Heat Transfer Assessment of Solar Distillation System Coupled with Parabolic Concentrator and Phase Change Material

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Abstract *– The current study has evaluated the performance and effectiveness of a solar still with a configuration of single slope in conjunction with a novel parabolic collector for desalination. The primary goal is to enhance solar energy usage by incorporating a copper tube and these tubes are in the shape of helix in concentric tube configuration with the parabolic trough collector. The aim of both (innovative design and application of paraffin wax) is to increase thermal efficiency and prolong the desalination process's operating time. According to the experimental data, the glass temperature peaked at 55.1°C, the ambient temperature peaked at 47.3°C, and the temperature which is contained in basin has peaked at 70°C. Between the covering of basin and water contained in basin, the system's maximum convective heat transfer coefficient was 3.09 W/m².K, while its highest evaporative HT coefficient was 47.94 W/m².K. By using PCMs, yield production increased by 12.42%. These results demonstrate how well the system optimizes solar energy capture, which raises the yield of desalinated water and system efficiency. The study shows that innovative solar desalination technology can be used as a sustainable way to alleviate the world's water shortage.*

Keywords – Helical Shape Focal Tube; Parabolic Trough Collector; Solar Still Basin; Phase Change Material; Heat Transfer.

1. INTRODUCTION

Water is used in a wide range of contexts and is essential to life in residential areas, industry, and agriculture. Water makes up 71% of the planet's total mass, whereas land is home to humans and other creatures for the most part of the globe. About 97% total water available on planet earth contained by seas, whereas the remaining 3% share of water comes from freshwater found in lakes, rivers, and groundwater. There is enough water here to suit everyone's needs and the requirements of other living things. Because of this, it is quite challenging for everyone to access safe drinking water. However, the considerable global decline in freshwater supply is primarily the result of human activity. Water scarcity is turning into a major worldwide problem. PCMs are thought of as thermal energy storage materials that can be combined with desalination systems because they employ latent heat [1]. During hot climate days, the daily efficiency was 85.3%. ESM (energy storing material) with a concentrator was utilised by Chaichan and Kazem [2]. They discovered that the overall yield had improved by 306.54%. A number of strategies for using PCMs to optimise latent heat storage systems were provided by M.E. Zayed et al. [3]. A modified SS with a maximum yield performance improvement of 64% in comparison to CSS was studied by Sampathkumar et al. [4]. Deshmukh and Thombre [5] investigated various materials for energy storage and succeeded in reaching a maximum water temperature of 83 °C. For sensible energy storage, A.E. Kabeel et al. [6] combined a SS with a material with a high thermal conductivity. In order to gather high-quality desalted water, concentrator aided systems offer a variety of opportunities for creative research. After integrating an inclined parabolic collector, S. Gorjian et al. [7] achieved a temperature of 150.7 °C. R.S. Subramanian et al. [8] increased output by 92.55% by the application of flat plate. A semi-circular collector was invented by R. Sathyamurthy et al. [9] in order to achieve a 16.66% increase in output. When a solar still and parabolic trough concentrator were tested, it was found that a temperature of more than 80°C could be easily achieved. R.S. Subramanian et al. [10] increased output by 92.55% using an economical flat plate collector. Single slope SS with a PTC and evaluated energy efficiency of and 42.12%. The intended outcome of this work is to use a newly constructed PTC and a single sloping solar still to experimentally evaluate the desalination process. Increasing the amount of solar energy utilised is the goal of the helical-shaped concentric copper tube that is inserted into the parabolic collector. The system performs better when a heating tube with a helical design has more surface area accessible for heat exchange. The utilization of a solar still and a parabolic reflector to increase efficiency makes this job novel. The creative approach of research may be evaluated by using the new collector design with copper tubes bended in helical shapes. The change indicated above increases the surface area for heat transmission. The PCM is paraffin wax. Furthermore, adding PCM broadens the energy storage system's operating temperature range. As a result, the desalination system's total efficiency and useful lifespan can be improved.

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2. MATERIALS AND METHODOLOGY

The parabolic collector utilized in this experiment was made of aluminum sheet coated with silver, which directed incident solar radiation down its focal line. A dark-colored surface of basin absorbs sunlight. Thermocouple of type K is used for all temperature based measurements. The HTC sun Power Meter is used to monitor sun radiation during experiments. Table 1 lists the characteristics of phase change material used such as paraffin wax, which is utilized as a material for energy storage. The selection of materials is determined by their cost-effectiveness and availability.

