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Using Concentrated Hybrid Photovoltaic System to produce fresh water

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Abstract

The study was conducted over the period of June to November 2018, aiming to assess the viability of harnessing solar energy for freshwater production across diverse environmental and input conditions. Throughout the assessment timeframe, there were fluctuations in the mass flux, with the highest rate recorded at 6 L/m²/hr in June 2018, and this subsequently decreased to 3 L/m²/hr by September 2018. These variations corresponded with a feed water concentration of 1%. The trans membrane coefficient specific to the utilized PTFE membrane was determined as 0.0017 kg/m²/Pa/hr. Additionally, the water output quantities recorded for feed water concentrations of 1.3% and 1.5% were approximately 5.5 L/m²/hr and 5 L/m²/hr, respectively. Energy consumption was observed to fluctuate between 2000 kJ/kg and 9000 kJ/kg, contingent upon the inlet feed water temperature and concentration. In terms of efficiency, the electrical efficiency of the system exhibited an average of 18%. In contrast, the thermal efficiency demonstrated an increase, averaging around 25%, ultimately contributing to an overall efficiency of 71%. While the results showcase the potential of the integrated CPV/T-DCMD system.

Keywords: Concentrated Flat Plate Solar Photovoltaic- thermal, Membrane Distillation, Water Desalination, Solar Energy, and Solar Desalination.

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الملخص

أجريت الدراسة خلال الفترة من يونيو إلى نوفمبر 2018، بهدف تقييم مدى جدوى تسخير الطاقة الشمسية لإنتاج المياه العذبة عبر ظروف بيئية ومدخلات متنوعة. طوال الإطار الزمني للتقييم، كانت هناك تغيرات في التدفق الجماعي، حيث تم تسجيل أعلى معدل عند 6 لتر/م²/ساعة في يونيو 2018، ثم انخفض هذا لاحقًا إلى 3 لتر/م²/ساعة بحلول سبتمبر 2018. تتوافق هذه التغيرات مع تغذية تركيز الماء 1%. تم تحديد معامل الغشاء الخاص بغشاء PTFE المستخدم بـ 0.0017 كجم/م²/باسكال/ساعة. بالإضافة إلى ذلك، بلغت كميات إنتاج المياه المسجلة لتركيزات مياه التغذية 1.3% و1.5% حوالي 5.5 لتر/م²/ساعة و5 لتر/م²/ساعة على التوالي. وقد لوحظ أن استهلاك الطاقة يتغير بين 2000 كيلو جول/كجم و9000 كيلو جول/كجم، ويتوقف ذلك على درجة حرارة الماء الداخل وتركيزه. ومن حيث الكفاءة، أظهرت الكفاءة الكهربائية للنظام متوسط 18%. وفي المقابل، أظهرت الكفاءة الحرارية زيادة، حيث بلغ توسطها حوالي 25%، مما ساهم في النهاية في تحقيق كفاءة إجمالية قدرها 71%. بينما تظهر النتائج إمكانات نظام CPV/T–DCMD المتكامل.

الكلمات المفتاحية: الألواح الشمسية المسطحة المركزة الكهروضوئية الحرارية، التقطير الغشائي، تحلية المياه، الطاقة الشمسية، تحلية المياه بالطاقة الشمسية.

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1-. INTRODUCTION

In regions abundant with solar energy and unrestricted access to seawater, solar desalination technology emerges as a pivotal solution. The application of solar energy to desalinate seawater aligns with green technology principles, offering an environmentally sound and economically viable alternative to conventional desalination methods [1]. The outcomes showed that the system, when combined with the salinity-gradient solar pond, was capable of producing 1.2 103 m^3 of fresh water per m^2 of membrane [2]. Results were 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. [3] Results were compared and showed that the flow is laminar, the connecting DCMD module to the SGSP could induce a marked concentration and temperature polarization phenomenon that reduces fluxes. Therefore, turbulence has to be created in the feed stream to reduce polarization. [4] This paper presented the challenge and efficient improvement of PV-TE in actual application. [5] This paper described various types of PV/T collectors such as air, water/air, and water PV/T collectors in terms of performance, design, fabrication, simulation, and experimental evaluation. [6]

2.Experimental Configuration:

The configuration of the experimental set-up is shown in Figure 1. The solar power loop and the MD module loop are the two basic loops that make up the system. Through the passage of these various streams through a heat exchanger, particular thermal energy quantities can be exchanged. The carefully gathered experimental data are fed into the data gathering system and archived every two minutes.

