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Experimental Analysis of Flat Plate Collector Solar Water Heater

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Abstract- In this paper experimental result of flat plate collector are presented. A solar water heater indoor unit is studied. In order to evaluate the performances of the prototype, the test was conducted over a period of three days to determine the performance of the setup. As this water heater is an indoor unit, halogen lamp has been used as a source of radiation, with the help of regulator radiation can be varying. Experiments were conducted by varying radiation and wind velocity and it is found out that the decrease in radiation leads to increase in collector time constant. Also with the reduction in radiation overall heat loss coefficient increases whereas heat removal factor reduces and hence efficiency decreases.

Keywords- *Collector time constant, Heat removal factor, Overall heat loss coefficient, Solar water heater, Thermosyphon action*

I. INTRODUCTION

There has always been a gap between supply and demand of electricity energy and the situation further worsen during peak hours when enormous heating load is switched on. If the heating load is switched over to non-conventional source of energy from conventional energy sources the gap can be bridged considerably. Solar energy is an ultimate source of renewable energy and it can be bridged the gap between demand and supply of electricity and it also saves money since its running cost is zero. Flat plate collector is widely used for domestic hot water, space heating and for applications requiring fluid temperature less than 80˚C. Heating water for domestic purpose is a simple and effective way of utilizing solar energy. A type of solar thermal collectors, relative thermal analyses and practical applications of each type is given in [1]. Collector efficiency is calculated [2]. Experiment was conducted in Bangladesh and data is collected for 12 months. It is found that FPC water heater can work without disturbance [3].This [4] paper suggests using a phase transition material as working fluid. It undergoes phase transition at a specific temperature and release latent heat which is used to heat the water.

It is suggested [5] that instead of leaving collector mount in a fixed position throughout a year it is suggest to tilt it monthly, seasonally or bi-annually. The experiment is conducted in order to find out long term performances of FPC by system advisor model [6]. In this [7] paper two FPC are studied one with conventional design and another is with new design i.e. in this collector the heat transfer directly takes place from the absorber plate to the fluid. Also the material used for absorber plate is GI but instead of Cu. And there is a small difference between the output temperatures while using a different collector. Experiment is carried out [8] whose result reveals that the performance of the water heater depends on the flow rate through the collector, the collector efficiency increases with the increase in flow rate and incident solar radiation. In this paper [9] an auxiliary tank filled with cold water is warmed by exposition to the sun and then transferred to the tank so that it will get heated quickly and by doing this efficiency of solar water heater is improved. This paper [10] studies some incentives which can be offered to consumers to increase the use of solar water heater.

II. SOLAR COLLECTORS

Solar collectors are the main component of active solar-heating systems. They absorb the sun's energy, transform its radiation into heat, and then transfer that heat to a working fluid (usually water or air). The solar thermal energy can be used in solar water-heating systems, solar pool heaters, and solar space-heating systems.

These designs are classified in two general types of solar collectors:

A. Non Concentrating collectors

The absorbing surface is approximately as large as the overall collector area that intercepts the sun's rays.

B. Concentrating collectors

Large areas of mirrors or lenses focus the sunlight onto a smaller absorber.

III. FLAT-PLATE COLLECTORS

Flat-plate collectors are the most common solar collector for solar water-heating systems in homes and solar space heating. A typical flat-plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a darkcolored absorber plate. These collectors heat liquid or air at temperatures less than 80°C.

Description of the system of The solar water heater subject of this study is composed

- Flat plate solar collector with characteristics given in Table 1.
- A horizontal storage tank of 100 litters capacity, insulated with Rockwool material and its insulation thickness-base and insulation thickness-side are 50 and 25 mm respectively.