Table 1: Property details of energy storage material (Paraffin Wax) [1].

Property	Value
Melting Point	331 K
Specific Heat	2480 J/kgK
Density	910 kg/m^3
Conductivity	0.22 W/mK
Latent Heat	210 kJ/kg
Boiling Point	643

3. EXPERIMENTAL SETUP

It has been decided to manufacture and test a solar still basin and parabolic collector at Gorakhpur, (26.76° N, 83.37° E). The basin area employed in the solar desalination system amounts to 744 inch^2 (33.46 x 22.05). A copper tube in helical shape is used in this experiment. These tubes have concentric tube configuration. Effective heat transfer is facilitated by the copper tube. These heat transactioning tubes are of two different dimensions. The small size tube which has been used in this experiment is 0.24 inches, whereas the other tube of higher dimension has numeri value of 0.63 inches. The tube's length is 35.43 inches, providing an adequate surface area for heat exchange as the fluid flows through it. Additionally, the setup includes a parabolic reflector, which focuses sunlight onto the copper tube to enhance heat absorption. The reflector has a length of 44.29 inches, a width of 59.06 inches. The focal length is 8.46 inches, which is the distance from the reflector to the point where the sunlight converges. These dimensions are critical for optimizing the system's efficiency by maximizing the concentration of solar energy onto the copper tube. The diametric diffrence between the tubes is utilised to fill with PCM. Schematic diagram of experimental setup is illustrated in Fig. 4, while Fig. 5 illustrates the real time view.

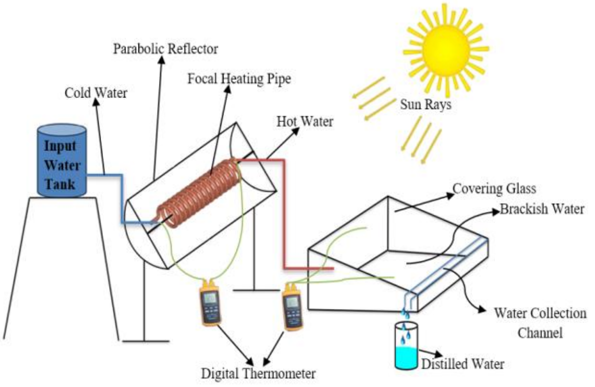

Fig. 1: Schematic view of setup utilised for experiment.

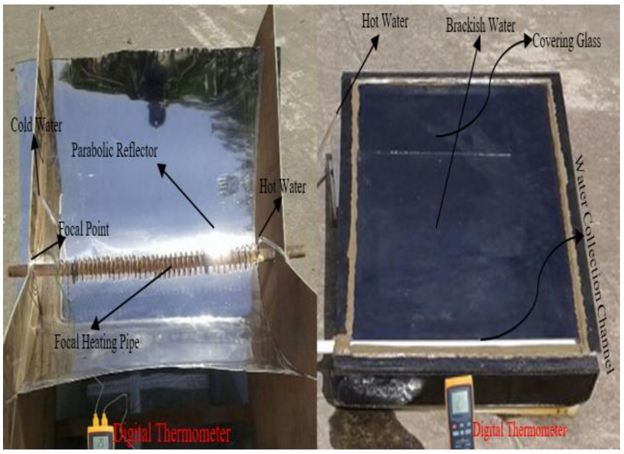

Fig. 2: Actual view of experimental setup.

4. ANALYTICAL FORMULATIONS AND MODELING

This section contains the quantitative formulas that control the solar desalination system's thermal dynamics. The convective HT, evaporative HT, and radiative HT mechanisms between the system components are all explained by using these formulations. The system performance under various operating situations is analyzed and predicted using the derived equations.

The following is an expression of the convective heat transfer coefficients [1]:

$$h_{conv,(wt,gl)} = 0.884\left[\left(T_{wt}-T_{gl}\right) + \frac{(T_{wt}+273.15)\left(P_{wt}-P_{gl}\right)}{(268900-P_{wt})}\right]^{\frac{1}{3}} \quad (1)$$

Evaporative heat transfer coefficients is defined as below

$$h_{evap,(wt,gl)} = 16.27\times10^{-3} \times h_{conv,(wt,gl)}\left[\frac{\left(P_{wt}-P_{gl}\right)}{\left(T_{wt}-T_{gl}\right)}\right] \quad (2)$$

