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Thermal modeling and performance of a single slope passive solar still with phase change material

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ABSTRACT

In this study a mathematical model is used to predict the performance of the solar still using the phase change material to enhance the thermal performance of the solar still. Experimental is conducted with and without using PCM like lauric acid and calcium chloride hexahydrate, and the result shows that thermal efficiency increase using PCM of about 21%, 20% in calcium chloride hexa hydrate and lauric acid than without using PCM in the solar still. A mathematical model is develop, which is used to find the temperature of glass cover, water and the basin for predicting the theoretical value in order to match with the experimental result. The comparison result shows the 95% of good agreement between the theoretical value and experimental results for glass, water and basin temperature. Enhancing the heat transfer is the major role in order to increase the productivity of water from solar desalination still.

Keywords: Passive solar still; Temperature; Mathematical model; Solar radiation

1. Introduction

Solar desalination is a process of separation of pure water from saline or sea water by using solar energy. The use of solar still is a cheap method of providing clean water. The solar assisted desalination system can be classified as: (i) passive (conventional) solar still and (ii) active (modified) solar still. The simple or conventional solar still consists of a black-painted copper or steel basin to receive solar radiation in which saline or sea water is kept. The basin is placed in a trapezoidal wooden box, which is covered by a glass cover at an angle between 10°–25° to the horizontal to retain the solar thermal energy inside the still due to greenhouse effect. That solar thermal energy is utilized to heat the saline or seawater. The space between the basin and wooden box is packed with glass wool insulation to reduce the heat loss through the sides and bottom of the still. Due to the existence of phase equilibrium between the saline water surface and air space, the air just over the water surface will be saturated with water vapour corresponding to the water temperature. With the solar radiation incident on the saline water, its surface temperature increases which causes the increase of saturated pressure of water vapour near the water surface corresponding to the water temperature. At that time the partial pressure of water vapour near the glass surface will be less as the temperature of the inner surface of the glass cover is lower than that of the water surface. The temperature difference between the water and inner glass surface causes the difference in partial pressures of water vapour which causes the transfer of water vapour from the basin water surface to glass surface and the condensation on the inner surface of the glass. The rate of evaporation of water vapour from the water surface depends on the rate of condensation of water vapour in the glass cover [1,2].

Even in the area of higher solar intensity, the annual performance of the still per square meter of aperture is limited to an average of about 2.5–3.0 L d^{-1}. Interest in the conventional solar still has been due to its simple design, construction and low operating and maintenance cost, mainly in remote areas with no electricity supply. However, its low

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productivity simulates and motivates the researchers to develop novel methods to enhance the still productivity.

Sivakumar et al. [3] develop a mathematical model, which is used to find the effect of heat capacity of the basin and glass cover on the performance and energy destruction of single slope passive solar still which solar still increased by 10.38% with considering heat capacity. El-Sebaii [4] develop the transit model is presented for triple basin solar still. Productivity of lower basin higher than productivity of middle and upper during the day time, and the behavior is reversed during night time. Aybar [5] develop a ISWD system can generate 3.5–5.4 kg/d distilled water as well as 40°C hot water generated, which is good enough for domestic usage. Simulation results are in good agreement with experiment study. Badran and Abu-Khader [6] investigated to increase in either ambient temperature or solar intensity which can increase solar productivity. Water depth decrease from 3.5 cm to 2 cm and productivity increase by 25.7%. Maximum efficiency occur in early afternoon due to high solar radiation. Overall heat loss coefficient increase until it read the maximum in the afternoon due to higher solar intensity and ambient temperature. Finally mathematical model gives good match with experimental results.

Tiwari and Tiwari [7] concluded that daily water yield has been found higher almost in every month for lower water depth. Daily water depth 0.02 m has been found 32.57% and 32.39% more than the daily yield of higher water depth 0.18 m in summer and winter respectively. And thermal model is validated up to .08–0.10 m depth. Arunkumar et al. [8] investigated PCM-integrated single slope solar still with CPC-CTSS has been investigated to enhance the productivity. After sunset, PCM act as a heat source for basin to maintain the temperature difference. And finally, circulating with cooling water, CPC-CTSS was found to be 3.5 L/m^2/d. El-Sebaii et al. [9] investigated that after sunset, PCM act as heat source basin until the early morning of next day. Day light productivity is found to decrease with increase m_{pcm}. Finally concluded that PCM is more effective at lower mass of basin water during winter. Murugavel et al. [10] investigated by using wick material like cotton cloth, light jute cloth, sponge sheet, and natural rock. Cotton cloth gives better productivity when compare to other material. Tripathi and Tiwari [11] investigated more yield is obtained during the off shine hours as compare for higher water depth due to storage effect. Numerous attempts have been made by many researchers to increase the rate of evaporation of water and utilize the maximum solar energy that strikes on the still to enhance the system efficiency which utilizes a minimum amount of still surface.

