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Phase Change Material on Augmentation of Fresh Water Production Using Pyramid Solar Still

S. Ravishankar[a]*, P.K. Nagarajan[b], D. Vijayakumar[c] and M.K. Jawahar[c]

[a]*Department of Mechanical Engineering, Hindustan Institute of Technology and Science ,Chennai, INDIA*

[b] *Department of Mechanical Engineering,S.A.Engineering College, Chennai, INDIA*

[c] *Department of Mechanical Engineering Veltech Multitech Dr.Rangarajan Dr.Sakunthala Engineering College, Chennai, INDIA*

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ABSTRACT: The augmentation of fresh water and increase in the solar still efficiency of a triangular pyramid is added with phase change material (PCM) on the basin. Experimental studies were conducted and the effects of production of fresh water with and without PCM were investigated. Using paraffin as the PCM material, performance of the solar still were conducted on a hot, humid climate of Chennai (13°5′ 2" North, 80°16′ 12"East), India. The use of paraffin wax increases the latent heat storage so that the energy is stored in the PCM and in the absence of solar radiation it rejects its stored heat into the basin for further evaporation of water from the basin. Temperatures of water, T_w, Temperature of phase change material, T_{PCM}, Temperature of cover, T_c were measured using thermocouple. Results show that there is an increase of maximum 20%, in productivity of fresh water with PCM.

Keywords: fresh water production, PCM, thermal energy storage,

1. Introduction

Solar energy can be used either for seawater desalination by producing the thermal energy required to drive the phase change processes or by generating the electricity required to drive the membrane processes. Solar desalination systems are classified into direct and indirect collection systems (Dunkle 1961). As their name imply, direct-collection systems use solar-energy to produce distillate directly in the solar collector, whereas in indirect collection systems, two sub-systems are employed. Conventional desalination systems are similar to solar systems because the same type of equipment is applied. The prime difference is that in the former, either a conventional boiler is used to provide the required heat or mains electricity is used to provide the required electric power, whereas in the latter, solar energy is applied.

Energy storage is being a boon for energy storage and eco-friendly technique. The best way of storing energy from the atmosphere for useful applications is thermal energy storage. By changing the phase transformation of material (LHTES) and change internal energy of material (SHTES) which are the techniques used in energy storage or heat recovery. These techniques can be integrated together for improving the energy storage. PCM's like organic, inorganic and eutectic can be used as latent heat storage and gravels, mild steel scraps, sponges can be used as sensible heat storage. Most researchers investigated the exergy and energy analysis of various latent heat and sensible heat thermal energy system. Also PCM's having ability to reduce the temperature fluctuation and enhance the thermal energy storage. Many reviews reported that preparation, thermal energy storage and thermal conductivity are the important properties of PCM based on paraffin wax as latent heat storage. For a practical

*Corresponding Author: +91-9094367381
Email: raviannauniv23@gmail.com

application such as solar desalination still, solar thermal collectors, solar PV/T collector's thermal conductivity plays a vital role.

PCM's are substances which are capable of storing energy and release a larger amount of heat when compared to sensible heat thermal energy storage. Also they are having a higher latent heat of fusion and lower melting point as the material changes (Radhwan 2004). PCM's having a greater impact on the applications such as net zero energy buildings, solar desalination, thermo-electric coolers, heat exchangers, solar water heaters etc.

A few researchers made theoretical and experimental investigation on the use of PCM as latent heat thermal energy storage in desalination technique. The transient thermal performance of a stepped solar still with a built-in LHTESS (for the heating and humidification of agricultural greenhouses) was investigated by (Radhwan 2004). The still has a simple design where the absorber consists of five of stepped small basins carrying the stagnant saline water. The basins are placed on slab containers filled with paraffin wax for thermal energy storage. Air was circulated between the hot basin water and the tilted glass cover, then flows back to the greenhouse. Results showing that the efficiency of the still is 57% with LHTESS while that of compared to 61% without LHTESS.

Wier type solar still was experimentally investigated by (Tabrizi 2010) and enhanced the performance of stepped solar still with built-in latent heat thermal energy storage. With LHTES the total yield obtained is 4.6 litres/m^2 and the efficiency approximately 57%. When compared to solar still without LHTES there is a decrease in 4% of efficiency. By varying the air flow into the basin the heat load of green house can be utilized for 24hr/day.

