Impact of Flat Plate Collector and Shallow Solar Pond in Escalating the Productive Distillate Yield in Single Slope Solar Still

M. Anbu Saravanan[a], S. Mari Vignesh[a], V. Shanmugapriya[a], R. Jayaprakash[b] and B. Selvakumar[a*]

[a] *Dept. of Physics, Kalasalingam Academy of Research and Education, Krishnankoil, India*
[b] *Dept. of Physics, Sri Ramakrishna Mission Vidhyalaya College of Arts and Science, Coimbatore, Tamil Nadu, India*

Abstract

Design and thermal analysis of single slope solar still combined with flat plate collector and shallow solar pond for enhanced productive yield has been carried out. Heat transfer modes, efficiency and performance ratio along with thermophysical properties such as thermal conductivity, dynamic viscosity and density were also predicted for single slope solar still under three modes of study. Daily distillate yield rate observed is about 1.98 litre/m^2, 2.99 litre/$m^2$and 3.168 litre/m^2 for single slope solar still alone, still coupled with FPC and SSP. Instantaneous efficiency observed during the study is in the range of 7.27% to 33.30%, 2.41% to 9.52% and 2.41% to 10.86% for the single slope still performance study alone, combine with FPC and combined with SSP. Even though the instantaneous efficiency in this mode is reduced than the single slope solar still, the distillate water collection rate is increased. Performance ratio observed for single slope solar still under three modes of study found to be in the range of 1.94 % to 7.65 %, 2.64 % to 8.78 % and 2.64 % to 10.46 % respectively. Performance ratio value is increasing steadily with respect to water temperature. It is inferred that the coupling effect of flat plate collector and shallow solar pond with the still causes the increase in temperature to the optimum value for evaporation. Thermal conductivity of water is analyzed and it is observed in the range of 26.87×10^{-3} Wm^{-2} °C^{-1} to 28.10×10^{-3} Wm^{-2} °C^{-1}, 26.93×10^{-3} Wm^{-2} °C^{-1} to 28.40×10^{-3} Wm^{-2} °C^{-1} and 26.97×10^{-3} Wm^{-2} °C^{-1} to 28.29×10^{-3} Wm^{-2} °C^{-1} for single slope still under three modes of study. Water temperature and thermal conductivity increase with respect to time and posses almost the same trend.

Keywords: Solar Still, Temperature, Distillate Yield, Flat Plate Collector, Shallow Solar Pond

1. Introduction

Water and energy along with climate issues have a close interconnection factors that infuse all the activities occurring in Earth. Rapid growth in human population and hasty industrial development results in greater demand for fresh water and energy for daily agricultural, domestic and industrial usage. Shortage of fresh water is a serious problem faced by people in semi-arid and arid regions along with many health problems due to contamination of water. It is observed that only 3% of available water can be used for needy and the remaining 97% of water found in ocean cannot be used for industrial or domestic purposes [1].

[*] Corresponding Author e-mail:solarselva@gmail.com

Desalination is the alternate method of converting the non-usable water to potable one. Desalination technology can be classified generally into thermal distillation and membrane process that are used in now a day worldwide [2]. Numerous works are carried out regarding the capability and analysis of these systems [3, 4]. It is found that around 15,000 desalination plant yielding the capacity of about 65 million m3/day for domestic consumption and industrial water production is observed [5]. Pyramid solar still with a concave absorber plate is found to yield about 4.1 litres/m2 with thermal efficiency of 45% [6]. Thermal efficiency of hemispherical glass cover with top cover cooling is found to increase from 34% to 42% [7]. Experimental and numerical investigation on single- and double-effect solar desalination systems have been reported in [8]. The effect of climatic parameters on single-slope solar stills has been reported in [9]. A comparative study on the effect of climatic conditions on a simple basin solar still has been investigated [10, 11].

The dependence of heat and mass transfer on the water depth in the basin area of a passive single slope solar still has been reported [12]. Investigations on design, construction and control of solar heating plants for large scale with view of generic and multi-variable levelized cost had been carried out [13, 14]. Results conclude that inlet temperature and weather conditions play major role in affecting the collector performance. Various methods to enhance the thermal performance of FPC’s had been carried out [15, 16]. Influence of various design parameters such as glass cover thickness, absorber plate thickness, absorber plate material, air gap between the absorber and top glass cover and the role of insulation materials on the thermal performance of FPCs are discussed briefly. Performance analysis of conventional single slope solar still and the impact of integrating a flat plate collector (FPC) and phase change material had been investigated [17, 18]. Results concluded that water collection is increased from 1.5 to 2.5 times than that of individual still distillate yield. Various modes of heat extraction had been analysed both theoretically and experimentally [19 SSP 1, 20 SSP 2, 21 SSP 3, 22 SSP 4]. Comparisons between experimental and theoretical results showed that good agreement has been achieved. It is inferred that SSP can be used as a source for the warm water required for domestic applications under normal clear climatic conditions. Combined effect of shallow solar pond in the enhanced productive yield of single slope still had been carried out [23 SSP 5, 24 SSP6]. Results conclude that 0.03 m is the optimum value of the flowing water thickness and 0.0009 kg/s is the mass flow rate for still coupled with SSP. It also infers that annual efficiency and average daily productivity of the still with SSP is found to be higher than those obtained without the SSP by 43.80% and 52.36% respectively.