Deshmukh and Thombre [12] investigated the performance of a single slope basin solar still have been analysed with sand and servatherm medium oil. For both, sand and servatherm medium oil, lower storage depth were found to yield higher productivity compared to conventional still. Faegh and Shafii [13] investigated a novel idea of storing the latent heat of condensing vapor in solar still by means of PCM as a thermal storage is experientially investigated. The yield increases by 86% as compare to the yield of the system without PCM and reaches to 6.555 kg/m^2 d with the efficiency of 50%. Arunkumar and Kabeel [14] conducted an experiment with and without PCM in the CCTSS. The PCM is loaded (450 g of paraffin wax/tube) is the specially design circular trough of the tubular solar still. The result shows that the fresh water production of CPC-CCTSS with and without PCM integration were 5779 ml/m^2/d and 5330 ml/m^2/d. Therefore the PCM enhanced the fresh water productivity by 8%. The main objectives of this experimental study is, (i) to find the effect of different mass of calcium chloride hexa hydrate and lauric acid on the performance and the internal and external heat transfer of the single slope single basin solar distillation system.

2. Experimental setup

Two single basin solar stills are fabricated and tested under field condition at the testing field of the School of Electrical Engineering, Velammal Engineering College, Tamilnadu, India. The basin liner is made of galvanized iron sheet of 0.5–1 m^2 with maximum height of 288 mm, and 1.4 mm thickness. The basin surfaces are painted with black paint to absorb the maximum amount of solar radiation incident on them. The condenser surface of the still is made of glass with 4 mm thickness and angle of inclination is 10° with horizontal. There are certain specifications needed for the used glass cover in the still, and they are (a) Minimum amount of absorbed heat, (b) Minimum amount of reflection for solar radiation energy, (c) Maximum transmittance for solar radiation energy, and (d) high thermal resistance for heat loss from the basin to the ambient. Glass covers have been framed with wood and sealed with silicon rubber which plays an important role to promote efficient operation as it can accommodate the expansion and contraction between dissimilar materials.

A collecting trough made by G.I. sheet is used in the still to collect the distillate condensing on the inner surfaces of the glass covers and to pass the condensate to a collecting flask. Steel rule is fixed along with inside wall for measuring water depths. The bottom and sides are insulated with 25 mm thick thermocole and 12.5 mm thick wood with thermal conductivity 0.015 W/mK and 0.055 W/mK respectively. The technical specifications of the solar still are shown in Table 1. The schematic view and photographic view of the solar still are shown in Figs. 1 and 2 respectively.

The experiments were performed in the February 2016 for typical days have been referred in this paper being the probable month of the year. The experiments were conducted on different three days in the campus of the Velammal Engineering College Chennai, India. All experiments were started at 9 AM local time and lasted for 24 h. In each day experiment constant water depth of 1 cm was used. During experimentation when switching over from one absorbing material to another the still was left idle, minimum for a day to attain steady state condition

The solar radiation transmitted through the glass cover and basin water is absorbed by the basin liner, PCM tubes and hence its temperature in increased. PCM is taken in the tube with different mass. The PCM used here is lauric acid and calcium chloride hexa hydrate. First the heat is stored as a sensible heat till the PCM reaches its melting point. By the time, the PCM is starting to melt and after complete melting of the PCM, the heat will be stored in the melted PCM as a sensible heat. In the evening time, when the solar radiation decrease, the still component to cool down, the liquid PCM transfer heat to basin liner, water until the PCM get solidified.

After when the water absorb the heat from solar radiation, it transfer heat to bottom surface of the glass cover by radiation, convection and evaporation. The heat is conducted through the cover and then transfer to surrounding by radiation to sky and by convection to ambient air.

Table 1
Technical specifications of the solar still

Parameter	Value
Area of basin, m^2	1
Mass of the basin, kg	8.95
Mass of the glass plate, kg	4.65
Specific heat of glass plate, J/kg k	477
Specific of heat of basin, J/kg k	840
Specific heat of saline water, J/kg k	3930
Absorbtivity of glass plate	0.05
Absorbtivity of water	0.05
Absorbitivity of basin	0.9
Effective emissivity	0.82
Thickness of insulation, m	0.254
Thickness of insulation, m	0.400
Thermal conductivity of thermocole, w/mk	0.254
Thermal conductivity of wood, w/mk	0.15
Stefen-Botlsmann constant, w/m^2 k^4	5.67*10^{-8}

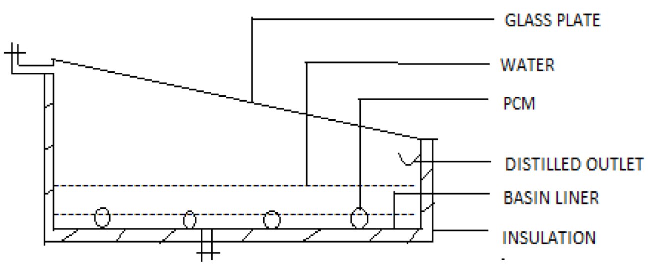

Fig. 1. Schematic diagram of solar desalination still setup.

