Performance of Single Slope Solar Still with Solar Protected Condenser

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ABSTRACT

To improve the performance of the single slope solar still, an absorber plate with block shaped fins and a Phase Change Material chamber (PCM) with slender shaped fins are used. Experimental investigations have been carried out on two solar stills, namely conventional solar still and a modified solar still with PCM. The influence of the depth of water and the mass of PCM on the performance of the modified solar still with PCM has been investigated. The fins were equipped in the basin of the solar still to augment evaporation of the basin water. To enhance the heat transfer between the phase change material and the absorber plate, slender shaped fins were welded on the upper of PCM's chamber. The condensation of solar still was increased by using a secondary condenser on the shaded side of single slope solar still. The added secondary condenser was shielded to keep the surface of the condenser cool. It was found that the productivity of the modified solar still in comparison with conventional solar still was enhanced during day and night.

Keywords: Solar still, PCM, Reflector, Condenser, Fins.

INTRODUCTION

Water is one of the most plentiful resources on earth, covering three fourths of the planet's surface. About 97% of the earth's water is saltwater in the oceans and 3% (about 36 million km^3) is fresh water contained in the poles (in the form of ice), ground water, lakes, and rivers, which supply most human and animal needs. Nearly 70% from this tiny 3% of the world's freshwater is frozen in glaciers, ice, etc. (Kalogirou, 2009). An escalating demand for potable water due to the population explosion and with deteriorating sources of potable water is becoming global problems. According to the World Health Organization (WHO), the permissible limit of salinity in water is 500 ppm (parts per million) for potable water, and for special cases up to 1000 ppm of total dissolved salts. Most of the water available has salinity up to 10,000 ppm and seawater normally has salinity in the range of 35,000-45,000 ppm. Desalination has evolved over the past few decades as a promising solution to water scarcity. Presently obtainable desalination technologies can be classified either as single-phase processes (e.g. reverse osmosis, electro-dialysis) or, as phase-change processes (e.g. distillation, solar stills). Of these, reverse osmosis, electro dialysis, and distillation processes require high quality motive energy derived from nonrenewable fossil fuel sources. These technologies thus contribute indirectly to greenhouse gas emissions and are not sustainable. In addition, the usage of fossil fuels continues to pollute the environment and adds to the cause of global warming. While solar stills driven by solar energy do not suffer from these shortcomings, they are geographically and technically limited for wider application due to low efficiency, low yield. Development of cleaner technologies that use renewable energy to produce potable water can be a sustainable solution to the global problem of potable water supply. Thus, a reasonable solution to this crisis is to produce freshwater from the available resource of earth's saline water via desalination. Thus, a sufficient and promising key is the use of renewable energy resources for desalination. Desalination using solar energy is increasingly becoming an attractive option (Maroo and Goswami, 2009).

For extensive solar energy utilization, most solar energy systems require thermal energy storage because it is discontinuous by its nature. Latent heat thermal energy storage (LHTES) is a potential system that has uppermost performance and reliability and has high storage density and almost constant temperature energy delivery. Theoretical and experimental efforts have been made by different investigators to develop LHTES units for cooling and heating. One major conclusion reported by most authors is that phase change materials have unacceptably low thermal conductivity, leading to slow charging and discharging rates (Agyenim et al., 2009). Lacroix and Benmadda (1997) presented an analysis of melting and solidification of Phase Change Material (PCM) from finned vertical wall. The result reveals that the presence of a few long fins embedded in PCM significantly accelerated the melting and solidification processes.

A solar still provided with energy storage material at its base has been devised and constructed, various factors have been investigated with the aim of maximizing the still productivity (Naim and El-Kawi, 2002). They enhanced the productivity at night time by using an emulsion of paraffin wax, paraffin oil and water as a storage material increases the overnight productivity. Al-Hamadani and Shukla (2011) found that the higher mass of phase change material (PCM) with lower mass of water in solar still basin significantly increased the daily productivity and efficiency; the distillate productivity of the solar still with PCM at night and on day increased by 127% and 30-35% respectively than without using PCM. Abdulhaiy (2005) and El-Sebaii et al.(2009) used phase change material (PCM) as an energy storage medium. The productivity of solar still with PCM storage medium were found to increase during night operation, which occurred due to higher temperature difference between water and glass cover at relatively lower ambient temperature.

The double slope solar still does not prove superior to single slope solar still (Dwivedi and Tiwari, 2009; Garg and Mann, 1976). However, single slope solar still with a condenser in the shaded region slopped increases the still efficiency by 50% (Fath and Elsherbiny, 1993), Fath and Hosny(2002) studied the thermal performance of a single sloped solar still with an additional condenser. They found that distillate yield was influenced by the intensity of solar radiation, bottom insulation, and mass of basin and the area of evaporation surface of the condenser. A passive solar still with separate condenser has been modeled and its performance was evaluated, results show that the distillate productivity of the present still is 62% higher than that of the conventional type(A. Madhlopa and Johnstone, 2009). Shukla and Sorayan (2005) designed a multiwick single slope solar still. To augment the productivity of solar still, Nafey et al. (2002) used floating aluminum perforated black plates, Abdallah et al.(2009) used various absorbing materials and Velmurugan et al. (2008) integrated fins at the basin of the still. Adding internal and/or external reflectors can be useful and inexpensive to increase the solar radiation incident on the basin liner as well as the distillate productivity of basin type still. The concept of using the internal reflectors instead of the external ones leads to increase in temperature of water basin without increasing the outer temperature of glass cover (El-Swify and Metias, 2002).

