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Heat transfer studies on solar still assisted with and without latent heat storage material

V.S. Vigneswaran*, G. Kumaresan, S. Elansezhiyan, R. Velraj

Institute for Energy Studies, Anna University, Chennai 600025, India, emails: vignesrahul@gmail.com (V.S. Vigneswaran), gkumaresan75@gmail.com (G. Kumaresan), mech.mallakhamb@gmail.com (S. Elansezhiyan), velrajr@gmail.com (R. Velraj)

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ABSTRACT

The main objective of this work is to enhance the yield of solar still using the latent heat storage capacity of the phase change material (PCM) and to compare the distillate yield of PCM-assisted solar stills with that of the conventional solar still (Type A). In this regard, three solar stills of equal dimensions were designed, constructed and tested under identical weather conditions. In one of the solar still, 16 numbers of tubes having a diameter of 25.4 mm (Type B) were incorporated at basin, to accommodate the paraffin PCM, whereas in another solar still, PCM was embodied in between the annulus of the outer tube of diameter 31.75 mm and the inner tube of diameter 6.35 mm (Type C). The conventional solar still (Type A) was exclusively used for the comparison of the yield of the other two modified solar stills embodied with PCM. The daily freshwater productivity was 2.832 L/m^2/d for Type C still, while the productivity of Type B and Type A still were 2.592 and 2.228 L/m^2/d, respectively. This yield of Type C still corresponds to 6% and 27% higher than Type B and Type A stills, respectively. The higher yield in Type C still is due to the enhanced heat transfer surface and reduced thickness of the encapsulated PCM which offers less resistance compared with Type B solar still. Thus, it is construed that the geometry with PCM encapsulated in the annulus is the best option among the configuration considered.

Keywords: Solar desalination; Phase change material; Solar still; Charging process; Heat transfer enhancement

1. Introduction

Water is not only essential for human survival; also plays a vital role in maintaining a sustainable environment and economy. With about 80% global workforce relying on adequate access to water supply, the demand for water increases with the increase in global population [1]. Even today about 2.4 billion people do not have access to improved drinking water, resulting in 26% of childhood deaths and being the cause for 25% disease affecting children below 5 years [2].

About 1% of global population relies on desalinated water produced using high energy intensive process such as multiple effect distillation, multi-stage flash desalination, thermal vapor compression, mechanical vapor compression, reverse osmosis and electrodialysis [3]. These plants not only contribute to global warming but also are inadequate to satisfy the water demand of needy people. Hence, the need of the hour is to find out a decentralized system which makes use of renewable energy to satisfy the water demand. Solar still is a viable option for fresh water production because places experiencing water scarcity are generally blessed with high solar energy resources. The low cost and environmental friendly nature also makes them an attractive choice [4]. But the main drawback of conventional solar still is its poor yield. Though the yield of the solar still depends on operational and design conditions; environmental conditions such as solar intensity, wind velocity, etc. are out of human control [5]. The depth of water in the still is one of the predominant operating conditions which influence still output, with the depth needed to be maintained at minimum level to enable increase in the convective and evaporative heat transfer coefficient [6–9].

* Corresponding author.

