International Journal of Advance Research and Innovation
Vol. 4(1), Jan-Mar 2016, pp. 335-342
Doi: 10.51976/ijari.411649

Article Info
Received: 20 Jan 2016 | Revised Submission: 10 Feb 2016 | Accepted: 28 Feb 2016 | Available Online: 15 Mar 2016

Thermal Performance of a Weir-Type Cascade Solar Still: an Experimental Study

Mahesh Kumar, Chaturbhuj Yadav** and Himanshu Manchanda****

ABSTRACT

Water is essential for all living creatures. It is abundantly available on earth surface but quantity of potable water is very less. Solar distillation is environmental friendly, economical and cheap water purification techniques. This technique is not commercialized yet because of its lower distillate output. In this communication weir-type cascade solar still with phase change material (PCM) are designed for increasing the productivity of still. Effect of three different phase change material (Bees wax, stearic acid and palmitic acid) of different melting point (61 oC, 55 oC and 54.3 oC respectively) have been studied on the performance of cascade weir type solar still. Maximum productivity of 2.35 litre/m2/day has been obtained with the use of palmitic acid as phase change material with the still. Mean values of convective, evaporative, radiative heat transfer coefficient with thermal efficiency of still has also been calculated and found to be 1.193, 13.13, 6.913 W/m2 oC and 24.58% respectively. The productivity of weir-type solar still with PCM is observed 33.69% higher than conventional still. Thermal efficiency of still with PCM is 35.46 % more than still without PCM.

Keywords: *Solar Still, Weir-Type, Solar Distillation, Heat Transfer Coefficients, Efficiency.*

1.0 Introduction

Energy and potable water are two main big issues faced by humanity today. Potable water is necessary for mankind and it also influences the social and economic development of a nation. Drinking of contaminated water causes many health problems and waterborne diseases. Moreover, the financial resources are allocated toward the efforts for searching the antidote of diseases. Consequently, the economic growth is decreased which cannot be acceptable for any country.

Water is available on ¾ of earth surface. The inexhaustible source of water is ocean but this is not useful for drinking and other activities where water is essential [1]. There are limited resources of potable water (lakes, rivers, underground water, etc.) that satisfied the required constituent of biological, physical and chemical. Among available resources 97 % water is salty. The human activities (population increase, improper disposal of wastes and poor agricultural practices) and environmental pollution have adversely affected the clean water. Water is basic need of all living creatures. It is used for many purposes such as drinking, cooling, agriculture, cooking, etc. For providing the drinkable water, its purification is necessary. The desalination/purification of water is done by many technologies. The some important techniques are listed in Table 1. membrane. Electric energy is required in membrane process either for driving high pressure pumps or for ionization in brackish water.

In thermal techniques water is evaporated and condensed for obtaining the fresh water from contaminated water. These processes are not cost effective at low demand of water, because a large amount of energy is required for driving these processes. These techniques used both renewable and non-renewable resources. The non- renewable resources are coal, petroleum, wood, etc. and the renewable resources are wind, solar, tidal, etc [2].

Recently, every nation focus on save the environment and use of non-renewable resources caused the environmental degradation. The anthropogenic activities and burning of fossil fuels caused the increase in ambient temperature and

---

**Corresponding Author: Mechanical Engineering Department, Guru Jambheshwar University of Science and Technology, Hisar, Haryana (India) (E-mail: mkshandilyal@gmail.com, raochaturbhuj@gmail.)*
***Mechanical Engineering Department, Guru Jambheshwar University of Science and Technology, Hisar, Haryana*
****Mechanical Engineering Department, Guru Jambheshwar University of Science and Technology, Hisar, Haryana*

pollution. Consequently, the renewable energy technologies for obtaining purified water are environmental friendly. Solar energy is freely available everywhere and inexhaustible.

This energy is utilized indirectly (ocean thermal, biomass, wind energies, etc.) and directly (heating of building and water, desalination, etc.) in variousactivities.

Solar distillation is the best substitute of other non-renewable energy based water purification techniques because it is driven with the help of solar energy Basic principle of solar desalination process is similar to as rain formation process [4].

2 0 Solar Still

A solar still is a device used for distillation/desalination of brackish/saline water into pure form as shown in Fig. 1.

Impure is filled inside the still basin and it is covered with ainclined cover of glass or plastic sheet.

The solar radiations fall on inclined surface. These solar radiations are partially absorbed, reflected and transmitted by inclined surface.

Among transmitted radiations partially absorbed by water surface and major portion is absorbed by bottom of basin which is black painted for higher absorption of solar radiation.