2.1 Basic Principle of the System:

The operation of the system follows a systematic sequence guidedby distinct processes:

Water heating and Collection:

The supply water tank initiates its functioning through the pump, as directed by the temperature control unit. The active pump directs the boiling water from the CPV/T system into the insulated tank. Circulation and Heat Exchange: Subsequently, the pump propels the heated water in a circulating pattern, the creation of a flow between the plate heat exchanger and the insulated tank. During this exchange, the temperature of the plate heat exchanger undergoes an increment, facilitated by the inflow of hot water and saline water. The feed saline water, in particular, experiences a temperature elevation as it navigates the plate heat exchanger, attaining a predetermined level. Distillation Process: As the saline water flows into the MD module, the distillation process is initiated. Here, the separation of fresh water from the salt water is realized, and the resulting fresh water finds its way to the cold-water tank. Cold-Water Flow and Temperature Control: The subsequent phase involves the circulation of cold water from the cold-water tank to the membrane module, a task managed by pump 4 A slight increase in the cold-water stream's temperature during this phase causes the temperature difference and, as a result, the water mass flux, to decrease. Extra heat is effectively dissipated using an air-cooled finned heat exchanger, which returns the temperature to the desired setting. Continuous Operation: The CPV/T system operates in a continuous mode, firm heating the water on the collector's backside as long as it remains exposed to solar irradiation. This coherent and cyclical operational scheme underscores the system's effectiveness in harnessing solar energy for water heating and distillation.

2.2. Membrane Distillation (MD) Loop:

In the experimental stage of this study, a direct contact membrane distillation (DCMD) design was selected for the MD module. The study specifically used a PTFE membrane made by Membrane Solution that had a nominal pore size of 0.45 m, a porosity level of 80%, and a thickness of 210 mm. As shown in Figure 2, the PTFE membrane sheet was carefully positioned in the physical setup between two symmetrical acrylic plastic blocks. These blocks boasted a thickness of 25 mm each, effectively creating two channels separated by a 2 mm interval gap on both sides. To ensure a watertight seal and to prevent any leakage between the concentrated and fresh water streams, the membrane, and the two acrylic blocks were securely sealed using 2 mm rubber along the perimeter. This MD loop configuration, centered on the DCMD setup, underpins the core mechanism of the study's distillation process.

Moreover, to further enhance the structural integrity of the membrane and promote stable turbulent water flow, 1 mm thick plastic spacers are positioned on both sides. As depicted in Figure 2, the membrane module features a flat configuration spanning 0.1334 m² (with dimensions of 0.23 m in width and 0.58 m in length). This module is equipped with distinct inlets and outlets catering to the counter flow movement of cold permeate and hot saline water.

These streams are systematically collected in two storage tanks positioned at the termination point of the system.

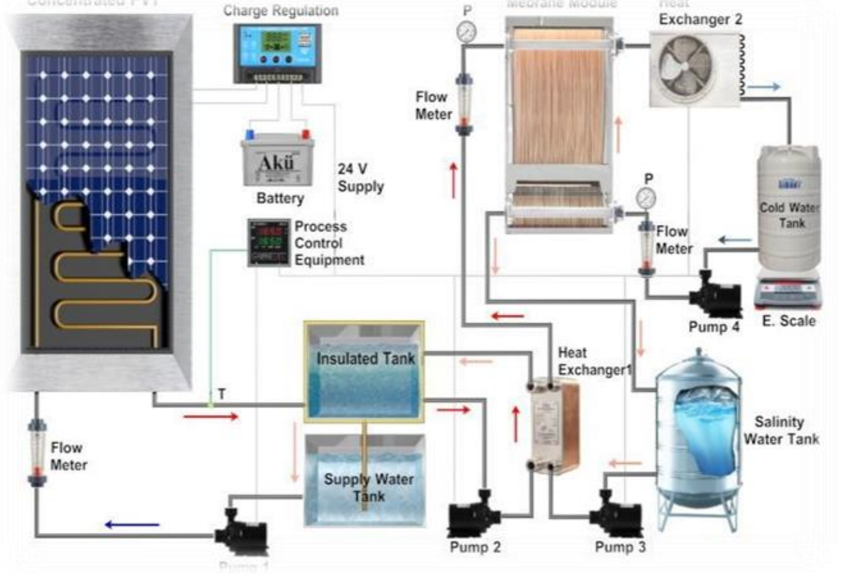

Fig.1 PVT / MD system

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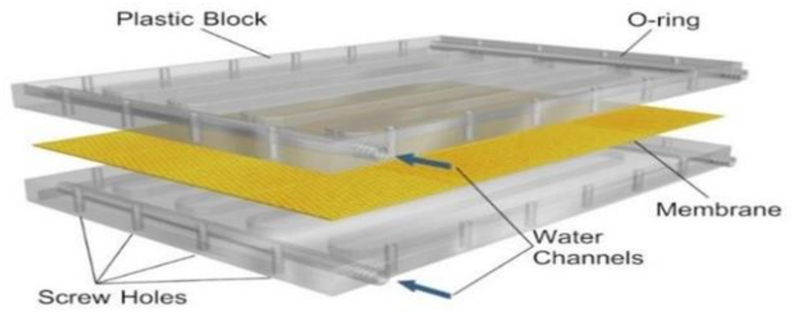