Prior to start of the experiment for next absorbing material till the completion of experiments for all absorbing material. The following parameters were measured every hour for a period of 24 h for fixed inclinations and for fixed water depth.

- Basin temperature
- Back wall temperature
- Side wall temperature
- Water temperature
- Glass temperature
- Moist air temperature
- Ambient temperature
- Air velocity
- Solar radiation
- Distillate output

Water, basin, glass and vapor temperatures were recorded with the help of k-type thermocouples and a digital temperature indicator having a least count of 0.1°C. Solar radiation is measured using pyranometer and the wind velocity is measured using digital anemometer. And a 30 mm steel rule is fixed inside wall used to measure water depth. And the readings were shown in Tables 2–5.

3. Mathematical model

The performance analysis is achieved by energy balance of the still. Fig. 3 shows the energy transfer processes for various components in the still, which have a direct effect on the output.

For simplifying the analysis, the following assumptions are considered:

- The level of water in the basin is maintained constant level.
- The condensation that occurs at the glass trough is a film type.
- The heat capacity of the glass cover, the absorbing material, and the insulation material are negligible.
- No vapor leakage in the still;
- The heat capacity of the insulator (bottom and side of the still) is negligible.

Fig. 2. Experimental setup.

Table 2
Without using phase change material

S. No	Time	I W/m^2	Back wall temp (T_{bi})	Side wall temp (T_{si})	Basin temp (T_b)	Water temp (T_w)	Glass temp (T_g)	Ambient temp (T_a)	Mass in ml (m_w)	Wind velocity m/s
1	09–10	480	41	39	33	29	31	30	0	0.06
2	10–11	610	54	44	47	31	44	42	0.07	0.06
3	11–12	695	45	49	49	42	50	48	0.09	0.07
4	12–13	880	41	48	48	46	51	47	0.085	0.04
5	13–14	840	50	49	49	43	50	48	0.07	0.09
6	14–15	780	42	53	55	55	42	41	0.08	0.06
7	15–16	695	38	49	51	51	37	36	0.06	0.09
8	16–17	510	35	50	49	49	35	34	0.07	1
	17–09								0.25	
Total									0.775	

Table 3
Using 70 ml of calcium chloride hexa hydrate

S. No	Time	I W/m^2	Back wall temp (T_{bi})	Side wall temp (T_{si})	Basin temp (T_b)	Water temp (T_w)	Glass temp (T_g)	Ambient temp (T_a)	PCM temp (T_{pcm})	Mass in ml (m_w)	Wind velocity m/s
1	09–10	480	41	41	37	40	43	36	38	0	0.06
2	10–11	610	49	44	40	39	46	36	39	0.06	0.08
3	11–12	695	56	47	43	36	48	38	39	0.11	0.06
4	12–13	880	60	48	43	36	50	39	41	0.14	0.09
5	13–14	840	67	43	48	40	45	46	49	0.17	1.00
6	14–15	780	66	56	46	44	58	48	47	0.13	1.10
7	15–16	695	58	52	44	46	54	48	46	0.08	0.03
8	16–17	510	54	47	44	44	50	46	46	0.07	0.06
	17–09									0.34	
Total										1.1	

Table 4
Using 100 ml of calcium chloride hexa hydrate

S. No	Time	I W/m^2	Back wall temp(T_{bi})	Side wall temp (T_{si})	Basin temp (T_b)	Water temp (T_w)	Glass temp (T_g)	Ambient temp (T_a)	PCM Temp (T_{pcm})	Mass in ml (m_w)	Wind velocity m/s
1	09–10	492	42	40	36	39	42	35	36	0	0.06
2	10–11	625	49	42	40	37	44	37	39	0.06	0.09
3	11–12	720	55	46	44	37	47	38	45	0.1	0.06
4	12–13	880	60	46	44	36	51	40	45	0.15	0.04
5	13–14	840	65	43	46	39	46	47	47	0.175	0.08
6	14–15	757	68	57	46	44	56	48	46	0.13	1.1
7	15–16	677	58	52	45	46	54	48	46	0.07	0.08
8	16–17	510	52	46	44	32	49	46	44	0.07	0.07
	17–09									0.38	
Total										1.135	

Table 5
Using 100 grams of lauric acid

S. No.	Time	I W/m²	Back wall temp (T_{bi})	Side wall temp (T_{si})	Basin temp (T_b)	Water temp (T_w)	Glass temp (T_g)	Ambient temp (T_a)	PCM Temp (T_{pcm})	Mass in ml m_w	Wind velocity m/s
1	09–10	492	40	43	39	39	43	41	38	0	0.05
2	10–11	625	49	53	47	34	45	44	44	0.09	0.06
3	11–12	720	60	48	56	37	47	45	55	0.085	0.08
4	12–13	880	65	50	59	33	52	48	58	0.07	0.07
5	13–14	840	66	51	63	34	49	47	63	0.1	0.04
6	14–15	757	63	47	62	36	55	53	62	0.065	0.07
7	15–16	677	61	47	61	35	54	48	58	0.06	1.0
8	16–17	510	45	37	46	26	44	42	45	0.06	0.06
	17–09									0.31	
Total										0.84	

