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Performance Analysis of Solar Thermal Flat Plate Collector using Different Heat Transfer Fluids

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Abstract

One of the major concern in the Indian energy sector are energy use and energy security and these two factors are greatly inter related too. Renewable energy sector contributes a lot to sustainable development technologies in which the ability of the future generation to meet their own needs are not affected by meeting the needs of present generation. The drastic increase in energy demand and related environmental issues have encouraged a lot of researchers for searching an alternative option to render the future energy demand. Since solar energy is clean, abundantly available and inexhaustible in nature, it is an interesting option among the renewable energy technologies. Nowadays, solar thermal technologies are the most popular due to ease of application, high conversion factors and economic viability. The performance of solar thermal technology is dependent on certain factors such as heat transfer fluids like water, air, antifreezes like ethylene glycol, propylene glycol, hydrocarbon oils etc., solar radiation, collector tilt, etc. The efficiency of a solar thermal system depends on the outlet temperature obtained using each of the heat transfer fluids. In this context, their performance analysis holds a greater importance. In this thesis work, a performance analysis on the flat plate collector system using different heat transfer fluids were done and compared. The experiment was conducted using varying concentrations of water and heat transfer fluid mixtures.

Keywords*- Ethylene glycol, heat exchanger, heat transfer fluid, heat transport, propylene glycol, solar thermal system, thermal efficiency*

I. INTRODUCTION

In the thesis work, the performance of a flat plate collector (FPC) system is experimentally and theoretically investigated and compared. The experimental readings taken were compared with the simulated results obtained from TRNSYS (Transient System Analysis) software. In order to simulate the collector and to plot various characteristic curves, TRNSYS software was used.. The temperature along the absorber was measured by means of temperature measurements at the inlet and outlet of absorber tubes or at the inlet and outlet portions of the collector using thermocouples.

Table 1. Factors affecting the performance of FPC system

Factors	Desirable features
Selective surfaces	High absorptivity, low emissivity [2]
Number of covers	Selective absorber surface-one cover Non-selective absorber surface-two covers
Collector tilt	$(\Phi+10^0)$ or $(\Phi+15^0)$ - winter application $(\Phi-10^0)$ or $(\Phi-15^0)$ - summer application [1,3]
Fluid inlet temperature	Lesser value yields more efficiency
Cover transmissivity	Higher transmissivity
Dust on top of the cover	Frequent cleaning of collector

Table 1 is meant for describing the various parameters that affect the performance of liquid FPC and also their effects on liquid FPC. Among these factors, collector tilt plays a major role in the performance of FPC.

II. EXPERIMENTAL SET UP

The alternate fluids that can be incorporated within the system include air, mixture of ethylene glycol and water, mixture of propylene glycol and water, hydrocarbon oils, nanofluids etc. Figure 1 illustrates the schematic representation of the proposed system. The ratio or proportion in which the fluid water mixture being selected anyway greatly affects the performance of the flat plate collector system in terms of the parameters like outlet water temperature, heat transfer capability, specific heat capacity, fluid density etc.[7]. The concentration of the fluid-water mixture is varied in the specified volume of the storage tank.

2.1. Design Steps

- Design and installation of a thermosyphon flat plate collector (FPC)
- Simulation of the collector using TRNSYS software
- A hardware set up for analysing the performance of FPC using fluids such as water, ethylene glycol and water mixture (80% :20% water to ethylene glycol ratio), propylene glycol and water mixture (80% :20% water to propylene glycol ratio)
- Design of an alternative storage tank for experimental purpose
- Calculating the thermal efficiency of the collector for each of the fluids
- Analysing the performance of the set-up with the above said fluids