The total productivity of still without LHTESS is slightly higher than the still with LHTESS in sunny days. There is a significant difference in productivity of still: 3.4 kg/m^{2}day for still with LHTESS and 2.1 kg/m^{2}day for still without LHTESS in partially cloudy day. Thus, still without LHTESS is preferred for sunny areas because of its simplicity and low construction costs and still with LHTESS is proposed for partially cloudy areas due to the higher productivity and its stable condition regard to change in the weather conditions. It has been proposed that the solar still with and without LHTESS have similar output. Also he proposed that the solar still with LHTESS are most applicable for cloudy areas. The inclination of the solar still influences the water forces the water to flow into the weir basin and will have larger residence time due to increase in the number of steps in the basin.

The experimental and theoretical investigations of the still with and without PCM were also carried out by, (Dashtban 2011) Using a weir on the edge of each step of the stills leads to even distribution of water onto the evaporation surface and increases the residence time. The convective heat transfer coefficient, very important parameter in the still modeling, should be determined from the produced experimental data for different still geometries and operational conditions. The Dunkle's relation cannot satisfy the thermal behavior of the newly designed still. Increasing the level of water on the evaporation surface and decreasing the air gap in the still lead to decrease and slightly increase in the total productivity of the still, respectively. For a least distance between water and glass shows a greater production of fresh water was about 7 kg/m^{2}day and a thermal efficiency of 64%. It is also found to be that the convective and evaporative heat transfer co-efficient keeps on decreasing while the driving force, the difference between water and glass keeps on increasing. Overall thermal efficiency and daily production of solar still without PCM were found to be 47% and 5.1 kg/m^{2}day.

2. Factors affecting the fresh water production

There are many solar still models are developed by researchers making Solar stills economical and more efficient. Solar Still performances are mainly evaluated by its fresh water (Delyannis 2003). The efficiency of the solar still depends upon the following important parameters are tilt angle of cover plate (Hay 1965), depth of water (Tripathi 2005), feed water flow rate, cover plate temperature, effect of wind on stills (El-Sebaii 2000), convective heat transfer from cover plate and side walls (Kumar 1996; Tiwari 1999), design of structures and shapes (Hay 1965, 1973), solar tracking, coating, external enhancement like heat pipe, coolers. Many researchers have conducted solar still performance evaluation based on the above said parameters.

2.1 Free surface area of water

The evaporation rate of the water in the solar still is directly proportional to the exposure area of the water. Thus the productivity of the solar still increases with the free surface area of the water in the basin. To increase the free surface area of the water, sponges are used at the basin water.

2.2 Water–glass temperature difference

The yield of a solar still mainly depends on the difference between water and glass cover temperatures. The temperature difference between water and glass are acting as a driving force of the distillation process.

3. Thermal Modeling of solar still

The following assumptions were made for the solar still for making the thermal modeling. The assumptions made are as follows:

a) Vapor leak proof.
b) Heat capacities of glass, absorber, and insulations are negligible.
c) Absorbed solar energy is lost to water and ambient.
d) Area of aperture is same.
e) Quasi steady state.

The energy received by the saline water in the still I (t) solar radiation and $Q_{cb\text{-}w}$ convective heat transfer between basin and water are equal to the summation of energy lost by $Q_{cw\text{-}g}$ convective heat transfer between water and glass, $Q_{rw\text{-}g}$ radiative heat transfer between water and glass, $Q_{ew\text{-}g}$ evaporative heat transfer between water and glass and energy gained by the saline water: The remaining is by evaporation, due to partial vapour pressure difference between the water surface and lower surface of the glass cover. Water evaporated condenses at the distillate collector through the glass cover. A small part of heat is lost to atmosphere through basin bottom and side wall by conduction and convection. For shallow basin still, the basin bottom surface and water are assumed as single element and the temperature is taken as constant for basin and water. Raw water is continuously supplied to the basin to keep the water mass in the basin always constant. This compensating water mass takes sensible heat to attain equilibrium with basin water. The transient energy balance equation for the basin water is given as (Malik 1982),

$$(m_w C_w + m_{em} C_{em}) \frac{dT_w}{dt} = Q_\tau \alpha_{b,w} - Q_{c,w\text{-}g} - Q_{e,w\text{-}g} - Q_{r,w\text{-}g} - Q_{b,w\text{-}a} - Q_{fw} \quad \textbf{(1)}$$