When the temperature of water in the basin increased, the evaporation starts from upper layer of water.

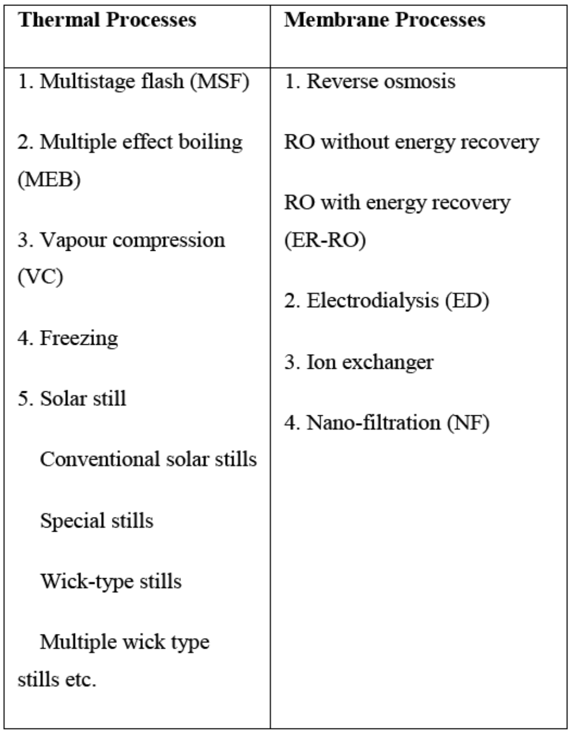
The temperature of successive layers increased, also and convection current inside the still carry the warm vapor-air mixtures to the glass cover which is cooler than the water surface temperature. Condensation process takes place under the glass surface and heat of condensation transmitted to the surrounding.

The condensed water flows down due to gravity and collected at outlet.

In distillation process salt and other impurities such as water borne pathogens, heavy metals, microbiological organism etc. removes from the water [5, 6].

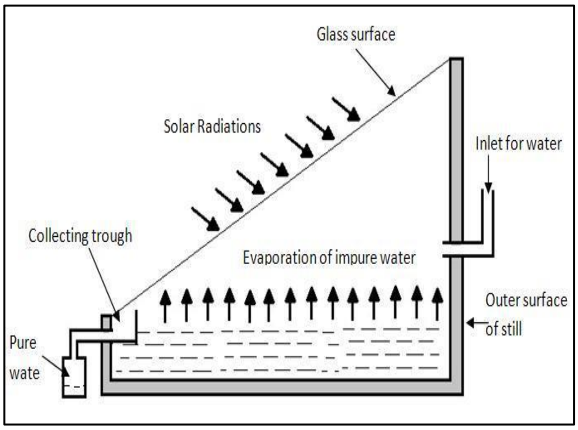
Solar distillation is highly promising and safe for environment. The outlet water is in the purist form as rain water [7].

Table 1: Desalination Process



Thermal Processes	Membrane Processes
1. Multistage flash (MSF) 2. Multiple effect boiling (MEB) 3. Vapour compression (VC) 4. Freezing 5. Solar still Conventional solar stills Special stills Wick-type stills Multiple wick type stills etc.	1. Reverse osmosis RO without energy recovery RO with energy recovery (ER-RO) 2. Electrodialysis (ED) 3. Ion exchanger 4. Nano-filtration (NF)

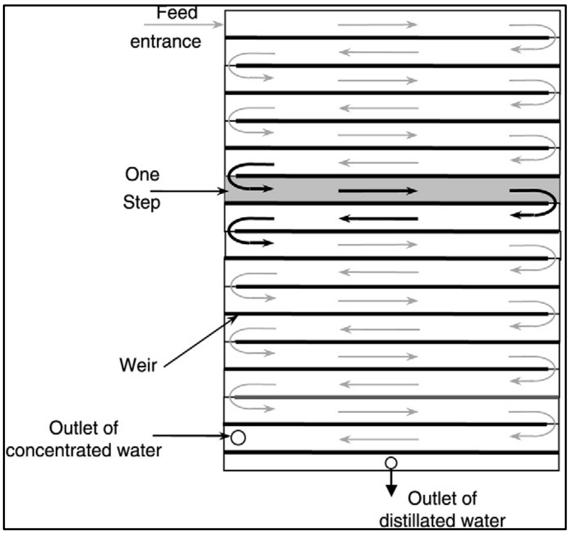
Fig 1: Conventional Solar Still



The solar still is mainly classified into active and passive solar stills. In passive solar still, distillation process is carried out by direct sun light only. They are operating nearly 60 oC. The single slope solar still has more productivity compared to the double slope solar still [8]. In active solar stills an extra amount of thermal energy is fed to the water in the basin for making evaporation faster in active solar still.