The aim of the present study was to develop a new design of solar still (NDSS) that increases the amount of distilled water in a solar still. This new design is compared and contrasted with a Conventional Solar Still (CSS). To verify the performance of the new design, a single slope passive solar still with PCM (lauric acid) integrated with an external condenser was built and used. The condenser was connected at its upper and lower parts of the back of the still. Thermal performances of CSS and NDSS were compared in typical sunny and partially cloudy days. Furthermore, the effect of the mass of water basin and mass of PCM on total productivity of the NDSS and CSS were investigated through 5 to 18 of June, 2012.

EXPERIMENTAL SETUP

Conventional Solar Still (CSS)

Schematic diagram and photograph of the conventional single slope solar still are shown in Figures la and 1b, respectively.

New Design Solar Still (NDSS)

Schematic diagram and photograph of the new design single slope solar still are shown in Figures 2a and 2b, respectively. The new design solar still and conventional solar still were designed based on the optimum inclination through the year for Varanasi city in India. The major components of this solar distillation system were evaporator, condenser

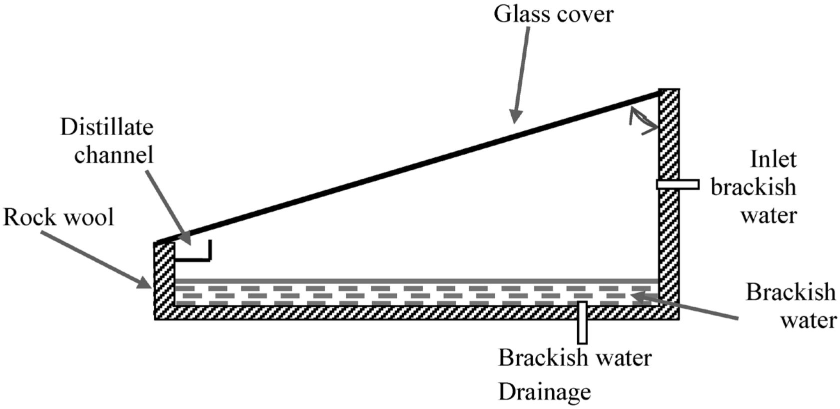

Figure 1a. Schematic diagram of passive solar still.

Figure 1b. Photograph of passive solar still.

and PCM chamber units. The two sides and back walls are covered with aluminium sheet plate, so these walls serve as the internal reflectors. This solar still forms three basins with saline water. Basin 1 was in the evaporator unit while basins 2 and 3 were stacked inside the condenser unit to recover heat from the first effect (Figure 2a). Basin 1 of (1 m x 1 m) of the test still (AR = 1) was constructed from mild steel sheet (0.002 m thick), painted black on the inner surface to optimize absorption of solar radiation. Basin liners 2 and 3 were made from iron sheet (0.0015 m thick) but they were not painted to reduce resistance to heat conduction. Basin 2 includes stepped basin with 5 steps, with area of 0.3 m^2. While basin 3 was inclined at 12° to enable distillate flow downward into the collection channels. The fins were added in basin 1 of NDSS to decrease the preheating time required for evaporating the still basin water. While using fins in the solar still, the area of the absorber plate increased. Hence, absorber plate temperature and saline water temperature increased. As the temperature difference between water and glass increases, productivity increased. In this work, five circular fins with height and diameter 35 mm, 155 mm, respectively were used. Slender shaped fins were welded on the upper of PCM's chamber. The operational and melting temperature of PCM, in fact, governs the applicability of different types of phase change materials. The lauric acid relates to the class of fatty acids that have superior properties such as melting congruency, good chemical stability and non-toxicity, good thermal reliability (Sarı, 2003; Sarı and Kaygusuz, 2002) over many other PCMs. Table 1 shows thermo-physical properties of Lauric acid. A temperature scanner (Altop Industries Ltd, Sn.1005164, model ADT 5003) with resolution 0.1°C has been used to record the temperature with k-type thermocouples in both system for different location. The solar radiation passes through the glass cover to heat saline water in basin 1 (first effect). Then, vapour from the first effect flows upward and condenses when it gets into contact with the inner side of the glass cover at lower temperature while part of the vapour flows into the condensing chamber to heat water in basin 2 (second ef-

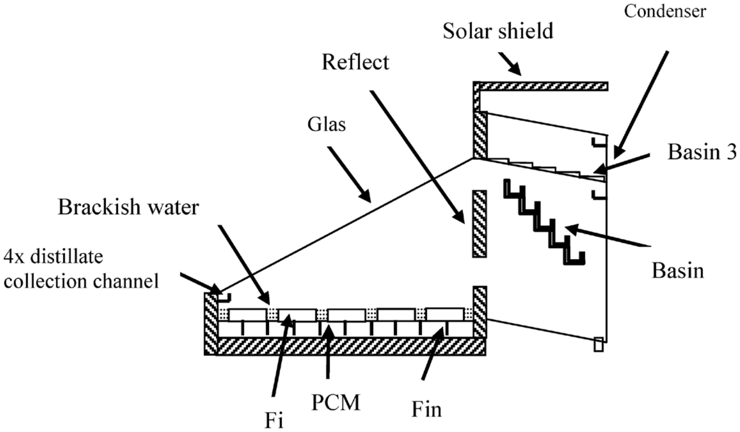

Figure 2a. Schematic diagram of new design solar still

Figure 2b. Photograph of new design solar still.

Table 1. Thermo-physical properties of Lauric acid

S.No.	Properties	Value
1	Melting point	40-43.9 °C
2	Latent heat of fusion	180 kJ/kg
3	Thermal conductivity	0.16 $Wm^{-1}\,{}^{o}C^{-1}$
4	Specific heat solid at 25 °C liquid at 44 °C	 2.1 $kJkg^{-1}\,{}^{o}C^{-1}$ 3 $kJkg^{-1}\,{}^{o}C^{-1}$
5	Density solid liquid	 1007 kg/m^3 862 kg/m^3

fect) and basin 3 (third effect). The transfer of water vapour from the still to the condenser could be done through one or more of the following mass transfer modes: diffusion, purging, and natural circulation.