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Much research work has been carried out on the enhancement of the yield of the solar still through changes in the design of the still using fins [10], wick material [11], dyes [12], suspended absorber plates [13,14], etc. The output of the solar still increased by 6.8% when their side walls was painted white [15]. The output of the still was higher when the inclination of the glass cover was equal to the latitude of the place [16]. The output of double basin still was higher than that of a single slope still [17] while the productivity of pyramid shaped still was lower than that of single slope still [18]. Efforts were also made to increase the yield of the solar still through use of sensible heat energy storage materials such as quartzite rock [19], washed stones, red brick pieces, cement concrete pieces, iron scraps, black granite gravel [20], charcoal [21], metallic wiry sponges [22], uncoated metallic wiry sponges, volcanic rocks and latent heat energy storage materials such as phase change material (PCM) [23,24]. Among these, latent heat energy storage was highly preferred to sensible heat storage due to its high storage density with a smaller temperature swing [25]. Amongst the available PCMs, paraffin wax was found to possess many desirable characteristics, such as high energy density, low vapor pressure during melting, chemical inertia, stability and non-toxicity [26]. But the main disadvantage of paraffin PCM is its poor thermal conductivity which results in charge/discharge of energy at a slower rate [27], leading to the requirement of heat transfer enhancement technique for implementation in PCM thermal storage applications. The encapsulation geometry also had an influence on the heat transfer rate during charging/discharging the energy stored in PCM [28]. Efforts were made to increase the thermal conductivity of paraffin by introducing metal beads in them [29]. Though the solidification/melting time reduced by 15% with the introduction of metal beads, there was a drop in energy storage capacity of paraffin with increase in number of metal beads. Increase in the heat transfer rate of PCM using stationary structures such as fins [30] and lessing rings [31] was reported. Increase in heat transfer rate of PCM is also possible by micro encapsulating PCM [32] and suspending nanoparticles in them [33,34]. However, the latent heat energy storage system used in solar still must be simple in construction and inexpensive as it is generally used in rural areas by low income people. Meanwhile, encapsulation of PCM in spherical and cylindrical geometries is not feasible as the water level in the still is usually maintained at around 2–3 cm. Hence, in this work, the PCM was enclosed in two different tube geometries.

2. Experimentation

In this study, three different single slope passive solar stills were designed and fabricated (as shown in Fig. 1) and their yields were compared. The basin of the solar still was made using a galvanized iron sheet with a thickness of 1.5 mm; the bottom of the basin was painted black using matte paint. The side walls of the still were coated with silver paint to enable reflection of solar radiation falling on it back to the absorber plate. The area of the absorber was 0.5 m^2. A transparent glass sheet of thickness 4 mm was used for enclosing the still at the top. The glazing was placed in such a way as to help that its tilt angle matching the latitude of Chennai, (13.01°N, 80.24°E) located at southern part of India. The still was made air tight by sealing the system using silicone sealant. A channel made of galvanized iron was affixed to the lower end of the glazing for collection of the distillate output. The still was insulated on its side and bottom using plywood of thickness 25.4 mm; the 30-mm gap between the basin and plywood was filled with saw dust.

The paraffin PCM incorporated with solar still was used for the storage of the excess heat energy available during sunshine hours. The differential scanning calorimetry (DSC) analysis of the PCM chosen for this study was done using Mettler Toledo – MT DSC2 instrument at a scanning rate of 1°C/min which is shown in Fig. 2. The thermo-physical properties of paraffin wax used in the experiment is shown in Table 1. The organic paraffin wax chosen was meant to enable storage of its energy was stored as latent heat, when the paraffin wax started to change from solid to liquid state at 55.1°C.

The Type A still, an ordinary conventional passive solar still, was taken and used for base reference. In Type B solar still, PCM was encapsulated inside a galvanized iron tube of length 0.69 m and diameter 25.4 mm. Each tube was filled with PCM to ensure 85% of its fill volume by PCM after solidification.

Fig. 1. Photographic view of (a) Type A, (b) Type B and (c) Type C.

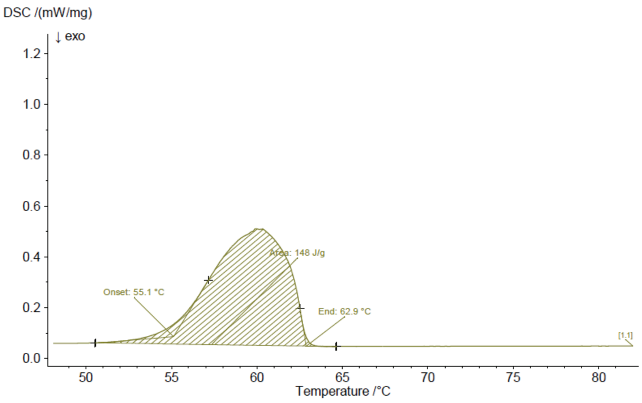

Fig. 2. DSC analysis of paraffin.