Weir type cascade solar still is an improved design of conventional solar still. In this type of solar still basin is in stepped form and each stepped has some section through which water will flow. Basic cross section view of absorber plate of weir type cascade solar still is shown in Figure 2. Some of the research works carried out on weir type solar still is discussed.

Fig 2: Absorber Plate of Weir Type Cascade Solar Still [10]



Sadineni et al., [9] designed a weir-type inclined solar still. The water flows from top basin to bottom basin and unevaporated water pumped back to top basin with the help of small pump. The productivity of still was observed 20% higher than conventional still. Tabrizi et al., [10] examined the effect of flow rate and mass transfer rate on a weir-type cascade solar still. They concluded that productivity of solar still is highly influenced with inlet water flow rates. The daily productivity observed was 7.4 and 4.3 kg/m2 at flow rate of 0.065 kg/min and 0.2 kg/min respectively. Tabrizi et al., [11] designed a weir-type cascade solar still combined with latent heat storage system. Productivity of weir-type cascade solar still with and without phase change material was compared. Dashtban and Tabrizi (2011) used 18 kg mass of paraffin wax as PCM for increasing the temperature of water in the basin in the lack of sun shine. The productivity of still was nearly 31% higher with the use of phase change material. Zoori et al., (2013) [13] analyzed the energy and exergy efficiencies of weir-type cascade solar still. Various parameters, i.e., water thickness, solar radiation, inlet water temperature, inlet brine flow rate, etc. for enhancing the productivity of still was considered. The maximum energy and exergy efficiencies were found to be 83.3% and 10.5% respectively with minimum flow rate of 0.065 kg/min. Al-Hamadani and Shukla (2011) [14] used the lauric acid as a heat storage medium for distillation of water. They concluded that productivity of still higher when mass of water in basin is lower as compare to mass of PCM.

Fig 3: Schematic View of Weir-Type Solar Still Set-Up

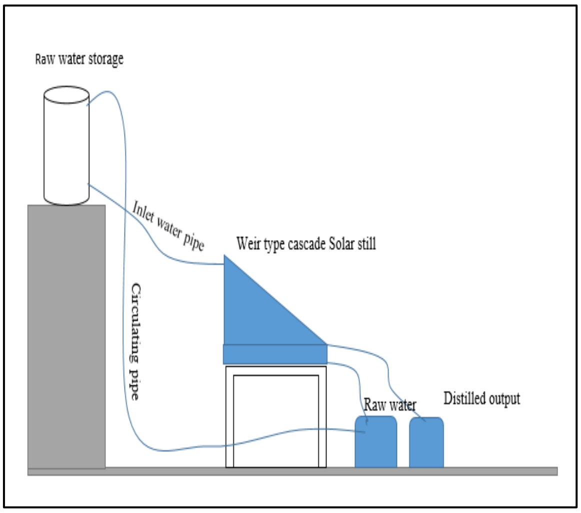
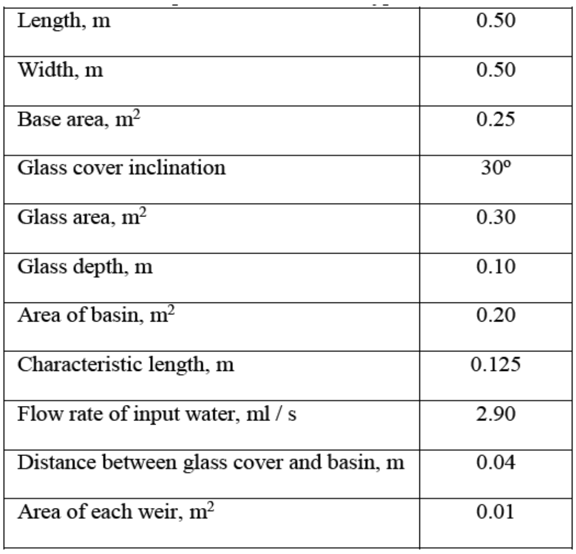


Table 2: Specifications of Weir-Type Solar Still



Length, m	0.50
Width, m	0.50
Base area, m^2	0.25
Glass cover inclination	30°
Glass area, m^2	0.30
Glass depth, m	0.10
Area of basin, m^2	0.20
Characteristic length, m	0.125
Flow rate of input water, ml / s	2.90
Distance between glass cover and basin, m	0.04
Area of each weir, m^2	0.01