Fig.2 Flat plat DCMD module

2.3 Solar Power Loop:

A crucial component of the system, the solar power loop, integrates a Concentrated Photovoltaic/Thermal (CPV/T) collector with the dual purpose of cost reduction and thermal efficiency enhancement. This CPV/T module, manufactured by Solimpeks Dimensions of Solar Corporation are 880 mm wide, 1640 mm long, and 105 mm high. It has a 1.8 L liquid capacity and offers nominal 180 W electrical and 680 W thermal power output. The CPV/T module was meticulously designed and fabricated to align with the system's requirements. The experimental setup, depicted in incorporates a through low- concentration receiver configuration. Notably, this through CPV/T system does not feature solar tracking mechanisms, resulting in a relatively low concentration rate. Importantly, this design choice obviates the need for external energy input to the system. The positioning of the system at the region's latitude of 40° ensures its year-round applicability.The strategic integration of the CPV/T system is highly suitable for complementing the MD unit. Its capacity to generate ample thermal energy required for MD unit operation, alongside the electrical energy necessary for powering the pumps, renders this hybrid system a coherent and efficient solution.

2.4 Experiment and Procedures:

The research procedures were carried out between June and November. Cold water is initially pumped into the CPV/T system from the supply water tank, as shown in Figure 1. The heated water fills the insulated feed tank after leaving the heating process by leaving through the PV/T module's back outlet. Upon reaching the predefined temperature at point T_c2, the process control equipment (PCE) triggers water pump 1, facilitating enhanced thermal and fluid flow. The PCE's temperature sensor, integrated within the CPV/T outlet pipe, actively engages when the collector's thermal capacity is insufficient. The PV/T module demonstrates inlet and outlet temperatures ranging from 23°C to 55°C. The saline water solution, having a concentration of 1%, is pumped from the saline water tank its flow goes over the heat exchanger (HE1), starting the process of water distillation. A portion of the thermal energy produced duringthis phase is transmitted via HE1 from the PV/T outlet waterto the saline water. The heated solution then continues through the MD module at a peak temperature that is normally regarded as acceptable for MD module functioning, often ranging between 30°C and 45°C. At the entrance and output sites, thorough temperature and pressure measurements are taken throughout the setup. Thermocouples and pressure gauges are deployed for this purpose, as depicted in Figure 1. To ensure the integrity of the MD operation, a continuous monitoring of permeate water conductivity is maintained to pre-empt any undesired mixing through the membrane sheet. Furthermore, considering the critical importance of preventing saline water penetration or membrane wetting during MD operation, stringent measures are implemented. Notably, the permeate water flow rate of 0.3 m^3/h and the feed water flow rate of 0.6 m^3/h are orchestrated in counter-flow directions on both sides of the membrane at critical locations in the membrane module, including the hot entry (Tf1), cold entrance (TP1), hot exit (Tf2), and cold exit (TP2), the temperatures of the bulk liquid phases are precisely measured. These thorough processes and monitoring systems highlight the accuracy and rigor maintained throughout the experimental endeavors. The temperatures reported, including those at the liquid-vaporinterface within the hot and cold films and the membrane surface, show minute changes. It is significant to note thatTable 1 provides a thorough description of the characteristics of measurement devices and the specific equipment used.

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Table 1 Equipment utilized and measurement instrument characteristics.

Equipment	Technical Specifications	Sensitivity
Thermometer	NTC.sensor.Tmeasurementrange: -10 ~ + 60 ºC.	Sensitivity:±0.5°C
Solar meter	Measurement range 0 ~ 2000 W/m².	Sensitivity: ± %5 W/m².
Data logger	RS485 (MODBUS), 15Channels, Ordell Mark,K type thermocouples	Standard: +/-2.2C or +/-.75% Special Limitsof Error:+/-1.1C .
Solar moule analyzer	Euro-test PV MI 3109	±(2.5%of.readin g + 6 digits)±(3% of reading+ 5 digits)
Circulations pumps	DC 25V, 22W, 800 l/h	-------------
PV/T **hybrid module**	Solimpex mark type excel PV-T.Nominal power: 300W, Isc: 9.94A, Voc: 36.25V, Vmp: 32.18 V. Dimensions: 1670x995x60mm	Positive tolerance, between 0 and +5Wp

Mass flow rates circulating on both sides of the membrane are meticulously determined, recording a feed side flow rateof 10 L/min and a permeate side flow rate of 5 L/min.

3.Results and discussion

3.1. Solar radiation & air temperature

Figure 4 illustrates the mean solar panel incident radiation and the typical air temperature recorded over the summer testing period.

