate Production and mass flux

The distillate produced by the temperature difference across the DCMD membrane was recorded using an overflow device erected from the top of the permeate reservoir. By using the mass of collected distillate, the membrane area and the time elapsed the mass flux could be calculated. The average distillate produced by the system is 348.3 ml, resulting in an average mass flux of 7.1 kg/m2/h. This was achieved at a NaCl concentration of 1 ± 0.1 %, a PTFE membrane area of 0.0491 m^2. It is possible to run a successful DCMD system off the wasted heat energy of a CPV solar cell. However, further theoretical analysis must be made to determine the temperature, pressure and mass flow rate losses based on a full-scale system. It is needed to accurately determine the inlet temperature, pressure and mass flux of the DCMD.

5. Conclusion

The work here presented shows the possibility to operate a DCMD system using the low temperature heat that can come from a CPV solar dish. An experimental rig has been designed and tested to prove the feasibility of this hybrid system. Experimental results have been obtained from several tests which signify that even at low membrane temperature differences of 18.82°C an average mass flux of 7.1 $kg/m^2.h$ can be achieved.

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