The transient energy balance equation for the glass cover is given as,

$$m_g C_g \frac{dT_g}{dt} = \alpha_{b,g} Q_i + Q_{c,w\text{-}g} + Q_{e,w\text{-}g} + Q_{r,w\text{-}g} - Q_{c,g-a} - Q_{r,g-a} \quad \textbf{(2)}$$

The convection heat transfer from the basin water to the cover plate becomes,

$$Q_{c,w\text{-}g} = h_{c,w\text{-}g} A_g (T_w - T_g) \quad \textbf{(3)}$$

The evaporative heat transfer from the basin water to the cover plate is written as,

$$h_{c,w-g} = 0.884 \left[(T_w - T_g) + \frac{(p_w - p_g)(T_w + 273.15)}{268900 - p_w} \right]^{\frac{2}{3}} \quad \textbf{(4)}$$

$$Q_{e,w-g} = h_{e,w-g} A_b (p_w - p_g) \quad \textbf{(5)}$$

$$h_{e,w-g} = h_{c,w-g} \left[\frac{M_w h_{fg} p_T}{M_a C_{pa} (p_T - p_w)(p_T - p_g)} \right] \quad \textbf{(6)}$$

The radiation heat transfer from the basin to glass cover is predicted from,

$$Q_{r,w-g} = \sigma \varepsilon_{w-g} A_b \left[(T_w + 273.15)^4 - (T_g + 273.15)^4 \right] \quad \textbf{(7)}$$

The heat loss from the basin to the surrounding is calculated using,

$$Q_b = UA_b (T_w - T_{atm}) \quad \textbf{(8)}$$

The heat taken by the replaced water is estimated from,

$$Q_{fw} = m_e C_w (T_{atm} - T_w) \quad \textbf{(9)}$$

The convection heat transfer coefficient from the cover to the atmosphere including the radiation effect is predicted using,

$$h_{c,g-a} = 5.7 + 3.8V \quad \textbf{(10)}$$

and the convective heat transfer is given as,

$$Q_{c,g-a} = h_{c,g-a} A_g (T_g - T_{atm}) \quad \textbf{(11)}$$

The instantaneous water production of the still is calculated,

$$m_e = Q_{e,w-g} / h_{fg} \quad \textbf{(12)}$$

The overall production of the still= $\sum m_e(t) \Delta t$ **(13)**

4. Experimental setup

The schematic diagram of the triangular pyramid solar still is shown in Fig. 1. The PCM is loaded in the bottom of the basin. Thickness of PCM is found to be 10mm and the bottom of the basin is coated with black paint to avoid loss of heat to the surroundings. Experiments were carried out from 7 h- 24 h.

Table 1 describes the different latent heat storage PCM with their thermo-physical properties. It shows that the melting point of paraffin wax and steric acid are same. The important parameter for an PCM is that the latent heat of fusion. Praffin parafin wax has larger latent heat of fusion of about 226 J/kg whereas for steric acid it is 169 J/kg. Table 1 summarises the parameters used in the experimental work.