Table 1
Thermo-physical properties of paraffin PCM

Phase change temperature range (°C)	Latent heat of fusion (kJ kg^{-1})	Density (kg m^{-3})	Specific heat (J g^{-1} K^{-1})	Thermal conductivity (W m^{-1} K^{-1})
57–58	205	920	2,140	0.24

190 g of PCM was filled in each tube and the ends were sealed from leakage (as shown in Fig. 3(a)). 16 numbers of galvanized iron tube painted black and filled with paraffin PCM were placed in the second still. The same amount of PCM was taken in the Type C still but was encapsulated in the annulus of 31.75 mm diameter tube and 6.34 mm diameter tube (as shown in Fig. 3(b)). 16 such tubes filled with PCM in its annulus was placed in Type C still, to ensure the presence of the same amount of PCM in both Type C and Type B solar still.

RTD PT-100 sensors were used for measurement of the temperature of the absorber plate, water, air gap, PCM, inner and outer surface of glazing. The accuracy of RTD transducer temperature conversion of the data logger was ±0.02°C. HP Agilent 34970A, data acquisition system was used for recording the temperature data at a scanning rate of 30 min throughout the experiment. The solar radiation was measured using pyranometer HUKSEFLUX CPO2 of accuracy ±1%. The experiments were carried out at the Institute for Energy Studies, Anna University, Chennai, India, during the year 2017 from 10th February to 2nd June. The still was filled with 12.5 kg of water before the start of experiment at 10:00 h and was refilled with water every half an hour based on the distillate output of respective stills. The uncertainty analysis was estimated by the error propagation method proposed by Strupstad [35] and the same are presented in Table 2. The sensitivity/accuracy of the measuring instruments used in the present study and the minimum value of the measured parameters were used to calculate errors.

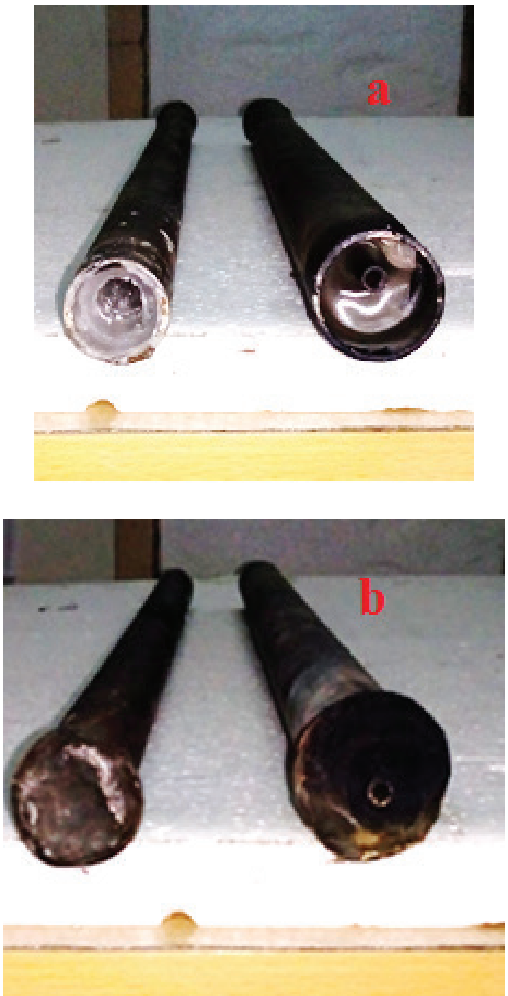

Fig. 3. Photographic view of PCM encapsulated in 25.4 mm tube and annulus of 31.75 mm and 6.35 mm (a) before encapsulation, (b) after encapsulation.

3. Results and discussion

The intensity of the solar radiation varied from 150 to 792 W/m^2 during the period of the experimentation. The performance of the solar stills with PCM and the conventional solar still was tested with the same mass of water under identical ambient conditions.