Different types of solar water heating methodologies using various materials and erratic dimensions has been carried out and their efficiencies along with performances had been studied extensively by different authors. The aim of this work is to study the enhanced performance of a single slope solar with coupled with flat plate collector (FPC) and shallow solar pond (SSP). Single basin solar still is one of the prevalent methods used to convert saline water to potable water. FPC is coupled with solar still for instantaneous transfer of heat energy to solar still, whereas SSP is coupled to still for heat transfer at off sunshine hours. As a result of combination of two different modes of heat transfer to single slope solar still, its distillate yield and performance variation is observed and tabulated.

2. Construction Details

2.1 Construction of Single Slope Solar Still

Single slope solar still of area 0.50 m x 0.50 m is designed using mild steel. Acrylic sheet 3mm thickness is used as the top cover for the still, which is placed over the grooves provided at all sides for uniform resting along with cushion supports. Bottom and sides of the basin are painted with black paint for good absorption of solar radiation and is filled with water to a height of 0.05 m. Two pipes are placed at a height of 0.06 m and 0.11 m respectively to maintain the water level inside the storage basin as 0.05 m and 0.10 m respectively. Water Collection segment is placed at the end of the still for collecting the evaporated water and it is of dimension 0.66 m x 0.038 m x 0.015 m. Outer box of the still is made up of wood of thickness 4mm with the dimension 0.70 m x 0.70 m. Sawdust and glass wool insulation are provided at bottom and side for minimizing the heat loss through it. Bushes are placed at the base of the still for uniform landing in the ground.

2.2 Construction of Flat Plate Collector

Copper sheet of 2 mm thickness of is used as absorber plate and is coated with black paint of 300 µm thickness to increase the efficiency of absorption. Total area of absorber plate is of dimension 0.82 m x 0.82 m. Eight vertical heat exchangers with distance of 0.10 m are fused together with the bottom and top tubes also to the absorber plate with perfect copper soldering act as liquid heat exchanger. Inlet is provided at the bottom of the header arrangement and outlet at top of the header arrangement. To increase the contact area of the absorber plate with copper tube, the absorber is clamped in such a way that the copper tube is completely covered by itself. The unclamped area of the absorber over the copper tube is soldered properly. This work is done in order to enhance the transferring of heat energy from absorber to the fluid passing through the tubes. Transparent glass sheet of thickness 3 mm is used as the top cover. Absorber plate along with the copper tube arrangement is properly fitted with the wooden frame made up off wood in order to prevent the bending of the absorber plate during the experimental study. Bottom surface of the wooden box is filled with glass wool about 0.10 m. A steel stand with the inclination of about 45°C is specially designed to hold the entire arrangement of the flat plate collector.

2.3 Construction of Shallow Solar Pond

General dimension of the shallow solar pond is 1 m x 1 m x 0.15 m. Pond is filled with the water to a height of 0.05 m and the surface is covered by a transparent polythene sheet. The top of the system is covered by a glass plate with wooden frames. It is tightened using bolts provided at the surface of the wall with cushions. Cushions are used to reduce the air leakage. Bottom of the pond is insulated by using thermocole (Insulator). Its sides are covered with the help of bricks and cement mortar. Pre-calibrated thermocouples are placed at height of 0.15 m, 0.45 m and 0.60 m for measuring the temperatures at various places. The gap between insulation layer and bricks wall is filled by pieces of thermocole.

3 Thermal Performance Study

Thermal performance study of acrylic single slope solar still is carried out from 9 a.m. to 5 p.m. for several weeks. Initially the still basin is filled with 15 litres of saline water. Thermal performance is carried out in three different modes namely

a) Single Slope Still alone
b) Single Slope Still Coupled with FPC
c) Single Slope Still Coupled with SSP

By placing pre-calibrated thermocouples at appropriate places, ambient temperature (T_{amb}), air temperature inside the still (T_a), water temperature inside the still (T_w), top acrylic cover temperature (T_c) are measured along with total solar insolation (I_s) at regular time intervals. Amount of distilled water collected for unit time per unit area is calculated using

$$M_w = \frac{Q_{ew}}{L} \tag{1}$$

Acrylic cover absorbs the incoming radiation and a small portion is reflected by it. Small portion heat is leaked through the bottom and sides of basin. Remaining portion of heat is used to raise the temperature of water, which causes evaporation. Efficiency of the still is calculated using the relation

