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# Experimental evaluation of a membrane distillation system for integration with concentrated photovoltaic/thermal (CPV/T) energy

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## Abstract

Results are presented for a concentrated solar photovoltaic and thermal powered membrane distillation (MD) system for seawater desalination. Solar intensity data was input into a mathematical model for the solar energy system and outlet temperature from the energy system was calculated. The MD module was tested for a fluctuating inlet temperature, as would be produced from a solar energy source. A maximum distillate flux of 3.4 $l/m^2h$ was recorded, though this did not correspond to the highest inlet temperature. An observed delay in the modules response to the fluctuations in temperature was due to the thermal mass of the MD unit. The conductivity of the distillate was measured to assess the effects of transient operation on the quality of the distillate produced. It was determined that although the quantity and quality of the distillate varied with the fluctuations in power supplied to the module, the effects were not significant enough to rule out the integration of the MD module with solar energy.

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*Keywords:*Solar Energy; Photovoltaic; Thermal; Desalination.

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## 1. Introduction

There is an increasing need for access to safe water sources, particularly for use as drinking water. With an abundant availability of seawater, interest in desalination processes such as membrane distillation (MD) is growing.

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The United Nations Millennium Development Goals, published in 2009, stated that 884 million people still do not have access to improved drinking water; of these, 84% live in rural areas [1]. Therefore, it is often the case that in areas with water scarcity there is also a lack of energy and infrastructure available, making it difficult to find the means to purify water. The solar powered MD system detailed in this paper is intended to overcome these problems, as it is a portable and self-contained system designed for use in remote locations.

When coupling a solar energy collector with desalination technology, several factors must be considered. The local availability of various renewable energy sources must be taken into account, along with the volume of drinking water required and the pollutants present in the local water source [2, 3, 4]. Numerous renewable energy sources have been used in combination with desalination technology, however solar driven systems are particularly of interest, as areas with the greatest water scarcity are also known to have the highest solar irradiance. The current study considers the development of a solar powered MD system, driven by a concentrated photovoltaic and thermal (CPV/T) energy system.

Membrane distillation is becoming an increasingly popular means of desalination among researchers. MD is a thermal membrane process, with operating temperatures of 40 to 80˚C. This lower operating temperature range gives MD an advantage over conventional distillation technologies, such as solar stills. Another advantage is lower operating hydrostatic pressure when compared to other membrane processes such as RO [5]. MD systems powered by solar energy can be economically completive with RO systems in remote locations [6,7].

A number of projects have been reported in the literature, were MD technology is coupled with a solar energy system. A numerical study was conducted by Koschikowski et al [8], the study looked at a solar thermal powered membrane distillation system that consisted of a 7m$^2$ spiral-wound membrane module and 12m$^2$ of solar thermal collector area. The outcome showed that the system, when located in Eilat, Israel, could produce 161 l/d on a clear day in the summer. Spiral wound MD membranes were manufactured by Fraunhofer ISE, allowing for a greater surface area of membrane within a relatively small module [9]. Koschikowski et al. [10] installed and tested 6 compact solar driven MD units in various locations. The first of these systems was placed in PozoIzquierdo (Gran Canaria) in December of 2004, followed by systems in Alexandria (Egypt), Irbid (Jordan), Kelaa de Sraghna (Morocco), and Freiburg (Germany). The final system was installed in Tenerife (Spain), in December 2007. These systems were designed to produce 60-150 l/day of fresh water.

Several larger scale systems have been installed incorporating a two-loop design, where separate seawater and solar loops that are connected by a heat exchanger. The first of the two loop systems was installed in Aqaba (2005) and the second in Gran Canaria (2006). These systems were designed to produce 1000 l/day, [10]. Cipollina et al. [11] recently installed a two-loop system in Pantelleria (Italy). This system produces up to 5000 l/day and is powered by solar energy and waste heat from diesel engines. In 2011, as part of the MEDISOL project, Guillén-Burrieza et al. [12] combined a flat sheet air gap membrane distillation system with 252 stationary flat solar collectors. Scarab AB manufactured the membranes, and each has a surface area of 2.8m$^2$. With temperatures of up to 85°C the maximum distillate flux registered was 7 l/m$^2$h. Multistage MD layouts were considered, in an effort to improve the thermal efficiency of the module.