Solar radiation absorbed by the absorber plate predominantly determined the performance of the solar still. It was observed from Figs. 4–6 that the ambient temperature and solar radiation increase and reaches the maximum value at mid-day and a gradual decrease from there on. Fig. 4 shows the variation in basin water temperature, air gap temperature and the glass temperature both at the top and bottom with respect to time for Type A solar still. In case of Type B solar still it is seen

Table 2
Uncertainty in measured and derived parameters

Measured parameter	
Length	±0.2%
Temperature	±0.3%
Solar radiation	±1%
Weight	±4.54%
Derived parameter	
Partial pressure for water vapor at water surface	±0.3%
Partial pressure for water vapor at interior glass surface	±0.3%
Evaporative heat transfer coefficient	±0.92%
Efficiency	±4.65

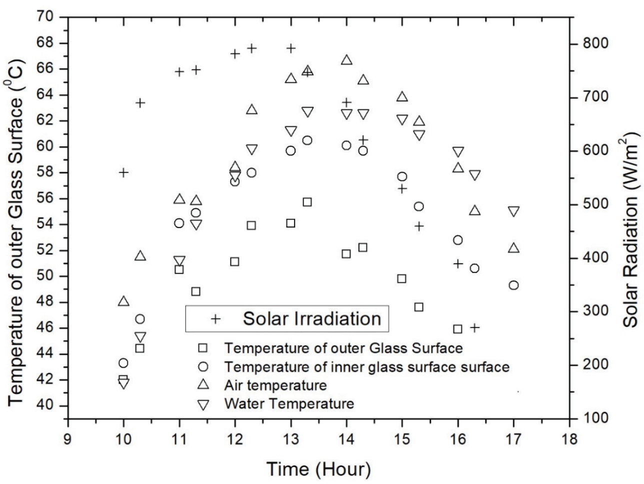

Fig. 4. Hourly solar radiation and temperature profile of Type A solar still.

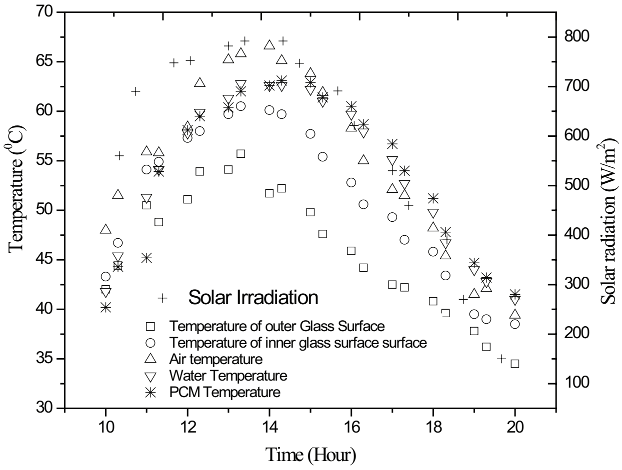

Fig. 5. Hourly solar radiation and temperature profile of Type B solar still.

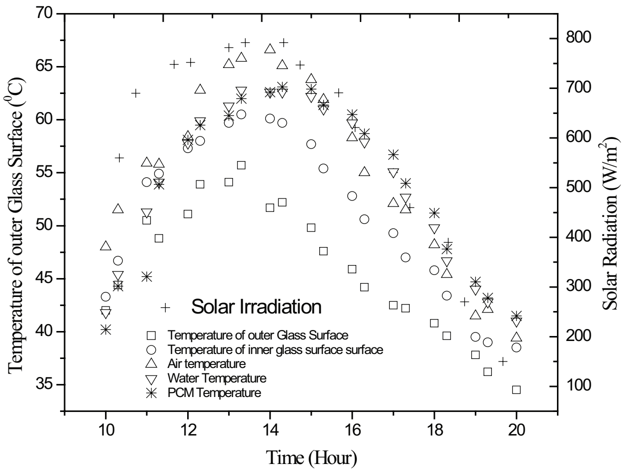

Fig. 6. Hourly solar radiation and temperature profile of Type C solar still.