$$\eta = \left({}^{M\,L}\!\big/_{I_s\,A\,t} \right) \tag{2}$$

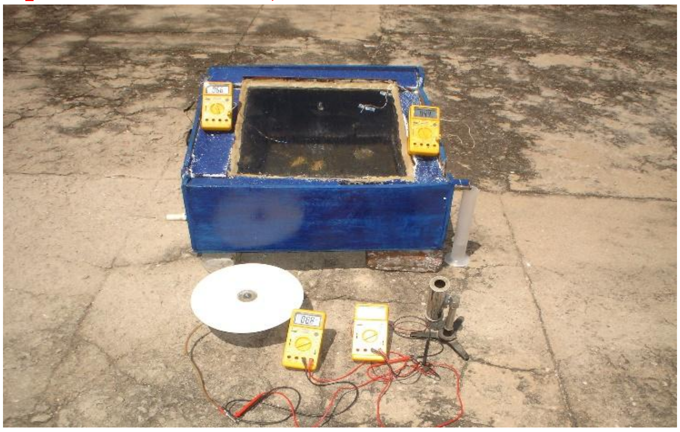


Fig (1) Single Slope Solar Still

A simple theory for the performance of flat plate collector was developed by Hottel, Woertz, Whiller and Bliss (HWB) method. The analysis assumes a steady state situation in which the liquid flows through the tubes bonded on the undesired of the absorber plate. Instantaneous collector efficiency is given by,

$$\eta = \left({}^{q_u}\!/\!{}_{A_p\, I_s} \right) \tag{3}$$

Fig (2) Single Slope Solar Still with Flat Plate Collector

Performance study of the pond is studied by filling the pond with 5cm thickness of water layer. Surface of the water is covered by using transparent polythene sheet and it acts as evaporation suppresser. Volume occupied by this layer is 39 liters. Hourly rise in temperature of the pond, solar radiation and ambient temperature are measured. Heat extraction is carried from pond by keeping flow rate as constant. Efficiency of SSP is defined according to HWB equation as rate of heat collection per unit SSP area (q) to the solar radiation incident on the surface of the pond. The hourly collection efficiency of a SSP is defined as

$$\eta = \left({}^{q}\!/\!{}_{I_s} \right) \tag{4}$$

Fig (3) Single Slope Solar Still with Shallow Solar Pond

4. Heat Transfer Modes in Solar Still

Heat and mass transfer coefficients for normal range of operation of a conventional solar still is proposed by R.V. Dunkle [25]. Heat is transported inside the still by free convection of air. It releases its enthalpy upon air coming into contact with the acrylic cover. Heat transfer per unit area per unit time due to convection is,

$$Q_{cw} = 0.884\left((T_w - T_g) + \left(\frac{(P_w - P_g)(T_w + 273)}{268.9\,x10^3 - P_w}\right)^{1/3}\right)(T_w - T_g) \tag{5}$$

Dunkle connects convective and evaporation heat transfer coefficients as

$$Q_{ew} = 16.273x10^{-3}\ h_{cw}\ R_1\left(T_w - T_g\right) \tag{6}$$

Using Stefan Bolzmann's constant, the Radiative heat transfer coefficient is given by,

$$Q_{rw} = \sigma\,\varepsilon\left[\left(T_w + 273\right)^4 - \left(T_g + 273\right)^4\right] \tag{7}$$

Due to the small thickness of the top cover, it is assumed that the lamp of the cover is uniform. Therefore, external convention loss from top cover to the outside atmosphere is calculated using

$$Q_{ce} = h_{ca}\left(T_g - T_a\right) \tag{8}$$

here, h_{ca} is a function of wind velocity and is given by J.A. Duffie and W.A. Beckman [26].

External radiation loss from the acrylic cover to the atmosphere is given by,

$$Q_{re} = \varepsilon_g\ \sigma\left[\left(T_g + 273\right)^4 - \left(T_{sky} + 273\right)^4\right] \tag{9}$$

Similarly, the external bottom loss from basin through base and sides is given by

$$Q_{be} = h_b\left(T_b - T_a\right) \tag{10}$$

Experimentally measured temperatures of evaporation and condensation surfaces are used to calculate the thermophysical properties.

$$k = 0.0244 + \left(0.7673x10^{-4}\right)T_{av} \tag{11}$$

$$\mu = \left(1.718x10^{-5}\right) + \left(4.620x10^{-8}\right)T_{av} \tag{12}$$

$$\rho = 353.44 / \left(273.35 + T_{av}\right) \tag{13}$$

5. Result and Discussion

The performance of the single slope solar still is analysed and also combined with shallow solar pond and flat plate collector. Radiative heat transfer (Q_{ri}), convective heat transfer (Q_{ci}) and evaporative heat transfer (Q_{ei}) under internal heat transfer modes are predicted. Similarly, external heat transfer modes by conduction heat transfer (Q_{be}), external heat transfer through radiation from the glass cover (Q_{re}) and heat transfer from acrylic cover to atmosphere by convection (Q_{ce}) are also estimated. Instantaneous efficiency, performance ratio, saturation vapour pressure and latent heat parameters are also calculated for the single slope solar still, which is combined with flat plate collector and shallow solar pond. Thermophysical properties of water such as thermal conductivity, density and viscosity are also estimated for three modes of analysis. Readings are recorded for number of clear sky days and almost equal average radiation received during the three studies are considered for the analysis and reported.