3.0 Experimental Set-up and Detail

In this communication a weir-type solar still is designed and tested. Schematic view and specification of experimental unit is shown in Figure 3 and Table 2. The various temperatures at different location of solar still were measured using calibrated Pt-100 thermocouples with a digital temperature indicator of 0.1 oC least count. The solar intensity was measured by solar power meter (MECO). The velocity of air was measured by anemometer (battery operated) by facing its propeller shaft toward the flow of wind. The mass of distilled water collected was measured with an electronic weighing balance (Capacity of 6 kg; Smartech) having a least count of 0.1 kg. The essential data of temperatures, wind velocity, sun radiations and distilled output was recorded at 7 a.m. to 6 p.m.

The experimental data was recorded after every 1 hour time interval. The amount of distilled water collected for each hour reading was obtained by subtracting two consecutive reading in a given time interval. Different sets of data of different parameters were obtained with or without use of phase change material.

4.0 Thermal Analysis

For calculation of productivity and efficiency the energy balance method is applied. The performance of solar still is defined as the quantity of water (liters) got evaporated from per unit area (m2) of basin in per day.

The performance also calculated with equating mass energy balanced equation for components of solar still.

Initially, it is assumed that the system at quasi-steady state condition, i.e., the hourly temperature is not varied. The basic assumption for applying thermal analysis is as follow:

- The still is air tight for stopping the saturated air flow out.
- The still is completely insulated for inhabitation of heat flow from sides.
- Considering a constant thickness of water and water layer is immobile.
- The immobile layer of water having a uniform temperature on the absorber surface.

4.1 Glass cover:

The thermal balance equation for glass cover is considered as

$I(t)\,\alpha g + h2\,(Tw - Tg) = h3{,}g\text{-}a\,(Tg - Ta) + (mg\,cg / Ag)\,(dTg / dt)$ (1)

where the equivalent heat transfer coefficient h2 = hrwg + hewg + hcwg from water surface to the glass cover. The Dunkle's relation is used for calculation of convective (hcwg), evaporative (hewg) and the radiative (hrwg) heat transfer coefficients [15, 16].

$$h_{cwg} = 0.884\left[T_w - T_g + \frac{(P_w - P_g)(T_w + 273)}{268.9\times10^3 - P_w}\right]^{1/3} \qquad (2)$$

$$h_{ewg} = 0.01623\times h_{cwg}.\left[\frac{P_w - P_g}{T_w - T_g}\right] \qquad (3)$$

$$h_{rwg} = \varepsilon_{eff}\times\sigma\,[\,(T_w + 273)^2 + (T_g + 273)^2](T_w + T_g + 546) \qquad (4)$$

$$h_{3,g\text{-}a} = 5.7 + 3\,V \qquad (5)$$

$$\varepsilon_{eff} = 1/(1/\varepsilon_w + 1/\varepsilon_g - 1) \qquad (6)$$

4.2 Saline / brackish water

Thermal balance equation for saline water is sum of evaporative, radiative and convective heat transfer between glass and water and energy sorted by saline water.

$I(t)\,\tau g\,\alpha w + h1\,(Tp - Tw) = h2\,(Tw - Tg) + (mw\,cw / Aw)\,(dTw / dt)$ (7)

Where, h1 is convective heat transfer coefficient between saline water and absorber plate.

4.3 Absorber plate

Thermal balanced equation for absorber plate

$I(t)\,\alpha p\,\tau g\,\tau w = h1(Tp - Tw) + Ub\,(Tp - Ta) + (mp\,cp / Ap)\,(dTp / dt)$ (8)

Where Ub is back loss coefficient.

4.4 Thermal analysis when PCM is used

The energy equation for glass cover and saline water remain same only change in absorber plate and also thermal energy analysis for PCM. The energy equation for absorber plate as follow:

4.5 Absorber plate

The energy equation is represent as,

$I(t)\,\alpha p\,\tau g\,\tau w = h1\,(Tp - Tw) + (kPCM / xPCM)\,(Tp - TPCM) + (mp\,cp / Ap)\,(dTp / dt)$

Where, the kPCM and xPcm are thermal conductivity and thickness of the PCM respectively.