from Fig. 5 that the maximum basin water temperature was about 63.4°C, while the PCM temperature, inner glass and the outer glass temperature were in the ranges of 43°C–63.1°C, 37.2°C–61.4°C and 34°C–55.7°C, respectively. Fig. 6 shows the maximum water temperature was about 62.8°C for Type C solar still, while the PCM temperature, inner glass and the outer glass temperature were in the ranges of 40.2°C–63.1°C, 38.5°C–60.5°C and 40.4°C–57°C, respectively. On the other hand, the maximum basin water temperature was about 69.4°C for the Type A solar still, while the inner and the outer glass temperatures were in the ranges of 45.1°C–66°C and 34.5°C–55.7°C, respectively. Solar stills with PCM generated fresh water even after sunshine hours because the PCM discharges the thermal energy stored in them only during off sunshine hours.

3.1. Distillate production

Fig. 7 shows the comparison between, fresh water productivity for all the three stills during the period from 10:00 h to 20:00 h. Solar still output depends on the solar radiation absorbed by it. Hence, the increase in solar radiation reaches its stated

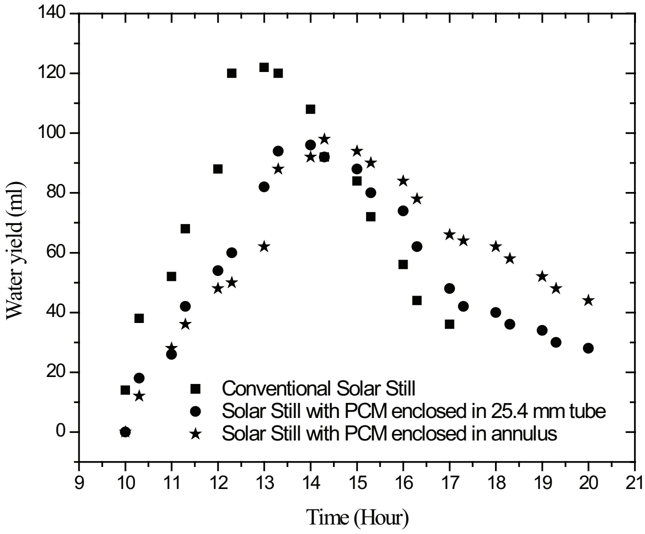

Fig. 7. Hourly yield of solar stills.

peak around 13:00 h as the day progressed and starts declining from thereon. This results in increase in the output of Type A still up to 13.00 h, and a decline started later and the still produced no distillate water after 17.00 h. The output of Type A solar still was higher than the output of the other two stills until 14.30 h as part of energy was stored in PCM both in the form of sensible heat and latent heat which affected the yield of solar stills. The output of the Type C still was less initially when compared with the output of Type B still, considering the requirement of more amount of energy for increasing the temperature of the encapsulation tubes, on whose annulus, the PCM was filled when compared with 25.4 mm tube. The PCM in both the still attained the maximum temperature of 63.1°C during the charging. Even the output remained almost equal during the charging span for both the stills. But Type C still discharged energy at a much faster rate than the Type B still. This is due to the evaporative heat transfer rate being 11% higher during discharge period (15:00 h to 20:00 h) for Type C still compared with Type B still. The above statement can be inferred from the higher temperature difference between the water and the inner glass cover in Type C solar still resulting in higher productivity of water. The temperature of PCM in annulus was lower than that of the PCM enclosed in 25.4 mm tube during discharge, as the thermal resistance caused by solidified PCM near the encapsulating surface was lower in Type C still. The maximum thickness of the solidified PCM near the encapsulation material surface was 12.7 mm for Type B solar still, whereas this thickness was only 6.35 mm for Type C solar still. This not only resulted in drop in thermal resistance due to the decrease in the thickness of the solidified PCM near the encapsulation material surface but also increased the surface area available for heat transfer between water and PCM.