Fig (4) shows the variation of temperature for water, air, inner surface of the cover, outer surface of the cover and ambient with respect to time in single slope solar still performance study. The maximum rise in water and air temperature inside the still is observed as 54 °C and 57.5 °C. Variation of ambient temperature is in the range of 31.5 °C to 37 °C during the study. Similarly, the variation of top cover temperature is in the range of 32 °C to 43.5 °C. Normally, the rise in top cover temperature affects the condensation of water vapor over the top cover.

Fig (4) Variation of temperature with respect to time for single slope solar still study

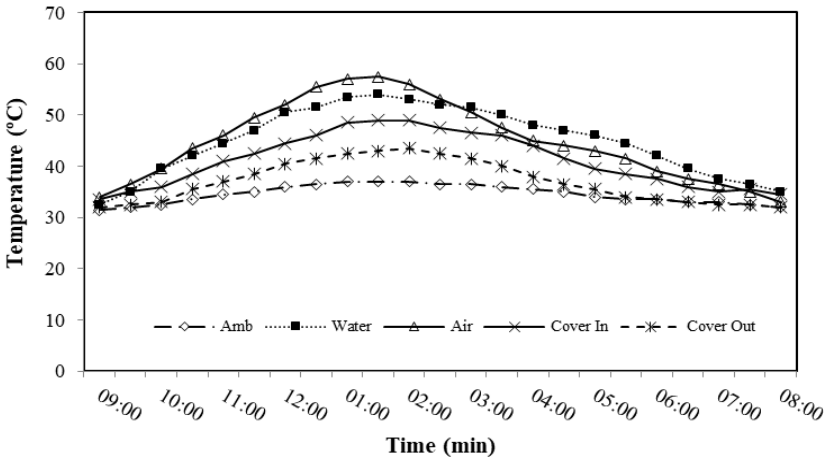


Fig (5) shows the variation of temperature for water, air, inner surface of the cover, outer surface of the cover of the still, water inlet and water outlet temperature of the flat plate collector and ambient temperature with respect to time in the single slope solar still performance combined with flat plate collector. The water temperature of the single slope solar still rises during the initial sunshine hours and it decreases due to decrease of radiation intensity. Maximum rise in water and air temperature is observed as 60 °C and 62 °C. Variation of ambient temperature is in the range of 33 °C to 37 °C during the study. Similarly, the variation of top cover temperature is in the range of 33 °C to 45.5°C. Flat plate collector inlet water temperature is in the range of 33 °C to 60 °C and 33 °C to 60.5 °C for outlet water temperature.
Due to the thermosyphon effect, heat energy is transferred from the flat plate collector to the single slope solar still. This process is confirmed by analyzing the temperature of the inlet, outlet and water temperature of the still. Therefore, water temperature of the still increases simultaneously along with the inlet and outlet water temperature of the still with respect to time and maintains inlet and outlet temperature almost a nearer value during 12.30 a.m. to 3.30 p.m. Collection rate is more only during 3.00 p.m. to 5.00 p.m. due to thermosyphon effect. Finally, the yield reduces in the evening due to the decrease of water temperature and evaporation rate. At off sunshine hours, water circulation to and from the flat plate collector is closed by using separate valves.

