International Journal of Advanced Scientific and Technical Research Issue 5 volume 2, March.-April.2015
Available online on http://www.rspublication.com/ijst/index.html ISSN 2249-9954

Experimental Investigation of a Solar Still with and without Phase Change Material (PCM) under Climatic Conditions of Dhahran, Saudi Arabia

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ABSTRACT

The scarcity of fresh water is an issue which need special attention as most of the world population suffers from clean water shortage which results in a lot of diseases and deaths. The aim of the work is to come up with a relatively cheap, portable and efficient system that can produce pure water by utilizing solar energy. The approach involve the experimental investigation of single sloped solar still with and without phase change material in winter season under climatic conditions of Dhahran, Saudi Arabia. Initially solar still was tested with different depth of water without phase change material and performance analysis are carried out on the basis of various factors that include solar intensity, ambient temperature, water temperature, and glass temperature, temperature of inlet water, and depth of water. The still was then tested with phase change material for the comparative analysis under same prevailing conditions. The purpose of using phase change material is storage of available solar energy during the day which can be used after the sunsets and solar still can work for longer period of time. The results showed that solar still with phase change material can produce the fresh water for longer period of time during the day (even after the sunset) as compared to the solar still without phase change material.

Key words: Solar still, water desalination, phase change material, solar energy.

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1. INTRODUCTION

The earth receives a large amount of energy from the sun. Because of the solar energy abundance and availability an attempt is made to design a simple and cheap system for water desalination which can be used on small scale to provide fresh water for human use. Because only 1% of the total earth water is available as fresh water which make the water desalination a big challenge for the present age. Lots of deaths are happening because of the water caused diseases. The system is a simple single slop solar still with a transparent glass. The idea of solar still is just to provide fresh water for home use and this idea can be utilized by the people living on hills or mountains to get fresh drinking water because at these places fresh water will not be readily available to them. Different researchers work has proved that water obtained from the solar still is pure and free of salts.

Two types of solar stills are there: one which uses no external source of heating other than the sun is called as passive solar still and the other one in which some external source of heating is provided is called as active solar still. This can also be of single or double slop. The basic designs of a single and double slop solar still are shown in Fig. 1 and 2 respectively. No doubt solar stills provides very small quantity of fresh water [1] but this system is simplest of all which needs no technical knowledge to operate, everyone can use it to get fresh water. For increment in productivity of the solar still many improvements have been tried by different people and they have proved very good results [2, 3]. In the present work another effort is made to improve the productivity of the system which is the use of phase change material. The purpose of this is to store the energy during day time and then when sun sets it releases the energy for the system to work for longer period of time.

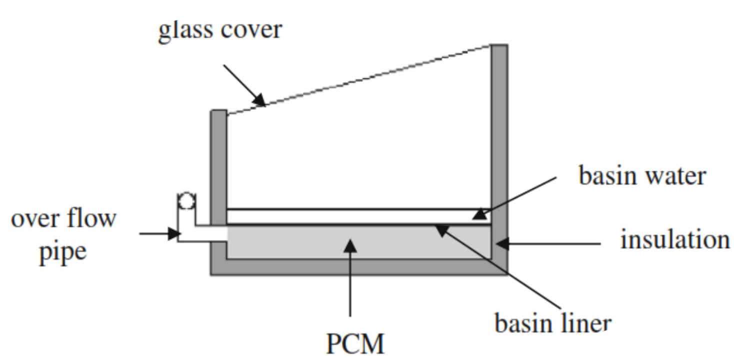

Fig. 1: Basic Model of the single sloped solar still.

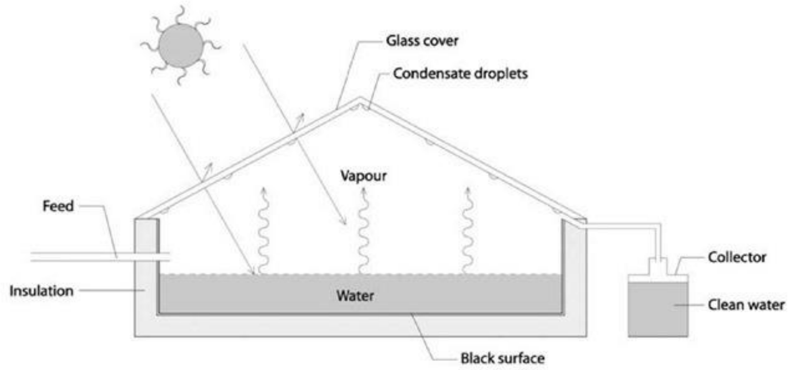

Fig. 2: Double slop solar still.

1.1. Concept of Phase Change Material (PCM)

Two modes of energy storage are there:

1. Sensible energy storage
2. Latent energy storage

In sensible energy storage system energy is stored as a temperature change in the system i.e. energy is stored as the temperature of the material increases and energy is released as its temperature decreases. While in latent heat storage system, energy as stored due to phase change and no temperature change occurs. Energy is stored as the material changes from solid to liquid or liquid to vapors and energy is given away when it solidify or regain its shape. Paraffin Wax is one of the good examples of phase change material for latent heat storage.

Phase change materials (PCM) are latent heat storage materials that stores the energy because of the phase change i.e. when a material changes from solid to liquid, or liquid to solid. The temperature remains almost constant when these materials stores and release thermal energy. The heat storage capacity per unit volume of PCMs are much higher as compared to sensible heat storing materials.