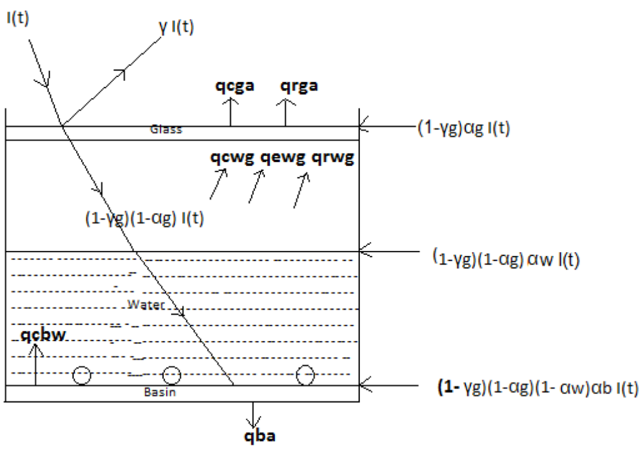

Fig. 3. Various components of conventional single slope solar still.

3.1. The still with the PCM with charging mode

The energy balance equation for the various element of the still during the daytime in charging mode can be written as:

Energy balance of the glass cover is

$$\left(1-\gamma_g\right)\alpha_g I(t)+h_{twg}\left(t_w-t_g\right)=h_{t1}\left(t_g-t_a\right) \quad (1)$$

where $h_{twg} = h_{cwg} + h_{ewg} + h_{rwg}$, is the total heat transfer coefficient from water to glass. h_{cwg}, h_{ewg} and h_{rwg} is convective, evaporative and radiative heat transfer coefficient from water to glass, where $h_{t1} = h_{cga} + h_{rga}$. Here h_{cga}, h_{rga} is convective, radiative heat transfer coefficient from glass to ambient

Eq. (1) can be rearranged as

$$T_g=\frac{1}{\left(ht1+htwg\right)}\left[\left(1-\gamma g\right)\alpha g\ I(t)\ +htwgTw+ht1\ Ta\right]$$

Energy balance of the water is

$$\left(1-\gamma_g\right)\left(1-\alpha_g\right)\alpha_w I(t)+h_{cbw}\left(T_b-T_w\right)= m_w C_{pw}\frac{dTw}{dt}+h_{cwg}+h_{ewg}+h_{rwg}\left(T_w-T_g\right) \quad (2)$$

where h_{cbw} is convective heat transfer coefficient from basin to water.

Eq. (2) can be rearranged as

$$\frac{1}{mwCpw}\left[\left(1-\gamma_g\right)\left(1-\alpha_g\right)\alpha_w I(t)+h_{cbw}T_b+h_{twg}T_g\right]= \frac{dTw}{dt}+\frac{\left(htwg+hcbw\right)Tw}{mwCpw}$$

For differential equation in the form of $\frac{dTw}{dt}$ + a1T_w = C1 solution is

$$Tw=\frac{C1}{a1}(1-e^{-ia1t})+T_{wi}e^{-ia1t}$$

Energy balance of the PCM is

$$\left(1-\gamma_g\right)\left(1-\alpha_g\right)\left(1-\alpha_w\right)\alpha_{pcm}I(t)= m_{pcm}C_{pcm}\frac{dTpcm}{dt}+h_{tube}\left(T_{pcm}-T_w\right) \quad (3)$$

where h_{tube}, is convective heat transfer coefficient from pcm to water.

Eq. (3) can be rearranged as

$$\frac{1}{mpcmCpcm}\left[\left(1-\gamma_g\right)\left(1-\alpha_g\right)\left(1-\alpha_w\right)\alpha_{pcm}I(t)\right]+\frac{htubeTw}{mpcmCpcm}= \frac{dTpcm}{dt}+\frac{htubeTpcm}{mpcmCpcm}$$

For differential equation in the form of

$$\frac{dTpcm}{dt} + a_2 T_{pcm} = C_2 \; solution \; is \; T_{pcm} = \frac{C2}{a2}\left(1 - e^{-ia2t}\right) + T_{pcmi} e^{-ia2t}$$

Energy balance of the basin is,

$$\left(1-\gamma_g\right)\left(1-\alpha_g\right)\left(1-\alpha_w\right)\alpha_b I(t) = h_{cbw}\left(T_b - T_w\right) + h_{cba}\left(T_b - T_a\right) \quad (4)$$

Eq. (4) can be rearranged as

$$T_b = \frac{(1-\gamma g)(1-\alpha g)(1-\alpha w)\alpha b I(t) + hcbwTw + hcbaTa}{hcbw + hcba}$$

where h_{cbw} and h_{cba} is convective heat transfer coefficient basin to water and convective heat transfer coefficient from basin to ambient.