Important parameters of a flat plate collector based solar water heating system:

A. Collector Time constant

Collector time constant is required to evaluate the transient behavior of a collector. It is define as the time required rising the outlet temperature by 0.632 of the total temperature increase from $T_{fo} - T_a$ at time zero to $T_{fo} - T_a$ at time infinity i.e. time at which the outlet temperature attains a stagnant value. It can be calculated from the curve between R and time as shown below. Where R is given as:

$$R=\frac{T_{fo}(t)-T_{fo}(0)}{T_{fo}(\alpha)-T_{fo}(0)} \quad (1)$$

Where,
$T_{fo}(t)$: Outlet water temperature at any time t
$T_{fo}(0)$: Outlet water temperature at time zero
$T_{fo}(\alpha)$: Outlet water temperature at infinite time (maximum temperature)

TABLE I. CHARACTERISTICS OF THE COLLECTOR

Dimension	1230×1850×100
Radiator	No of tube = 10, L=12.7, Di=12.7mm
Absorber	Copper, 0.5 mm thickness
Insulation **Back** **Lateral**	Rockwool 50mm 25mm
Tempered glass	Thickness=4mm Transmission=0.85

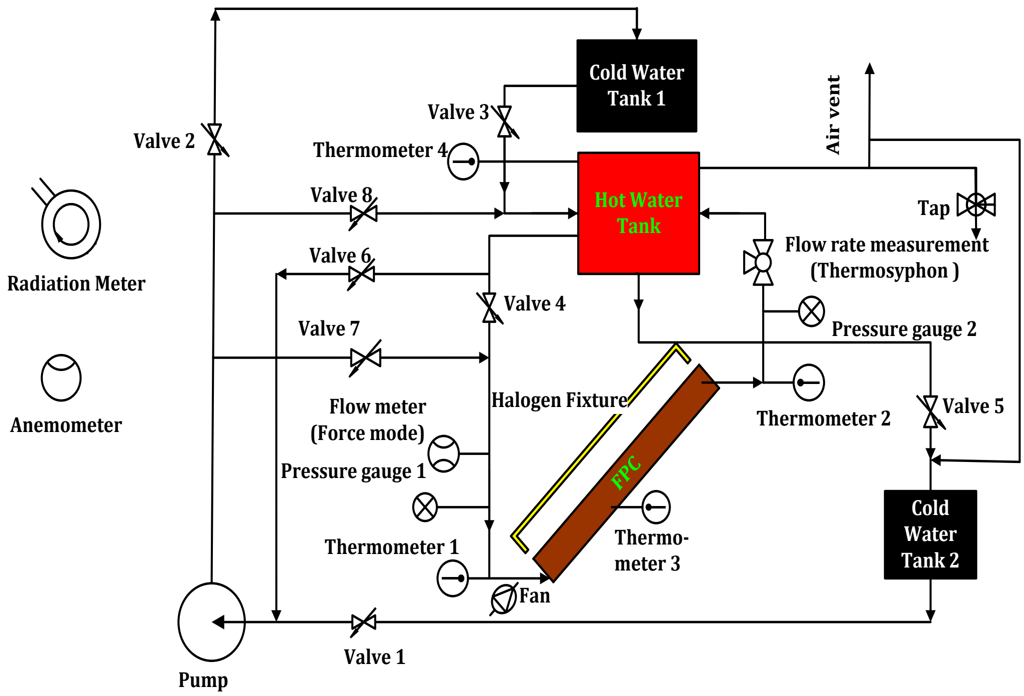

Figure 1. Schematic diagram of the experimental setup

B. Heat Loss coefficient (U_L)

U_L is the overall heat transfer coefficient from the absorber plate to the ambient air. It is a complicated function of the collector construction and its operating conditions.

In simple term it can be expressed as:

$$U_L=U_t+U_b+U_e \quad (2)$$

According to Klein (1975), the top loss coefficient can be calculated by using the flowing formula.

$$U_t=\left\{\frac{\frac{1}{N}}{\frac{C}{T_p}\left[\frac{T_p-T_a}{N+f}\right]^{0.33}+\frac{1}{h_a}}\right\}+\left\{\frac{\sigma\,(T_p+T_a)(T_p{}^2+T_a{}^2)}{\left(\varepsilon_{p+0.05N(1-\varepsilon_p)}\right)^{-1}+\frac{2N+f-1}{\varepsilon_g}-N}\right. \quad (3)$$