Thermal properties should favor a suitable temperature of phase transition with high latent heat and good heat transfer capabilities. Physically, it should have high density and follow small volume changes during transition. Chemical properties include long term chemical stability of the material without any toxicity and fire hazards.

1.2. Classification of PCMs

PCMs can be categorized as organic, inorganic and eutectics on the basis of latent heat of fusion and melting temperature. A classification of PCMs is given in Figure 3. Organic materials melt and freeze frequently without phase separation that help to retain their latent heat of fusion. Organic materials can be further categorized as paraffin and non-paraffin. Paraffin wax are mostly straight chain n-alkanes CH_3–(CH_2)–CH_3 with and with the increase in chain length of paraffin wax, melting point and latent heat of fusion increase. Non-paraffin have the advantage of higher heat of fusion but comes at the expense of higher cost. Inorganic materials can be further classified as metallic and salt hydrate. The heats of fusion of these materials degrade with cycling and these do not super cooled appreciably. Eutectic PCMs are combination of two or more components and shows minimum melting temperature. Eutectic almost melts and freezes without phase separation. Different PCMs with low melting temperature (below 400^{o}C) are summarized in Table 1. A latent heat storage material should have following properties:

- Low melting point so that it can melt at low temperature.
- High latent heat of fusion value.
- No or very small volume change during the phase change.
- Negligible super cooling or superheating.
- Must have good performance for repeated cycles for a long period of time.
- Should have low cost.

Table 1: Different PCMs with low melting temperature [4].

Melting point and latent heat of fusion: paraffin's			
No. of carbon atoms	Melting point	Latent heat of fusion	Group
14	5.5	228	I
15	10	205	II
16	16.7	237	I
17	21.7	213	II
18	28	244	I
19	32	222	II
Melting point and latent heat of fusion: non-paraffin's			
Materials	Melting point	Latent heat of fusion	Group
Formic acid	7.8	247	III
Glycerin	18	198	III
D-Latticacid	26	184	I
Methylpalmitate	29	205	II

Camphenilone	39	205	II
Docasylbromide	40	201	II
Melting point and latent heat of fusion: fatty acids			
Material	Melting point(^{0}C)	Latent heat(kJ/kg)	Group^a
Aceticacid	16.7	184	I
Polyethyleneglycol600	20–25	146	I
Capricacid	36	152	–
Eladicacid	47	218	I
Lauricacid	49	178	II
Pentadecanoicacid	52.5	178	–
Melting point and latent heat of fusion: salt hydrates			
Material	Melting point(^{0}C)	Latentheat(kJ/kg)	Group^a
$K_2HPO_46H_2O$	14	109	II
$FeBr_36H_2O$	21	105	II
$Mn(NO_3)_26H_2O$	25	148	II
$FeBr_36H_2O$	27	105	II
$CaCl_212H_2O$	29	174	I
$LiNO_32H_2O$	30	296	I
List of organic and in organic eutectics			
Material	Melting point(^{0}C)	Latent heat(kJ/kg)	Group^a
$CaCl_26H_2O+CaBr_26H_2O$	14.7	140	–
Triethylolethane+water+urea	13.4	160	I
$C_{14}H_{28}O_2+C_{10}H_{20}O_2$	24	147.7	–
$CaCl_2+MgCl_26H_2O$	25	95	II
CH_3CONH_2 +NH_2CONH_2	27	163	II
Triethylolethane+urea	29.8	218	I

Group I, most promising; group II, promising; group III, less promising; insufficient data.

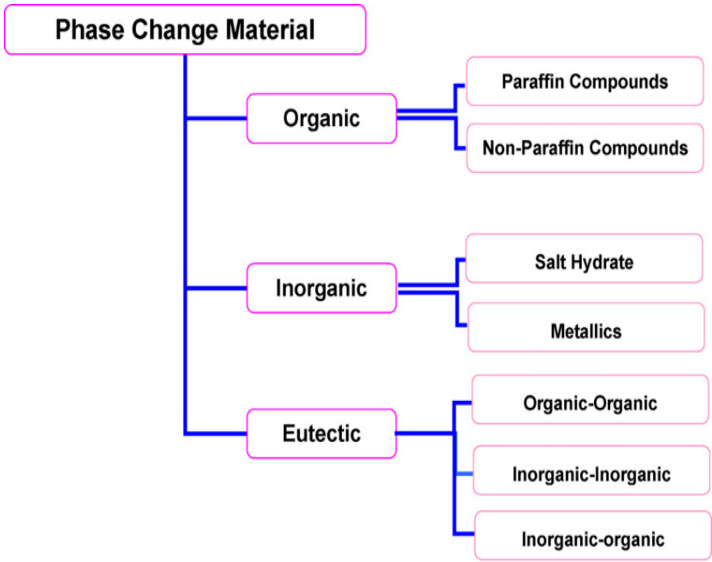

Fig. 3: Classification of PCMs [4].