3.2. The still with the PCM with discharging mode

The energy balance equation for the various element of the still during night time in discharging mode can be written as,

Energy balance of the glass cover is

$$\left(1-\gamma_g\right)\alpha_g I(t) + h_{twg}\left(T_w - T_g\right) = h_{t1}\left(T_g - T_a\right) \quad (5)$$

where $h_{twg} = h_{cwg} + h_{ewg} + h_{rwg}$, is the total heat transfer coefficient from water to glass. h_{cwg}, h_{ewg} and h_{rwg} is convective, evaporative and radiative heat transfer coefficient.

Eq. (5) can be rearranged as

$$T_g = \frac{1}{\left(h_{t1} + h_{twg}\right)}\left[(1-\gamma g)\alpha g I(t) + h_{twg} T_w + h_{t1} T_a\right]$$

Energy balance of PCM is

$$\frac{mpcmCpcm}{Apcm \; \Delta T} = h_{cond}\left(T_{pcm} - T_b\right) + h_c\left(T_{pcm} - T_w\right) \quad (6)$$

Here $h_{condpcmb}$ is conductive heat transfer coefficient from pcm to basin and h_{cpcmw} is convective heat transfer coefficient from pcm to water.

Eq. (6) can be rearranged as,

$$T_{pcm} = \frac{\frac{mpcmCpcm}{Apcm \; \Delta T} + hcondTb + hcTw}{(hcond + hc)}$$

Energy balance of the water is,

$$h_{cbw}\left(T_b - T_w\right) + h_{cpw}\left(T_{pcm} - T_w\right) = \frac{mw\,Cpw}{Ab\Delta T} + h_{twg}\left(T_w - T_g\right) \quad (7)$$

Eq. (7) can be rearranged as

$$T_w = \frac{\frac{mw\,Cpw}{Ab\Delta T} - htwgTg - hcbwTb - hcpwTpcm}{-hcbwTw - hcpwTw - htwgTw}$$

Energy balance of the basin is,

$$h_{cbw}\left(T_b - T_w\right) = h_{cba}\left(T_b - T_a\right) \quad (8)$$

Here h_{cbw} is convective heat transfer coefficient from basin to water and h_{cba} is convective heat transfer coefficient from basin to ambient.

Eq. (8) can be rearranged as

$$T_b = \frac{hcbw\,Tw - hcond\,b - a\,Ta}{hcbw - hcond\,b - a}$$

3.3. The still without PCM

Energy balance of glass cover is

$$\left(1-\gamma_g\right)\alpha_g I(t) + h_{twg}\left(T_w - T_g\right) = h_{t1}\left(T_g - T_a\right) \quad (9)$$

Eq. (9) can be rearranged as

$$T_g = \frac{1}{(ht1 + htwg)}\left[(1-\gamma g)\alpha g I(t) + htwgTw + ht1Ta\right]$$

Energy balance of water is

$$(1-\gamma_g)(1-\alpha_g)\alpha_w I(t) + h_{cbw}\left(T_b - T_w\right) = m_w C_{pw}\frac{dTw}{dt} + h_{cwg} + h_{ewg} + h_{rwg}\left(T_w - T_g\right) \quad (10)$$

Eq. (10) can be rearranged is

$$\frac{1}{mwCpw}\left[\left(1-\gamma_g\right)\left(1-\alpha_g\right)\alpha_w I(t) + h_{cbw} T_b + h_{twg} T_g\right] = \frac{dTw}{dt} + \frac{(htwg + hcbw)Tw}{mwCpw}$$

For differential equation in the form of

$$\frac{dTw}{dt} + a1 T_w = C1 \; solution \; is T_w \frac{C1}{a1} = \left(1 - e^{-ia1t}\right) + T_{wi} e^{-ia1t}$$

Energy balance of basin is

$$\left(1-\gamma_g\right)\left(1-\alpha_g\right)\left(1-\alpha_w\right)\alpha_b I(t) = h_{cbw}\left(T_b - T_w\right) + h_{cba}\left(T_b - T_a\right) \quad (11)$$

Here h_{cbw} is heat transfer coefficient from basin to water and h_{cba} is heat transfer coefficient from basin to ambient.

Eq. (11) can be rearranged as

$$T_b = \frac{(1-\gamma g)(1-\alpha g)(1-\alpha w)\alpha b I(t) + hcbw\,Tw + hcbaTa}{hcbw + hcba}$$

4. Properties of PCM

Thermal conductivity of calcium chloride hexa hydrate is 0.540 (liquid 39°C) and 1.088(solid, 23°C) during the liquid and solid state. The density of calcium chloride hexa hydrate is 1562 (liquid, °C) and 1710 (solid, 25°C).