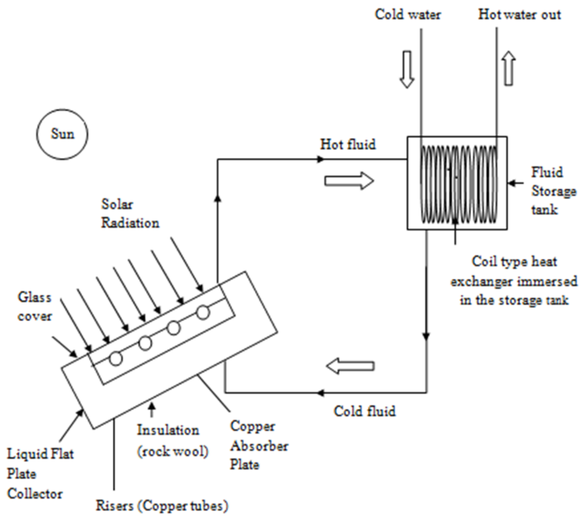

Figure 1. Schematic diagram showing proposed system

There was a need for an additional coil type heat exchanger to be immersed inside the fluid storage tank in order to transfer the heat available from the hot fluid circulating inside the tank to water which is flowing through the coils. The heat exchanger is a coil of tubing in the storage tank. The proposed prototype is being illustrated in the figure 1, which consists of a liquid FPC of area 2 square meters, a fluid storage tank of 20 litres capacity and a coil type heat exchanger immersed in the tank.

III. EXPERIMENTAL PROCEDURE

The flat plate collector is installed at a slope of 20 degrees facing southwards located in a latitude of 9.55000N and longitude of 76.78330E. This specific slope of 20 degrees is recommended in order to attain proper thermosyphon action for the FPC system. The experimental studies are conducted during the month of April, May, June and July. The readings for the experiment are taken within a duration of 20 minutes on each day.

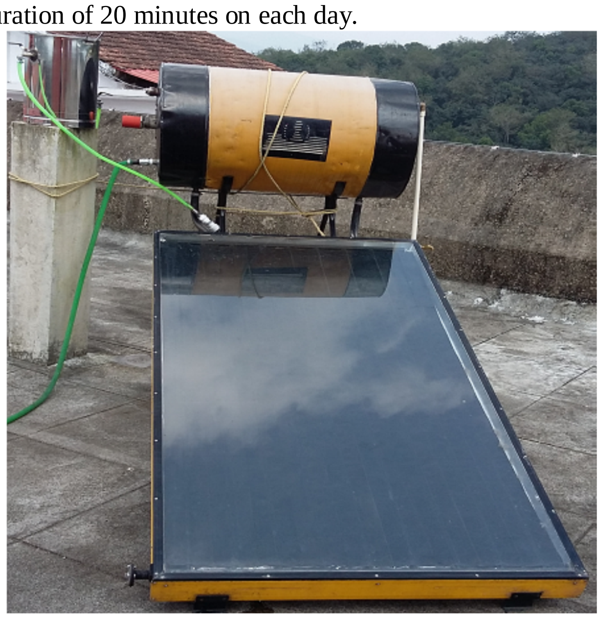

Figure 2. Liquid FPC installation on the roof top of Research Square building at Amal Jyothi College of Engineering, Kanjirapally

The liquid FPC installed for experimental purpose is being illustrated in figure 2. The system consists of a hot water storage tank of 100 litres capacity and a FPC of area 2 square meters. The hot water storage tank is being located at about 1.5 meters above the at plate thermal collector system from ground level. The slope of at plate solar thermal collector is 20 degrees which was measured using a magnetic slope detector. In the system described here, the cold water supply is provided from a make-up tank through inlet pipe which is located at about 10 cm above the bottom base of storage tank. The tank is fixed and placed firmly on a vertical stand. The outlet for hot water is located at about 10 cm from the upper portion of the tank. The hot water outlet temperature at the top of the storage tank is obtained with the help of a tap fitting attached to the top portion of tank.

Table 2. Flat plate collector system specifications

Tank Capacity	Cylindrical - horizontally assembled, Stainless steel, 100 litres
Tank Size	Ø360, Length 950mm
Panel Size	2080mm L x 1050mm W x 100mm H
Absorber Material	Copper
No. of Fins	9 No's per collector
Header Tubes	Copper, Ø25 mm, 22 SWG.
Riser Tubes	Copper, Ø12.5 mm, 24 SWG
Collector Box	Aluminium-50 microns
Slope	20 degrees
Top Cover/Glazing	Toughened glass, 4mm thick
Insulation Bottom and side	Rock wool, 50 mm 48 kg/m³ density

As the fluids available are costly in nature, an alternate tank needs to be designed with 20 to 24 litres of capacity which is able to undergo thermosyphon action with the collector of area 2 square meters. The material used for tank construction is stainless steel which is able to store the heat trapped inside without much losses. The following design equations are used for the above said purpose.