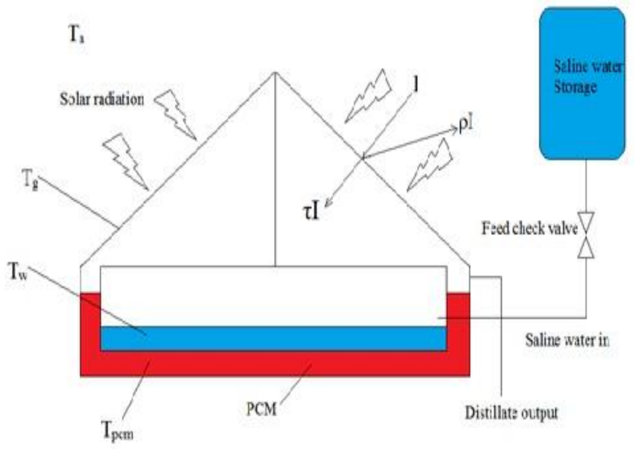

Fig. 1 Schematic diagram of the triangular pyramid solar still

Table 1
Thermo physical properties of different PCM materials

Description	Paraffin wax	Acetamide	Erythritol	Steric Acid
Chemical Formula	-	-	$C_4H_{10}O_4$	-
Molecular weight	-	-	122.2	-
Melting point (°C)	52	82	118	52
Latent heat of Fusion (kJ/kg)	226	263	339.8	169
Heat conductivity (W/m K)	0.24	-	2.64	0.26
Specific heat capacity (kJ/kg K)	2.95	-	1.38	1590
Density of liquid/solid (kg/m³)	818/-	998/1159	-/-	847/965

5. Experimental uncertainty

Instrument used for finding out the radiation, temperature of various elements in the solar still, wind velocity, and collection of water are pyranometer, thermocouple, anemometer and collecting jar. The minimal error occurred in instrument is the ratio of minimum gradient and minimum value of the output measured.

Table 2
Experimental parameters

Parameter	Symbol	Value
Transmissivity of glass	τ_c	.88
Emissivity of glass	ε_c	.98
Density of water	ρ	995 kg/m³
Latent heat of vaporization	h_{fg}	2376 kJ/kg
Latitude	φ	11⁰ North

6. Results and discussion

Fig. 2 shows the hourly variation of distillate output on different test days without PCM. The maximum output of 4300 ml/m²/day was achieved without any phase change material on the still basin. The productivity of fresh water is higher than that of still with PCM during higher solar intensities. This is due to some of the energy absorbed by the absorber plate and releasing its heat to the PCM decreasing the temperature of the absorber and water temperatures. It is observed that the maximum hourly distillate was occurred during the mid-day about 600-700 ml/hr. On the other basis Fig. 3 shows the effect of PCM material on the basin improves the hourly distillate output. During the absence of solar radiance the heat absorbed by the PCM released increasing the temperature of water in the basin. This improves the efficiency of still.