Thermal conductivity of lauric acid is 0.147 (liquid, 50°C) and and the density is 870 (liquid, 50°C) and 1007 (solid, 24°C).

Due to thermal conductivity and density of calcium chloride hexa hydrate is higher when compare to lauric acid, the production rate of distilled water for calcium chloride hexa hydrate is higher than the lauric acid. So the thermal storage absorption is high for the calcium chloride hexa hydrate due to high density. When the density is increases the thermal storage is also increases, so the production of water after sun set is also increases.

5. Numerical calculation

Hourly variation of solar radiation I and ambient temperature T_a on summer days is use for numerical calculation. The numerical calculation is obtained in the excel sheet to find the solution of energy balance of the solar still element with and without the PCM. The value of the relevant parameter is used for numerical calculation is shown in the table.

For the still with and without the PCM, numerical calculation were started assuming the initial temperature of various component of the still and the PCM to be equal to ambient temperature at t = 0. Using known initial values of the various temperatures, different internal and external heat transfer coefficient are calculated. The obtained value of the different heat transfer coefficient along with configuration and climatic parameters, the temperature of the still element and the PCM as well as the hourly production of PCM may then be calculated for a time interval Δt. The procedure is repeated with the value of different temperature for an additional time interval Δt and so on, until the solution coverage for 24 h. Numerical calculation has been formed for different mass of lauric acid and calcium chloride hexa hydrate in order to study the effect of this parameter on the still performance.

5.1. Estimation of heat transfer coefficient

The radiative heat transfer coefficient from glass to ambient is

$$h_{rga} = \frac{\varepsilon_g \sigma \left(Tg^4 - Tg^4\right)}{Tg - Ta}$$

The convective heat transfer coefficient from t glass to ambient,

$$h_{cga} = 5.7 + 3.8V$$

The convective heat transfer coefficient between the water to glass is,

$$hcwg = .884\left[Tw - Tg + \frac{(Pw - Pg)(Tw)}{268.9 * 10^3 - Pw}^{0.33}\right]$$

Here

$$P_g = e^{\left(25.317 - \frac{5144}{Tg}\right)}, P_w = e^{\left(25.317 - \frac{5144}{Tw}\right)}$$

The radiative heat transfer coefficient is between the water and glass is,

$$h_{rgw} == \frac{\varepsilon_g \sigma \left(Tg^4 - Ta^4\right)}{Tg - Ta}$$

The evaporative heat transfer coefficient between the water and glass is,

$$h_{ewg} = 16.273 * 10^{-3} hcwg \frac{\left(Pw - Pg\right)}{\left(Tw - Tg\right)}$$

By using the thermo physical parameter, Eqs. (1)–(4) are simplified and the solution of still on charging mode as follows,

$$Tg = 99.30425 * 10^{-3} I(t) - 2.24026 * 10^{-1} Tw + 1.22403 Ta \quad (12)$$

$$T_w = 2.168 * 10^{-6} I(t) + 6.842 * 10^{-3} T_b - 5.6414 * 10^{-5} T_g + 0.993 T_{wi}$$

$$T_{pcm} = 8.068 * 10^{-5} I(t) + 5.862 T_w + .0454 T_{pcm} \quad (14)$$

$$T_b = 2.724 * 10^{-4} I(t) + 0.906 T_w + 0.093 T_a \quad (15)$$

The solution of still during discharging mode, Eqs. (5)–(8) become

$$T_g = 99.30425 * 10^{-3} I(t) - 2.24026 * 10^{-1} T_w + 1.22403 T_a \quad (16)$$

$$T_{pcm} = -3157 + 0.0939 T_b + 0.906 T_w \quad (17)$$

$$T_w = -72.48689 + 3.996 * 10^{-3} T_g + 0.498 T_b + 0.498 T_{pcm} \quad (18)$$

$$T_b = 1.115 T_w - 0.115 T_a \quad (19)$$

The solution of the still without PCM, Eqs. (9)–(11) become

$$T_g = 99.30425 * 10^{-3} I(t) - 2.24026 * 10^{-1} T_w + 1.22403 T_a \quad (20)$$

$$T_w = 2.168 * 10^{-6} I(t) + 6.842 * 10^{-3} T_b - 5.6414 * 10^{-5} T_g + 0.993 T_{wi} \quad (21)$$

$$T_b = 4.90621 * 10^{-3} I(t) + 9.06040 * 10^{-1} T_w + 9.39597 T_a \quad (22)$$

The various measured temperature and yield in passive mode for 30 mm water depth are taken for the conventional solar still without using any phase change material for each hour interval and is shown in Table 2.

The various measured temperature and yield in passive mode for 1 cm water depth are taken for the conventional solar still using 70 ml of calcium chloride hexa hydrate for each hour interval and are shown in Table 3.