1.3. Background of Solar Still with PCM

Clean water is the basic need of everyone and most of the world population is suffering from the scarcity of clean water. There is a need to of easily available and simple methods for the production of fresh water. The use of solar still for the production of fresh water is oldest method. Although, the efficiency of solar still is not much high but because of its portability, simplicity, and economical advantages it is a central focus for many researchers. Lot of work has been done to improve the solar still productivity. One of the method is to use energy storage systems that can store either latent or sensible storage. In this method heat dissipated from the bottom of the still is stored for the use at the night time or when solar radiations are not there. Latent heat storage units have the advantage of higher heat storage capacity and heat utilization at constant temperature.

Many researchers published their work on using PCMs as energy storage medium for many applications that involve solar water heating for domestic purpose [5, 6]; solar cookers [7], and green- houses [8]. The effect of using PCMs in solar still is investigated by few researchers. The work involve the use of paraffin wax as a PCM in steeped solar still with built-in latent heat thermal energy storage for heating and humidification of agricultural greenhouse [9]. The author mainly investigate the effect of PCM layer thickness and effect of mass flow rate of air on the system performance. Results of this study reveals that the greenhouse heat load is decreases with the decrease of air flow rate that significantly affect the still performance. A yield of 4.6 liter/m^2 with an efficiency of 57% has been obtained [10].

Another study involve the transient performance analysis of a single basin solar still that has single slope and integrated with stearic acid as a storage material beneath the basin liner of the still [10]. The study involve the energy balance formulation of various still components and their analytical solution. Numerical investigation is also being carried out for year-round performance of the still under the climatic conditions of Jeddah, Saudi Arabia. One of the objective of the study is to analyze daily productivity and still efficiency for different quantity of stearic acid. The results indicate the increase in productivity with increasing mass of PCM. Comparisons analysis of still with 3.3cm PCM (stearic acid) layer under water and without PCM reveals the daily productivity of 9.005 (kg/m^2) with an efficiency of 85.3% in summer season. The study also shows noticeable improvement of still performance in winter season with small depth of water in the basin.

2. EXPERIMENTAL SETUP

The setup involves a single sloped solar still with its basin made of fiber glass. The dimensions of the basin are 1.1 × 1.1 m^2. The inner case is painted black to absorb maximum solar radiations. The top of the still is tapered and a window glass of about 3 mm thickness is places on it. Silicon is used to seal the system and to make it air tight. Four thermocouples are placed at the following positions to measure the required temperatures:

1. inside the water to measure water temperature.

2. above the water to measure the temperature of the space in between glass and water.

3. inside the glass to measure glass inside temperature.

4. above the glass to measure glass outer temperature.

The still is filled with water of about 2 inch height and put into operation. The black surface absorbs the radiation transmitted by the glass and transfers it to the water which is heated up and evaporation starts. The vapors formed due to the evaporation condense inside surface of the glass and flows into the bucket designed to collect the fresh water. The system is placed in a place where radiations from sun can reach to it for maximum period of time i.e. away from shading. The photographic view of the experimental setup is shown in Fig. 4.

Fig. 4: Experimental setup.

3. SYSTEM PERFORMANCE

The experiment carried out for different days in the month of December under the climatic data of Dhahran, Saudi Arabia. First solar still performance was observed with only water (without phase change material). Solar radiation flux, and different temperature from thermocouples attached at four different locations (water, air, inside glass, outside glass) were noted using a temperature read out after every 15 minutes from 9 am to 7 pm. Productivity of the system was also noted. This is repeated for three different days. Solar energy falling on the still can be obtained as:

$$Q = A_g \times G_T \quad \textbf{(1)}$$

Where,

A_g= Glass area (m^2).

G_T= Solar radiations flux (W/m^2).

Q=Energy falling on the still (W).

4. RESULTS WITHOUT PCM

The results obtained for different temperatures and the productivity while solar still operating without PCM are presented in the Table 2, 3, and 4. Also the results are presented in the form of graphs to show the variations with respect to the time. Figure 5, 6, and 7 show the variations of solar flux with respect to time for different days of December, 2014. As it can be seen from the bar chart that the radiation flux increases up to noon time and then decreases to a value of zero. Figure 8 to 13 shows the variations of temperature and the distillated water obtained, for December 4, 5, and 6. For December, 4 the total productivity was 1.05 liters and as it can be seen from the above three figures that obtained productivity value depends on the solar flux i.e. productivity is more for the hours when solar flux is more. For 5th December, 2013, total productivity value was about 0.9 liters because of the partly cloudy weather.

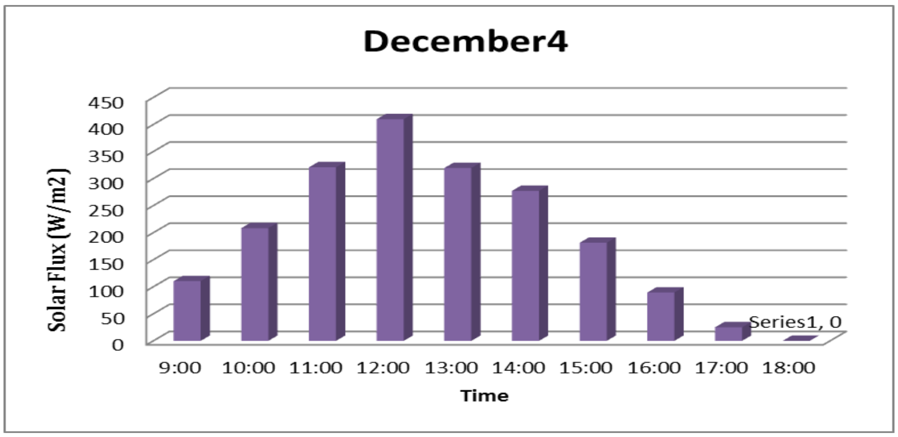

Fig. 5: Solar radiation flux for 4th December, 2014.