4.6 Phase change material (PCM)

Thermal equation of PCM is as, (KPCM / xPCM) (Tp - TPCM) = (kins / xins) (TPCM - Ta) + (Mequ / Ap) (dTPCM / dt) (10) Where kins are the thermal conductivity of insulating material and xins is the thickness of insulating material. Mequ is equivalent heat capacity of PCM and it is represented at different phase as follow:

$M_{equ} = m_{PCM} \times c_{s,PCM}$ for $T_{PCM} < T_m$

$M_{equ} = m_{PCM} \times L_{s,PCM}$ for $T_m \leq T_{PCM} \leq T_m + \delta'$

$M_{equ} = m_{PCM} \times c_{s,PCM}$ for $T_{PCM} > T_m + \delta'$

Where L_{PCM} is latent heat of PCM

The productivity of distilled water form still is calculated as

$$m'_{ew} = \frac{q_{ewg}.A_w.3600}{L_w} = h_{ewg}.A_w.(T_w - T_g).3600/L_w \quad (11)$$

$L_w = 3.1615 \times 10^6 [1 - (7.616 \times 10^{-4}. T_i)]$, $T_i > 70$ °C

$L_w = 2.4935 \times 10^6 [1 - 9.4779\times10^{-4}.T_i + 1.3132\times10^{-7}.T_i^2 - 4.7974\times10^{-9}.T_i^3]$, $T_i < 70$ °C

Where $T_i = (T_w + T_g) / 2$ (12)

The efficiency of still is ratio of evaporation to the incident solar energy given as

$$\eta_{passive} = \frac{\sum m'_{ew}.L_w}{A_p \int I(t)dt} \times 100 \quad (13)$$

Where dt is small interval for measuring the solar radiation.

5.0 Results and Discussions

The thermal coefficients are calculated with the help of Dunkle's relation. The variation of the different parameters, i.e., outer glass temperature, inner glass temperature, water temperature, solar intensity with time is shown in the Fig. 4-7. The water temperature in basin is more with the use of phase change material because heat is transferred from the phase change material to the basin after peak value of the solar intensity. The variation in hourly productivity against time of weir-type solar still is shown in Fig. 8.