The various measured temperature and yield in passive mode for 1 cm water depth are taken for the conventional solar still using 100 ml of calcium chloride hexa hydrate for each hour interval and are shown in Table 4.

The various measured temperature and yield in passive mode for 1 cm water depth are taken for the conventional solar still using 100 g of lauric acid for each hour interval and are shown in Table 5.

Table 6
Using 150 grams of lauric acid

S. No	Time	I W/m^2	Back wall temp (T_{bi})	Side wall temp (T_{si})	Basin temp (T_b)	Water temp (T_w)	Glass temp (T_g)	Ambient temp (T_a)	PCM Temp (T_{pcm})	Mass in ml (m_w)	Wind velocity (m/s)
1	09–10	490	43	43	43	43	41	42	42	0	0.06
2	10–11	630	49	41	45	45	46	44	43	0.085	0.07
3	11–12	700	56	49	54	57	55	53	55	0.07	0.06
4	12–13	900	48	41	46	50	46	44	52	0.12	0.08
5	13–14	865	49	46	45	52	40	41	53	0.11	0.04
6	14–15	780	51	45	48	52	47	45	50	0.1	0.06
7	15–16	675	48	45	45	49	45	44	48	0.08	1.1
8	16–17	535	48	45	47	47	45	44	47	0.07	1.2
	17–09									0.32	
Total										0.955	

The various measured temperature and yield in passive mode for 1 cm water depth are taken for the conventional solar still using 150 g of lauric acid for each hour interval and are shown in Table 6.

6. Result and discussion

The mathematical equations are derived to study the temperature of glass cover, water and the basin. The temperature of all the element is solved by using excel sheet which are the main effect of solar heat transfer enhancement.

Case 1: Comparison of glass cover temperature

Table 7 and Fig. 4 show that the temperature comparison between the theoretical and experimental value of glass cover. The temperature in increasing up to a peak time and reduce during after 3 o'clock. The theoretical value for glass temperature is obtained by mathematical model and it is finally compare with the experimental result. This show the good agreement between the experimental and theoretical results and the error comparison between the each reading is about 4–7%.

Case 2: Comparison of water temperature

Table 8 and Fig. 5 show that the temperature comparison between the theoretical and experimental value of water. The temperature in increasing up to a peak time and reduce during after 3 o'clock. The theoretical value for glass temperature is obtained by mathematical model and it is finally compare with the experimental result. This shows the good agreement between the experimental and theoretical results and the error comparison between the each reading is about 2–3%.

Case 3: Comparison of basin temperature

Table 9 and Fig. 6 show that the temperature comparison between the theoretical and experimental value of basin

Table 7
Comparison between experimental and theoretical value hourly glass temperature

Time	T_g (Experimental)	T_g (Theoretical)
009–10	31	34.69019
010–11	44	50.14005
011–12	50	55.8108
012–13	51	55.41195
13–14	50	56.93589
14–15	42	45.12112
15–16	37	39.10621
16–17	35	35.38491

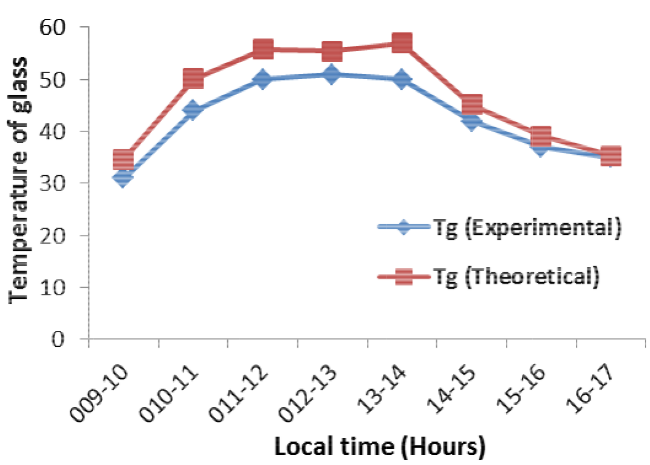

Fig. 4. Comparison between experimental and theoretical value hourly glass temperature.

Table 8
Comparison between experimental and theoretical value hourly water temperature

Time	T_w (Experimental)	T_w (Theoretical)
009–10	29	28.797
010–11	31	30.783
011–12	42	41.706
012–13	46	45.678
13–14	43	42.699
14–15	55	54.615
15–16	51	50.643
16–17	49	48.657

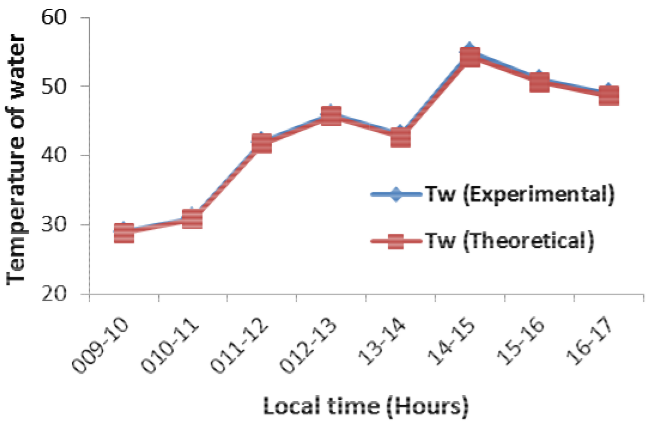

Fig. 5. Comparison between experimental and theoretical value hourly water temperature.