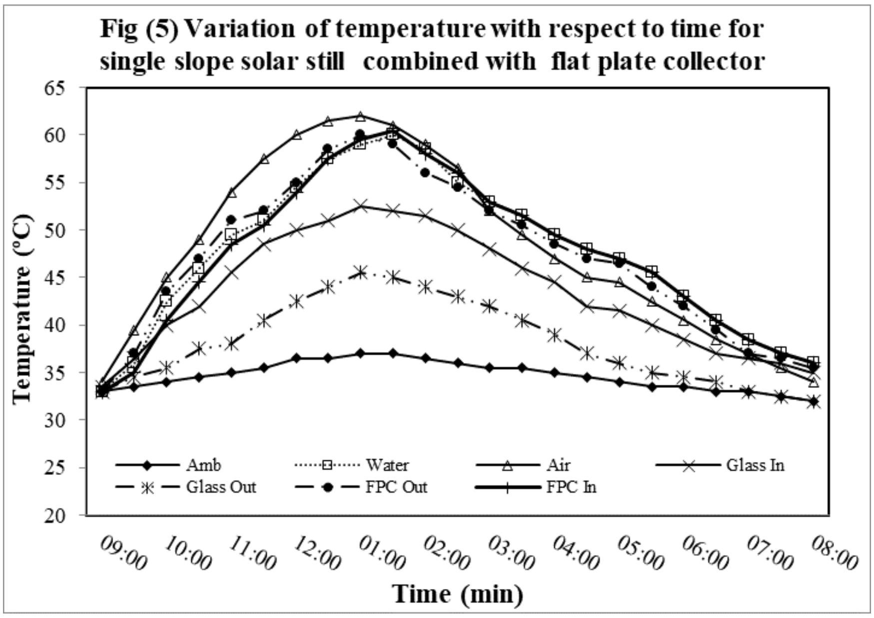


Fig (6) shows the variation of temperature for water, air, inner surface of the cover, outer surface of the cover of single slope solar still, water temperature of pond, water inlet and water outlet temperature of the shallow solar pond and ambient temperature with respect to time in single slope solar still performance combined with shallow solar pond. Variation of ambient and top cover temperature is in the range of 32.5 °C to 37 °C and 33 °C to 44°C. Maximum rise in water and air temperature of solar still is observed as 58 °C and 61.5 °C. Inlet and outlet water temperature of the shallow solar pond is in the range of 33 °C to 58 °C and 34 °C to 59 °C. Similarly, the maximum air and water temperature inside shallow solar pond is about 61.5 °C and 71.5 °C. Water temperature inside the still is maintained even at off sunshine hours due to due to the circulation of water through the shallow solar pond. As a result, distillate yield obtained from the still is not slowed even at off sunshine hours. The yield rate difference is more for the regular intervals measured between 2.00 p.m. and 5.00 p.m. and finally the yield starts to reduce after 11.00 p.m. due to the decrease of water temperature and evaporation rate.

Fig (6) Variation of temperature with respect to time for single slope solar still combined with shallow solar pond

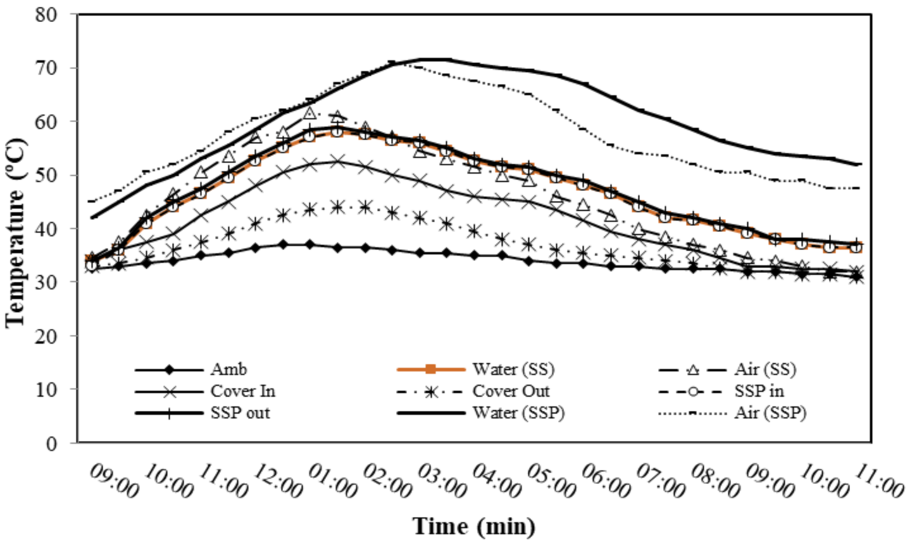


Fig (7) shows the variation of solar radiation and water collection with respect to time for the single slope solar still under three modes of study. Radiation increases linearly with time and reaches the maximum value from 12 p.m. to 2 p.m. and then decreases. Radiation received during this study is in the range of 60.38 W/m^2 to 1050.69 W/m^2, 108.69 W/m^2 to 1074.85 W/m^2 and 108.69 W/m^2 to 1038.62 W/m^2 for single slope still performance study under three modes of study with average radiation of 766.88 W/m^2 during the study. The variation of distilled water collection observed is in the range of 0.01 kg to 0.041 kg, 0.013 kg to 0.0595 kg and 0.013 kg to 0.0535 kg for the single slope still performance study under three modes of study. Water collection is increased linearly during the initial hours even though the instantaneous yield rate at regular intervals is less because the initial radiation is completely utilized for the warm up temperature than the distillate yield. Due to instantaneous heat transfer from FPC, enhanced distillate output is observed during sunshine hours. Due to continuous heat gain from the shallow solar pond, water collection is maintained even at off shine hours due to the coupling effect.

Fig (7) Variation of solar insolation and water collection with respect to time for single slope solar still under three modes of study