3.1. Alternate aluminium tank design

Heat transfer due to convection,

$$\dot{Q}_{conv} = UA\Delta T \quad (1)$$

Heat loss due to conduction,

$$\dot{Q}_{cond} = \dot{m}C_p(T_o - T_i) \quad (2)$$

Under steady state condition,

$$\dot{Q}_{cond} = \dot{Q}_{conv} \quad (3)$$

$$\dot{m}C_p(T_o - T_i) = UA(Toeg - Tieg) \quad (4)$$

$$A = \pi DL = \frac{0.0345*4187*(65-27)}{1507.93*(55-27)} \quad (5)$$

$$= 0.14\ m^2 \quad (6)$$

Therefore, L= 2.97 m (7)

where,
C_p is specific heat of liquid in J/kgK or J/kg^{0}C
T_0 is outlet hot fluid temperature
T_i is inlet hot fluid temperature
ΔT is cold fluid inlet and outlet temperature difference
T_{oeg} is EG outlet temperature
T_{ieg} is EG inlet temperature
U is overall heat transfer coefficient in W/m^{2o}C
A is heat transfer surface area of the coiled type heat exchanger
$m^{\cdot}$ is mass flow rate of water (cold fluid)
L is length of copper coil in meters

Figure 3. Inner side of the FPC alternate stainless steel tank showing the coil and lid part

The stainless steel tank considered is of 22 litres in capacity. The diameter of tank is 28.1 cm with a height of about 40 cm. The coil material is copper and is wound with a single turn diameter of 0.16 m with four number of turns. The outer diameter of the coil is about 0.98 cm with an inside diameter of 0.9 cm. The coil type heat exchanger fitted within the stainless steel tank lid is shown in the figure 3 given below. There are two valves fitted on the outer opposite sides of the stainless steel tank. One is the inlet valve for delivering the fluid to the inlet side of the FPC and the second one is the outlet valve for collecting the hot water available at the outlet of the FPC. The inlet valve is situated at a distance of about 10 cm from the bottom most portion or base of the tank. The outlet valve is situated at a depth of about 10 cm from the top most portion of the tank. These two valves were well screwed and then welded tightly to the tank.

3.2. Instruments Required

The following instruments were used for the measuring the different parameters of FPC during the experimental purpose and were tabulated in table 3. The measurements on the following parameters were taken viz inlet temperature, hot water outlet temperature, glass cover temperature of the FPC panel, solar irradiation, wind speed, ambient temperature and mass flow rates. The mass flow rate of the fluid is measured using a beaker and stopwatch. The outlet temperature is measured using a digital thermometer for a duration of 20-30 minutes. The inlet temperature, temperature of glass cover and surface temperature of hot water storage tank are measured using an infrared thermometer.

Table 3. Measuring instruments used for experimental purpose

Instruments/Equipments required	Purpose
Solar Insolation meter	Radiation measurement
Digital multimeter	Outlet temperature measurement
Thermocouple	Temperature measurement
Infrared Thermometer	Temperature measurement
Magnetic slope detector	Slope measurement
Digital Anemometer	Ambient temperature and wind speed measurement
Stopwatch-beaker arrangement	Mass flow rate measurement

An electronic digital anemometer model is used to measure air flow velocity over the glass cover. A solarimeter is used to measure the hourly total solar radiation intensity. A copper constantan thermocouple with a digital temperature indicator having a least count of 0.1 is used for measuring the temperatures of water and glass cover. The ambient temperature can also be measured with the help of a digital anemometer.