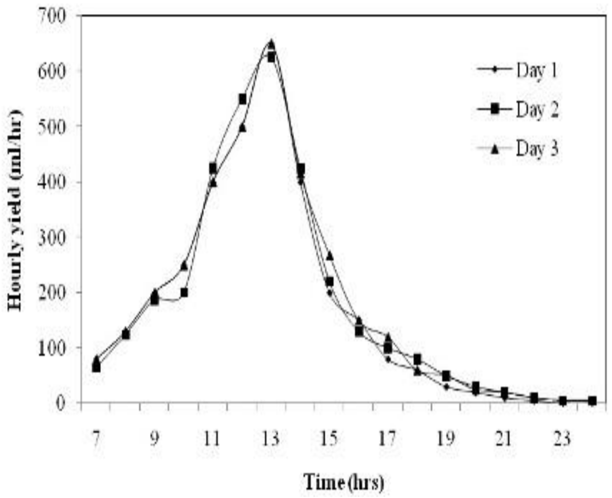

Fig. 2 Hourly variation of distillate output on different test days without PCM

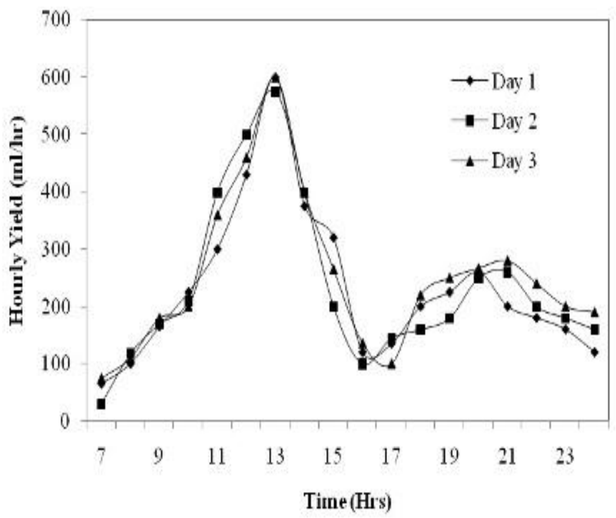

Fig. 3 Hourly variation of distillate output on different test days with PCM

Fig. 4 shows the variation of still efficiency without addition of PCM material. The effect of solar radiance on the still efficiency improves a lot. A maximum efficiency of 35% occurs for a solar radiance of 1000 W/m^2. It is noted and a clear view of increase in efficiency in the morning time and reaches the maximum and then slowly decreasing during the afternoon.

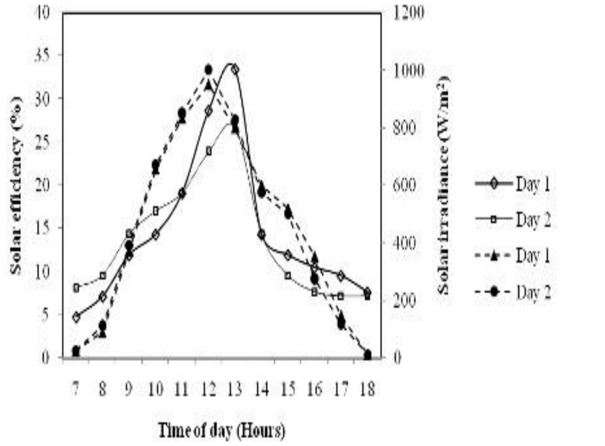

Fig. 4 Variation of solar efficiency and solar radiation without PCM

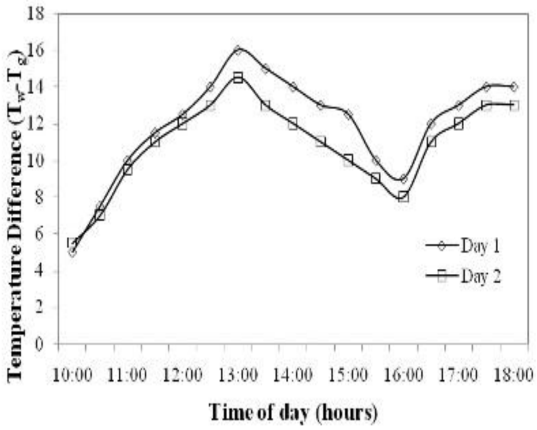

Fig. 5 Variation of temperature difference between glass and water temperature with effect of PCM