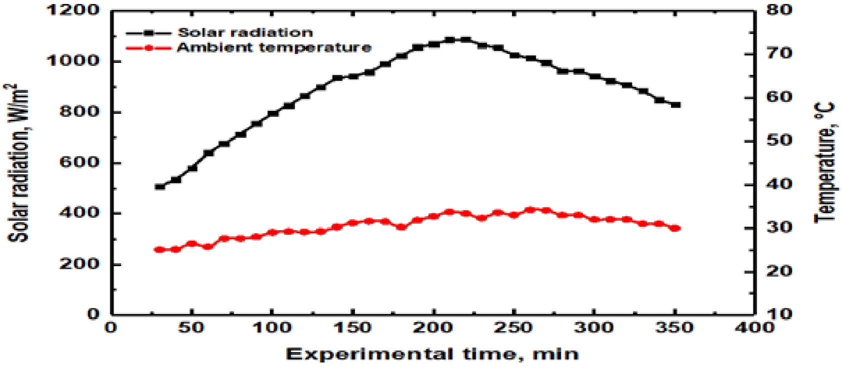

Figure 4. The average sun radiation along with ambient temperature

Following the procedure previously described, reflectors were added to the PV-thermal system to improve the utilization of thermal energy. Figure 5 illustrates the impact of these reflectors.

The graph strongly indicates that the amount of solar radiation that hits on the panel has been steadily increasing. With reflectors, the maximum value reaches 1103 W/m² at 13:00 PM, whereas without reflectors, it peaks at 1075 W/m² around 13:20 PM. The improvement varies between 18% and 20% in the beginning of the day and early hours, drops to 10% later, and then varies further around 1% and 6% in the afternoon. Throughout the testing period, the radiation increased by an average of 5.3%.

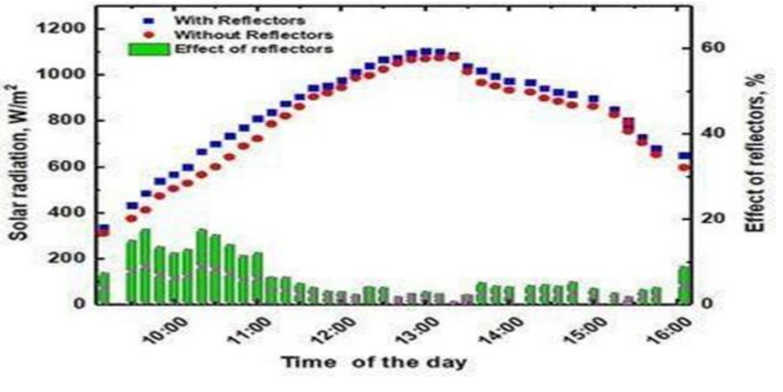

Figure 5 shows how the PV-thermal system is influenced by incident solar radiation without as well as with the inclusion of reflectors.

3.2 Analysis of the CPVT Panel's energy efficiency

The average amount of electricity produced by the CPVTsystem is shown in Figure 6. This calculation is based on the voltage and current measurements that were taken. The average electric power output falls within the range of 130 Wto 240 W. This power can be utilized during the distillation method to operate the pumps. The thermal energy delivered to the water by the CPVT system, which consists of two components—heat acquired from sunlight as well as heat produced by photovoltaic (PV) cells during energy generation—is the primary goal of the system. The quantification of this thermal energy necessitates the implementation of only the mass flow rate and the variation in water temperature of the input and output. The equation (4.30) is used to do this computation.

The results in relation to thermal energy are presented in Figure 7. Throughout the experiment, the thermal heat thatis transmitted to the water varies from 250 W to 570 W. Three hours into the experiment, the panel's greatest thermaloutput was measured to be 1350 W. Approximately 60% of the total energy output is now being provided by the thermalenergy gain.

