Numerical and Experimental Investigation of Dual Purpose Solar Collector

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***Abstract-* Solar water heating and air heating are a sustainable choice for obtaining thermal energy over a variable temperature range from the solar energy. The dual purpose solar collector (DPSC) is a flat plate type collector can be used for heating the water and air simultaneously using solar radiation resulting in optimum uses of energy and space. The system consists of horizontal parallel water tubes and vertical air channel for heating water and air using a same absorber plate. A mathematical model by ε- NTU method has been developed and the experiment was carried for DPSC. Experimental and numerical result shows the performance of solar collector has been increased as compared to single air or water heater.**

Keywords- Solar Collector, Solar Radiation, Thermal Efficiency, Solar Water Heating.

I. INTRODUCTION

A solar collector is a particular kind of heat exchanger that transforms solar radiant energy into heat. Solar air heating is a process for delivering heat from a solar collector through which air is circulated. In most space-heating applications, the heated air may be supplied directly to the living space as needed and may also be supplied to some type of heat storage device for later transfer to the living space. There are many ways in which air can be heated by solar energy. Air can be passed in contact with solar absorbing surface as flat metal plates, finned plates or ducts, corrugated or roughened plates of various materials, screen through which the air passes, and overlapped glass plates between which the air flows. Flow may be straight through, serpentine, above, below, or the both two sides of the absorber plate, or through porous absorber material. In simplest form, the solar air collector differs from the liquid type only in the shapes and size of the fluid passage in contact with the absorber.Heating of water for bathing, washing, or commercial purpose is one of the oldest and most cost effective uses of solar energy. The temperature levels required (40-60^{0}C) can be produced efficiently by simple, relatively inexpensive collection devices. A variety of techniques, ranging from very simple to complex, have been employed to produce hot water using solar energy. A blackened absorber plate and tubes with water placed in sunlight represents possible the simplest approach to a solar hot- water system. [1]

Assari et al. [2] designed and made the collector in a way that it can be used for heating the air and water simultaneously. In his design vertical tubes are attached to on the absorber plate and three different kinds of channels are used to enhance the performance of DPSC, such as: triangular fin, rectangular fin, and without fins. Simulation result shown that, the channels with rectangular fin have better performance compared with others, values of heat exchange effectiveness for straight (rectangular) fin is better than the triangular fin. Hence, heat delivery in this situation is higher.I. Jafari et al [3] was carrying the energy and exergy analysis of DPSC.The triangular air channel was used in the analysis. Results show the air section of DPSC increase heat delivery and efficiency of collector much at higher water inlet temperature.

Arun Venu et al. [4] incorporate a porous medium to improve the thermal performance of a DPSC. The porous matrix is added below the absorber plate of the collector to improve the performance of the system. The overall thermal efficiency of the modified collector is increases from 34.60% to 46.03% over inlet water temperature. Assari, M.R [5] again analyzed the DPSC at a different air velocity in the air heater. The result shows that, average efficiency of the single-purpose system is 67.8 %, while for the dual purpose system the efficiency is 71.6% and 72.3% for air speeds of 2.8 and 3.2 m/s, respectively, which is much higher. Alireza Mohajer et al. [6] designed a hybrid system which facilitates a dryer system and provides consumptive hot water. Experiments were carried out to dry a mixture of vegetable at constant air and water flow rate. The system reduces the costs and the space for installation.

In this paper, our main objective is to improve the thermal performance of DPSC. For the purpose, changes are made in the design developed by Assari M.R. and studied its performance. Horizontally parallel blackened copper tubes are attached to the top of the absorber plate. While the conjunction of the V-shaped air heater is on the bottom side of the same absorber plate. A mathematical model based on ε-NTU method. Results are validated with the experimental measurements and they have shown that the model can give accurate results.