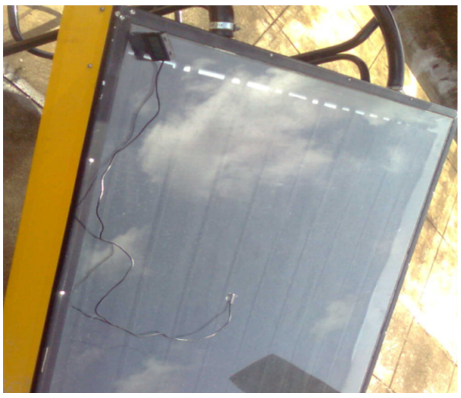

Figure 4. Measurement of glass cover temperature using thermocouple

IV. ECONOMIC ASSESSMENT OF THE SYSTEM

The methods or tools used for the cost analysis of the system is described in table 4 and table 5 given below. After investing money into a solar thermal system, it is desirable to find out in what time period the invested money is recovered[12]. For an electric heater, there will be cash flow every year. But in case of a solar water heater, cash flow only in the first year and later there will be no cash flows like a storage electric water heater.

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Table 4. Parameters required for economic evaluation of the solar FPC system

Parameters (for 100L capacity)	**Electric heater**	**Solar water heater**
Annual electricity production (kWh)	16	31.06
Investment cost (Rs.)	1,00,000	28,500
Capital Recovery Factor (CRF) (%)	0.1736	0.1102
Discount Rate (%)	10	10
Lifetime of the system (years)	9	25

Since the payback period of solar water heater is lesser than that of electric water heater, solar water heater is the more economically viable option. Thus, a solar water heater pays back its initial investment within 0.4370 years when compared to an ordinary storage type electric heater having a payback period of 2.9762 years. The net present values of both heaters are greater than zero. Since the NPV of solar water heater is more than that of electric water heater, solar water heater is the more economically viable option. The IRR of electric water heater is less than that of solar water heater and hence solar water heater is the more economically viable option.

Table 5. Tools for evaluating and comparing economic viability of solar FPC system and ordinary electric heater

Tools or factors used	**Storage type electric heater**	**Solar water heater**
Simple Payback Period (SPP)	2.98 years	0.4370 years
Net Present Value (NPV) (Rs.)	Rs. 93,548.4	Rs. 5, 63, 292.2
Internal Rate of Return (IRR) (%)	0.1194	1.6125
Benefit to Cost Ratio (B/C ratio)	3.02	57.2

As the B/C ratio of solar water heater is more than that of electric water heater, solar water heater is the more economically viable option. Hence after doing economic analysis on the two systems, it can be concluded that solar water heater is the best economically feasible option compared to electric heater.

V. SIMULATION RESULTS

The inlet temperature of the entire set up is set to 20^0C with a mass flow rate of 40 kg/hr. The specific heat capacity of fluid (water) is loaded as 4187 J/kgK at about 44^0C and density as 1000 kg/m^3.It is observed from the simulation results that as solar radiation increases, the outlet temperature of the system also rises to a maximum value. The temperatures at different positions of the tank differs according to the incident solar radiation[8]. The construction of the tank is an important parameter under consideration while interpreting the simulated results. The TRNSYS model diagram for solar water heating system is illustrated in figure 5.

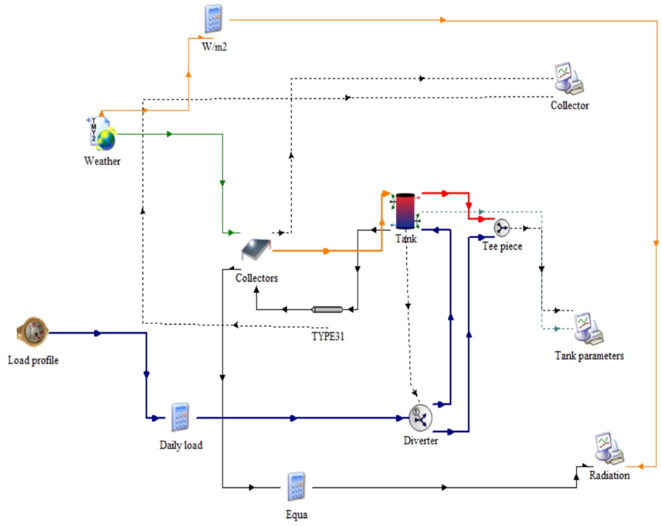

Figure 5. TRNSYS model diagram for solar water heater

Further more, for the simulation of the same FPC, the various parameters like thermal conductivity (k), specific heat (C_p) and density (ρ) values are loaded into the blocks specified for the collector (Type 73) in the model diagram[9]. The established model diagram can be further processed by changing the values of fluid density[4], fluid specific heat, tank volume, variable inlet positions, tank loss coefficient, efficiency mode, collector area and boiling point. The different plots or graphs that were utilized for the purpose of comparison are variation of tank temperature with respect to time, variation of collector temperature with respect to time and variation of solar radiation and useful heat gain with respect to time and these graphs are portrayed in figures 6 and 7.