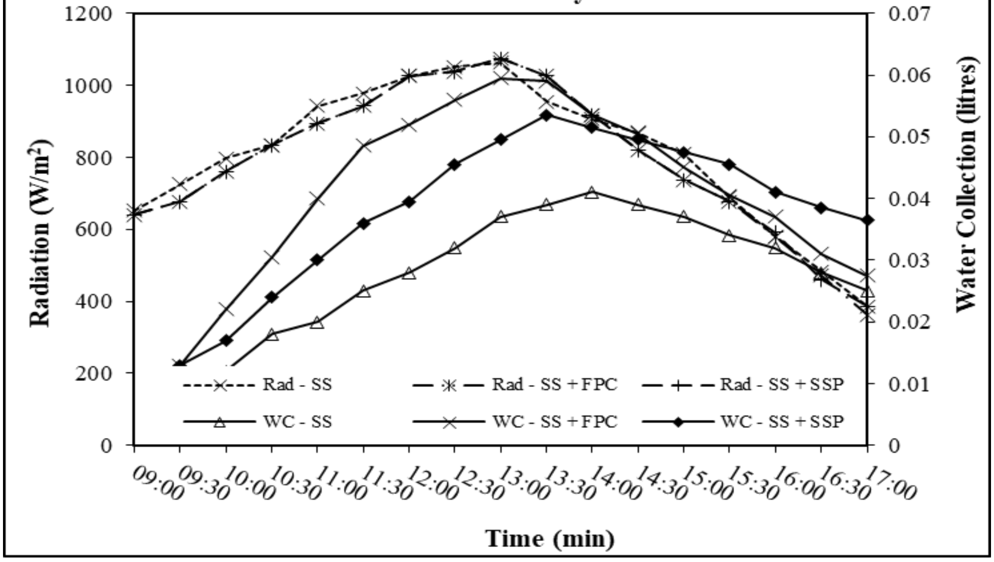
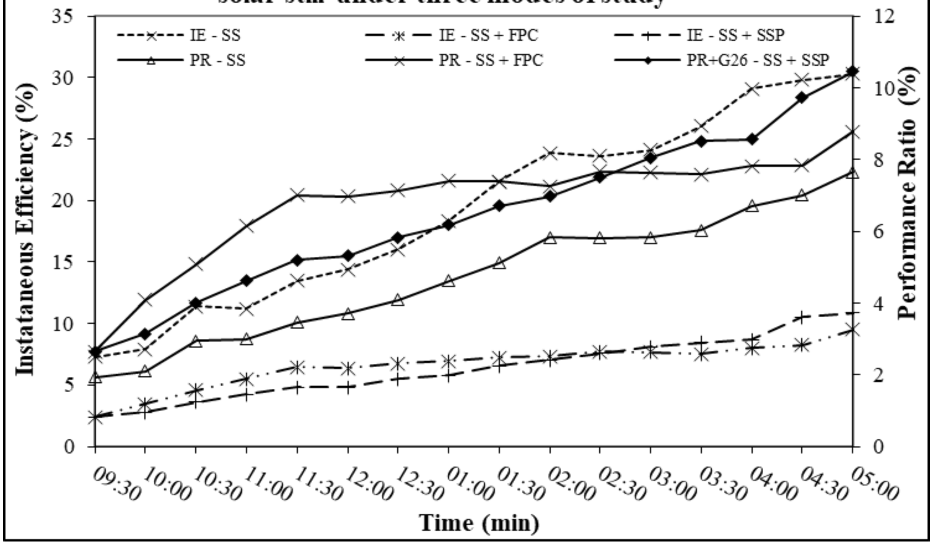


Fig (8) shows the variation of instantaneous efficiency and performance ratio with respect to time for performance study of single slope solar still under three modes of study. Instantaneous efficiency observed during the study is in the range of 7.27% to 33.30%, 2.41% to 9.52% and 2.41% to 10.86% for the single slope still performance study alone, combine with FPC and combined with SSP. Efficiency of the combined performance is found to be less because the total area of the combined system is larger than the still area. Even though the instantaneous efficiency in this mode is reduced than the single slope solar still, the distillate water collection rate is increased.

Fig (8) Variation of instantaneous efficieny and performance ration with respect to time for single slope solar still under three modes of study



Performance ratio observed for single slope solar still under three modes of study found to be in the range of 1.94 % to 7.65 %, 2.64 % to 8.78 % and 2.64 % to 10.46 % respectively.

Performance ratio value is increasing steadily with respect to water temperature. It is inferred that the coupling effect of flat plate collector and shallow solar pond with the still causes the increase in temperature to the optimum value for evaporation.

Fig (9) shows the variation of water temperature and thermal conductivity with respect to time. Water temperature rises with respect to incident radiation and is found to be in the range of 54 °C, 60 °C and 58 °C for all the three modes of study. Instantaneous increase in water temperature is observed in case of still with FPC due to the coupling effect. Whereas in case of still coupled with SSP, water temperature is maintained even at off sunshine hours due to thermosyphon effect. Thermal conductivity of water is analyzed and it is observed in the range of 26.87×10^{-3} Wm^{-2} °C^{-1} to 28.10×10^{-3} Wm^{-2} °C^{-1}, 26.93×10^{-3} Wm^{-2} °C^{-1} to 28.40×10^{-3} Wm^{-2} °C^{-1} and 26.97×10^{-3} Wm^{-2} °C^{-1} to 28.29×10^{-3} Wm^{-2} °C^{-1} for single slope still under three modes of study. Water temperature and thermal conductivity increase with respect to time and posses almost the same trend. It is inferred that the density of water increases with respect to increase in water temperature and it starts to decrease as water temperature decreases.