II. MATHEMATICAL MODEL OF DPSC

A. Collector Design Details

Detail Configuration of the designed collector is given as follows:

- Absorber plate material: Black painted Copper sheet
- Absorber plate Dimension: 0.9652 m x 0.6604 m
- Absorber plate Thickness: 0.5 mm
- Air channel material: galvanized 0.65 mm

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- Air channel area: 0.0015 m^2
- Air channel size: Triangular with an angle of 60^0
- Air channel length: 0.9652 m
- Number of air channel: 6
- Water tube material: copper
- Inside diameter of tube D_i :0.0102 m
- Length of tube on absorber plate: 7.92 m
- Circulating fluid: Distilled water
- Number of glass cover: 1
- Collector tilt : 25^0 C
- Capacity of water tank: 50 Liters
- Thickness of back insulation (δ_b): 40 mm
- Thickness of side insulation (δs): 20 mm

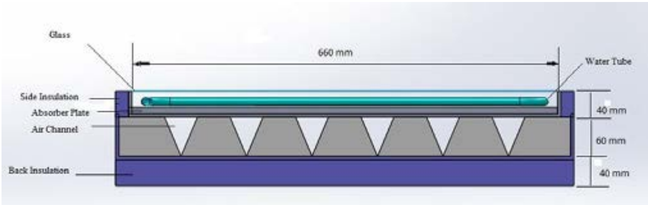

Fig. 1. Schematic Drawing of DPSC

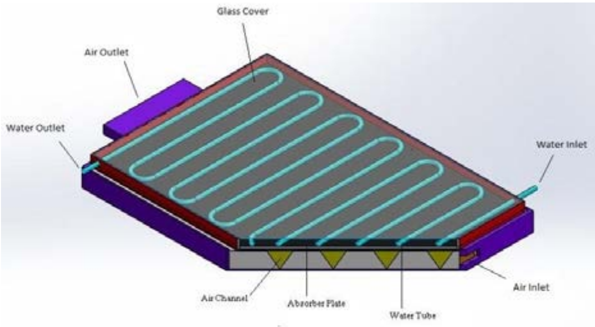

Fig. 2. Picture of DPSC

B. *Input Parameter*

- Emittence of glass: 0.93
- Emittence plate: 0.88
- Absorber plate absorptance: 0.98
- Thermal conductivity of insulation: 0.030 W/m ^{0}C
- Solar radiation: 500 – 900 W/m^2
- Wind speed: 1.3 m/s
- Air flow rate: 0.0024 kg/s m^2
- Mass flow rate of water: 0.02 kg/s

C. *Assumptions*

The assumptions for the mathematical model of DPSC are listed below;

- Absorber plate, back and side surfaces, water tube, air channels, are in mean temperature (Tpm).
- Air flow through channels is assumed homogeneous.
- Water flow through tubes is assumed homogeneous.
- Performance is steady state.
- Conduction and radiation in water tubes and air channels are considered negligible
- Convection and radiation in back and side surfaces are considered negligible.
- Construction is of sheet and zig-zag tube type.
- There is no absorption of solar energy by a cover in so far as it affects losses from the collector.
- Heat flow through a cover is one dimensional.
- There is a negligible temperature drop through a cover.
- The covers are opaque to infrared radiation.
- There is one-dimensional heat flow through back insulation.
- Temperature gradients around tubes can be neglected.
- Gradients of temperature between the tubes and in the direction of flow can be considered independently.
- Properties are independent of temperature.
- Loss through front and back are to the same ambient temperature.
- Dust and dirt on the collector are negligible.
- Shading of the collector absorber plate is negligible.

D. *Energy Balance Equation of the Collector*

In steady state, the performance of a solar collector is described by an energy balance that shows the distribution of incident solar energy into useful energy gain, thermal losses, and optical losses.

$$q_u = A_c F_R [S - U_L (T_{pm} - T_a)] \quad \text{(W)} \qquad (1)$$

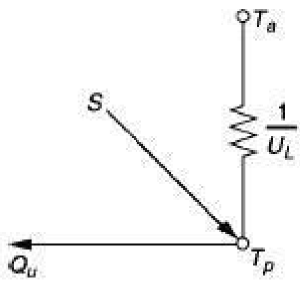

Figure 3: Equivalent thermal network for flat-plate solar collector.