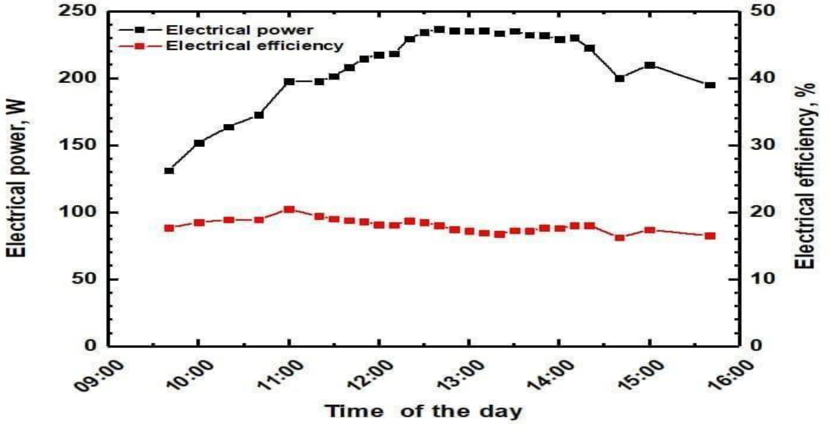

Figure 6. Electricity produced on average

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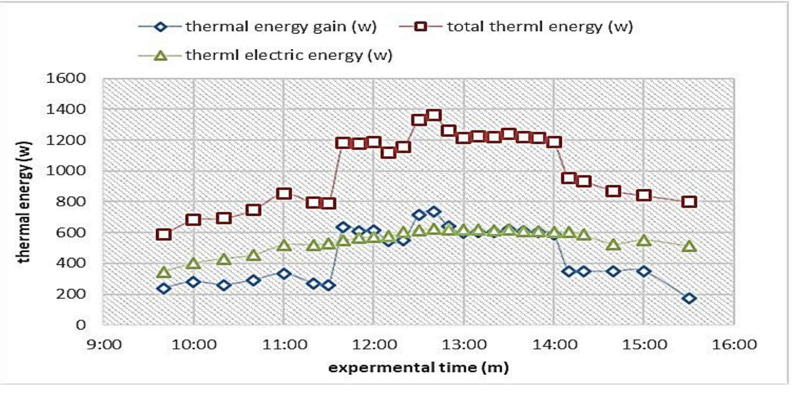

Figure 7 the fluctuation in thermal energy extraction fromthe CPVT system.

The CPV/T system's electrical (ηe), thermal (η_th), and total (η_T) efficiencies are shown in Figure 8. It is clear from comparing these efficiencies with the radiation levels shown in the previous figure that fluctuations in radiation have a major influence on the efficiency of electricity production. Changes in solar radiation, on the other hand, have a significant impact on thermal energy gain efficiency.

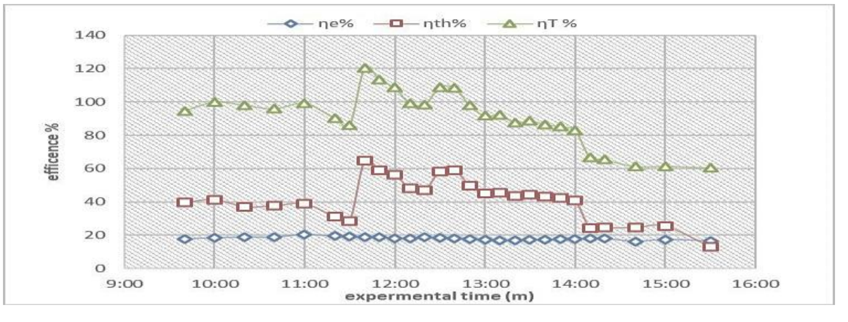

Figure 8 displays the CPVT system's power efficiency (ηe), thermal efficiency (ηth), and overall efficiency (ηT).

3.3 Efficiency of Membrane Distillation

3.3.1 Effect of Feed Water Temperature

With an average feed temperature of T_f1 = 42°C, Figure 9 indicates the variation in feed water temperature throughout the distillation process. A salinity of 1% (10g/L), feed and permeate water

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circulation flow rates of 0.6 and 0.3m3/h, and the injection of cold fresh water TP1 into the saturate channel at temperatures that varied between 20 to 23°C were all kept constant. These temperatures were used to forecast permeate water mass flux, heat flux across the membrane, and thermal energy consumption using the mathematical model. It took about 3 hours for the water temperature in the storage tank to stabilize and attain a steady-state level. Furthermore, Figure 5.16 demonstrates theway radiation affects the concentrated thermal pv system, which generates heat at the CPV/T's base. The temperature differential between feed water inlet and outlet is observable.During the initial phase of the experiment, there was a temperature difference of approximately 5 to 6°C between permeate water inlet and outlet. This disparity gradually diminished to approximately 2°C after approximately 3 hours of experimental runtime. Moreover, the permeate water temperature experienced a slight increase from 20°C to23°C, representing heat loss in the membrane distillation process. Ultimately The water mass flux averaged 5 kg/m2 per hour.