Fig (9) Variation of water temperature and thermal conductivitywith respect to time for single slope solar still under three modes of study

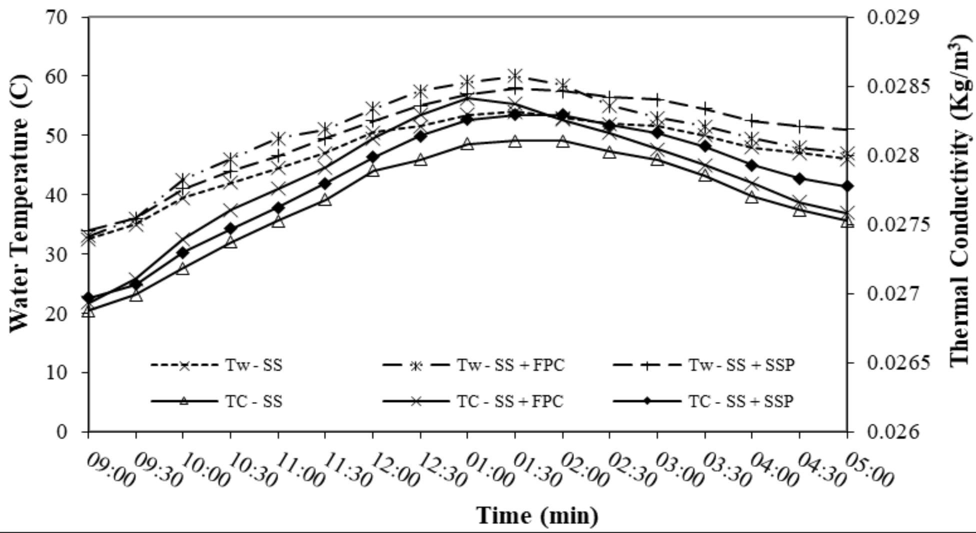


Fig (10) shows the variation of dynamic viscosity and density of water with respect to time. The dynamic viscosity of water is predicted in the range of 18.67×10^{-6} Nsm^{-2} to 19.40×10^{-6} Nsm^{-2}, 18.70×10^{-6} Nsm^{-2} to 19.59×10^{-6} Nsm^{-2} and 18.72×10^{-6} Nsm^{-2} to 19.52×10^{-6} Nsm^{-2} for single slope still under three modes of study. Density of water is predicted for still under three modes of study and it is observed as 11.56×10^{-1} kgm^{-3} to 10.99×10^{-1} kgm^{-3}, 11.53×10^{-1} kgm^{-3} to 10.85×10^{-1} kgm^{-3} and 11.51×10^{-1} kgm^{-3} to 10.90×10^{-1} kgm^{-3}. It concludes that the density decreases with respect to increase in viscosity and it starts to increase with the decrease in viscosity.

Fig (10) Variation of density and viscosity with respect to time for single slope solar still under three modes of study

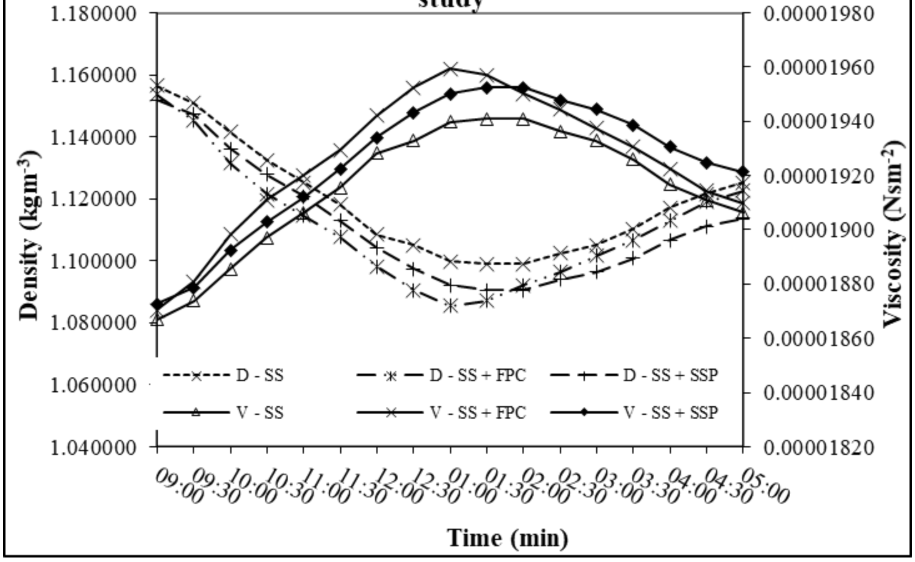
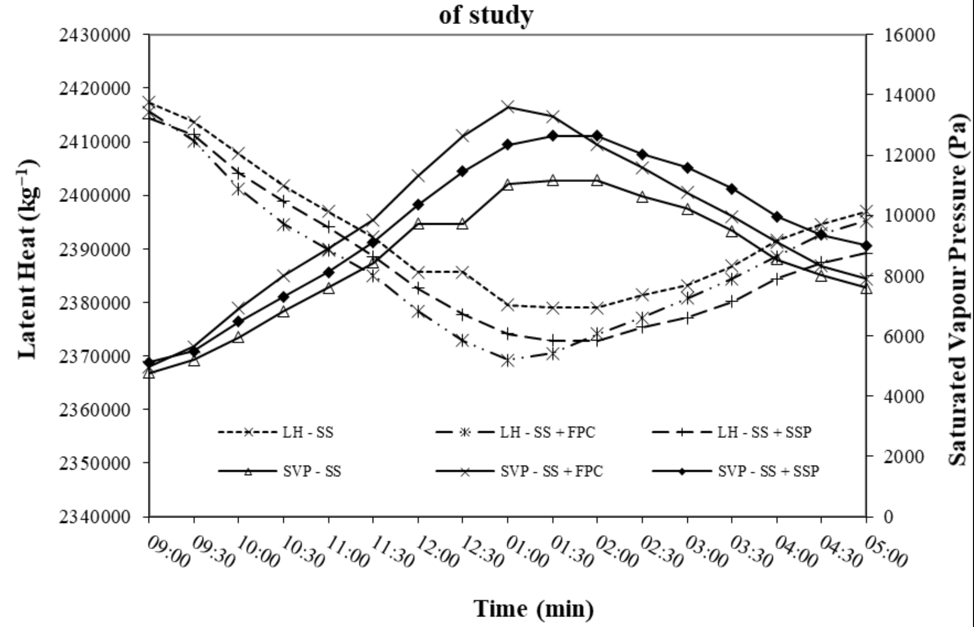