The current investigation presents research on a two-loop solar desalination system, comprising of a concentrated photovoltaic/thermal energy source and membrane distillation unit.

When combining seawater desalination with a solar energy source, it is necessary to investigate how fluctuations in the energy source influence the operation of the MD unit. Solar intensity is known to fluctuate largely throughout the day, subsequently so will the inlet seawater temperature on the MD unit. This transient operation of the MD unit will affect the quantity and the quality of the distillate produced. To investigate this effect the inlet temperature to MD unit was varied, mimicking the temperatures that would be achieved using a solar energy system on a particular day.

## 2. Two loop solar desalination system

The system investigated in this study contains two distinct loops, the energy loop and the MD loop, which are connected via a heat exchanger. A schematic diagram of the system is presented in figure 1, F indicates the location of the flow meter and C indicates conductivity probe.

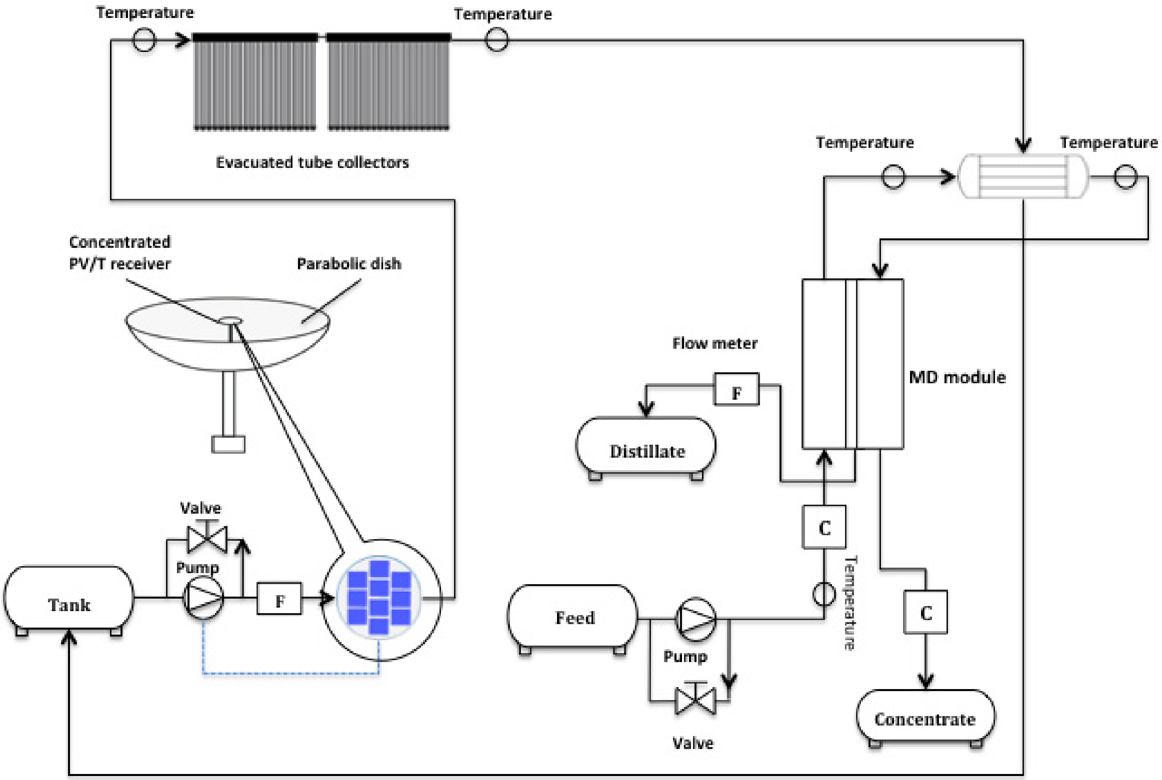

Figure 1: Schematic diagram of a two loop solar desalination system

### 2.1. The MD loop

The MD module used in the experimental part of this research has an air-gap configuration and planar geometry similar to that of a plate heat exchanger. The system includes a heat recovery system aimed at lowering the specific energy consumption. There are three channels, the hot channel, distillate channel and the cold channel. A hydrophobic membrane is placed between the distillate channel and the hot channel. Ambient seawater flows through the cold channel, heating up as it passes through. Therefore the seawater water is preheated before it reaches the solar collector. The preheated water passes through the solar collectors, where it is heated further. The seawater then flows through the hot channel and along the membrane, where pure water vapour can pass through forming a distillate stream.