P_{wt} , Partial pressure measured at water temperature for saturated vapour

P_{gl} , Partial pressure measured at glass temperature for saturated vapour [1]:

$$P_{wt} = e^{\left(25.314 - \frac{5144}{T_{wt}+273.15}\right)} \tag{3}$$

$$P_{gl} = e^{\left(25.314 - \frac{5144}{T_{gl}+273.15}\right)} \tag{4}$$

The coefficients of radiative heat transfer can be expressed as follows [1]:

$$h_{rad,(wt,gl)} = \varepsilon_{eff}\left[T_{wt} + T_{gl} + 546\right]\sigma\left[(T_{wt} + 273.15)^2 + \left(T_{gl} + 273.15\right)^2\right] \tag{5}$$

Total Effective Emissivity of system is used in the analysis and it can be evaluated as follows [1]:

$$\varepsilon_{eff} = \left(\frac{1}{\frac{1}{\varepsilon_{wt}} + \frac{1}{\varepsilon_{gl}} - 1}\right) \tag{6}$$

ε_{wt} , emissivity of water; ε_{gl} , emissivity of glass cover
The expression determines the radiative heat transfer coefficient through taking into account the variation in thermal radiation that the sky and the glass surface emit [8].

$$h_{rad\_gl,am} = \frac{\varepsilon_g \sigma\left(\left(T_{gl} + 273\right)^4 + \left(T_{sky} + 273\right)^4\right)}{\left(T_{gl} - T_{sky}\right)} \tag{7}$$

The radiative heat transfer is computed using this formula ($q_{rad,\ gl,am}$) between glass cover surface and sky [8].

$$q_{rad\_gl,am} = h_{rad\_gl,am} \times \left(T_{gl} - T_{sky}\right) \tag{8}$$

This equation provides an estimate of the effective T_{sky}, which contains the term of ambient air temp. (T_{am}) [8].

$$T_{sky} = 0.0552 \times T_{am}^{\ 1.5} \tag{9}$$

This equation calculates heat transfer coefficient ($h_{conv,\ gl,am}$) for the convective HT from the glass surface when the wind speed (V) is greater than 5 m/s [9].

$$h_{conv\_gl,am} = 5.7 + 3.8V \qquad V>5 \tag{10}$$

This equation is used when the wind speed is 5 m/s or less [9].

$$h_{conv\_gl,am} = 2.8 + 3.0V \qquad V\leq 5 \tag{11}$$

The convective heat transfer is computed utilizing this formula ($q_{conv,\ gl,am}$) between the surrounding air and the glass surface [9].

$$q_{conv\_gl,am} = h_{conv\_gl,am} \times \left(T_{gl} - T_{am}\right) \tag{12}$$

The coefficient of entire loss of thermal heating energy take place from glass covering to ambient surrounding is provided as [9]

$$h_{t\_gl,am} = h_{conv\_gl,am} + h_{rad\_gl,am} \tag{13}$$

The entire value of heat lost take place to the ambient and which passes through glass covering can be written as follows [9]:

$$q_{t\_gl,am} = q_{rad\_gl,am} + q_{conv\_gl,am} \tag{14}$$

5. RESULTS AND DISCUSSION

In the solar desalination experimental setup, the temperature variations observed throughout the day are closely linked to the diurnal solar radiation cycle in **Fig. 3**. The ambient temperature rises from 34.9°C at 08:00 AM to a peak of 47.3°C at 1:00 PM, before gradually decreasing to 34.1°C by 20:00. The basin water temperature starts at 36.8°C at 08:00 and achieves its highest point of 70°C at 13:00, after which it decreases to 35.2°C by 20:00. Similarly, the glass temperature has started rising from 33.8°C at 08:00 AM to 55.1°C at 15:00, then drops to 33.1°C by 20:00. The greatest increment in water temperature is caused by the constant absorption of solar radiation energy obtained from sun, peaking later than the ambient temperature. Whereas the glass temperature lags slightly behind, influenced by both the heated water and ambient air. The overall pattern demonstrates typical solar desalination behavior, where peak water temperature coincides with the highest solar radiation, facilitating optimal evaporation.