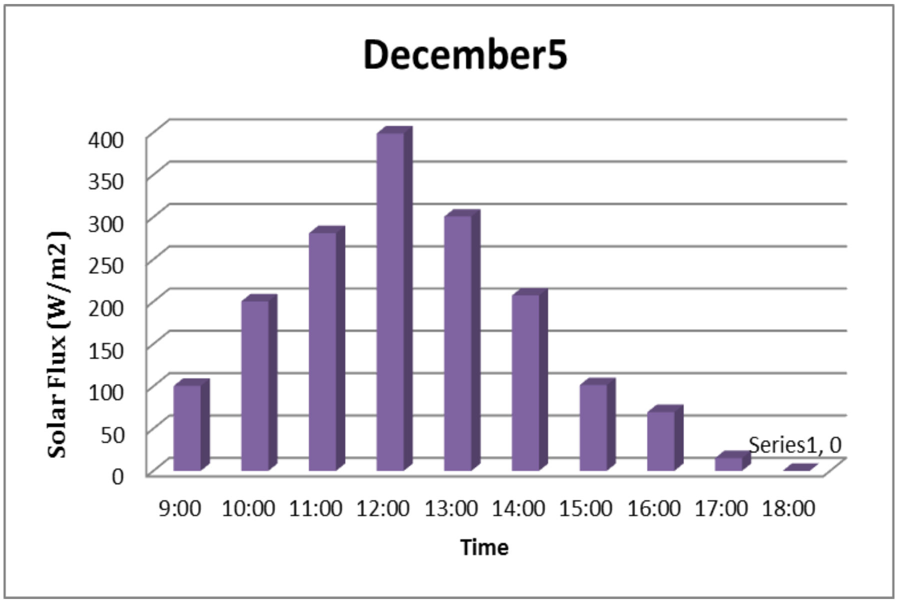

Fig. 6: Solar radiation flux for 5th December, 2014.

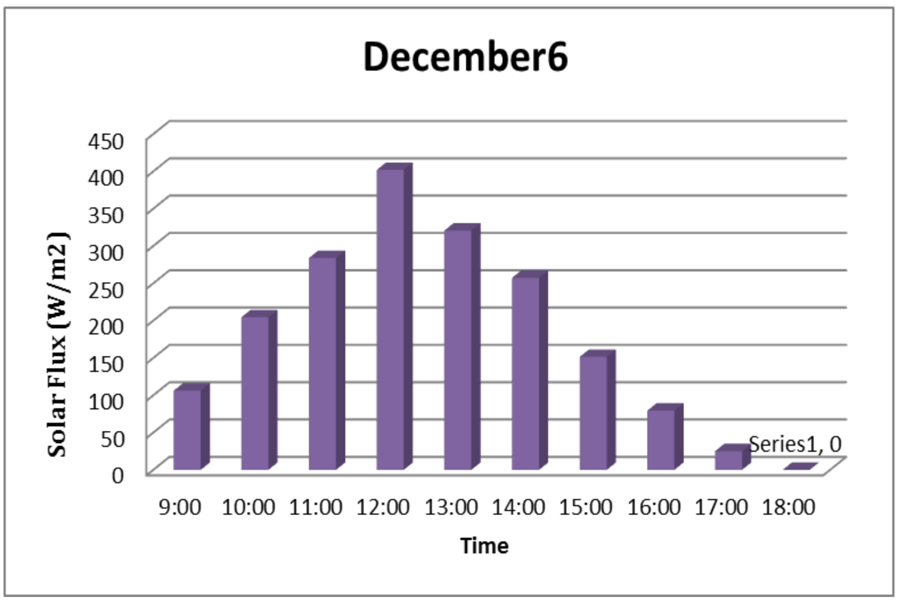

Fig. 7: Solar radiation flux for 6th December, 2013.

Table 2: Temperature variations and productivity on 4th December, 2014.

Time (Hours)	Water Temperature (ºC)	Air Temperature (ºC)	Glass inside Temperature (ºC)	Glass outside Temperature (ºC)	Solar Radiations (W/m^2)	Productivity (ml)
9:00	16.9	18.4	17.3	18.3	110.4	15
10:00	20.9	28.3	29	39.1	208.4	50
11:00	31.6	36.9	39.7	44.4	320.9	95
12:00	39.2	41.4	42.7	45.6	409.9	147
13:00	42.8	43.8	42.5	45.2	319.6	249
14:00	43.3	43.2	40.7	42.9	277.3	253
15:00	40.2	38.9	35.6	36.9	181.4	100
16:00	35.7	33.3	30.5	30.8	89.4	65
17:00	31	26.8	24.1	23	25	37
18:00	24.9	21	18.5	17.2	0	20