The evaporation rate of both the Type B and Type C solar still was 27% higher compared with Type A still during 15:00 h to 17:00 h when the PCM started discharging its stored energy. This caused an inconsequential difference between the output of the stills with PCM during daytime as shown in Fig. 8. But there was an increase in the productivity of the Type C still during nocturnal hours due to the availability of surface area for heat transfer between PCM and water which

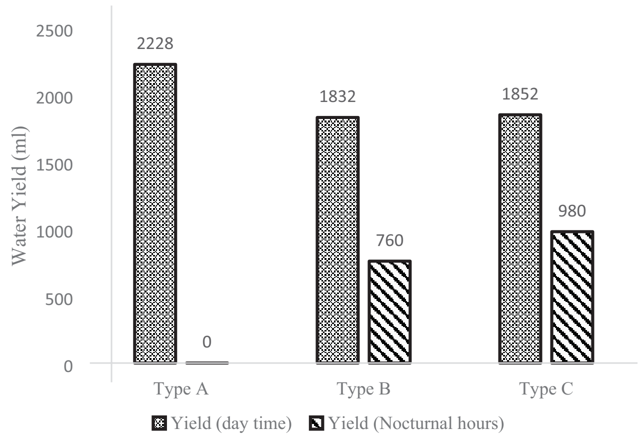

Fig. 8. Yield of the still during day time and nocturnal hours.

was 0.083 m^2 in this still and much higher than 0.055 m^2 surface area available in for PCM enclosed in 25.4 mm tubes resulting in higher evaporation rate during 17:00 h to 20:00 h. The output of Type C still during nocturnal hours was 29% higher in comparison with Type B still.

The conventional passive solar still produced yield of 2.228 L/m^2/d though the stills with PCM produced water of lesser quantity during sunshine hours as against conventional passive still. However, the overall yield of these (Type B and Type C) stills per day was higher due to its extended operation during the nocturnal hours. The yield of Type B and Type C solar stills was 2.592 and 2.832 L/m^2/d, respectively. Thus, the overall output of the Type B and Type C still increased by 21% and 27%, respectively, when compared with Type A solar still. The efficiencies of the Type A, Type B and Type C stills were 33.4%, 38.8% and 42.4%, respectively.

4. Conclusion

In the present work, a comparison has been made between the enhancement achieved in the distillate yield obtained from the solar stills assisted with PCM with the yield obtained from the conventional solar still. PCM was encapsulated in the solar still in two different geometries and experimental investigation of its effect on solar still performance was made under the weather conditions of Chennai city (India). During the period of low intensity solar radiation and after the sunshine hours, the encapsulated PCM acted as a heat reservoir for the basin water, thereby helped in maintaining a higher temperature difference between water and the inner glass cover. The recommendation made from the results obtained from the experimental study is that encapsulating the PCM in a geometry with higher surface area will produce an appreciable enhancement in the distillate water production also during non-sunshine hours. The following conclusions were arrived at based on the experimental results.

- The daily freshwater productivity of the Type B solar still and Type C solar still is higher than that of the Type A solar still by 21% and 27%, respectively.
- Type C solar still possessed a higher efficiency (42.4 %) compared with the efficiency of Type B (38.8%) and Type C solar still (33.4%).
- The evaporation rate of Type B and Type C solar stills is 27% higher than Type A solar still when the PCM discharges the energy between the period 15:00 h and 17:00 h. The evaporation rate of Type C solar still is 11% higher than Type B.
- To be specific, the yield of Type C solar still during non-sunshine hours was 29% higher than Type B solar still, as the thermal resistance caused by solidified PCM near the encapsulating surface was lower in Type C still. The drop in thermal resistance is due to the decrease in thickness of solidified PCM near the encapsulation material surface. Thus, it is construed that the geometry with PCM encapsulated in the annulus is the best option among the configuration considered.

Therefore, it is recommended to pack the PCM in an encapsulation geometry which not only has higher surface area for heat transfer to reduce the charging/discharging span but the thickness of solidified PCM near the encapsulating surface should be lower to decrease the thermal resistance caused by it during discharging process.

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