RESULT AND DISCUSSION

An experimental study during 5th June 2012 to 18th June, 2012 was carried out to compare the thermal performance of NDSS and CSS. The mass water 10, 15, 20 and 30 kg are used for basin 1. The mass water of basin 2 and basin 3 is 4.3 and 7.4 kg respectively. The mass of PCM is varies between 10 to 30 kg for NDSS. The mass water 10, 15, 20 and 30 kg are used for the CSS. Figure 3 shows the solar intensity and the hourly yield produced on 9th June 2012.

Temperature of System Components

Figure 4 shows the variation of the observed temperature of glass cover (T_{gc}), saline water (T_{wb1}), condenser cover ($T_{co,NDSS}$), glass cover ($T_{gc,CSS}$), saline water ($T_{w,CSS}$) on a 9th June 2012. It is observed that the values of Tgc for the CSS ($T_{gc,CSS}$) are higher than those of the NDSS ($T_{gc,NDSS}$) from about 10:00 hr to 18:00 hr, with maximum values of $T_{gc,CSS} = 57°C$ and $T_{gc,NDSS} = 50°C$. In addition, the temperature of water in basin for the CSS ($T_{w,CSS}$) is higher than that of the NDSS ($T_{wb1,NDSS}$)

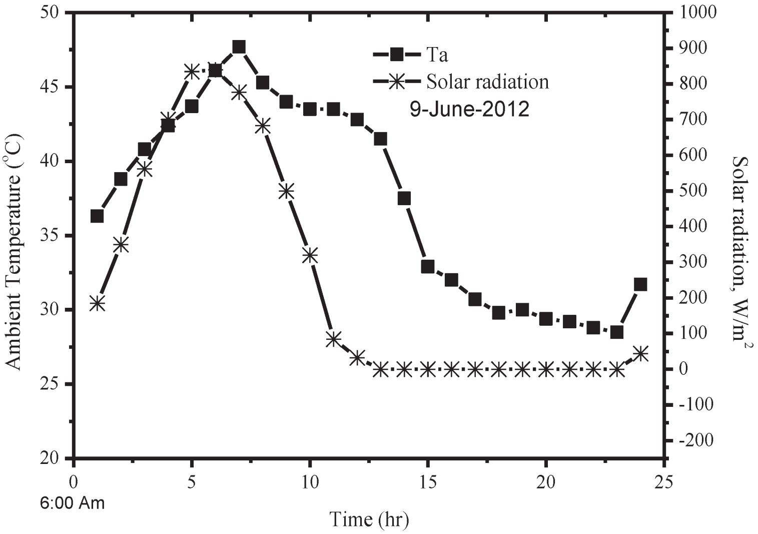

Figure 3. Daily variation of ambient temperature and solar intensity

from about 8:00 hr to 13:00 hr. But after that the temperature of water in basin for the CSS ($T_{w,CSS}$) is lower than that of the NDSS ($T_{wb1,NDSS}$). It should be mentioned that part of the heat from the evaporator basin flows into the condenser chamber by purging, diffusion and circulation which would tend to lower the glazing temperature of the NDSS (El-Bahi and Inan, 1999; Fath and Elsherbiny, 1993; A. Madhlopa and Johnstone, 2009).

Sunny and Entirely Cloudy Day

An experimental study in sunny and partially cloudy 8th June 2012 and entirely cloudy 7th June 2012 days were carried out to compare the thermal performance of NDSS and CSS. Figures 3a and 3b illustrate the daily productivity of NDSS and CSS in typical sunny and cloudy days, respectively. The mass water of CSS is 20 kg, but for NDSS water masses are 20 kg, 4.3 kg and 7.4 kg for basin 1, basin 2 and basin 3 respectively.

Figure 3a indicates that hourly productivity in NDSS at morning is higher because NDSS has more area of water surface evaporation. But when the height of solar radiation about 9am to 11am the CSS is reading are higher than NDSS because, some of the absorbed solar energy is used to increase the PCM temperature and the solid fins of basin 1, the absorber temperature is higher than the PCM and this trend is inverted

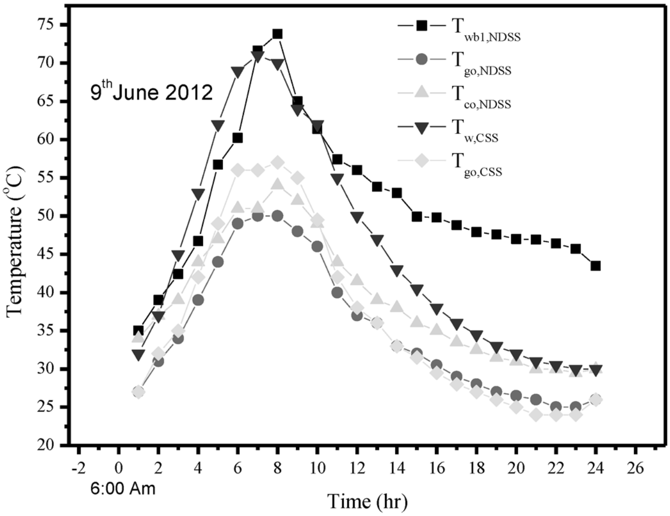

Figure 4. Variation of experimental temperature of saline water in basin 1 of CSS and NDSS on 9th June 2012.

in the low solar radiation intensity. It is clear from Figures 5a and 5b that the hourly productivity at night is significant for NDSS because of using the stored energy. Total productivity for NDSS and CSS is 5710 and 4295 ml/m^2 day for sunny day (8th June 2012) and 1675 and 1095 ml/m^2 day for entirely cloudy day (7th June 2012), respectively. It is also observed that there is a significant difference in the total productivity for the sunny day and entirely cloudy day.