### 2.2. The energy loop

A concentrated photovoltaic/thermal collector was designed, with the aim of reducing the cost of the energy system and also increasing its efficiency. The collector uses high concentrating optics, allowing for a smaller area of receiver to be used. Given that the receiver, particularly the photovoltaic cells, is the most expensive aspect of such a system, this greatly reduces the overall cost of the energy system. The receiver incorporates a hybrid design, where a thermal collector is placed directly beneath the PV cells. This therefore makes use of the waste heat generated by the cells, which must be removed by cooling to prevent a decrease in the cells efficiency. This hybrid design is ideal for combination with MD, as it provides the thermal energy required to drive the MD unit and well as electrical energy to power the pump and tracking devices.

The energy system was simulated, solar intensity data collected at Heriot-Watt University in Edinburgh on the 21nd ofJune, 2012 and used in this study. The energy system used in the model comprises evacuated tube collectors and a parabolic dish with a hybrid PV and thermal receiver (CPV/T). The evacuated tube collectors have an area of 5.7m$^2$ and an efficiency of 65%. The parabolic dish has an aperture area of 1m$^2$ and a receiver area 0.002m$^2$, giving a concentration ratio of approximately 500x. III-V multijunction photovoltaic cells were used in the model; each has an efficiency of 36%.

## 3. Simulation of the energy system

The 21st was a sunny day with cloudy spells in the morning, giving rise to large fluctuations in the solar intensity, as shown in figure 2. Data for the solar irradiance was collected using CMP-11 pyranometers from Kipp&Zonen. These pyranometers use temperature compensated detector technology to generate voltage, which can be converted to solar irradiation by use of a sensitivity factor.