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E. Heat Removal Factor

Heat Removal Factor is given as:

$$F_R = \frac{\varepsilon_f m_f\, Cp_f}{U_L A_p + \varepsilon_f m_f\, Cp_f} \quad (2)$$

F. Absorbed Solar Radiation

$$S = (\tau\alpha)_{ave}\, I_T \quad (3)$$

G. Collector Overall Heat Loss Coefficient

It is the sum of the top, bottom, edge loss coefficients and heat removal coefficient.

$$U_L = U_t + U_b + U_e \quad (4)$$

Top Heat Loss Coefficient:

An empirical equation for U_t was developed by Klein (1979) following the basic procedure of Hottel and Woertz (1942) and Klein (1975). This new relationship fits the graphs for U_t for plate temperatures between ambient and 200^0 C to within ± 0.3 W/m^2 C.

$$U_t = \left\{ \frac{N}{\frac{C}{T_{pm}}\left[\frac{T_{pm}-T_a}{(N+f)}\right]^{e}} + \frac{1}{h_w} \right\}^{-1} + \frac{\sigma\,(T_{pm}+T_a)(T_{pm}^2+T_a^2)}{(\varepsilon_p + 0.00591\, N h_w)^{-1} + \frac{2N+f-1+0.133\varepsilon_p}{\varepsilon_g} - N} \quad (5)$$

Where

$f = (1 + 0.089h_w - 0.1166h_w\varepsilon_p)(1 + 0.07866N)$

$C = 520(1 - 0.000051\beta^2)$ for $0^\circ < \beta < 70^\circ$; for $70^\circ < \beta < 90^\circ$, use $\beta = 70^\circ$

$e = 0.430(1 - 100/T_{pm})$

Bottom Heat Loss Coefficient:

Heat transfer from the back of DPSC is assumed to be one dimensional conduction. Thus, the back loss coefficient U_b can be obtained:

$$U_b = \frac{1}{R4} = \frac{k}{\delta_b} \quad (6)$$

Edge Heat LossCoefficient:

The losses through the edge should be referenced to the collector area.

$$\mathbf{U_e} = \frac{(L_1+L_2).L_3 K_1}{L_1 L_2 \delta_s} \quad (7)$$

H. Heat Exchange Effectiveness

Effectiveness (ε) is defines asactual heat delivery to maximum heat delivery that can transfer to fluids:

$$\text{Effectiveness } (\varepsilon) = \frac{\text{Actual heat delivery (Q)}}{\text{max.possible heat delivery(Qmax)}} \quad (8)$$

In DPSC model two fluids flows simultaneously, so the effectiveness of heat transfer for water and air given as:

Effectiveness for Water

$$\varepsilon_w = \frac{m_w Cp_w (Tw_o - Tw_i)}{m_w Cp_w (T_{pm} - Tw_i)} = \frac{(Tw_o - Tw_i)}{(T_{pm} - Tw_i)} = 1 - \exp\left[-\frac{h_w A_w}{m_w Cp_w}\right] \quad (9)$$

Effectiveness for Air

$$\varepsilon_a = \frac{m_a Cp_a (Ta_o - Ta_i)}{m_a Cp_a (T_{pm} - Ta_i)} = \frac{(Ta_o - Ta_i)}{(T_{pm} - Ta_i)} = 1 - \exp\left[-\frac{h_a A_a}{m_a Cp_a}\right] \quad (10)$$

I. ε- NTU Relation

For convenience in practical applications, a dimensionless parameter termed as the number of (heat) transfer units (NTU) is defined as,

$$NTU = \frac{h_f A_f}{m_f Cp_f} \quad (11)$$

Where, h_f is the heat transfer coefficient between water and tubes.

This is obtained from Nusselt number relation for constant surface temperature, laminar flow, circular tube:

$$Nu = \frac{hD}{k} = 3.66 \quad (12)$$

For a circular tube of length *L* subjected to constant surface temperature, the average Nusselt number for the *thermal entrance region* can be determined from (Edwards et al., 1979) [2]

$$Nu = 3.66 + \frac{0.065\left(\frac{D}{L}\right)Re.Pr}{1+0.04\left[\left(\frac{D}{L}\right)Re.Pr\right]^{\frac{2}{3}}} \quad (13)$$