Where

$$C=365.9(1-0.00883\beta+0.0001298\times\beta^2) \quad (4)$$

$$f=(1+0.04h_a-0.0005h_a{}^2)*(1+0.091N) \quad (5)$$

$$h_a=5.7+3.8v \quad (6)$$

The heat loss from the bottom of the collector is first conducted through the insulation and then by a combined convection and infrared radiation transfer to the surrounding ambient air. However the radiation term can be neglected as the temperature of the bottom part of the casing is very low. Moreover the conduction resistance of the insulation behind the collector plate governs the heat loss from the collector plate through the back of the collector casing. The heat loss from the back of the plate rarely exceeds 10% of the upward loss. To calculated the bottom loss coefficients we can use the following formula

$$U_b=\frac{k_b}{x_b} \quad (7)$$

In a similar way, the heat transfer coefficient for the heat loss from the collector edges can be obtained by using the following formula

$$U_e=U_b\left(\frac{A_e}{A_C}\right) \quad (8)$$

C. Heat Removal Factors (F_R)

Heat removal factor can be considered as the ratio of the heat actually delivered to that delivered if the collector plate were at uniform temperature equal to that of the entering fluid.

$$F_R=\frac{\text{Actual useful energy gain}}{\text{Useful energy gain if the entire collector were at fluid inlet temperature}}$$

$$F_R=\frac{\dot{m}\,C_p\left[T_{fo}-T_{fi}\right]}{A_c\left[I_t\tau_0\alpha_0-U_L(T_{fi}-T_a)\right]} \quad (9)$$

D. Thermal Efficiency of the Collector (η)

It is the ratio of the Useful heat gain to the Total input energy. Mathematically,

$$\eta=F_R\left[(\tau_0\alpha_0)-\frac{U_L(T_i-T_a)}{I_t}\right] \quad (10)$$

Experiments were performed on the setup for three days. Being an indoor setup halogen tubes are used for radiation. Each tube is of 300W and 18 such halogen tubes are used to form a radiation source. The setup is provided with regulator to vary the radiation. It is also provided with different sensors to measure temperature and pressure at different location. To know the mass flow rate open the three ways valve and note the time required to fill a desire amount of water in the water level marking bottle.

IV. ASSUMPTIONS

To perform different experiments with this set-up a number of assumptions need to be made.

1. The collector is in a steady state.
2. The headers cover only a small area of the collector and can be neglected.
3. Heaters provide uniform flow to the riser tubes.
4. Flow through the back insulation is one dimensional.
5. Temperature gradients around tubes are neglected.
6. Properties of materials are independent of temperature.
7. No energy is absorbed by the cover.
8. Heat flow through the cover is one dimensional.
9. Temperature drop through the cover is negligible.
10. Covers are opaque to infrared radiation.
11. Same ambient temperature exists at the front and back of the collector.
12. Dust effects on the cover are negligible (if otherwise mention)
13. There is no shading of the absorber plate (if otherwise mention)

V. OBSERVATION TABLE

TABLE II. FOR HIGHEST RADIATION LEVEL: RADIATION LEVEL = 724.86 W/M², WIND SPEED = 1.07M/SEC, WATER MASS FLOW RATE = 0.0061 KG/SEC

Sr No.	Time (t, min)	Ambient Temperature (T_a, °C)	Inlet Water Temperature (T_{fi}, °C)	Plate temperature (T_p, °C)	Outlet Water Temperature (T_{fo}, °C)	Water temperature in the Storage tank (T, °C)	Inlet Water Pressure (Pi, Kpa)	Outlet Water Pressure (Pout, Kpa)
1	0	26	26	28.3	27.9	28.6	307.5	313.7
2	10	26.5	26.5	60	46.1	29.1	308.6	316
3	20	26.9	26.5	62.3	48.2	29.9	308.6	316
4	30	27.5	26.5	62.7	49.3	35.6	308.5	316.1
5	40	28.1	27.0	63.5	51	41.2	308.8	316.1
6	50	28.5	27.5	64.3	52.4	44.1	306.5	314.7
7	60	28.9	27.6	64.8	53.5	45.1	308.5	314.3
8	70	29.1	27.6	65.5	55.4	46.2	305.6	314.3
9	80	29.1	27.6	66.1	56.7	47.6	305.5	314.3
10	90	29.1	27.7	66.8	58.3	49.2	305.1	314.2
11	100	29.1	27.8	68.6	59.5	50.2	305.1	314.3
12	110	29.5	27.9	69.1	62.1	51.9	304.6	314.2
13	120	29.5	28	69.7	64	52.9	304.9	314.2
14	130	29.8	28.2	70.9	66.1	53	304.7	314.1
15	140	29.8	28.5	71.4	67.5	52.5	304.4	314.2
16	150	30	28.8	72.8	68.7	52.4	304.4	314.1
17	160	30	29.3	74	70	52.5	304.3	314.1