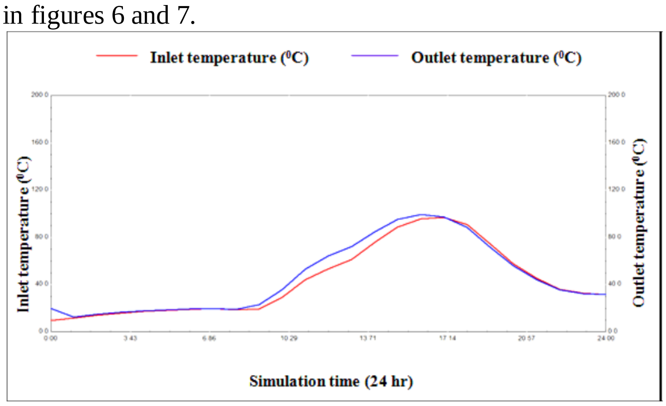

Figure 6. Variation of collector temperature with respect to time

During noon time, the maximum useful heat gain was observed to be about 1250 W from the graph which was less compared to that with fluid as water-ethylene glycol mixture. The maximum solar radiation was found to be about 670 W/m^2.

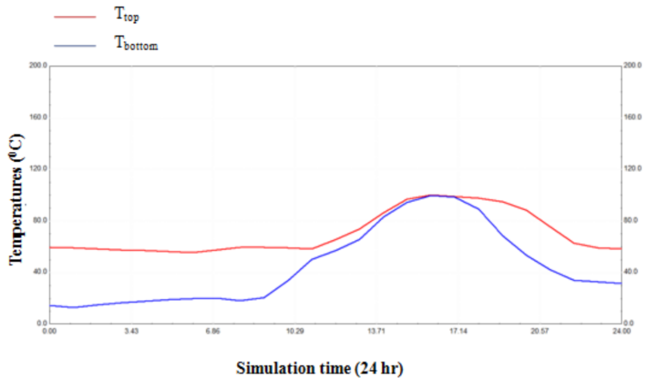

Figure 7. Variation of tank temperature with respect to time

From the graph shown above, it was observed that during the initial stages, the variation of temperature in the tank was almost constant and later on the temperature varies with the increase in solar radiation.

VI. RESULTS AND DISCUSSIONS

The outlet temperature obtained maximum was about 65^{0}C with the existing system i.e., using water as the heat transfer fluid under a fair atmospheric condition. The efficiency was calculated and found to be almost 58 to 62%. with an available solar radiation in the range of 450 to 898 W/m^2. At 20^{0}C inlet temperature, the outlet temperature during simulation peaked around 60^{0}C.

6.1. Experimental results using water

This section include several readings like inlet temperature, outlet temperature, glass cover temperature, mass flow rate and solar radiation incident on the collector surface taken within the system for about 30 minutes time duration. The values of inlet temperature, outlet temperature, glass cover temperature and efficiency which are obtained experimentally using water as the heat transfer fluid are tabulated in the tabulation column given below as in table 6.

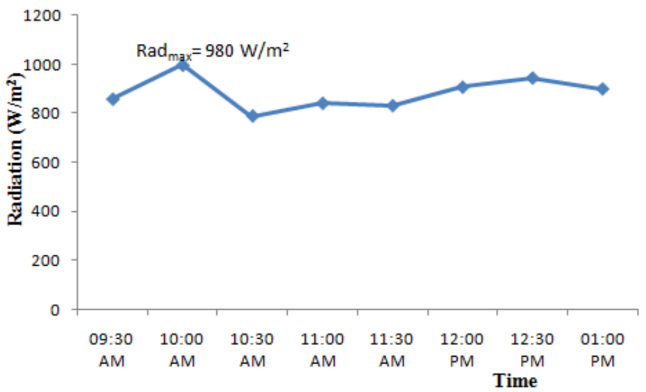

Figure 8. Variation of solar radiation with respect to time on (28-4-15)

From the above graph, it was observed that the maximum solar radiation was found to be 980 W/m^2 on that particular day which was an appreciable solar irradiance for the collector to work effectively.