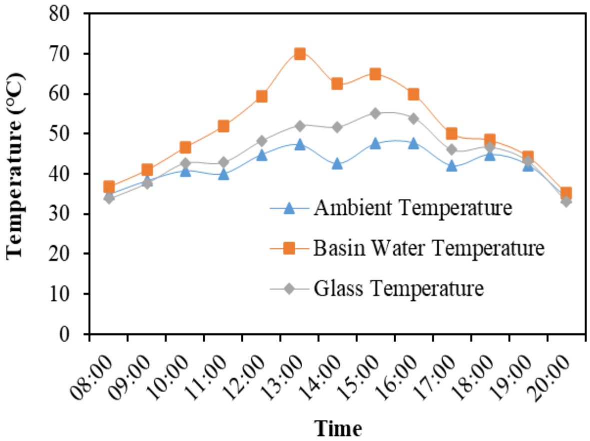

Fig. 3: Thermal behaviour of ambient air, water contained in basin, and glass: a comparative study.

Fig. 4: show the variation in wind speed throughout the day in the solar desalination experimental setup significantly affects the temperature of system by influencing convective HT. In the morning, wind speed increases from 2.11 m/s at 08:00 to 4.61 m/s at 10:00, enhancing loss of heat taking place in convective manner from the glass surface and likely reducing the glass temperature. At 11:00, wind speed drops back to 2.11 m/s, reducing convective cooling and potentially allowing the glass temperature to rise. Around midday, wind speed fluctuates, reaching a low of 0.69 m/s at 13:00, which would minimize convective heat loss and result in higher glass temperatures. However, as wind speed increases again to 3.39 m/s at 15:00 and 4.39 m/s

at 16:00, convective cooling intensifies, leading to a decrease in glass temperature. In the late afternoon and evening, wind speed varies, peaking at 4.00 m/s at 19:00 before slightly decreasing to 3.75 m/s at 20:00, which promotes convective cooling and helps lower the glass temperature even further as the outside temperature starts to decline. This pattern highlights the significant role of wind speed in modulating the temperature of the system.

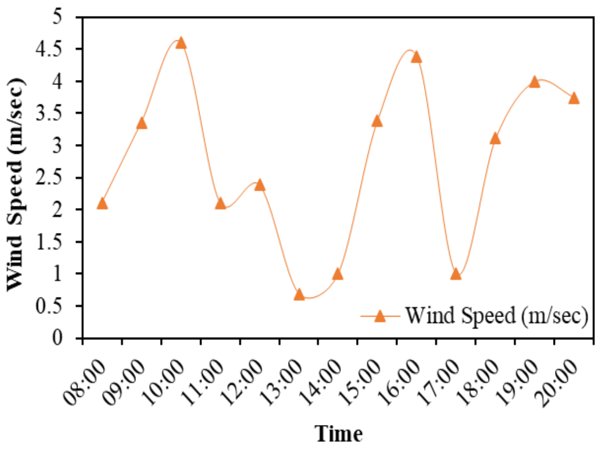

Fig. 4: Time-Based Analysis of Wind Speed During Experiments.

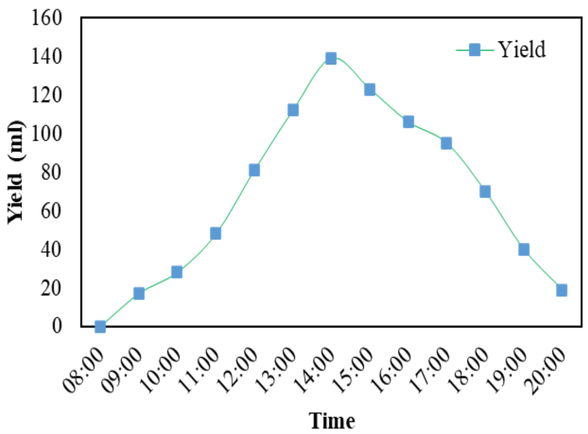

Fig. 5: Yield output variation of experimental setup

Fig. 5 shows yield output of the solar desalination experimental setup varies throughout the day. The yield closely following the changes in solar radiation and temperature. The yield peaks at 139 ml at 14:00, coinciding with the period of maximum solar intensity and highest water temperature, which drives the greatest evaporation and condensation. After 14:00, the yield begins to decline, dropping to 123 ml by 15:00, 70 ml by 18:00, and finally down to 19 ml by 20:00 as solar radiation decreases and the system cools, reducing the evaporation rate. This variation highlights the dependence of the desalination yield on solar energy, with the highest outputs occurring during midday when temperatures and solar input are at their peak. The total output of yield obtained from the modified system is 878 ml. Applications of energy storage material exhibited 12.42% improvement in yield output as compared to without PCM coupled system. This system resulted an output yield of 781 ml [29] when PCM is not integrated.