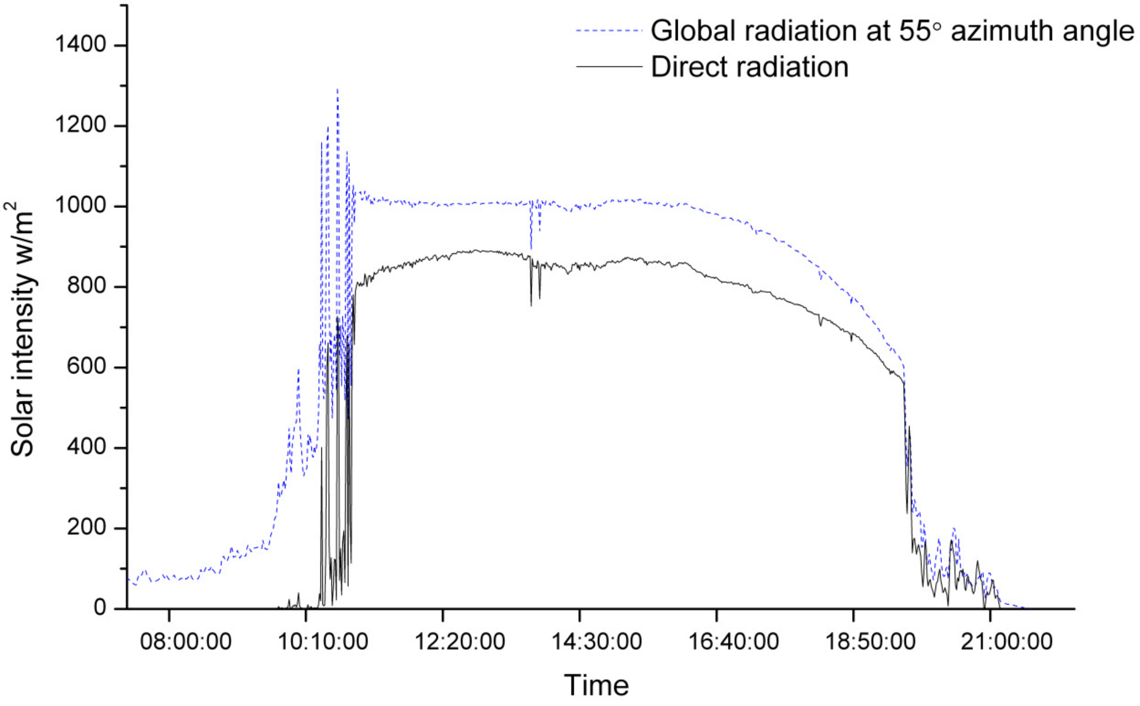

Figure 2: Solar intensity on the 21st of June 2012, Edinburgh, UK, (55N, 3W)

Data from 10.15 to 10.55am on the morning 21st June 2012 was used as an input to the mathematical model for the energy system.The solar intensity data was converted into values of heat flux via energy balance calculations, taking into account a thorough study of optical and thermal losses.

The final outlet temperatures from the energy system were calculated and are shown in figure 3.

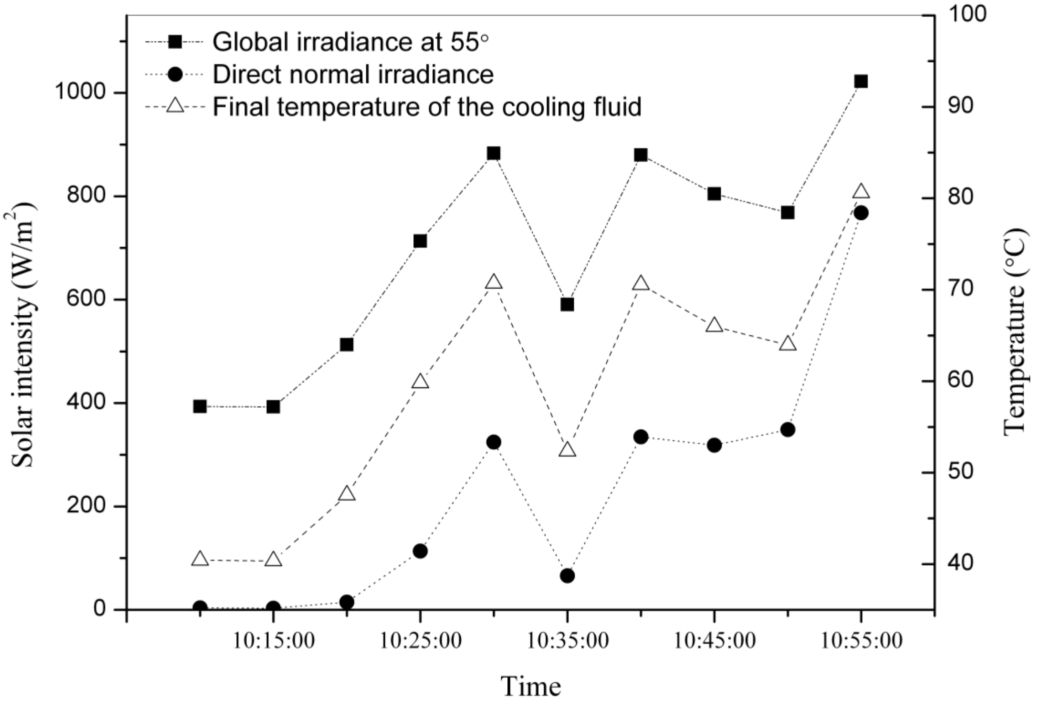

Figure 3: Solar intensity during the morning of the 21st of June 2012 is plotted to the left.

The values of final temperature from the energy system were then reproduced in the lab with the use of a heat bath, and this energy was supplied to the MD unit. The experimental set up of the MD system is detailed in the following section.