Daytime Productivity

Figures 6 through 9 reveal the variation of the daytime productivity with variation the mass of the mass of water 10, 15, 20 and 30 kg for basin 1 in the NDSS and for the basin of CSS with 10 kg of PCM. The daytime productivity of CSS is higher than NDSS with 10 kg of water (see Figure 6). The reason of this higher readings of CSS is because the little mass of water (2 cm depth of basin water), thus water immediately is heated and evaporated. But with NDSS the system is gradually heated; part of vapour will circulate inside the integrated condenser. These higher readings of CSS get reduced with mass of 15,20 and 30 kg, see Figures 5, 6 and 7. Figure 8 shows higher performance of NDSS. Furthermore NDSS yields better results after 2 pm, as shown in Figures 6 through 9.

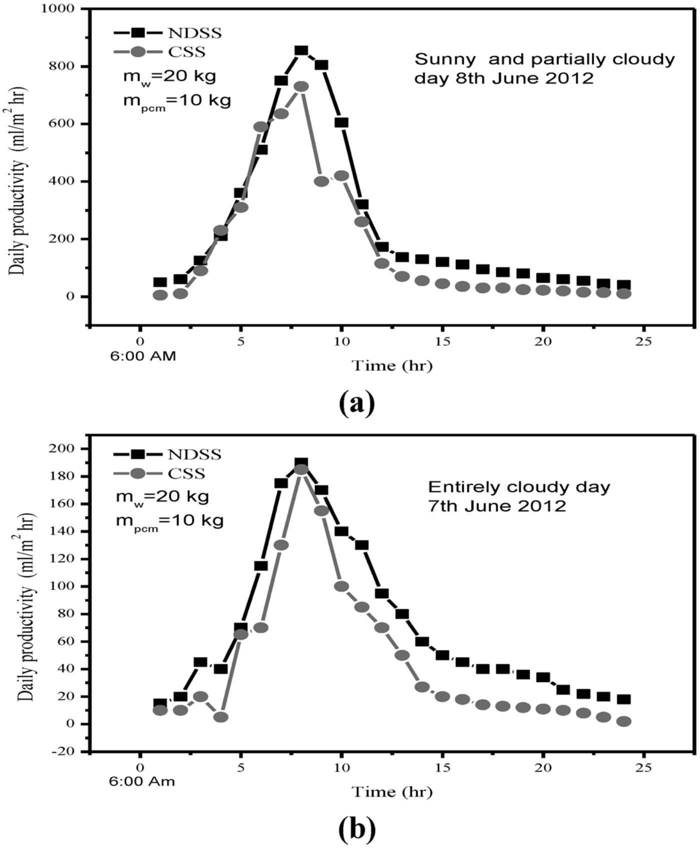

Figure 5. Variations of hourly productivity with time for NDSS and CSS (a) typical sunny day, 8th June 2012 and (b) entirely cloudy day 7th June 2012.

Variation of Daytime Productivity with Altered Mass of Pcm

Figures 10, 11 and 12 present variations of the daytime productivities with m_{pcm} for different masses of basin 1 water $m_{w,b1}$ for NDSS. Assessment of figures indicated that daytime productivity increases with time. Also the productivity of NDSS of m_{pcm} = 10 kg with $m_{w,b1}$ = 20 kg is a higher value as shown. The reason may be that when the mass of PCM increases, the energy absorbed from basin liner by the PCM increases. Another reason may be the diffusion, purging and circulation inside the integrated condenser increase the convection, evaporating and condensation of vapor water, with the help of the cooler temperature of integrated condenser. The low glass temperature will increase the condensation of water vapor.

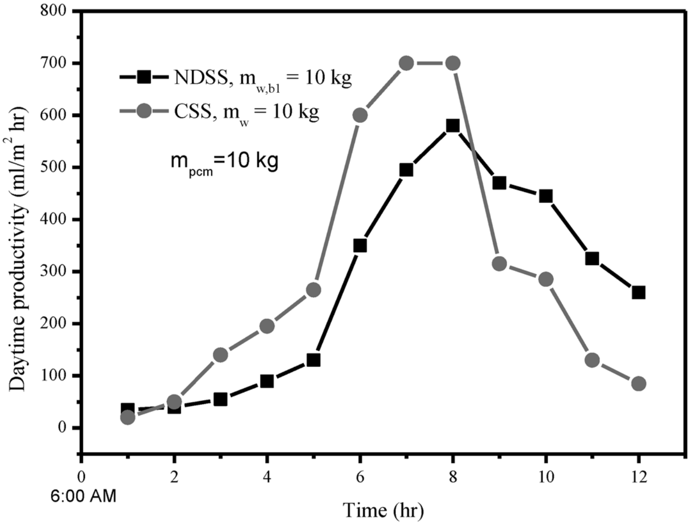

Figure 6. The daytime productivity of NDSS and CSS for $m_{w,b1}$ = 10 kg, m_{pcm} = 10 kg and m_w = 10 kg

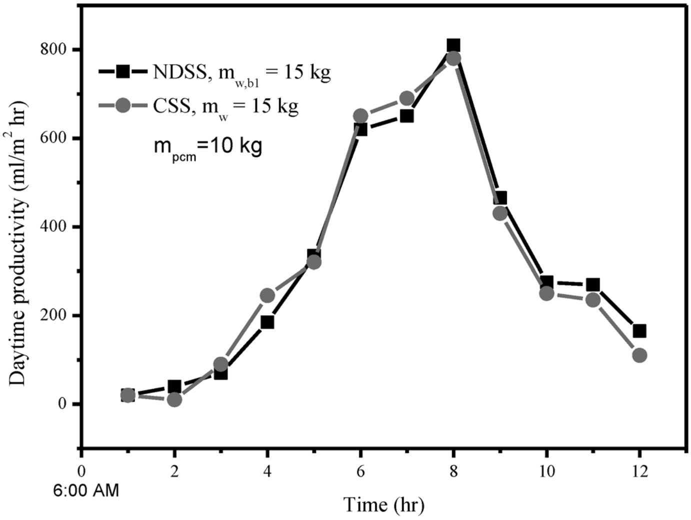

Figure 7. The daytime productivity of NDSS and CSS for $m_{w,b1}$ = 15 kg, m_{pcm} = 10 kg and m_w = 15 kg