Table 6. Experimental values using water as fluid

Date	Time	T_{fo} (%)	m· (kg/s)	Efficiency (%)	Radiation (W/m^2)
28-4-15	9:30 am	53	0.03048	55.3	856.8
	10:00 am	54	0.0305	58.1	997.15
	10:30 am	55	0.0333	62.2	787.5
	11:30 am	58	0.01369	63.5	830.2
	12:00 pm	58	0.01445	61.142	906.5
	1:00 pm	56	0.0244	62.156	899.5
29-4-15	10:05 am	53	0.03048	62.3	704.2
	10:55 am	45	0.0133	64.8	767.2
	11:35 am	53	0.03048	65.6	391.3
	12:05 pm	55	0.03048	62.6	825.3
	12:35 pm	58	0.03048	60.3	865.9
	1:05 pm	60	0.03048	60.3	881.3
06-5-15	1:40 pm	53	0.01576	69.9	242.2
	2:20 pm	51	0.01576	68.1	441.7
	3:25 pm	52	0.01576	67.6	535.5
	3:55 pm	55	0.01576	69.2	696.5
	4:25 pm	54.5	0.01576	68.4	648.2

The experiment was conducted on most of the warm sunny days of the month April 2015 with a collector tilt of 20 degrees. The collector tilt was fixed and FPC was not allowed to track the sun according to the solar radiation available. The best readings were plotted as graphs as seen in figures 8 and 9 respectively.

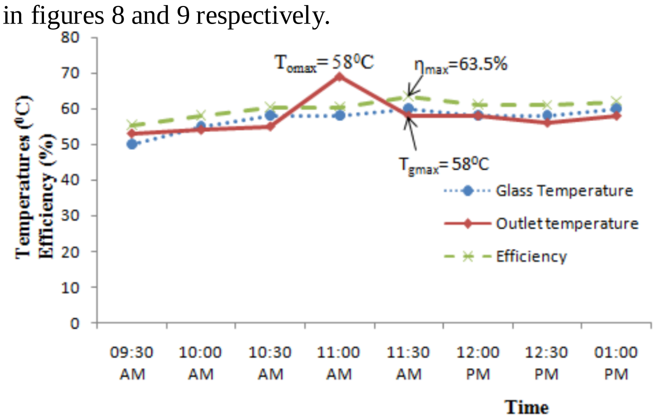

Figure 9. Variation of efficiency, outlet and inlet temperatures with respect to time on (28-4-15)

Also, the combined variation of efficiency, outlet and inlet temperatures of the FPC with respect to time are illustrated in the figure 9 shown above. From the graph, it was also observed that the maximum efficiency and outlet temperature of the collector was found to be 63.5% and 58^{0}C. The inlet temperature remained almost constant throughout the whole day of the experiment.

6.2. Experimental results using water-ethylene glycol mixture

The ratio of water and ethylene glycol mixture is 80:20.ie, 80% of the tank capacity is water and 20% is ethylene glycol [5]. Thus for a designed tank capacity of 22 litres, the quantity of water taken was 17.6 litres and the quantity of ethylene glycol used in the mixture was 4.4 litres. Also, the heat transfer coefficient designed for the coil type heat exchanger was almost 1507.93 W/m^2K for a coil length of 2.5 meters.