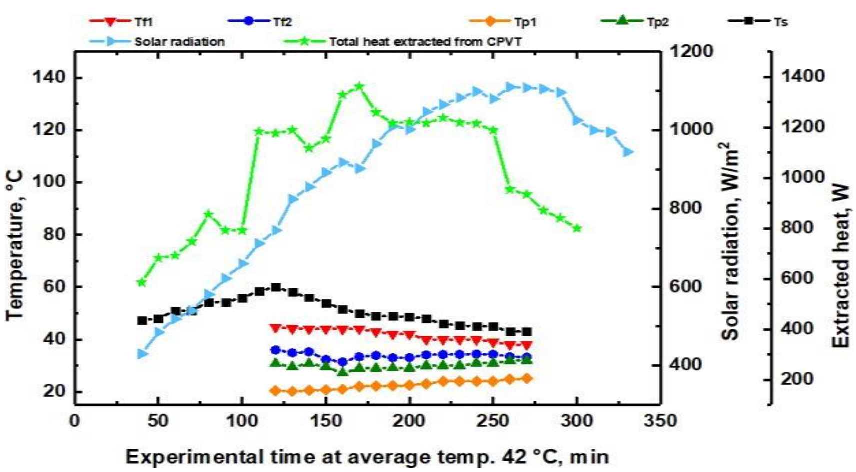

Figure 9 illustrates the temperature change at T 42 Cthroughout the distillation process.

The relation of the value of thermal energy generated by CPVT and the resulting feed water temperature is displayed in Figure 9. In the scenario where a higher extractionvolume is permitted It is clear that

as the energy levels reachto an average of 1000 W, the collection tank's temperature steadily increases to 60°C. As a result, the initial feed water temperature (Tfin) increases to 44°C, indicating the potential for membrane distillation (MD) processes. The peak temperature is reached around 2 hours into the MD operation, and the system maintains a steady state for an additional 3 hours. This temperature differential of approximately 15 degrees between feed and permeate water generates the necessary driving force to achieve a permeate water production rate of 3.7 kg/m²/hr. Also, the increased energy extraction speeds up the process at first, leading the feed temperature to start dropping after around 2 hours after the experiment's start. This depiction encapsulates a total experimental timeframe of approximately 6 hours, showcasing the most productive daylight hours. The thermal energy extraction from the CPVT is illustrated in Figure 10 while the mean feed water temperature becomes 35°C. The graph illustrates that the experiment achieved a steady-state process in under 2 hours. This relatively quick attainment of stability is attributed to the elevated thermal energy consumption, which was at 1350 W in comparison to previous experiments. Moreover, the water temperature in the tank stays constant.
At 60°C, with the other temperatures in the experiment remaining consistent throughout.

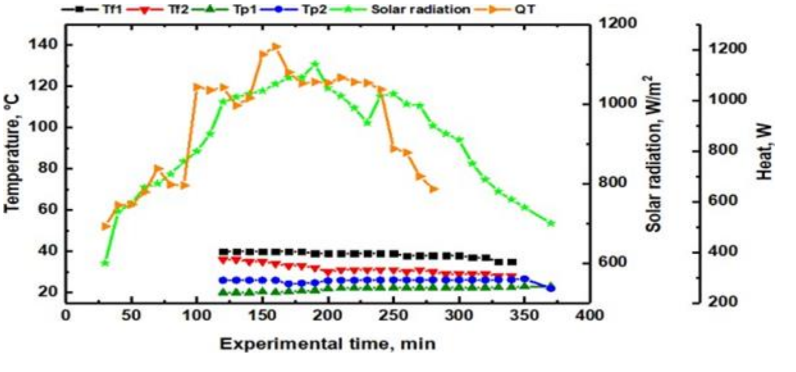

Figure 10. The temperature fluctuationexperienced throughout the distillation process lastly

Figure 11 shows that in the last trial, when the CPVT was capable of delivering, a lower feed water temperature of 30°C was achieved. (1). Notably, the graph also reveals an experimental duration of approximately 6 hours and 40 minutes,

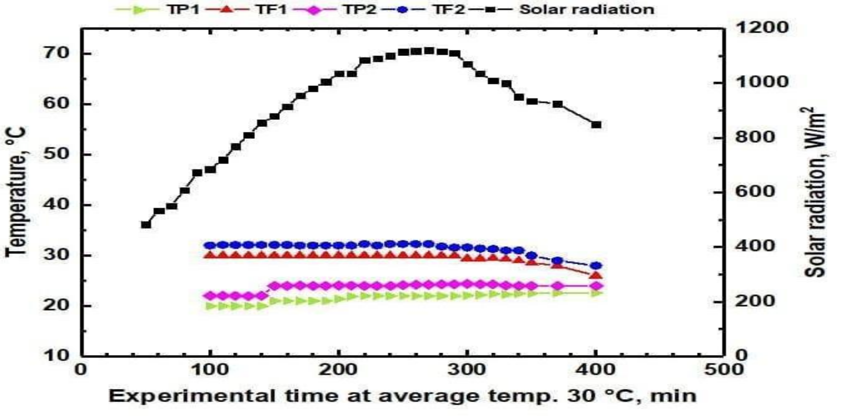

Figure 11 the temperature fluctuation at 30°C within thedistillation process

3.3.2 Impact of Feed Water Concentration

One factor that might have a variety of consequences on the membrane distillation (MD) technique is the concentration or salinity of the water. By penetrating the surface and filling the membrane pores with salt precipitation, it has the potential to reduce the membrane permeability. Additionally, higher concentrations require more energy, particularly at the membrane-water interface, which leads to in the temperature polarization phenomena. As a consequence, the temperature difference across the feed and permeate water streams is minimized. A collection of trials carried out at various concentrations and settings is shownin Table 2. It is clear that the CPVT system can produce an average of 6 kg/m2/hr of fresh water at lower concentrations and higher feed temperatures.