TABLE III. FOR MEDIUM RADIATION LEVEL:RADIATION LEVEL = 581.53 W/M², WIND SPEED = 1.07M/SEC, WATER MASS FLOW RATE = 0.0043 KG/SEC

Sr No.	Time (t, min)	Ambient Temperature (T_a, °C)	Inlet Water temperature (T_{fi}, °C)	Plate temperature (T_p, °C)	Outlet Water temperature (T_{fo}, °C)	Water temperature in the Storage tank (T, °C)	Inlet Water Pressure (Pi, Kpa)	Outlet Water Pressure (Pout, Kpa)
1	0	26.3	26.3	28.6	27.9	28.5	312.7	305.2
2	10	27.3	27.1	58.8	47.3	31.1	315.2	307.9
3	20	28.1	27.1	59.5	47.8	33.3	316.1	308.9
4	30	28.1	27.1	59.7	48.2	36.4	316.1	308.7
5	40	28.1	27.2	62.6	52.4	39.8	314.4	305.8
6	50	28.5	27.2	62.7	53.9	41	314.4	305.6
7	60	29	27.2	63.4	54.4	43.1	314.2	305.8
8	70	29.2	27.3	64.8	55.4	44.9	314.6	305.6
9	80	29.2	27.4	65.5	57.5	46.7	314.4	305.3
10	90	29.5	27.4	66.2	58.8	48.4	314.5	305.4
11	100	29.5	27.6	68.5	60.9	49.4	314.3	305.4
12	110	29.5	27.7	68.7	63.8	49.8	314.3	305
13	120	29.5	27.7	69.6	65.5	49.5	314.4	305
14	130	29.8	28	70.5	67	49.3	314.3	304.9
15	140	29.8	28.3	71.6	68	49.2	314.3	304.5
16	150	29.8	28.5	71.9	69.2	49	314.3	304.7
17	160	30	28.8	73	70.4	49.1	314.2	304.4
18	170	30	29.2	74.1	71.9	49.5	314.3	304.5
19	180	30	29.6	74.7	73.1	50	314.1	304.3
20	190	30	30	75.8	74.1	50.5	314.2	304.3

TABLE IV. FOR LOW RADIATION LEVEL: WIND SPEED = 1.47M/SEC, RADIATION LEVEL = 493.74 W/M², WATER MASS FLOW RATE = 0.0049 KG/SEC

Sr No.	Time (t, min)	Ambient Temperature (T_a, °C)	Inlet Water temperature (T_{fi}, °C)	Plate temperature (T_p, °C)	Outlet Water temperature (T_{fo}, °C)	Water temperature in the Storage tank (T, °C)	Inlet Water Pressure (Pi, Kpa)	Outlet Water Pressure (Pout, Kpa)
1	0	26.4	26.4	42.3	38.4	36.7	315.5	308.8
2	10	27	29.8	57.8	48.1	34.3	316.2	308.9
3	20	27	30.1	59.1	48.3	37.4	314.6	306.8
4	30	27	30.1	60.5	53.3	33.9	314.4	306.0
5	40	28.1	30.2	61.2	54.9	41.2	314.5	306.2
6	50	28.1	30.2	61.4	55.3	42.1	314.5	305.6
7	60	28.1	30.3	61.5	55.6	43.8	314.5	305.9
8	70	28.1	30.4	61.6	55.9	45.6	314.5	305.8
9	80	28.1	30.4	61.6	56.3	46.8	314.5	305.7
10	90	28.1	30.5	61.8	56.8	47.8	314.5	305.6
11	100	28.1	30.6	62	56.9	48.4	314.5	305.6
12	110	28.1	30.8	62.4	57.7	49.2	314.4	305.7
13	120	28.1	30.9	62.6	57.8	49.5	314.4	306.6
14	130	28.1	31.1	62.9	58.5	50	314.5	305.8
15	140	28.1	31.2	63.1	58.5	50.4	314.5	305.8
16	150	28.5	31.4	63.3	59.3	50.9	314.4	305.6
17	160	28.5	31.7	63.5	59.5	51.2	314.5	305.7
18	170	28.5	32.2	64.2	60.6	51.5	314.4	305.2
19	180	29	32.6	64.2	60.5	51.8	314.5	305.5
20	190	29	33	64.7	61.5	52.2	314.3	305.5
21	200	29	33.5	65	61.7	52.5	314.3	305.5
22	210	29	34	66.3	63.2	52.9	314.3	305.3
23	220	29	34.5	66.6	63.2	53.3	314.3	305.3