## 4. Experimental MD set up

The equipment used consists of a peristaltic pump (Watson Marlow) and a flow meter (Omega). The sensors used in the set up were as follows: four T-type thermocouples (TC Direct), piezo pressure sensors (Honeywell), and a conductivity meter (Vernier) measuring from 0-2000 µS/cm. The distillate output flowed into a beaker placed on a scale; the scale logged the weight to a computer via the HyperTerminal program. The rate of increase in weight was then used to determine the distillate flow rate. A schematic diagram of the experimental apparatus is shown in Figure 4.

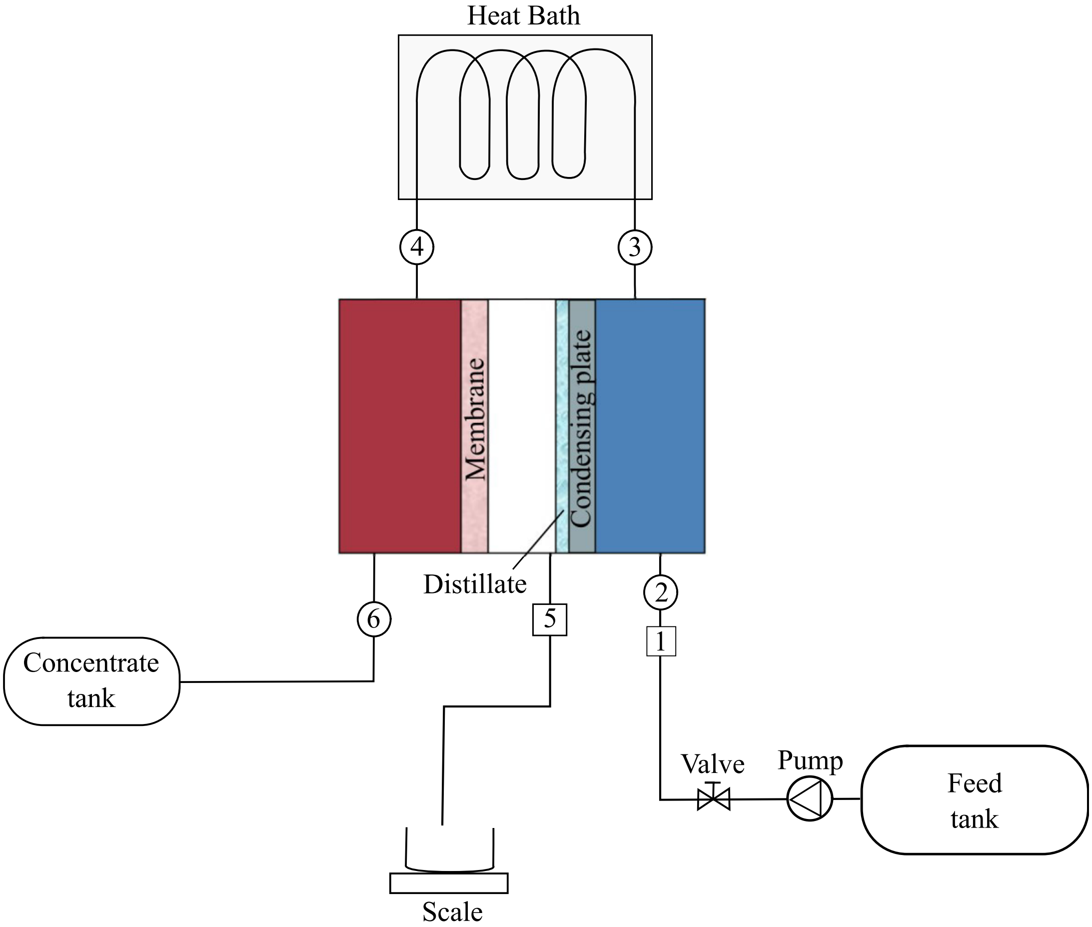

Figure 4: Schematic diagram of experimental setup: (1) feed conductivity sensor, (2) T1-cold inlet thermocouple, (3) T2-cold outlet thermocouple, (4) T3-hot inlet thermocouple, (5) distillate conductivity meter, (6) T4- hot outlet thermocouple

The feed seawater was pumped at flow rate of 0.6 L/min. The experiment ran for 45 minutes. The conductivity probe was connected to the distillate outlet, to measure the conductivity of the distillate water throughout the experiment, at a frequency of 1 Hz.