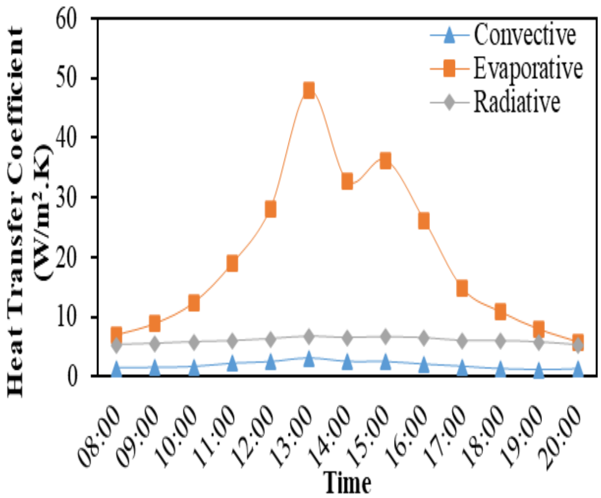

Fig. 6: Comparative study of HT coefficients between water contained in basin and glass cover of basin

Fig. 6 illustrates that the coefficients of HT between glass cover of basin and water in solar desalination system change during the day in different patterns. The coefficient of HT of convective manner increases from 1.412 W/m².K at 08:00 to a peak of 3.09 W/m².K at 13:00, before declining to 1.247 W/m².K by 20:00. The evaporative HT coefficient shows the most significant change, starting at 7.009 W/m².K at 08:00 and surging to 47.94 W/m².K at 13:00, then decreasing to 5.857 W/m².K by 20:00. The radiative heat transfer coefficient varies more gradually, rising from 5.322 W/m².K at 08:00 to 6.772 W/m².K at 13:00, and then reducing to 5.263 W/m².K by 20:00. The trends indicate that evaporative heat transfer is the dominant mechanism, particularly during midday when solar input is highest, while convective and radiative heat transfers play significant but secondary roles in the system's thermal balance. These variations reflect the interplay between solar radiation, temperature gradients, and phase change processes, crucial for the desalination efficiency of the setup.

Fig. 7 illustrate the fluctuations observed in coefficients of HT between glass cover and ambient surrounding in the solar desalination setup vary significantly throughout the day. The radiative heat transfer coefficient starts at 32.72 W/m².K at 08:00, decreases to a minimum of 23.62 W/m².K at 14:00, and then rises again to 32.93 W/m².K by 20:00. The convective heat transfer coefficient begins at 9.134 W/m².K at 08:00, peaks at 16.63 W/m².K by 10:00, drops to a low of 4.884 W/m².K at 13:00, and then increases to 15.97 W/m².K by 16:00. The total heat transfer coefficient follows a similar kind of trend, starting at 41.854 W/m².K at 08:00, peaking at 44.82 W/m².K at 10:00, dropping to 29.42 W/m².K at 14:00, and then rising to 46.98 W/m².K by 20:00. These variations indicate that radiative heat transfer is more effective during the morning and evening, while convective HT becomes more significant during the day. The midday reduction in heat transfer coefficients suggests a period of thermal equilibrium, where heat transfer is less effective as there is less temperature differential found between glass cover used with basin and the surrounding ambient conditions.

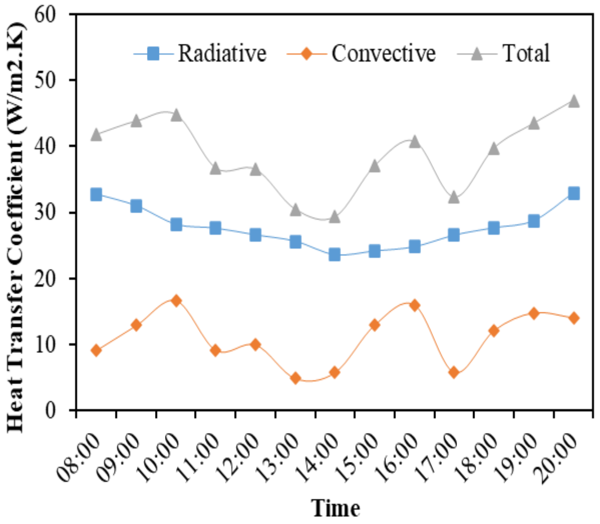

Fig. 7: Time-Based Variations in HT Coefficient Between Glass cover of basin and Ambient surrounding