Fig 4: Variation in Outer Glass Temperature Against Time

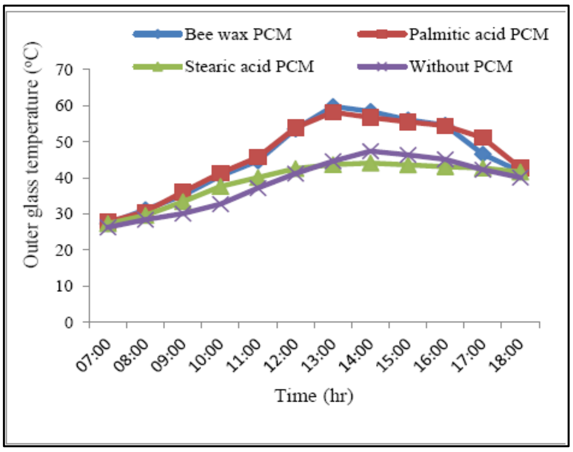


Fig 5: Variation in Inner Glass Temperature Against Time

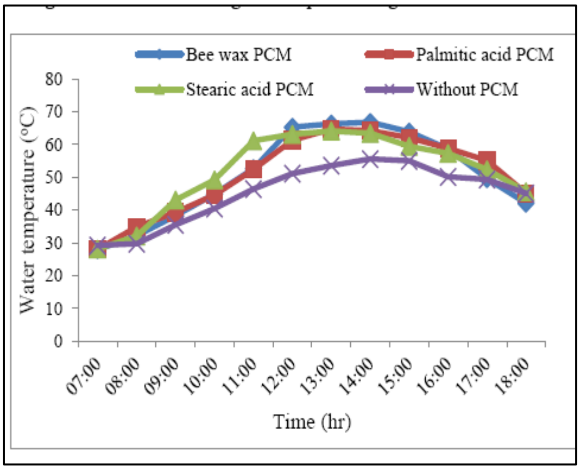


Fig 6: Water Temperature Against Time

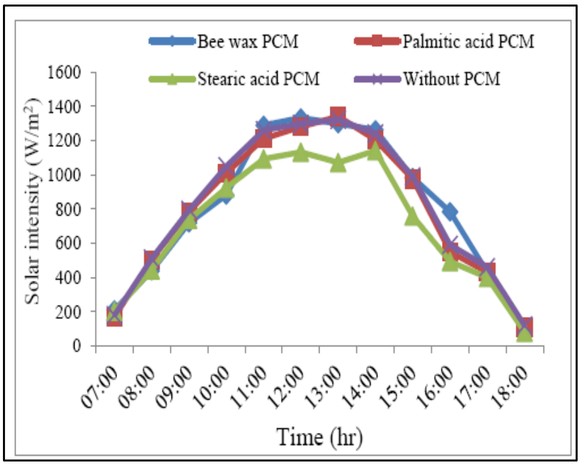


Fig 7: Solar Intensity Against Time

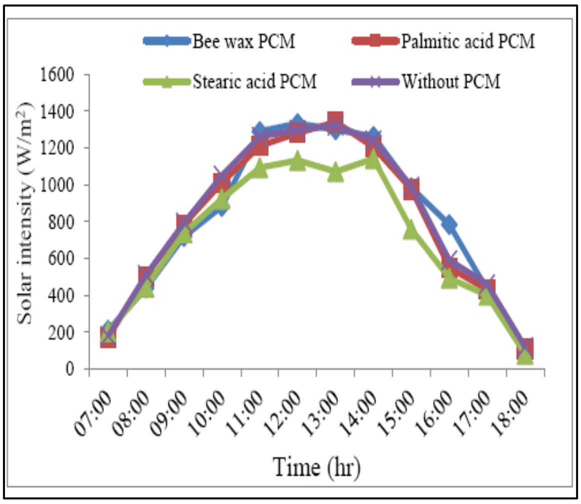


Fig 8: Distilled Water Collected Against Time

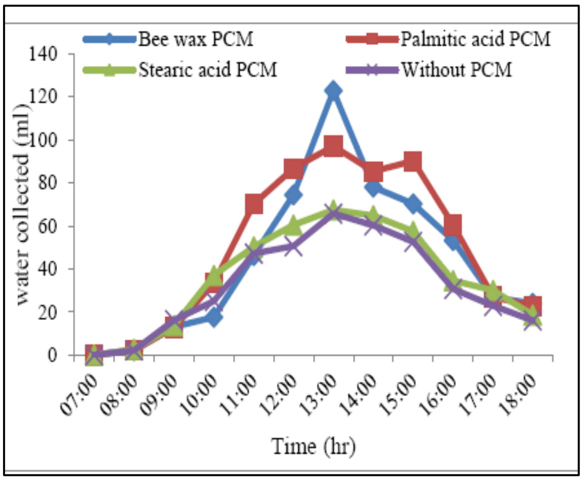


Fig 9: Hourly Variations of Phase Change Mater

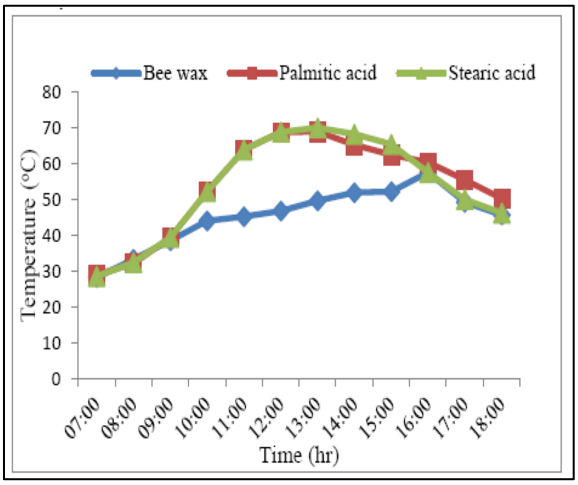
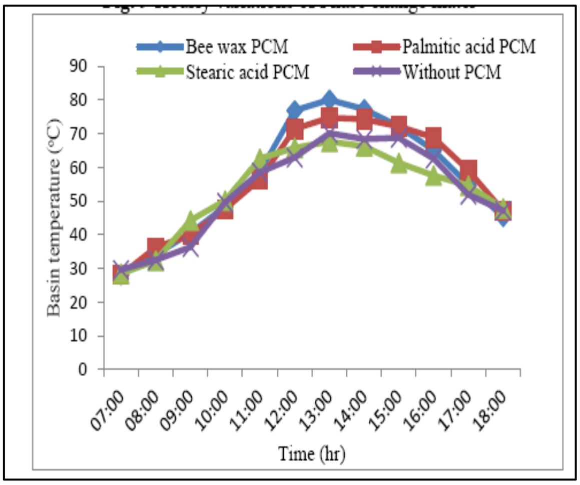


Fig 10: Basin Temperature Against Time



The hourly variation of temperature of phase change material is represented into Fig. 9. The hourly variation of basin temperature is shown in the Fig. 10.