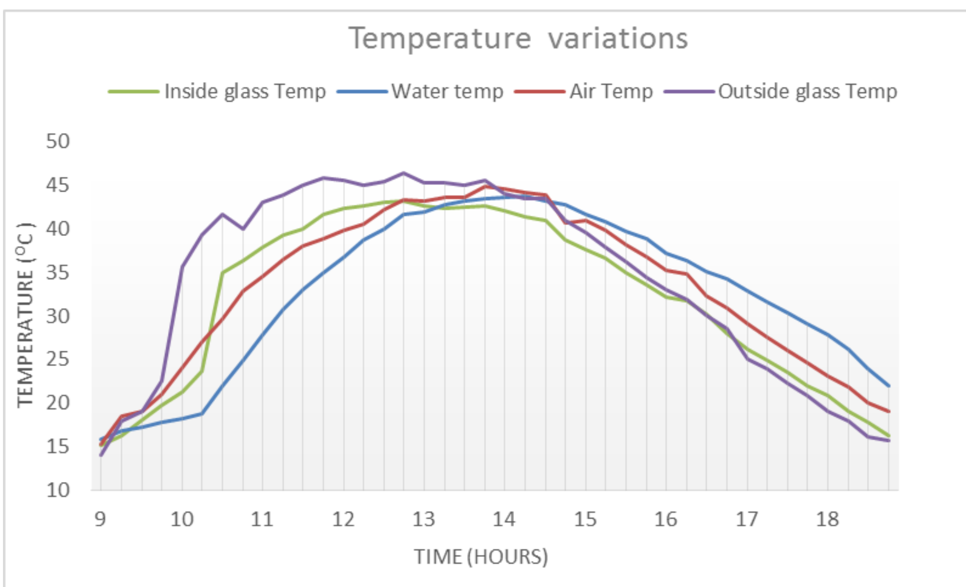

Fig. 8: Variation in temperatures with time of the day (4th December, 2014).

Fig. 9: Productivity for 4th December, 2014.

Table. 3: Temperature variations and productivity on 5th December, 2014.

Time (Hours)	Water Temperature (ºC)	Air Temperature (ºC)	Glass inside Temperature (ºC)	Glass outside Temperature (ºC)	Solar Radiations (W/m^2)	Productivity (ml)
9:00	17.8	20.8	19.8	22.1	100.4	10
10:00	23.4	28.3	27.2	31.2	200.4	45
11:00	31	33.6	33.8	37.5	280.9	64
12:00	37	38.1	39	41.7	398.9	140
13:00	41	42	39.2	43	300.6	245
14:00	41.3	41.8	38.3	41.3	207.3	240
15:00	39.1	38	34.5	35.2	101.4	85
16:00	35.3	33.4	30	29.2	69.4	58
17:00	27.3	26.4	25.2	23.8	15	34
18:00	22.8	20.5	19	19.9	0	17

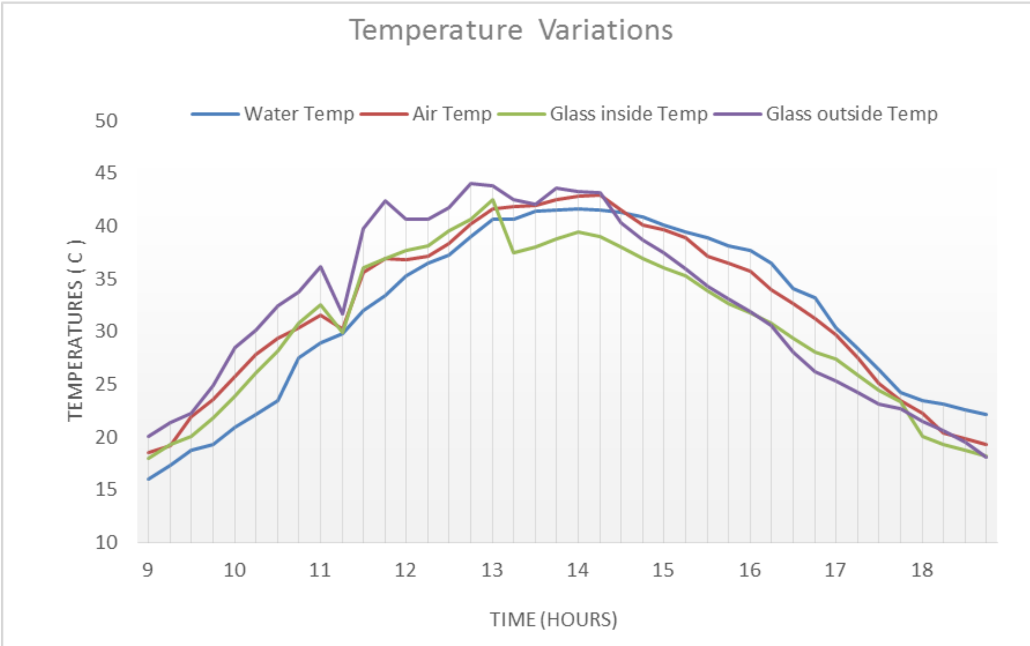

Fig. 10: Variation in temperatures with time of the day (5th December, 2014).