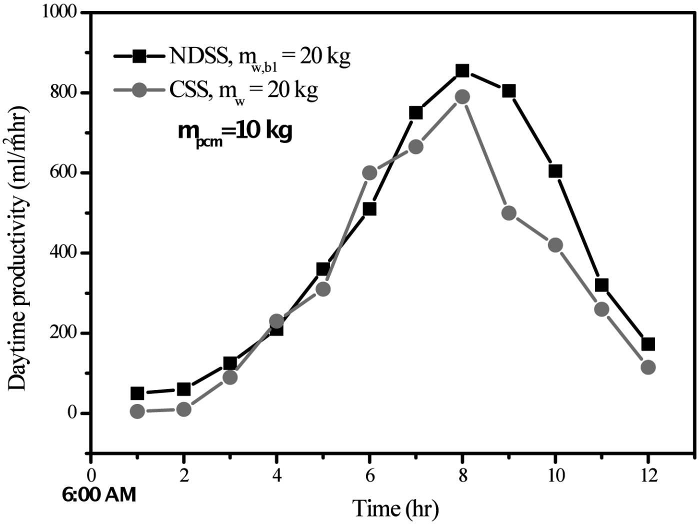

Figure 8. The daytime productivity of NDSS and CSS for $m_{w,b1}$ = 20 kg, m_{pcm} = 10 kg and m_w = 20 kg

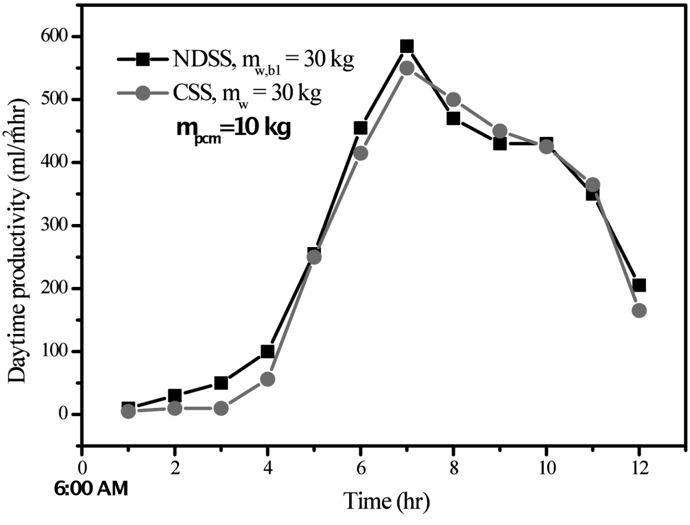

Figure 9. The daytime productivity of NDSS and CSS for $m_{w,b1}$ = 30 kg, m_{pcm} = 10 kg and m_w = 30 kg

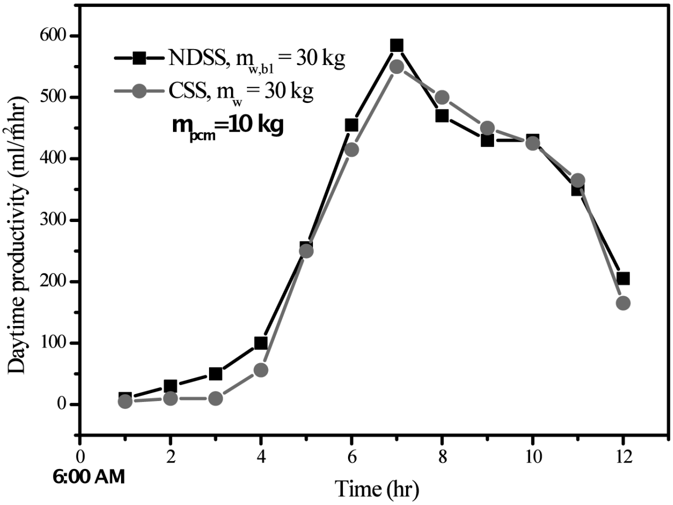

Figure 10. Variation of daytime productivity of NDSS for m_{pcm} = 10, 20 and 30 kg with m_w = 10 kg

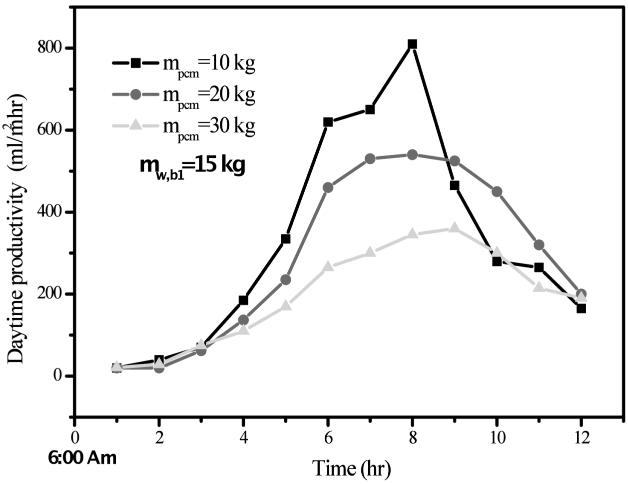

Figure 11. Variation of daytime productivity of NDSS for m_{pcm} = 10, 20 and 30 kg with m_w = 15 kg