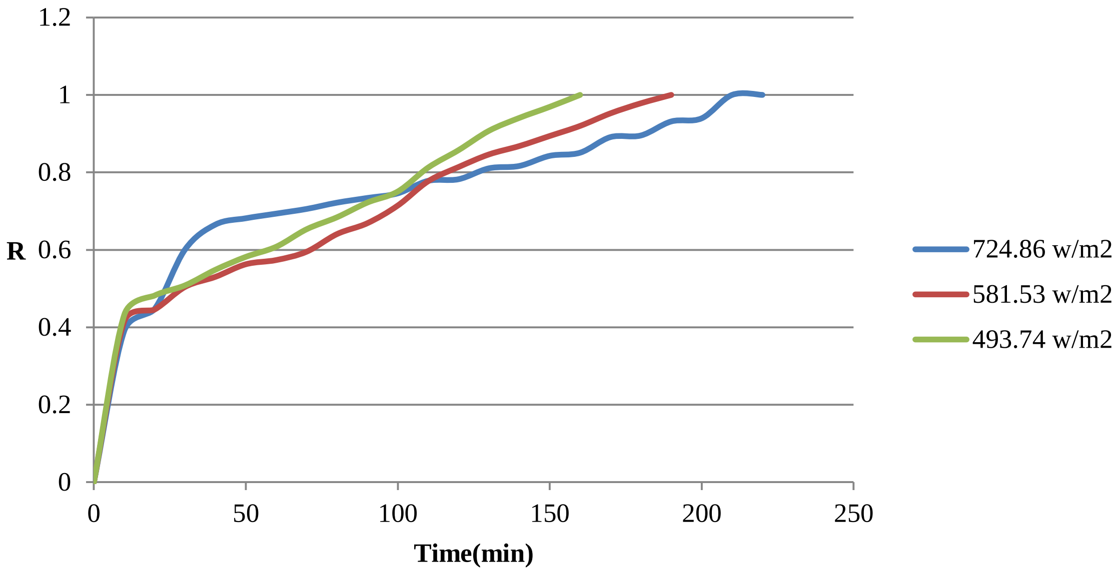

Figure 2. Graph drawn for the three experimental results (R vs. Time)

Figure 2 shows that with the decrease in radiation collector time constant increases but since warm water was been used for lowest radiation level (493.74 w/m^2) its collector time constant is less than that of medium radiation level (581.53 w/m^2)

Time at which the outlet temperature attains a stagnant value is collector time constant (0.632 of the total temperature). And in around 10 minutes 63.2% of the total outlet temperature is achieved.

Now from the calculated values it can be seen that top loss coefficient dominates both the base loss coefficient as well as the side loss coefficient. The base loss coefficient and the side loss coefficient are constant since the parameter required to calculate it are constant. And the top heat loss coefficient is a function of various parameters which includes the temperature of the absorbing plate, ambient temperature, wind speed, emissivity of the absorbing and the cover glass plate, etc. Since these parameter keeps on varying the value of top loss coefficient keeps changing. Heat removal factor depends upon the factors like inlet and outlet water temperature, the ambient temperature, area of the collector etc. The importance of heat removal factors remains with the efficiency of the system. For a high efficient system a higher value of heat removal factor is must.

The values of overall heat loss coefficient, heat removal factor and efficiency is find out by putting the experimental values in the above mentioned formulae's.