Table 7. Experimental values using water ethylene glycol mixture as fluid on 6-7-15

Time	T_i (^0C)	T_o (^0C)	T_g (^0C)	T_a (^0C)	Radiation (W/m^2)	Efficiency (%)
9:45 am	29.6	57	46.4	29.9	832	48
10:00 am	29.1	57.5	46.8	30.1	852	51
10:15 am	29	58.9	37.6	30.4	893	52
10:30 am	28	61.3	38	30.5	920	53
11:00 am	28.7	62	39.8	30.6	938	50
11:30 am	28.8	50	40.5	35.2	942	54
12:00 pm	28	52	42.5	34.1	1008	54.5
12:15 pm	29	54	43	35	1082	55
2:00 pm	29	54	43.5	35	1090	55.9
2:15 pm	30	55	43	34	1095	56
2:30 pm	30	56	42.5	33	1072	57.9
2:45 pm	30	57	44	35	1084	58
3:00 pm	30	57.5	44.5	35	1126	55
3:30 pm	30	55	46	35	1156	54
4:00 pm	30	54	46	35	1168	52
4:30 pm	30	54.5	46	34.5	1170	52

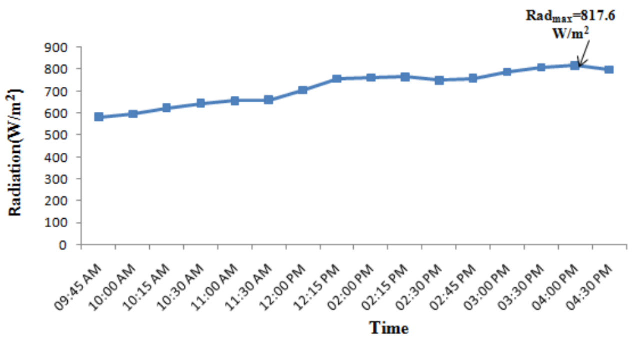

Figure 10. Variation of solar radiation w. r. t time on (6-7-15)

From figure 10, it was observed that the maximum solar radiation was found to be 817.6W/m^2 on that particular day which was an appreciable solar irradiance for the FPC to work effectively. The solar radiation values at first slightly increases linearly with time and then till noon. After that it remains slightly decreasing in nature till 2: 45 pm and again goes on increasing till 4: 30 pm.

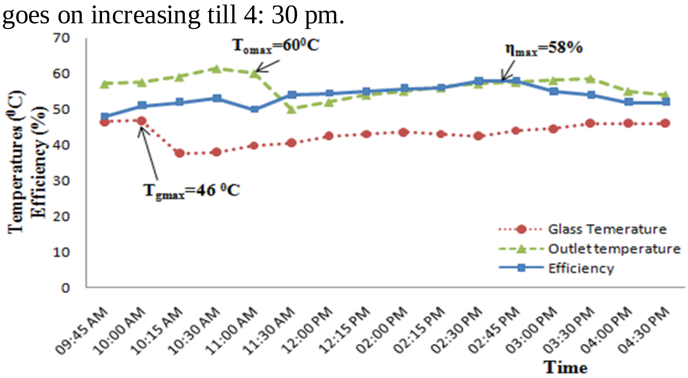

Figure 11. Variation of efficiency, outlet temperature and glass cover temperature w.r.t time on (6-7-15)

Figure 11 shown illustrates the combined variation of efficiency, outlet temperature and glass cover temperature with respect to time. The maximum outlet temperature which was obtained by using the mixture of water and ethylene glycol was almost 60 to 62^{0}C. The maximum temperature obtained on the top of glass cover was about 46.8^{0}C which was comparatively lesser compared to that with the fluid as water. The maximum efficiency obtained was about 58%. But, by increasing the concentration of water in the water-ethylene glycol mixture, both the outlet temperature and glass cover temperature can be further increased as the viscosity of water is less compared to that of ethylene glycol.

6.3. Experimental results using water-ethylene glycol mixture

The following plots (figure 12 and figure 13) were obtained for the experimental study conducted on the liquid FPC with a mixture of water and propylene glycol solution as the fluid. These graphs were plotted based on the readings obtained from table 8 and is tabulated below.