Table 2. Experiments with different amounts

Water concerted / Feed temperature	1 %	1.3 %	1.5 %
30°C	2.50	2.30	1.90

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35°C	3.90	3.50	3.40
38°C	4.60	4.20	4.0
40°C	5.60	5.20	4.9
42°C	5.90	5.40	5.1

The three sets of studies performed at concentrations of 1%, 1.3%, and 1.5% are compared, and it is shown that therewas a little decrease in water flux during operation. Figures 12 show this, the graphs illustrate a decline in water production with an increase in concentration. However, this reduction is not substantial, considering that the system still achieves a high mass flux rate while maintaining reasonable energy consumption levels. Additionally, the change in water flux appears to exhibit a slightly exponential trend rather than a linear one. The three sets of studies performed at concentrations of 1%, 1.3%, and 1.5% are compared, and it is shown that therewas a little decrease in water flux during operation.

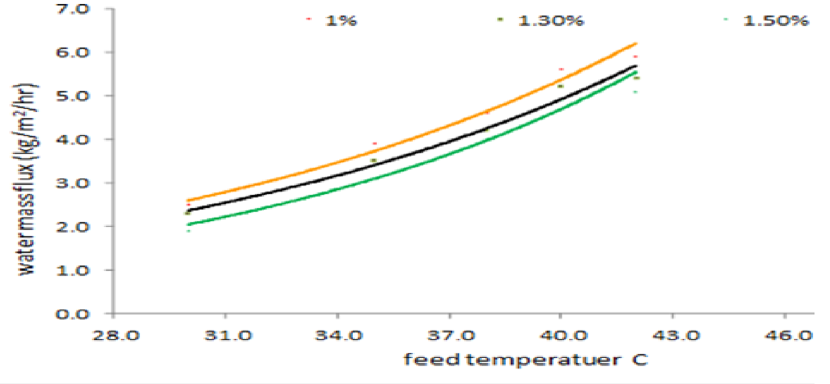

Figure 12 depicts the relationship between varying feedwater concentrations and the resulting mass flux.

3.3.3 CPV/T and Membrane mathematical representation (DCMD)

We applied the MATLAB program in order to validate the outcomes. Figures 13 and 14, show case the model validation using various experiments and conditions. If it water temperature becomes 40°C, the model's forecast of the mass flux continuously stays slightly below the experimental values. By this point, the theoretical mass flux slightly outperforms the experimental data, indicating an expected rate of increase as the feed water increases in temperature. Figure 14 highlights that the 1% concentration experiment demonstrates greater mass flux compared to both experimental and theoretical values at 30°C, measuring 2.3 kg/m2/hr and 2.5 kg/m2/hr, correspondingly. Discrepancies between experimental and theoretical readings can be attributed, in part, to the impact of temperature polarization at elevated feed water temperatures. The amount of heat available for water evaporation reduces as a consequence of the thick thermal layer at the membrane surface absorbing an increasing amount of the energy from the hot stream. At 42°C, the theoretical prediction is 6.3 kg/m²/hr, while the experiment records 5.9 kg/m²/hr.