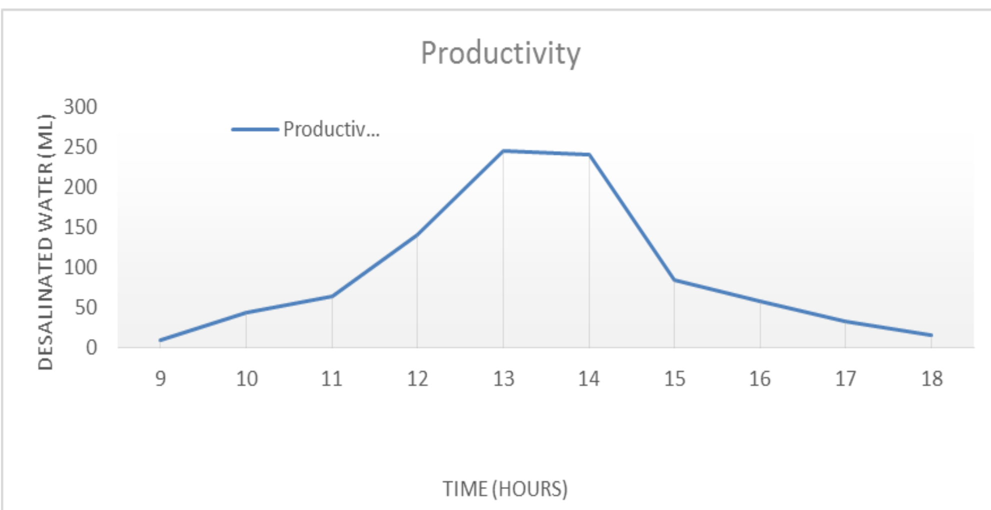

Fig. 11: Productivity for 5th December, 2014.

Table 4: Temperature variations and productivity on 6th December, 2013.

Time (Hours)	Water Temperature (C)	Air Temperature (C)	Glass inside Temperature (C)	Glass outside Temperature (C)	Solar Radiations (W/m^2)	Productivity (ml)
9:00	18.5	20.6	20.2		106.1	12
10:00	23.6	28.2	27.3	31.2	204.4	49
11:00	31.4	34.2	34.9	36.6	283.9	58
12:00	37.9	38.	39.4	42.5	401.9	145
13:00	42	42.5	39.7	43	320.6	250
14:00	42.2	42.3	38.2	41	257.3	246
15:00	38.2	37.2	33.8	34.6	151.4	78
16:00	34.7	32.3	28.8	27.8	79.4	60
17:00	27.6	27.3	24	23.6	25	39
18:00	22.3	20.4	19	19.1	0	22

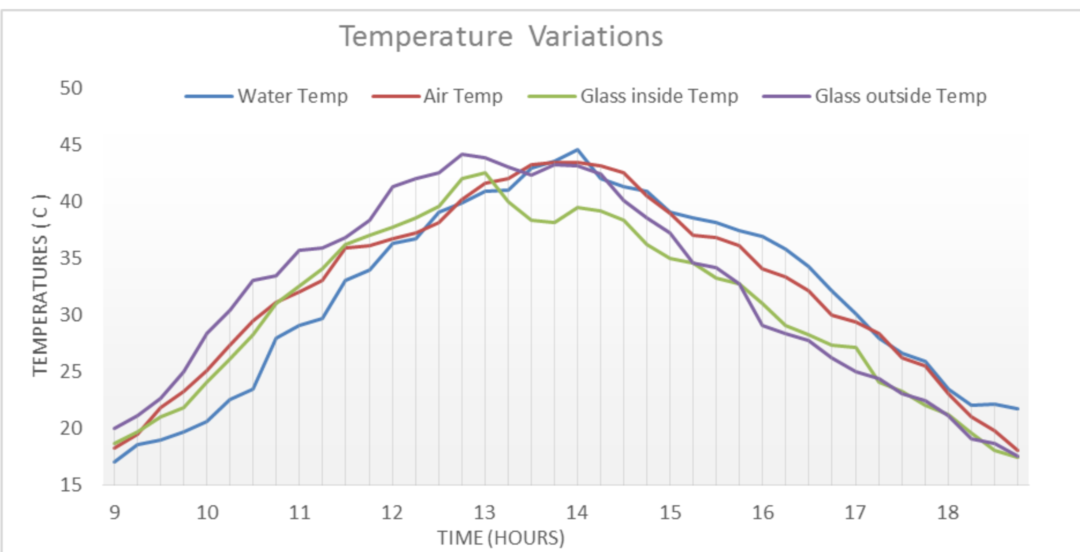

Fig. 12: Temperature variations for 6th December, 2013.