Table 8. Experimental values using water-propylene glycol mixture on 7-8-15

Time	Radiation (W/m^2)	T_{glass} (^0C)	T_0 (^0C)	Efficiency (%)
9:00 am	844	34	41	51
9:30 am	850	33	41	51
10:00 am	890	34	42	53
10:30 am	995	34.5	43	54
11:00 am	1010	43	44	54.55
11:30 am	1148	43.3	46	53.5
12:00 pm	1295	40	48	53.45
1:00 pm	1456	42	50	55
1:30 pm	1463	42.9	52	54.74
1:45 pm	1522	43	52	55.54
2:00 pm	1152	43.5	50	55.5
2:30 pm	1168	44	52	55.67
3:00 pm	1179	44	51	55.55

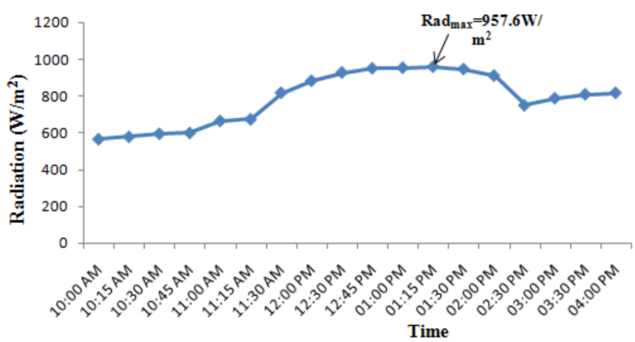

Figure 12. Variation of solar radiation with respect to time 7-8-15

From figure 12, it was observed that the maximum solar radiation was found to be 957.6 W/m^2 on that particular day. The solar irradiance gradually increases till 11:15 am on 7-8-15, then it increases and remains steadily at 960 W/m^2. After that the value of solar radiation then decreases till 4:00 pm.

Similarly, the variation of efficiency, outlet temperature and glass cover temperature were plotted with respect to time in the following figure 13.

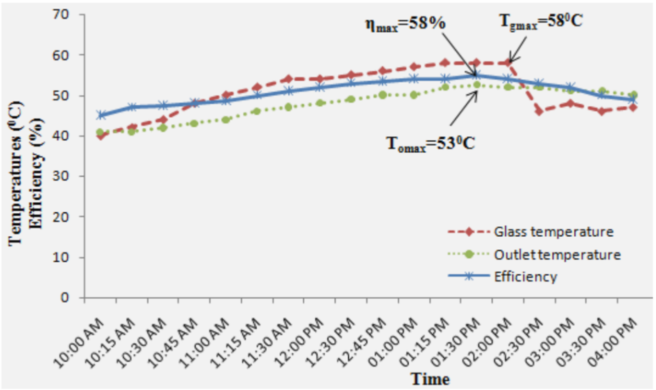

Figure 13. Variation of efficiency, outlet and glass cover temperature with respect to time on 7-8-15

The figure 13 shown above indicates a maximum efficiency of 58%with a maximum outlet temperature of 53^0C and glass plate temperature of 58^0C. The inlet temperature for the experimental period was in the range of 28 to 30^0C with a mass flow rate in the order of 0.0345 kg/s.

VII. CONCLUSION AND FUTURE SCOPE

The maximum outlet temperature obtained using water-ethylene glycol mixture as heat transfer fluid in the proportion 80:20 was about 56^0C. experimentally. The peak outlet temperature during simulation was around 59 to 60^0C with an inlet temperature of 29^0C. The simulation study and experimental results holds a better agreement in the case of an existing solar thermal FPC system with the specifications considered. The outlet temperatures available from the FPC system varies according to the incident solar radiation striking upon the system.

By using a mixture of water and propylene glycol, maximum outlet temperature was obtained to be 62 to 64^0C. This was less compared to that of water but, the fluid as water suffers from the problem of corrosion. Moreover, the varying concentrations of these fluids with water mixture will yield more outlet temperatures[6]. Since ethylene glycol and propylene glycol are antifreeze solutions, they are not vulnerable to the problem of corrosion.

The maximum outlet temperature using a mixture of water and propylene glycol was obtained to be lesser compared to that of water but, the fluid like water suffers from the problem of corrosion. Since ethylene glycol and propylene glycol are antifreeze solutions, they are not vulnerable to the problem of corrosion. Moreover, the varying concentrations of these fluids with water mixture yields more outlet temperatures. Also, nanofluids in the field of thermal system can yield better temperatures, but they are costly in nature [11]. Furthermore, the future developments in flat plate collector systems like transparent insulating materials as absorbers can yield temperatures even up to100^0C [10].

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