TABLE V. CALCULATION OF OVERALL HEAT LOSS COEFFICIENT FOR DIFFERENT RADIATIONS

U_L for 724.86 w/m² Radiations	U_L for 581.53 w/m² Radiations	U_L for 493.74 w/m² Radiations
2.7586	2.8155	2.4923
2.5141	2.5498	2.4824
2.5237	2.5583	2.484
2.5294	2.559	2.4891
2.5365	2.5658	2.4962
2.5422	2.5694	2.4966
2.5468	2.5754	2.4968
2.5505	2.5808	2.4969
2.5525	2.5829	2.4972
2.5546	2.5874	2.4976
2.5606	2.5945	2.4983
2.5654	2.5952	2.4986
2.5675	2.5981	2.4991
2.574	2.6035	2.4996
2.5758	2.6073	2.4999
2.5825	2.6084	2.5036
2.5869	2.6138	2.5044
	2.6179	2.5048
	2.6201	2.5088
	2.6244	2.5098
		2.5104
		2.5131
		2.5133

TABLE VI. CALCULATION OF HEAT REMOVAL FACTOR FOR DIFFERENT RADIATIONS

F_R for 724.86 w/m² Radiations	F_R for 581.53 w/m² Radiations	F_R for 493.74 w/m² Radiations
0.0361	0.0267	0.2688
0.3723	0.3367	0.4171
0.4114	0.3436	0.4156
0.4312	0.3502	0.5298
0.4537	0.4185	0.5605
0.4709	0.4425	0.5696
0.4908	0.4495	0.5745
0.5246	0.4641	0.5794
0.5491	0.4974	0.5885
0.5777	0.5180	0.5979
0.5987	0.5499	0.5983
0.6451	0.5966	0.6128
0.6793	0.6230	0.6132
0.7148	0.6445	0.6253
0.7365	0.6538	0.6236
0.7539	0.6744	0.6264
0.7706	0.6897	0.6353
	0.7094	0.6488
	0.7243	0.6415
	0.7359	0.6547
		0.6498
		0.6751
		0.6657

TABLE VII. CALCULATION OF EFFICIENCY FOR DIFFERENT RADIATIONS

η for 724.86 w/m² Radiations	η for 581.53 w/m² Radiations	η for 493.74 w/m² Radiations
2.94%	2.17%	21.93%
30.37%	27.5%	33.44%
33.63%	28.18%	33.26%
35.33%	28.73%	42.40%
37.19%	34.32%	45.14%
38.59%	36.36%	45.87%
40.29%	37.04%	46.24%
43.08%	38.26%	46.61%
45.09%	40.99%	47.34%
47.43%	42.75%	48.06%
49.13%	45.34%	48.06%
53.01%	49.16%	49.17%
55.79%	51.34%	49.17%
58.73%	53.11%	50.07%
60.44%	53.79%	49.91%
61.84%	55.42%	50.19%
63.07%	56.65%	50.81%
	58.14%	51.72%
	59.23%	51.17%
	60.04%	52.09%
		51.54%
		53.37%
		52.46%

VI. CONCLUSION

Experiments were performed at different input parameters i.e. by varying radiation level and wind velocity. It can be said that with the decrease in radiation level overall heat loss coefficient increase. Heat removal factor at low radiation is less as compared to higher radiation level. Hence at higher radiation level we get high efficiency whereas at lower radiation level we get somewhat less efficiency. Also with the decrease in radiation collector time constant increases since time required for outlet temperature to rise 0.632 of its final value increases.

VII. NOMENCLATURES

A_c : Area of the collector (m^2)

A_e : Area of the edge (m^2)

k_b , k_e : Conductivity of the back and edge insulation ($\frac{W}{mK}$)

$\dot{m}$: Water mass flow rate ($\frac{kg}{sec}$)

N: Number of glass cover

T_a: Ambient temperature (^{0}C)

T_P: Plate temperature (^{0}C)

U_t , U_b , U_e : Top , bottom and edge heat loss coefficient respectively.

v: Wind velocity ($\frac{m}{sec}$)

w: Distance between two risers (mm)

x_b , x_e :Back and Edge insulation thickness (mm)

ε_p: Emissivity of the absorbing plate

ε_g: Emissivity of the glass cover

$T_{fo}(t)$: Outlet water temperature at any time t

$T_{fo}(0)$: Outlet water temperature at time zero

$T_{fo}(\alpha)$: Outlet water temperature at infinite time (maximum temperature)

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