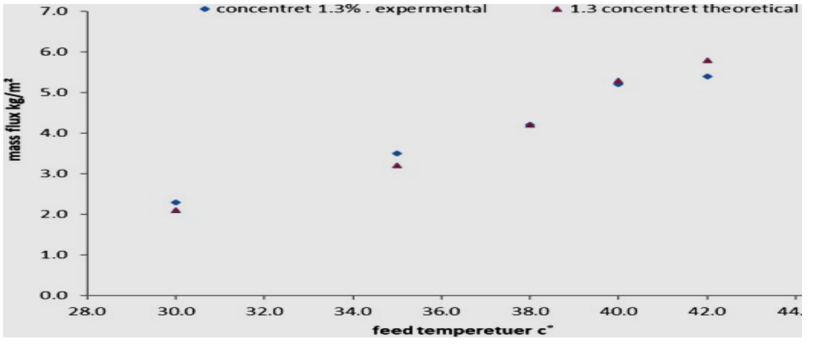

Figure 13 Temperature and mass flow of the feed -water at 1.3% Concentrate

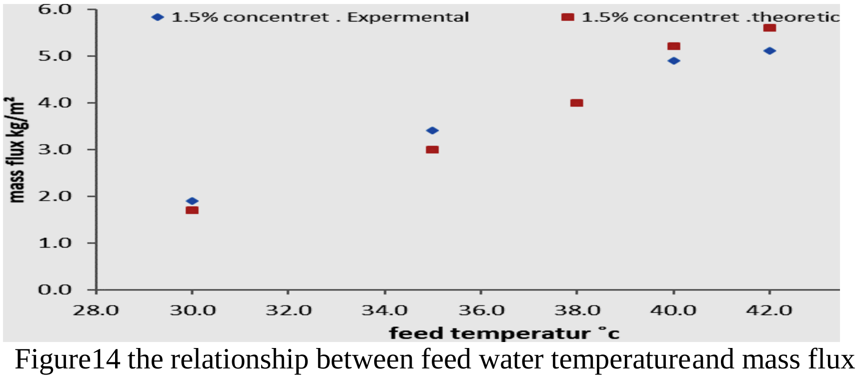

Figure14 the relationship between feed water temperatureand mass flux for a 1.5% concentration in the membrane distillation process.

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In Figure 15, the relationship between the energy consumed by the DCMD unit and the resulting production of fresh water is depicted. This energy consumption rate demonstrates an increase either due to higher feed water temperatures or increased saline water concentrations. The CPVT unit exhibited a minimum energy generation of approximately 1200 W, which translated to a freshwater production rate of 2.5 kg/m²/h when the solution concentration was 1%. Conversely, the maximum energy consumption per square meter of the membrane was recorded at around 6000 W/m², leading to a production rate exceeding 6 kg/m²/h. As a result, we can estimate the specific energy consumption for this combined CPVT and DCMD model to be roughly 1 kW/m² of thermal energy per 1 kg/m² of fresh water produced in a single hour of operation during sunny periods. This provides a useful benchmark for understanding the energy-water relationship in this particular configuration.

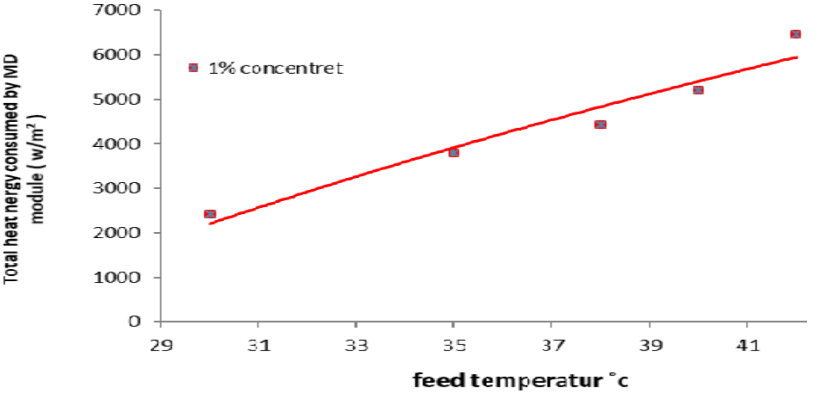

Figure 15 the DCMD unit's usage of energy, focusingspecifically on the case where the concentration is 1%.

4- Conclusion

1- The computer model accurately predicted both water mass flux and total heat transfer rates, showcasing a commendable alignment with the experimental data.

2- The experimental findings displayed a remarkable concurrence, with an accuracy exceeding 85%, when compared to predictions based on the Knudsen diffusion model—a mechanism that holds prominence in this context.

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3- The mass flux exhibited variability, ranging from a peak of 6 L/m²/h at the close of June 2018 to 3 L/m²/h by the end of November 2018, specifically when the feed water concentration stood at 1%.

4- Feed water concentrations of 1.3% and 1.5%, the corresponding freshwater production rates were approximately 5.5 L/m²/h and 5 L/m²/h, respectively.

5- The mass transfer component of overall heat transfer increased as the difference in temperature increased.

6- The hybrid system coupling Direct Contact Membrane Distillation (DCMD) with Concentrated Photovoltaic- Thermal (CPV/T) demonstrated an indirect linkage through its wall heat exchanger, resulting in sustainable freshwater production.

7- Maximum feed water temperature peaked at 43°C during daylight hours, while the hot water collection tank achieved 55°C. Depending on the temperature and concentration of the inflow feed water, this system's energy consumption ranged from 2000 kJ/kg to 9000 kJ/kg.

8- Thermal heat transmitted to water varied between 250 W and 570 W. The highest heat output from the panel reached 1350 W/m², manifesting about 60% of the total energy.

9- The peak energy sup-ply measured around 6000 W, facilitating the production of over 6 kg/m²/hr of fresh water. This leads to an estimated specific energy consumption of approximately 1 kW/m² of thermal energy for generating 1 kg/m² of fresh water within a single hour during sunny periods.

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