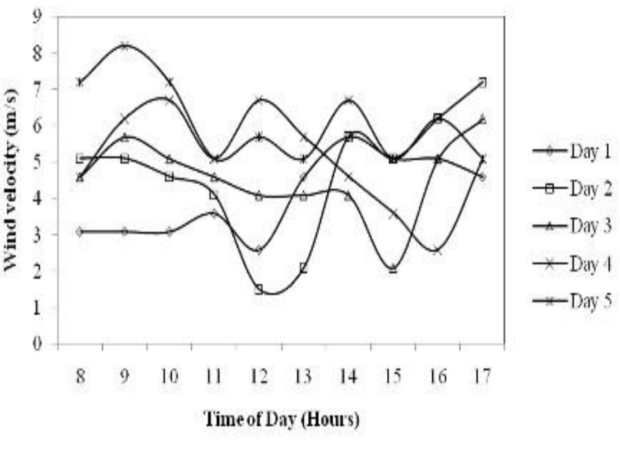

Fig. 6 Hourly variation of wind velocity on various experimental days

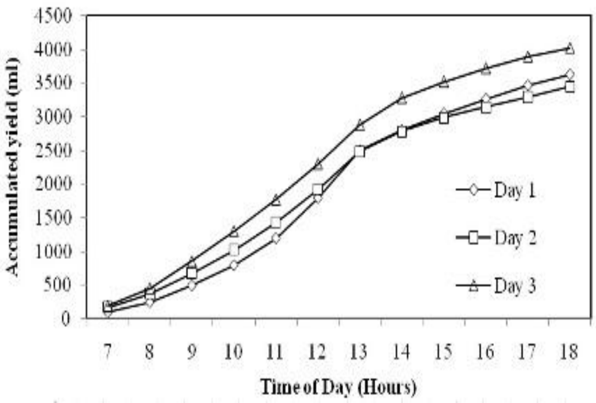

Fig. 8 Accumulated fresh water production without PCM

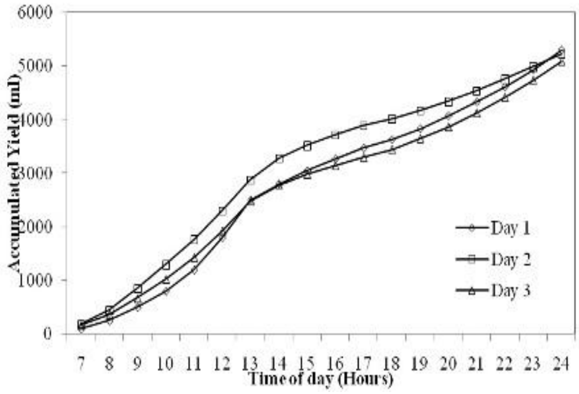

Fig. 9 Accumulated fresh water production with PCM

The important parameter that affects the production of fresh water from the solar still is the temperature difference between water and glass. The temperature difference of water and glass acts as a driving force of desalination process. Higher the temperature difference increases the productivity and evaporation rate. Fig. 5 depicts the variation of temperature difference between water and glass. It shows that the temperature difference between after 4:00 pm increasing slowly to reach a maximum temperature difference of 14^{0}C.

Fig. 6 compares the hourly variation of wind velocity on different experimental days. The effect of wind velocity is a man parameter for condensing of water over the glass surface. Higher the wind velocity decreases the fresh water production. The driving for created by the water and glass will be affected due to higher velocity of wind over the surface.

Fig. 7 and Fig. 8 show the comparative analysis of accumulated fresh water with and without PCM from the solar still. It is found that without PCM fresh water production found to be an average of 4 litres per day, whereas with PCM effect it is found to be 5.3 litres per day. The increase in fresh water production found to be 24.52%. The increase in fresh water production is due to the heat released from the PCM through the basin to water hence the evaporation rate increases.

7. Conclusions

A triangular pyramid solar still with built-in latent heat thermal energy storage system was fabricated to improve the still productivity. Another still with the same characteristics without PCM was also constructed for investigation of the internal convective heat transfer coefficient. Moreover, the experimental and theoretical investigations of the still with and without PCM were also carried out, and the important conclusions were drawn:

a. Solar still presents some specific advantages for their use in these areas due to its easier construction using locally available materials, minimum operation and maintenance requirements and friendliness to the environment for producing portable water.
b. Using a 1m^2 area of solar still the average production of fresh water about 4.2 liters/m^2 without PCM effect is possible.
c. The effect of introducing PCM in the above setup shows an increase of 20% in the production of fresh water.
d. The effect of wind on the solar still shows there is a decrease in productivity during the morning hours.
e. The daily efficiency was found to be 60% with PCM and 45% without PCM.
f. Solar radiation on the test days reveals that the maximum intensity occurred during the mid-day, and the productivity shows that the solar radiation and production rate are directly proportional.
g. The temperature difference between water and glass varies from 10-15.5^{o}C during the off-shine period.

Nomenclature

A	Area (m^2)
C	Specific heat capacity (J/kgK)
h	Heat transfer Co-efficient (W/m^{2}K)
h_{fg}	latent heat of vaporization (J/kg)
I	Total Radiation (W/m^2)
p	Partial pressure (N/m^2)
V	Wind velocity (m/s)
Q	Heat transfer (W)

Greek symbols

α	absorptivity
β	inclination of the plane cover with horizontal (deg)
φ	Latitude (deg)
η	Efficiency (%)
σ	Stefen Boltzman Constant (5.67 x 10^{-8} W/m^{2}K^4)
ω	hour angle (deg)
ε	emissivity

Subscripts

a	air
atm	atmosphere
b	basin
c	convection
e	evaporation
fw	feed water
T	total
w	water
em	energy storage material
g	glass

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