The stearic acid and palmitic acid have maximum temperature at 13:00 pm. The palmitic acid has more energy storage capacity. Initial the energy stored in the form of sensible heat till reach its melting point of the phase change material. The phase changed process take placed at a constant temperature.

As the temperature start decreasing at 14:00 the latent heat of PCM released gradually till the solidification take placed of the phase change material. The mean values of evaporative heat transfer coefficient, convective, radiative heat transfer coefficient, heat transfer coefficient from glass to surrounding, productivity and equivalent heat transfer coefficient are tabulated in Table 3.

Table 3: Mean Value of Various Coefficients and Thermal Efficiency Of Still

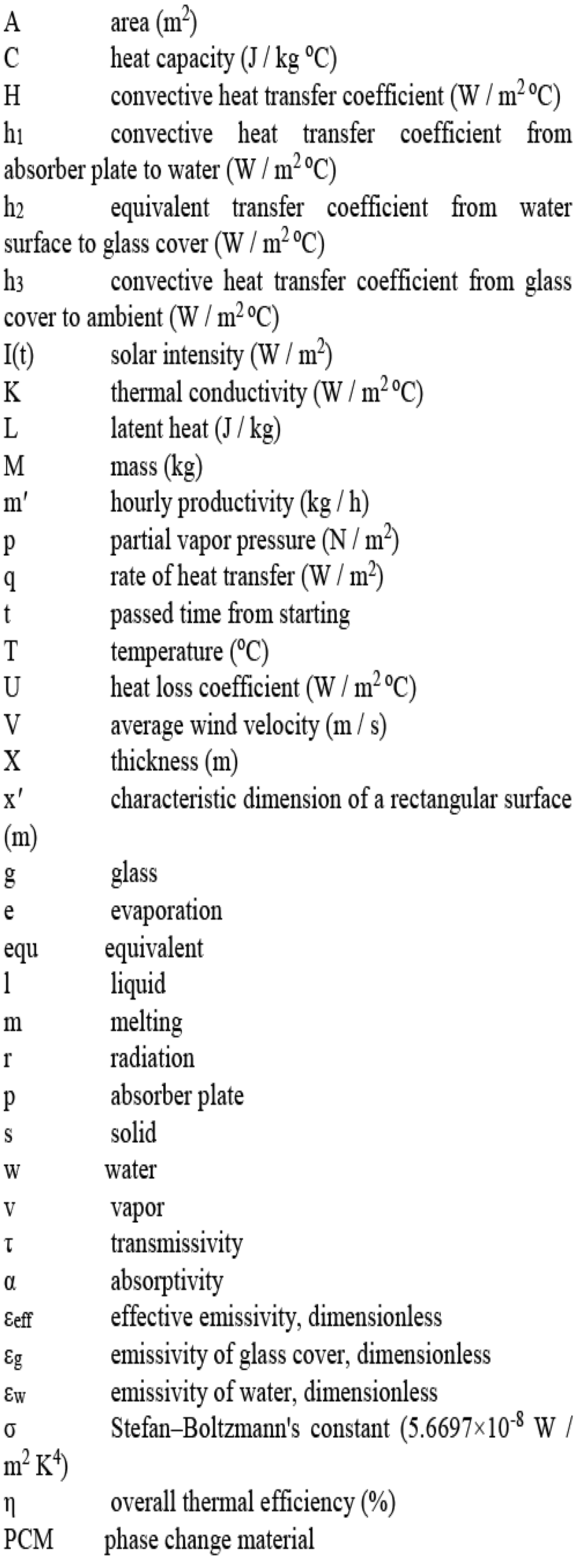
	Palmitic acid PCM	**Stearic acid PCM**	**Without PCM**	**Bee wax PCM**
h_{cwg} (W / m^2 °C)	1.193	2.010	1.433	1.291
h_{ewg} (W / m^2 °C)	13.13	20.606	12.805	14.325
h_{rwg} (W / m^2 °C)	6.913	6.536	6.221	6.552
$h_{3,g-a}$ (W / m^2 °C)	11.20	26.608	10.300	8.830
η %	24.58	20.610	15.870	21.710
h_2	21.236	29.152	20.459	22.168

4. With the use of the phase change material, the productivity of still is observed to increase about 34 % than without phase change material.

5. The maximum productivity and the thermal efficiency of the still are 2.4 kg / m2 day and

1.6 kg / m2 day, 25 % and 16 % for with and without phase change material still respectively.