## 5. Experimental results and discussion

Solar intensity fluctuates throughout the day; therefore the heat flux output from a solar collector will also vary. When combined with an MD desalination unit, a fluctuating solar heat source will have an impact on the quantity and the quality of the distillate produced. During a single test, lasting 45 minutes, the temperature of the MD hot inlet was altered to mimic the final temperature from the energy system as calculated from a mathematical model.

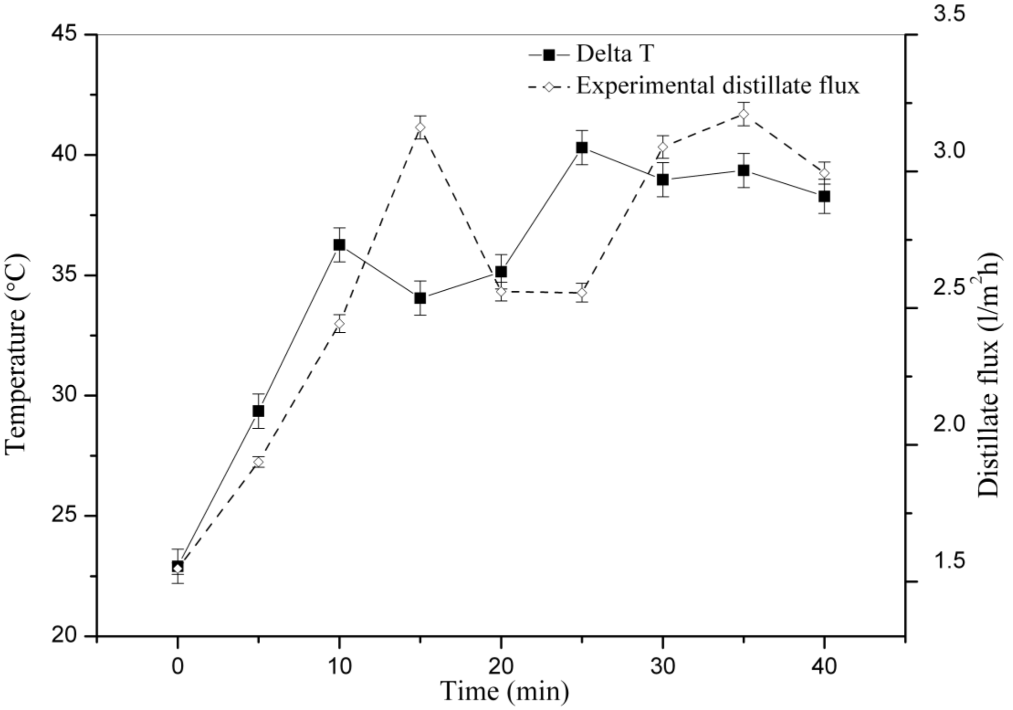

Figure 5: Distillate flow rate plotted to the right, and MD inlet temperature to the left, throughout the duration of the experiment

The trend of the distillate flux and the average temperature difference across the membrane can be seen in figure 5. Given the small surface area of the membrane in this test module the distillate flow rate was very low. Therefore the data for the distillate flux was averaged over 5 minute periods. The temperature difference across the membrane gives rise to a vapour pressure difference. The vapour pressure difference is the driving force for mass flux across the hydrophobic membrane; therefore the distillate output follows the same trend as the temperature. However the distillate flux appears to show a delayed response to the fluctuations in temperature, this delay is due to the thermal mass of the MD unit.

Conductivity measurements were taken in order to monitor the quality of the distillate. A conductivity probe placed in the distillate output line gave readings every second, throughout the duration of the experiment. These values were averaged over 5 minutes and are presented in figure 6.