Variation of Productivity on Night with Altered Mass of Pcm

The key point of using PCM is to increase the productivity at night. Figure 13 depicts the influence of adding mass of PCM on the productivity during night time; Productivity increases with the increase of the

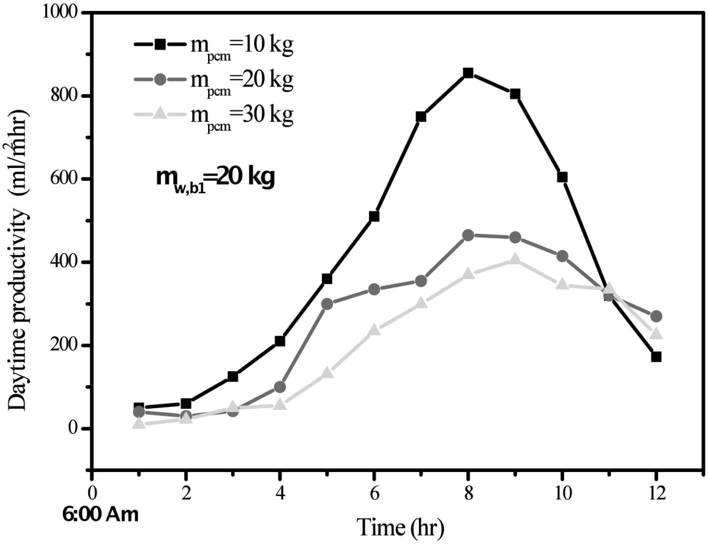

Figure 12. Variation of daytime productivity of NDSS for m_{pcm} = 10, 20 and 30 kg with m_w = 20 kg

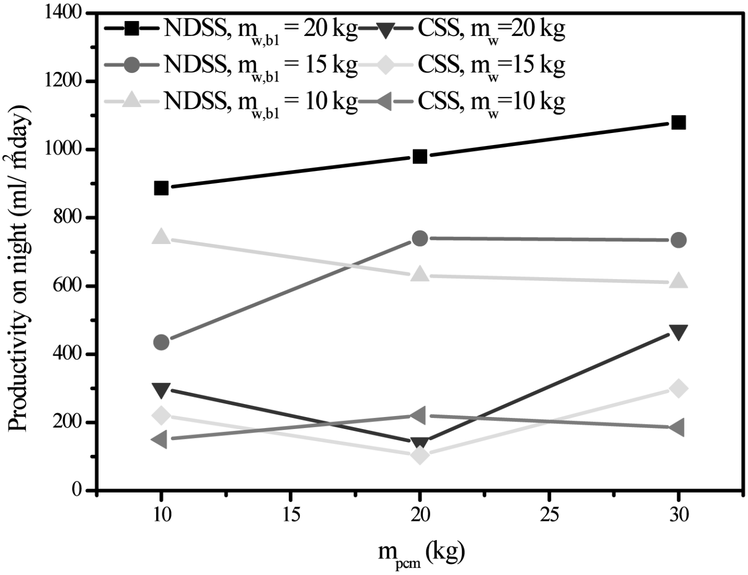

Figure 13. The productivity on night of NDSS and CSS for m_{pcm} = 10, 20 and 30 kg with m_w = 10, 15 and 20 kg

mass of PCM.

The fluctuation in curves is because the difference in the solar radiation and the cloudy day. Table 2 depicts the productivity of 10, 20 and 30 kg of PCMM with 20 kg of water. The difference in productivity for 30 kg PCM with 10 kg PCM is nearly 193 ml/m^2 kg. This value if we compared with the daytime productivity of NDSS that has 20 kg of basin 1 water with 10 kg of PCM. But the daytime productivity of NDSS that has 20 kg of basin 1 water with 10 kg of PCM is greater 2.339 kg/m^2 day compared with 20 kg of basin 1 water with 30 kg of PCM. Thus 10 kg of PCM is suitable for storage system. However the price of 30 kg of PCM is costly if compared with 10 kg of PCM.

Variation of Daily Productivity with Altered Mass of Pcm

The daily productivity is represented in Figures 14, 15 and 16. It is clear that the highest productivity within 20 kg of water basin 1 with 10 kg of PCM (see Figure 14).

In order to have a comparison, amounts of total productivity of the designed stills and other still configurations are provided in Table 3.

STATISTICAL ANALYSIS

The productivity of NDSS was optimized using response surface methodology (RSM) provided by STATISTICA 8 software. A standard RSM design tool known as Central Composite Design (CCD) was applied to study the parameters affecting the performance of NDSS. The central composite experimental design (CCD) is a suitable design for sequential experiments to obtain appropriate information for testing lack

Table 2. The daytime and on night productivity of NDSS of 10, 20 and 30 kg of PCM with 20 kg of water

Mass of PCM kg	Mass of water kg	Productivity on night, kg/m^2 day	Daytime Productivity on kg/m^2 day
10	20	887	4.823
20	20	980	3.132
30	20	1080	2.484