Heat transfer coefficient in the air side for the channel in which air is flow over the smooth plate, is given as

$$Nu_D = 0.0158 Re_D^{0.8} \quad (16)$$

J. DPSC Efficiency

A measure of collector performance is the collection efficiency, defined as the ratio of the useful gain for a some specified time period to the incident solar energy over the same time period:

$$\eta = \frac{\int Qu\, dt}{Ac \int Gt\, dt} \quad (17)$$

If conditions are constant over a time period, the efficiency reduces to,

$$\eta = \frac{Qu}{I_T\, Ac} \quad (18)$$

III. EXPERIMENTAL SETUP

The experiment is designed to investigate the system performance. Ambient, inlet water, outlet water, inlet air, outlet air, absorber plate, storage tank temperature, air & water flow rate, solar radiation, this parameter are measured during experimentation.Temperatures are measured using K-type thermocouple with the accuracy of ± 1^0C. The water flow rate is measured by a flow meter at the outlet of the collector. The Pyranometer is used to measure solar radiation. The thermocouple for measuring ambient temperature is placed in the shade, during the days of measurement.

The collector is tilted 25^0 to the horizontal surface and oriented to the south of the Solar Research Centre, Shri Sant Gajanan Maharaj College of Engineering Shegaon, M.S. India. Latitude 20º46' 47.91" N - Longitude: 76º40' 5.12'' E. The experimentation was conducted during 17 to 22 May 2018.

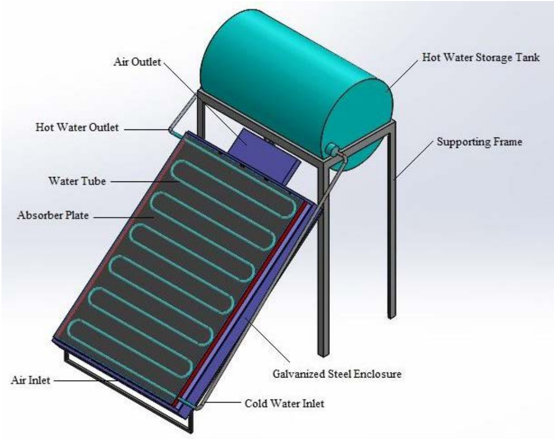

Fig. 4(a). Schematic View of Experimental Setup.

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IV. RESULT& DISCUSSION

TABLE I. VARIATION OF INLET-OUTLET FLUID, AMBIENT & ABSORBER PLATE AVERAGE TEMPERATURE (AVERAGE OF READING OF DATE 17 MAY – 22 MAY 2018.

Time	Temperature (^{0}C)								
	Atmospheric Temp. (T_a)	Absorber plate average (T_p)	Inlet Water (T_{wi})	Outlet water (T_{wo})	T_{wo}- T_{wi}	Storage Tank average (T_s)	Air inlet (T_{ai})	Air outlet (T_{ao})	Ta_o- Ta_i
9	33	40	32	36	4	33	32	35	3
10	35	47	34	40	6	35	35	40	4
11	37	52	37	45	8	39	38	42	4
12	39	57	41	50	9	43	41	47	6
13	40	54	43	51	8	46	41	46	5
14	38	54	44	50	6	47	40	45	5
15	37	52	44	48	4	48	39	43	4
16	36	50	45	48	3	50	39	41	2

TABLE II. DIFFERENCE BETWEEN ACTUAL & THEORETICAL RESULT FOR DPSC

Time	Heat Gain (Theoretical) (W)	Heat Gain (Actual) (W)	Differences (%)	Efficiency (Theoretical) (%)	Efficiency (Actual) (%)
9	210.92	182.59	(+) 13.43	66.20	57.29
10	303.44	276.4	(+) 8.91	63.47	57.81
11	345.45	355.1	(-) 2.78	66.91	68.77
12	376.28	407.04	(-) 8.17	66.93	72.40
13	368.46	360.14	(+) 2.26	68.81	67.26
14	288.17	276.4	(+) 4.08	63.67	61.07
15	199.38	187.62	(+) 5.89	56.87	53.52
16	137.18	135.68	(+) 1.09	53.80	53.22

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TABLE III. EFFECTIVENESS FOR WATER AND AIR