Nomenclature



A	area (m^2)
C	heat capacity (J / kg ^{o}C)
H	convective heat transfer coefficient (W / m^2 ^{o}C)
h_1	convective heat transfer coefficient from absorber plate to water (W / m^2 ^{o}C)
h_2	equivalent transfer coefficient from water surface to glass cover (W / m^2 ^{o}C)
h_3	convective heat transfer coefficient from glass cover to ambient (W / m^2 ^{o}C)
I(t)	solar intensity (W / m^2)
K	thermal conductivity (W / m^2 ^{o}C)
L	latent heat (J / kg)
M	mass (kg)
m′	hourly productivity (kg / h)
p	partial vapor pressure (N / m^2)
q	rate of heat transfer (W / m^2)
t	passed time from starting
T	temperature (^{o}C)
U	heat loss coefficient (W / m^2 ^{o}C)
V	average wind velocity (m / s)
X	thickness (m)
x′	characteristic dimension of a rectangular surface (m)
g	glass
e	evaporation
equ	equivalent
l	liquid
m	melting
r	radiation
p	absorber plate
s	solid
w	water
v	vapor
τ	transmissivity
α	absorptivity
ε_{eff}	effective emissivity, dimensionless
ε_g	emissivity of glass cover, dimensionless
ε_w	emissivity of water, dimensionless
σ	Stefan–Boltzmann's constant (5.6697×10^{-8} W / m^2 K^4)
η	overall thermal efficiency (%)
PCM	phase change material

References

[1.] S. Gorjian, B. Ghobadian, T.T. Hashjin, A. Banakar, Experimental performance evaluation of a stand-alone point-focus parabolic solar still, Desalination, 352 ,2014, 1–17

[2.] M. Kumar, H. Manchanda, Sugandha, R. Singhal, Solar water distillation and its importance for community, NCARES, 43,2015

[3.] H. Manchanda, M. Bashyal, M. Kumar, A review on solar water purifier, NCAME, 2014

[4.] Riahi, K.W. Yusof, M.H. Isa, B.S.M. Singh and N. Sapari, Solar Stills Productivity with different Arrangements of PV-DC Heater and Sand Layer in Still Basin: A Comparative Investigation, Research Journal of Applied Sciences, Engineering and Technology 8-11,2014, 1363-1372

[5.] M.K. Gnanadason, P.S. Kumar, G. Jemilda, S.S. Jasper, Effect of Nanofluids in a Modified Vacuum Single Basin Solar Still, International Journal of Scientific & Engineering Research 3, 1,2012

[6.] G. Gowrisankar, R. Jayaprakash, T. Arunkumar, Thermal performance and analysis of low cost spherical solar still with charcoal absorber, Indian Streams Research Journal I,4,2011

[7.] D.W. Medugu and L.G. Ndatuwong, Theoretical analysis of water distillation using solar still, International Journal of Physical Sciences 4 (11), 2009, 705-712,

[8.] R.S. Hansen, C.S. Narayanan, K.K. Murugavel, Performance analysis on inclined solar still with different new wicks materials and wire mesh, Desalination, 358, 2015

[9.] S.B. Sadineni, R. Hurt, C.K. Halford, Theory and experimental investigation of weir-type inclined solar still, Energy Conversion & Management, 33 (2008) 71-80

[10.] F.F. Tabrizi, M. Dashtban, H. Moghaddam, K. Razzaghi, Effect of water flow rate on internal heat and mass transfer and daily productivity of a weir-type cascade solar still, Desalination 260, 2010, 239-247

[11.] F.F. Tabrizi, M. Dashtban, H. Moghaddam, Experimental investigation of weir-type cascade solar still with built in latent heat thermal energy storage system, Desalination 260,2010, 248-253

[12.] M. Dashtban and F.F. Tabrizi, Thermal analysis of a weir-type cascade solar still integrated with PCM storage, Desalination 279, 2011, 415-422

[13.] H.A. Zoori, F.F. Tabrizi, F. Sarhaddi, Comparison between energy and exergy efficiencies in a weir type cascade solar still, Desalination, 325,2013, 113-121

[14.] A.A.F. Al-Hamadani, S.K. Shukla, Water distillation using solar energy system with lauric acid as storage medium, International journal of energy engineering, 1,2011, 1-8

[15.] G.N. Tiwari, Solar energy, Fundamentals, Designs, Modeling and Applications, CRC Press, New York, 2002

[16.] A.K. Tiwari, G.N. Tiwari, Effect of water depths on heat and mass transfer in a passive solar still: in summer climatic condition. Desalination 195 (1), 2006, 78-94