Table 9
Comparison between experimental and theoretical value hourly basin temperature

Time	T_b (Experimental)	T_b (Theoretical)
009–10	33	34.95787
010–11	47	48.30063
011–12	49	55.17859
012–13	48	56.08943
13–14	49	56.67628
14–15	55	49.05654
15–16	51	43.17859
16–17	49	39.26774

liner. The temperature in increasing up to a peak time and reduce during after 3 o'clock. The theoretical value for glass temperature is obtained by mathematical model and it is finally compare with the experimental result. This show the good agreement between the experimental and theoretical results and the error comparison between the each reading is about 10%.

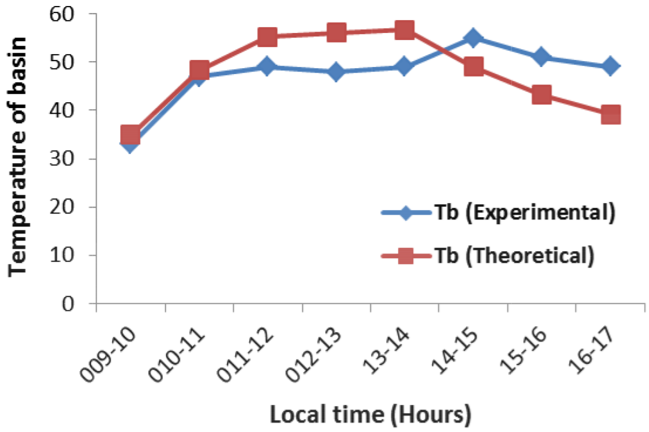

Fig. 6. Comparison between experimental and theoretical value hourly basin temperature.

7. Conclusion

A single slope solar still has been instigated under hot climatic condition. Calcium chloride hexa hydrate and lauric acid is used as a PCM in the basin liner to enhance the productivity during the night time. From the result achieved the following conclusions have been drawn:

1. Reduce the loss of heat to surrounding when we use PCM as a storage material and thermal efficiency is high of about 21% and 20% for calcium chloride hexa hydrate and lauric acid when compare without using PCM.
2. It is found that the highest productivity result when we use high amount of PCM
3. It is consider there is a 95% of good match between the experiment result and mathematical model for temperature of glass cover, water and the basin liner.
4. Thermal conductivity and density is more in calcium chloride hexa hydrate when compare to lauric acid, so the thermal performance is more by improving water production level in calcium chloride hexa hydrate when compare to lauric acid and without using PCM.

Symbols

m_w	—	Mass of water (kg)
m_{pcm}	—	Mass of PCM (kg)
C_{pw}	—	Specific heat of water (J/kg K)
C_{pb}	—	Specific heat of basin (J/kg K)
C_{pg}	—	Specific heat of glass (J/kg K)
I(t)	—	Hourly incident solar radiation (W/m^2)
T_a	—	Ambient temperature, (°C)
T_g	—	Temperature of glass, (°C)
T_w	—	Temperature of water (°C)
T_b	—	Temperature of basin, (°C)
T_{PCM}	—	Temperature of PCM, (°C)
T_{sky}	—	Temperature of sky, (°C)
h_{cwg}	—	Convective heat transfer between water to glass(W/m^2 K)

h_{ewg} — Evaporative heat transfer between water and glass (W/m^2 K)
h_{rwg} — Radiative heat transfer between water and glass (W/m^2 K)
h_{cga} — Convective heat transfer between glass to ambient (W/m^2 K)
h_{rga} — Radiative heat transfer between glass to ambient (W/m^2 K)
h_{cbw} — Convective heat transfer between basin and water (W/m^2 K)
h_{tube} — Convective heat transfer between tube and water (W/m^2 K)
h_{cba} — Convective heat transfer between basin and ambient (W/m^2 K)
$h_{cond,pcm-b}$ — Conductive heat transfer between pcm to basin (W/m^2 K)
$h_{c,pcm-w}$ — Convective heat transfer between pcm to water (W/m^2 K)
V — Wind velocity (m/s)
P_w — Partial pressure of water vapour at the glass surface, N/m^2
P_g — Partial pressure of water vapour at the glass surface, N/m^2

Greek

α_g — Absorptivity of glass cover
α_b — Absorptivity of basin liner
α_w — Absorptivity of water
α_{pcm} — Absorptivity of PCM
γ_g — Reflectivity of glass cover
σ — Stefan Boltzmann constant
Δ — Difference

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