Time	Effectiveness for Water (ε_w)	Effectiveness for Air (ε_a)
9	0.50	0.38
10	0.46	0.42
11	0.53	0.29
12	0.56	0.38
13	0.62	0.38
14	0.60	0.36
15	0.50	0.31
16	0.60	0.18

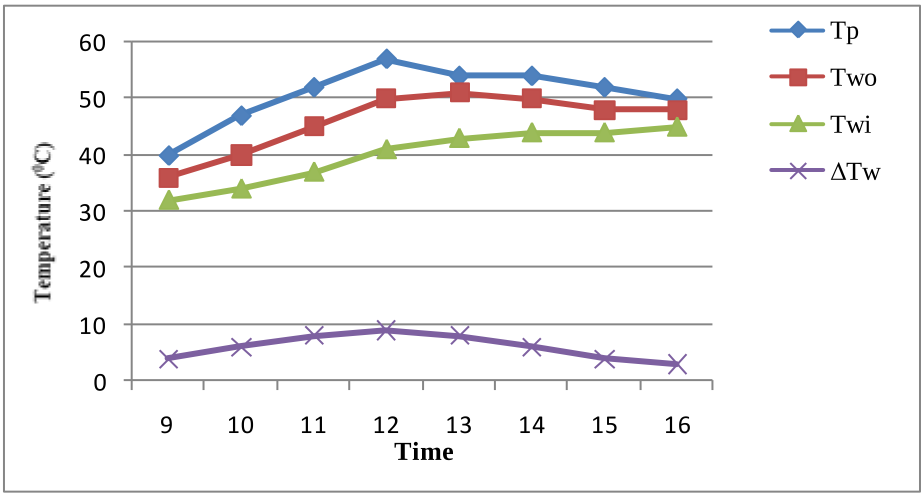

Fig. 5. Variation of inlet, outlet, absorber plate average and difference between inlet and outlet water temperatures.

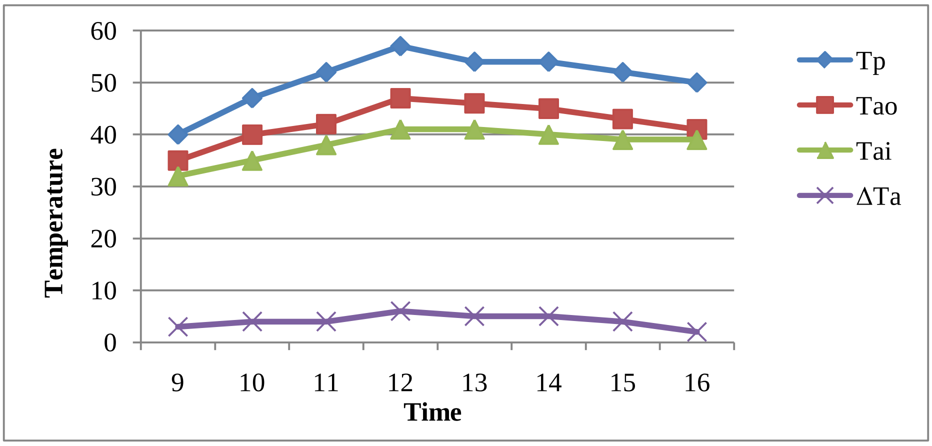

Fig. 6.Variation of inlet, outlet, absorber plate average and difference between inlet and outlet air temperatures.

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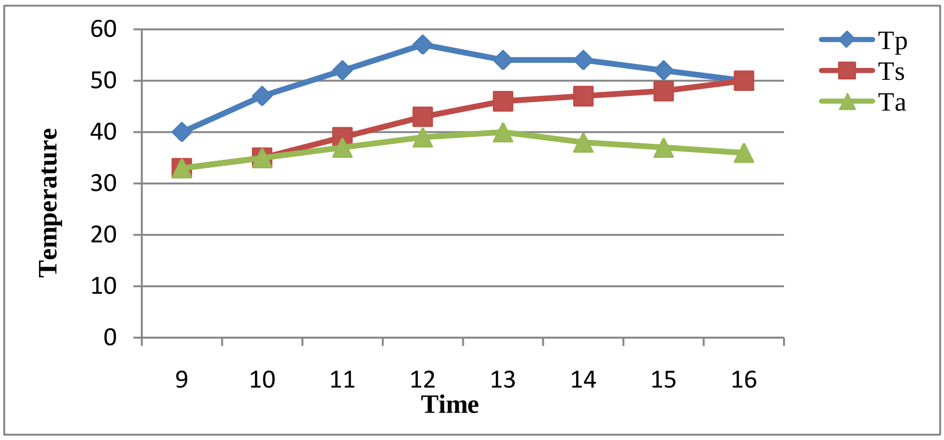