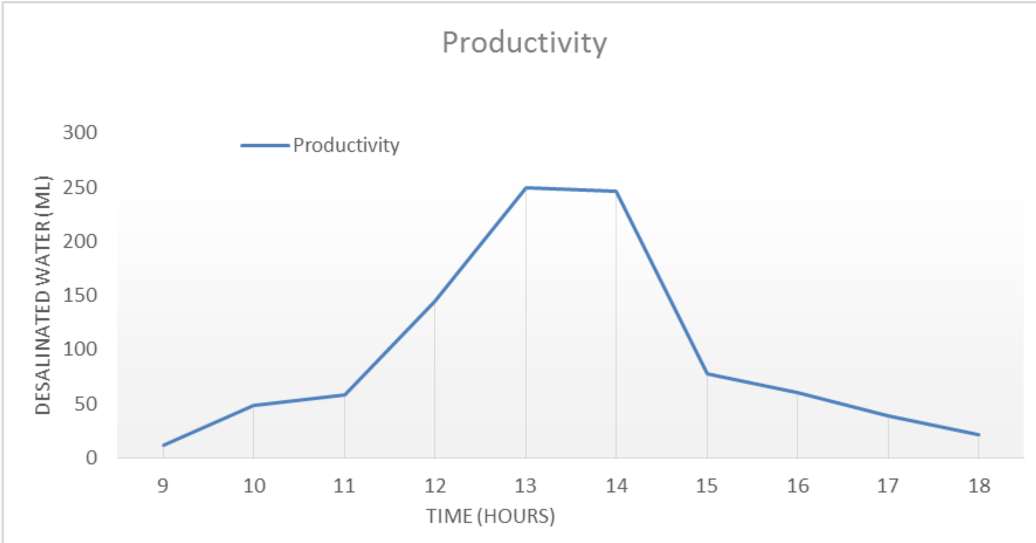

Fig. 13: Productivity for 6th December, 2013.

5. RESUTS WITH WAX AS PCM

After testing the solar still without phase change material now the wax is placed in the solar still in the form of a net as shown in the Fig. 14. The solar still was tested for the whole day and the results obtained are presented below in the form of Table 5 and in the Fig. 15, 16, and 17.

Fig. 14: Solar still with PCM.

Table 5: Temperature variations and productivity on 30th December, 2013.

Time (Hours)	Water Temperature (ºC)	Air Temperature (ºC)	Glass inside Temperature (ºC)	Glass outside Temperature (ºC)	Solar Radiations (W/m^2)	Productivity (ml)
9:00	20.1	19.4	18.3	17.3	111.4	17
10:00	24.9	27.3	29.1	38.1	207.4	51
11:00	28.6	37.9	39.5	43.4	310.7	100
12:00	35.2	42.4	42.7	44.6	405.2	157
13:00	43.1	43.9	41.7	43.2	309.1	259
14:00	41.7	43.7	41.6	40.5	271.3	243
15:00	39.2	36.1	34.6	35.9	180.3	110
16:00	36	32	31.5	32.8	90.4	67
17:00	33.9	27.8	23.1	22.1	30	57
18:00	28.7	21.4	18.5	17.2	0	49
19:00	26	20.7	17.4	15.6	0	35
20:00	24	18.9	16.2	13.5	0	20

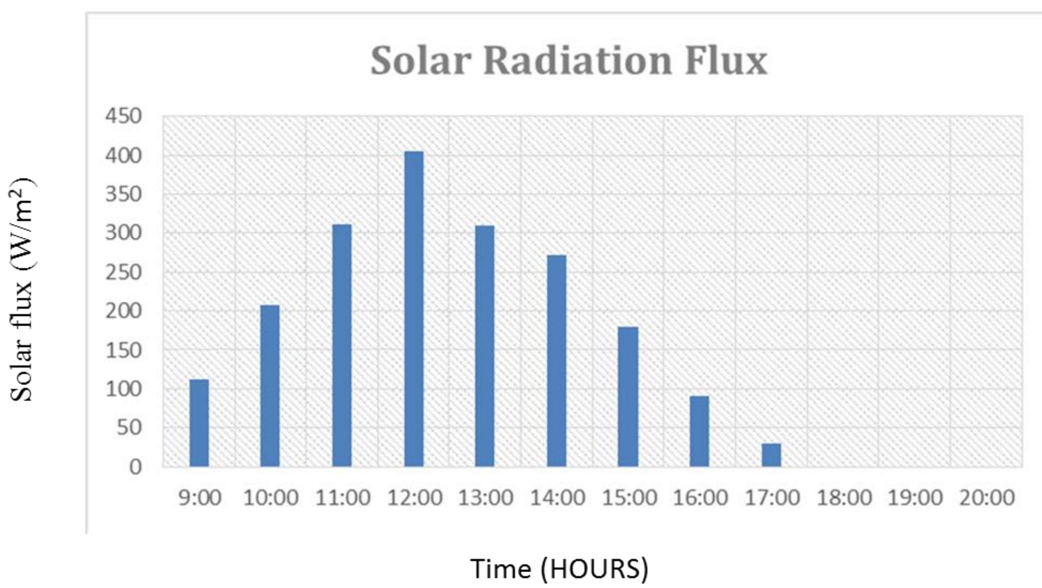

Fig. 15: Solar radiation flux for 30th December, 2013.