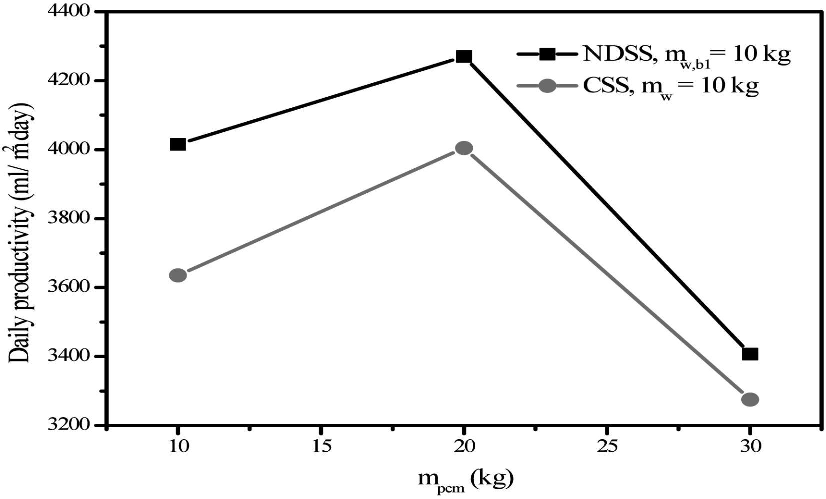

Figure 14. Variation of Daily productivity of NDSS with CSS for $m_{w,b1}$ = 10 kg, m_{pcm} = 10, 20 and 30 kg and m_w = 10 kg.

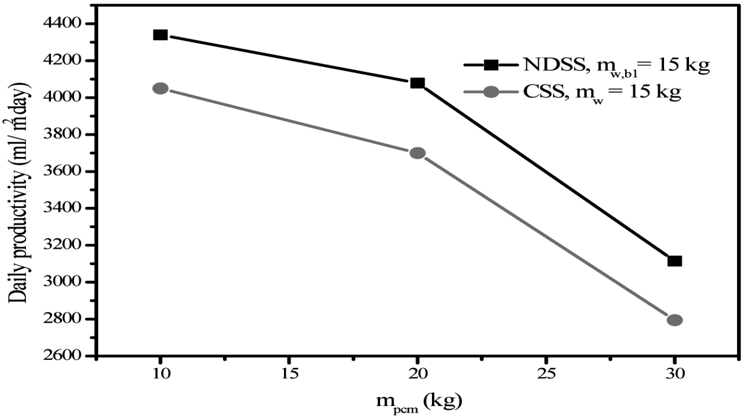

Figure 15. Variation of Daily productivity of NDSS with CSS for $m_{w,b1}$ = 15 kg, m_{pcm} = 10, 20 and 30 kg and m_w = 15 kg.

of fit without a large number of design points (Montgomery, 2001; Myers RH and Montgomery, 2000). A two-level, three-factor central composite experimental design was used to optimize the independent variables to achieve maximum productivity. A total of twenty experiments, including six replications at the centre point, were conducted. The replicates at the centre point were used to evaluate the pure error. Table 4 shows the

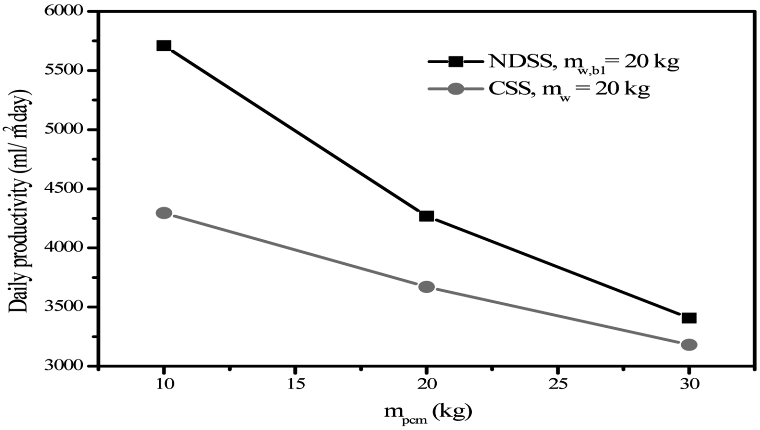

Figure 16. Variation of Daily productivity of NDSS with CSS for $m_{w,b1}$ = 20 kg, m_{pcm} = 10, 20 and 30 kg and m_w = 20 kg.

Table 3. Comparison between total productivity of the designed still with other still configurations.

Still type	Date	Productivity (kg/m² day)
Designed NDSS (present work)	08/06/2012	5.71
Designed still with LHTESS (Tabrizi et al., 2010)	23/05/2009	4.85
Designed still with a separate condenser (Amos Madhlopa, 2009)	2009	4.59
Inclined type with black fleece (Aybar et al., 2005)	May, 2004	2.995
Basin type only (Velmurugan et al., 2008)	16/08/2006	1.88
Basin type with sponge (Velmurugan, et al., 2008)	13/08/2006	2.26
Basin type with wick (Velmurugan, et al., 2008)	06/04/2006	4.07
Basin type with fin (Velmurugan, et al., 2008)	28/08/2006	2.81

Table 4. The independent variables and levels used for experimental design.

Independent variables	Codes	Variable levels		
		-1	0	+1
Temperature difference between water and glass cover (˚C)	X_1	6	13	20
Ambient temperature (˚C)	X_2	20	35	50
Solar radiation W/m²	X_3	260	630	1000

independent variables and levels used for experimental design.

Three identified independent parameters are, X_1: temperature difference between water and glass cover (6-20°C), X_2: ambient temperature (20-50°C) and X_3: solar radiation (260–100 W/m^2 hr). The response chosen was productivity of NDSS. The quality of fit for the model was evaluated by the coefficients of determination (R^2) and its regression coefficient significant (analysis of variances (ANOVA)) were checked with Fisher's test (F-test) (Montgomery, 2001). Response surfaces and contour plots were developed using the quadratic polynomial equation obtained from regression analysis of experimental data by keeping two of the independent variables at a constant value while changing the other one.