Fig (11) shows the variation of saturation vapour pressure and latent heat inside the single slope still for three modes of studies. Saturation vapour pressure reaches maximum value when water collection is more and tends to decrease when water collection decreases.

Fig (11) Variation of latent heat and saturated vapour pressure with respect to time for single slope solar still under three modes of study



Saturation vapour pressure is predicted in the range of 4774.98 Pa to 11171.33 Pa, 4980.48 Pa to 13609.64 Pa and 5121.7 pa to 12646.83 Pa for slope solar still under three modes of study. Difference in saturated vapour pressure is very less at higher temperature compared to the warm up period. Latent heat value is found to increase when the saturation vapour pressure starts to decrease. It concludes that the latent heat is decreased at higher order of temperature. Latent heat value observed is in the range of 2417317.42 to 2378981.95kg^{-1}, 2415532.23 to 2369297.23 kg^{-1} and 2414341.57 to 2372934.56 kg^{-1} for solar still under three modes of study. Latent heat is fully utilized for boosting the condensation commencing at lower temperature from 9.00 a.m. to 1.30 p.m. Thus, the effect of latent heat is not completely utilized for condensation at higher temperatures.

In the solar still, the evaporative heat transfer coefficient (Q_{ei}) is the major heat loss and is greater than the other two modes together. It is observed that the radiative heat transfer coefficient (Q_{ri}) and convective heat transfer coefficient (Q_{ci}) do not vary much in comparison to evaporative heat transfer coefficient (Q_{ei}). This indicates the strong dependence of evaporative heat transfer coefficient (Q_{ei}) on the operating water temperature (T_w).

Table: 1: Heat Transfer Values:

	Q_{ci} (W/m^2)	Q_{ri} (W/m^2)	Q_{ei} (W/m^2)	Q_{ce} (W/m^2)	Q_{re} (W/m^2)	Q_{be} (W/m^2)
Single slope Solar Still	14.28	47.97	114.46	32.13	77.84	4.35
Single slope Solar Still combined with Flat Plate Collector	17.57	57.07	156.15	38.71	84.08	5.32
Single slope Solar Still combined with Shallow Solar Pond	19.06	60.22	160.86	33.66	79.22	5.98

Table: 2: Thermophysical Properties:

	Thermal Conductivity (Wm^{-2} °C^{-1})	Dynamic Viscosity (Nsm^{-2})	Density (kgm^{-3})
Single Slope Solar Still	26.87x10^{-3} to 28.10x10^{-3}	18.67x10^{-6} to 19.40 x10^{-6}	11.56x10^{-1} to 10.99x10^{-1}
Single Slope Solar Still combined with Flat Plate Collector	26.93x10^{-3} to 28.40x10^{-3}	8.70x10^{-6} to 19.59 x10^{-6}	11.53x10^{-1} to 10.85x10^{-1}
Single Slope Solar Still combined with Shallow Solar Pond	26.97x10^{-3} to 28.29x10^{-3}	18.72x10^{-6} to 19.52 x10^{-6}	11.51x10^{-1} to 10.90x10^{-1}

Conclusion:

The performance of the single slope solar still combined with flat plate collector and shallow solar pond is studied. The effect of water temperature in the still causes the increase in distillate yield. The combined performance results confirmed that even smaller surface area of the top cover in the still can also produce more distillate yield. The saturation vapour pressure and latent heat also plays a major hole in production of distillate yield.

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