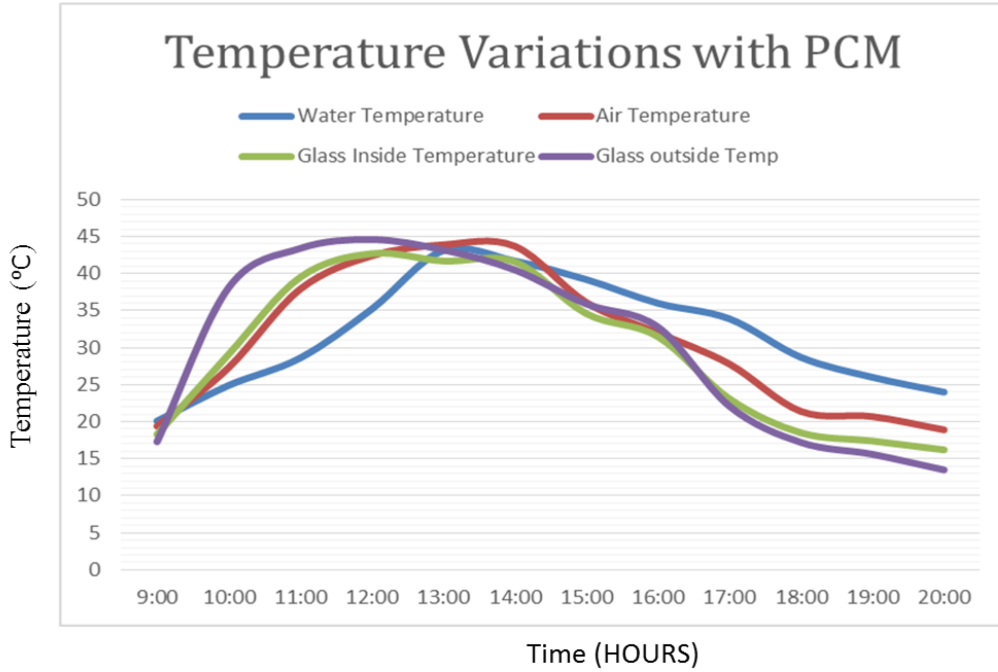

Fig. 16: Temperature variations for 30th December, 2013.

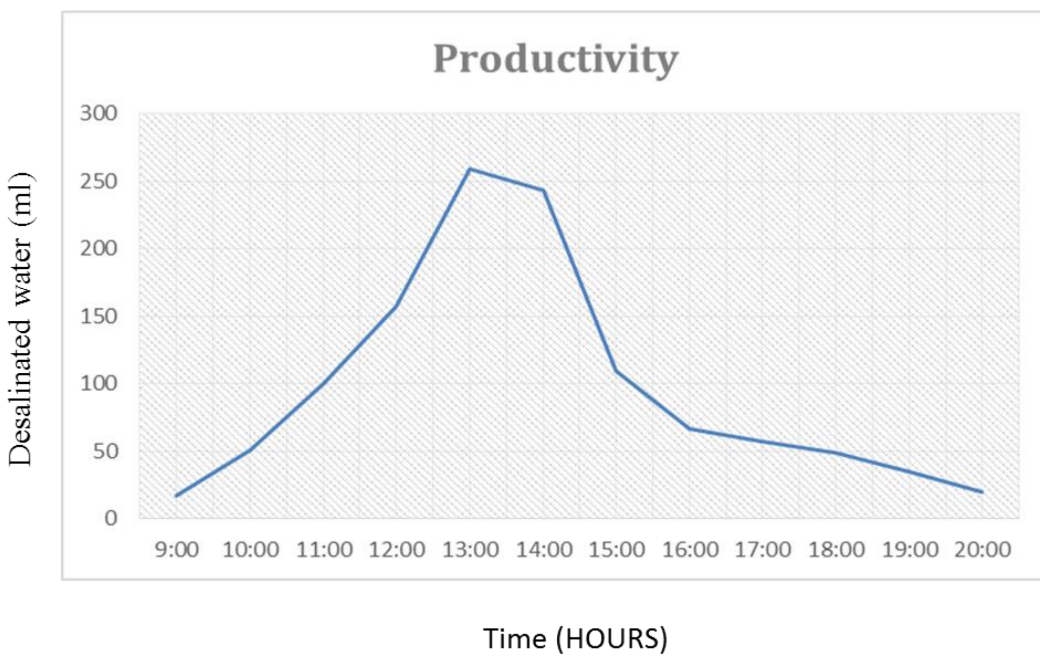

Fig. 17: Productivity for 30th December, 2013.

6. DISCUSSIONS

Initially, the solar still was tested for three days without PCM with approximately 2 inch depth of water. The results for temperatures and productivity with respect to time shows that temperatures are dependent on incident solar radiations which directly affects the productivity. The productivity increases up to 1.30 pm of the day and then starts decreasing again because of the variations in the solar flux. Water temperature is lower than the glass outside temperature at the start but at the end it is more than the glass outside temperature because of the energy storage in the water and it loses heat slowly.

Comparative analysis of glass outside, glass inside, air and water temperature indicates that due to the lower value of solar flux, the achieved temperature is lower with maximum temperature values are obtained between 1:30 – 2:30 pm when solar radiations intensity was maximum. Figure 6 shows that solar radiations intensity is decreased due to bad weather as compared to the other days that is why the temperatures achieved for that day are not very much high.

Table 5 shows the results for different temperatures and productivity with wax as phase change material. As amount of wax used was small that is why there was only a small increase in the productivity obtained. Total productivity obtained by using PCM is 1.3 liters which is more than when still was tested without PCM. This is because of the increased operational time of the solar still. As it can be seen from the Table 5 and the Fig. 16 that after sunset the temperature drops very slowly while this drop was faster when there was no PCM. This is because of the released energy by the Wax which was stored during sun shine hours.

CONCLUSION

The performance of solar still with wax as PCM is better than when it is operated without PCM. The reason behind insignificant increase in solar still is small amount of wax relative to the amount of water. Small productivity increase is also dictated by lower solar flux that is not enough to melt the PCM that have higher melting point. The amount of heat absorbed was able to maintain the water temperature only up to four hours after sunset. Better performance is expected with small amount of basin water or optimum amount of PCM that is enough to heat the basin water for complete period of time in the absence of solar flux.

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