Optimization of Parameters

The response surface methodology was used for the optimization of parameters. Among the models that can be fitted to the response (linear, two factor interaction (2FI) and quadratic polynomial), the quadratic model was selected as it is the best model due to its highest order polynomial with significance of additional terms. The model equation based on the coded values (X_1, X_2 and X_3 as temperature difference between water and glass cover, ambient temperature and solar radiation respectively) for the productivity of NDSS was expressed by Eq. (1).

$$\begin{aligned} Y = {} & 378.97 + 84.99X_1 + 50.65X_1^2 + 38.7X_2 - 31.9X22 + \\ & 171.1X_3 - 18.7X_3^2 - 6.8X_1X_2 + 30.6X_1X_3 \end{aligned} \tag{1}$$

The result of statistical analysis of variance (ANOVA) was carried out to determine the significance and fitness of the quadratic model as well as the effect of significant individual terms and their interaction on the chosen responses. The p-value (probability of error value) is used as a tool to check the significance of each regression coefficient, which also indicates the interaction effect of each cross product. The smaller the p-value, the bigger is the significance of the corresponding coefficient (Montgomery, 2001). In the case of model terms, the p-values less than 0.05 indicated that the particular model term was statistically significant. From the ANOVA results, the main model terms suggested that variables with significant influence on productivity of NDSS response were temperature difference between water and glass cover (X_1) ambient temperature (X_2), solar radiation (X_3), and the interaction terms were found to exist between the main factors (X_1 X_2 and X_1 X_3), while the significant quadratic terms were temperature difference between water and glass cover (X_1^2), ambient temperature (X_2^2) and solar radiation (X_3^2). The lack of fit test with p-value of 0.0521, which is not statistically significant ($p\text{-value} > 0.05$ means the test is not significant) showed that the model satisfactorily fitted to experimental data. Insignificant lack of fit is most wanted, as significant lack of fit indicates that there might be contribution in the regression or response relationship that is not accounted for by the model (Noordin et al., 2004). The predicted values versus actual values for productivity of NDSS with adjusted R^2 value of 0.95 indicated that the predicted values and experimental values were in reasonable agreement (Figure 17.). It means that the data fit well with the model and give a convincingly good estimate of response for the system in the range studied.

The developed second-order regression model (Eq. 1) is complex with many variables. It is difficult to understand the effect of different independent variables from the regression model, but graphical representations are easier to interpret. Contour and response surface plots were drawn (not shown in the paper) to observe the effect of solar radiation, ambient temperature, difference temperature of water and glass on productivity of NDSS. These plots were generated by holding one of the variables at its mid-point and varying the other two variables to obtain the response. The elliptical shape of the curves indicated a strong interaction between the variables. Therefore, it is concluded that the generated model showed reasonable predictability and sufficient accuracy for the productivity of NDSS in the experimental conditions used.

CONCLUSIONS

Two solar stills, NDSS and CSS were constructed for comparing the performance of the stills productivity in sunny and cloudy days. The effect of mass water and mass of PCM were also investigated on the total productivity of stills. The experiments were conducted in typical days under weather conditions of Varanasi, India. The concluded results are presented as follows:

Using integrated condenser will reduce the glass temperature. The saline water in basin 1 and basin 2 will also be heated and evapo-

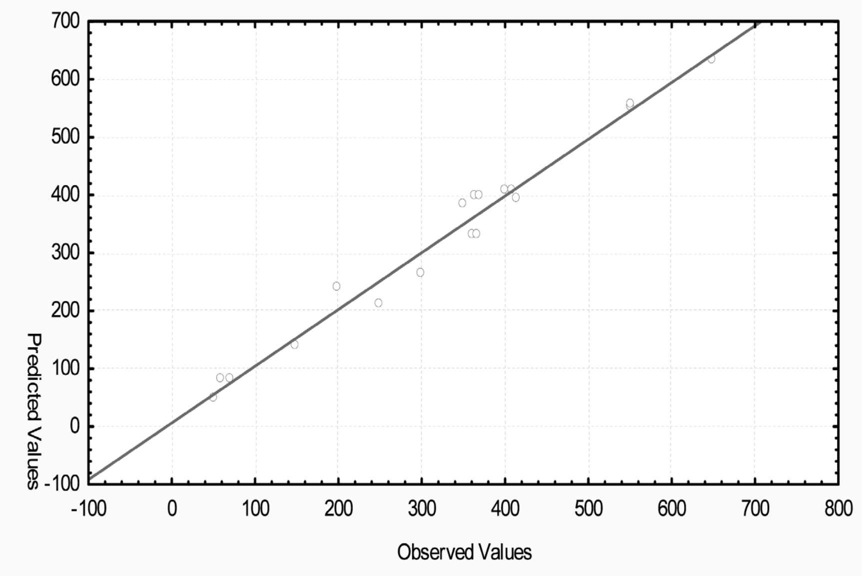

Figure 17. Predicted versus experimental productivity of NDSS

rated to increase the productivity of the solar still because the temperature of integrated condenser is lower than evaporator. The shielded condenser will keep the outer wall of condenser cool. To get benefit from circulation of the water vapor inside integrated condenser, the stepped basin 2 is housed in the condenser from left and right side and free from other side to let the mixture to circulate.

- The daily productivity of NDSS is slightly higher than the CSS in all days 5.71 kg/m^2 day for NDSS and 4.295 kg/m^2 day for CSS. Thus, NDSS is favored for sunny and partially cloudy days due to the higher productivity.

- The productivity during night time of NDSS is mostly higher than the CSS in all days. This increase is due to the increase of the mass of PCM. Thus it is necessary to consider using it in solar still system. Furthermore, the transferred heat from the PCM to the saline water during discharge process is enough to produce high amount of distillated water because of decreasing in operating temperature which is compared with low ambient temperature at night condition.

NOMENCLATURE

A	Area, m^2
AR	aspect ratio (dimensionless)
m	Mass, kg
T	Temperature, °C

Subscripts

1	first
2	second
3	third
a	ambient
b	basin
co	condenser cover
gc	glass cover
w	water

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