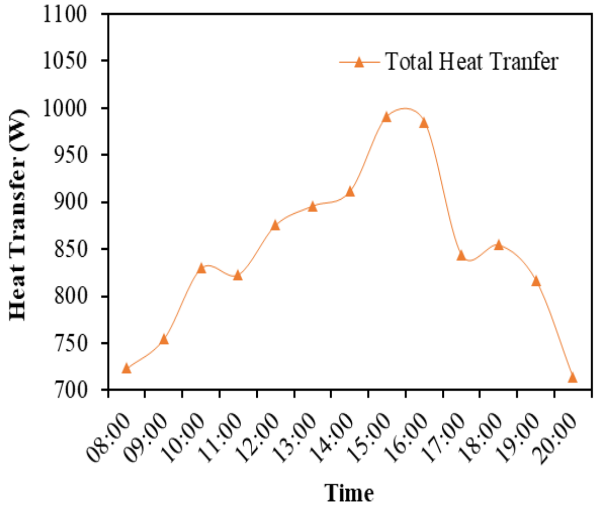

Fig. 8: Heat transfer variations between glass and ambient

Fig. 8 shows temperature variation between glass cover and ambient environment in solar desalination experimental setup is reflected in the heat transfer values, which show a distinct diurnal pattern influenced by solar radiation. From 08:00 to 16:00, the heat transfer increases from 723.55 W/m² to a peak of 991.28 W/m² at 3:00 PM, in adherence to the period of maximum solar radiation when the position of sun reaches at its highest point, intensifying the heating effect on the glass. After 16:00, the heat transfer begins to decrease, dropping to 985.41 W/m² at 16:00 and further to 817.12 W/m² by 19:00, reflecting the decline in solar radiation as the sun sets. By 20:00, the heat transfer value decreases to 713.95 W/m², indicating a decreased temperature differential between the glass and the surrounding atmosphere as a result of cooling effect during evening. This pattern highlights the direct relationship between solar intensity, glass temperature, and heat transfer, with the peak at 15:00 and subsequent decline illustrating the system's response to the natural cycle of solar heating and cooling.

6. CONCLUSIONS

In this experimental investigation of a solar thermal distillation system, a novel PTC utilized and coupled with a helical-shaped copper tube to enhance the performance and effectiveness of solar energy utilization. The ambient temperature rose from 34.9°C at 08:00 to a peak of 47.3°C at 1:00 PM, while the temperature of water which is contained by basin has increased from 36.8°C to a maximum of 70°C during the same period, facilitating optimal evaporation. The glass temperature peaked at 55.1°C at 15:00. The system's yield peaked at 139 ml at 14:00, closely aligned with maximum solar radiation, gradually decreasing to 19 ml by 20:00. The total desalination yield was 878 ml, showing a 12.42% improvement when energy storage materials were applied, compared to 781 ml without the PCM-coupled system. Heat transfer analysis revealed that the evaporative HT coefficient increased from 7.009 W/m².K at 08:00 to 47.94 W/m².K at 13:00, making it the dominant heat transfer mechanism, while the convective HT coefficient peaked at 3.09 W/m².K at 13:00 and coefficient of radiative HT reached 6.772 W/m².K at the same time. These results demonstrate that the system effectively harnesses solar energy for desalination, with significant temperature variations throughout the day driving the evaporation process. The incorporation of paraffin wax as PCM has enhanced the thermal storage capacity, extending the operational duration of the system. This study demonstrates the extent to which solar desalination systems can increase water yield and efficiency, providing a feasible method to deal with water constraint.

NOMENCLATURE

Abbreviations

CSS	Conventional Solar Still
Ne	Nano Enhanced
PCM	Phase Changing Material
SDS	Solar Distillation Systems
NP	Nano Particle
SS	Solar Still
PTC	Parabolic Trough Collector
HT	Heat Transfer

Symbols

A	Area (m^2)
h	Coefficient of Heat Transfer (Watt/m^2 K)
i	Rate of Interest (%)
I	Irradiation of solar energy (Watt/m^2)
L	Latent Heat (Joule/kg)
P	Partial Pressure of Saturated Vapour (N/m^2)

Q Heat (W)
q Heat ($Watt/m^2$)
T Temperature (°C)

Subscripts

am Ambient
conv Convective
evap Evaporative
eff Effective
gl Covering Glass
pc Parabolic collector
rad Radiative
t Total
wt Water

Greek Letters

ε Emissivity
σ Stefan-Boltzmann Constant

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