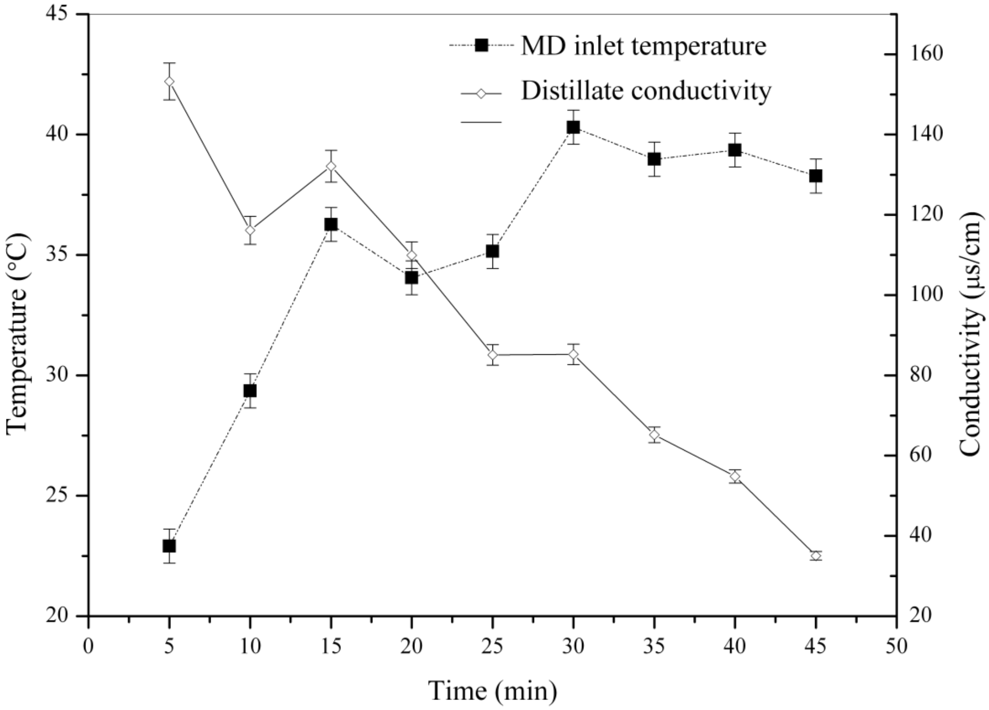

Figure 6: Distillate conductivity throughout the duration of the experiment.

The World Health Organisation (WHO) stipulated that the taste threshold for the sodium chloride is in the range of 200–300 mg/l [12]. The highest values of conductivity were recorded at the start of the experiment, when the membrane was cold and the inlet seawater temperature was at its lowest. Initially, the conductivity of the distillate was 156 μ s/cm; this can also be expressed as 115.2 mg/l. This value is significantly below the taste threshold; therefore the distillate would not have a salty taste. As the inlet feed temperature increased the conductivity of the distillate decreased, until reaching a final value of 35 μ s/cm.

Several groups investigating MD systems have observed a similar trend, [9,13]. E. Guillén-Burrieza et al. suggested that this could indicate the presences of salt crystals on the surface and within the pores of the membrane at the start of the experiment, due to its intermittent use [13]. Where as, D. Winter et al. suggested that this decrease was due to flushing out of surface contaminates left behind during the production process [9].

## 6. Conclusions

Results have been presented for a bench scale Membrane Distillation system, for use with evacuated tube and CPV/T solar collectors. A combined mathematical and experimental approach was used. Solar data was collected at Heriot-Watt University in Edinburgh on the 21st of June 2012 and used in this study. The solar intensity data was then converted into values of heat flux via energy balance calculations. The energy flux was then recreated in the laboratory with the use of a heat bath, and this energy was supplied to the MD unit. A maximum distillate flux of 3.4

$l/m^2h$ was recorded. The conductivity of the distillate decreased throughout the duration of the experiment, from 156 μs/cm to 35 μs/cm. Although the distillate conductivity was higher at the start of the experiment it was always within guidelines for safe drinking water. The conclusion is that although fluctuations in the distillate flow rate and conductivity were observed, they were not significant enough to rule out transient operation of the MD module.

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