Fig. 7.Variation of ambient, absorber plate and storage tank temperature with time

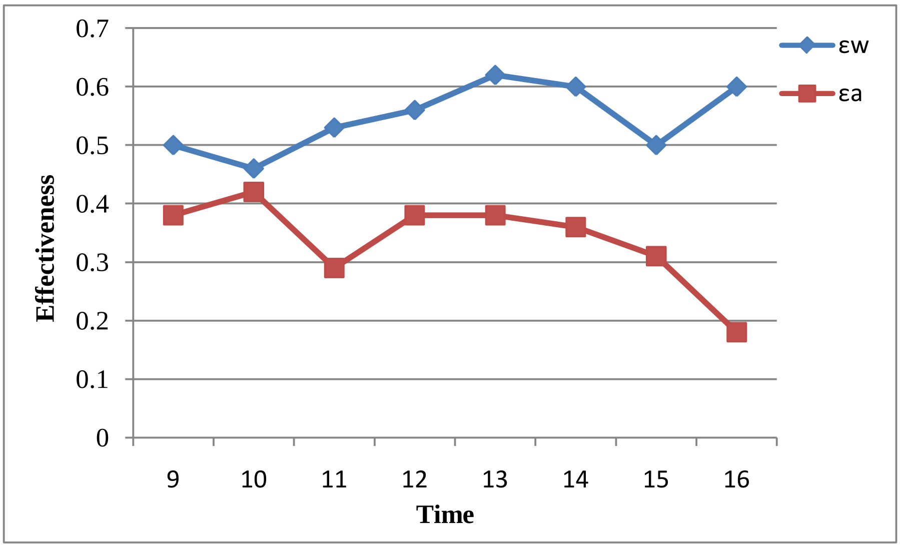

Fig.8. Effectiveness for water and air with time

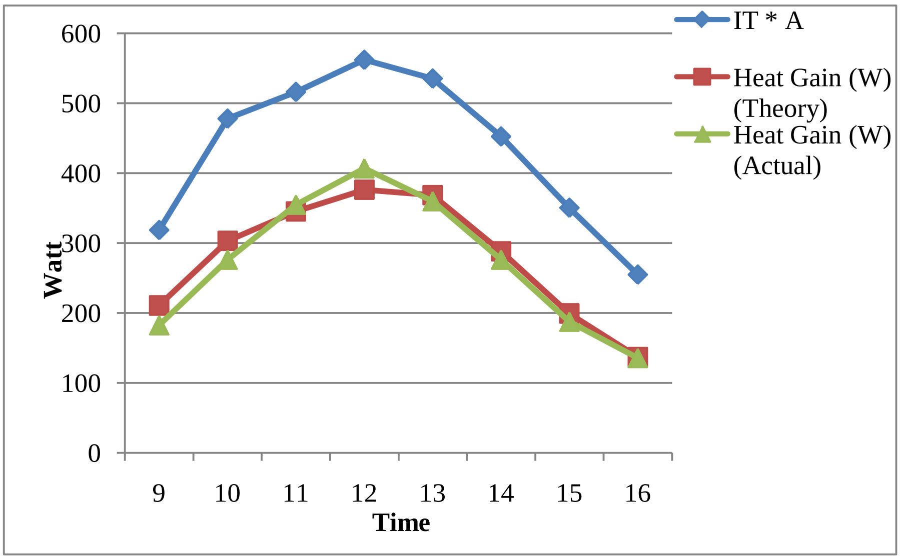

Fig. 9. Incident solar radiation on the collector and useful heat gained

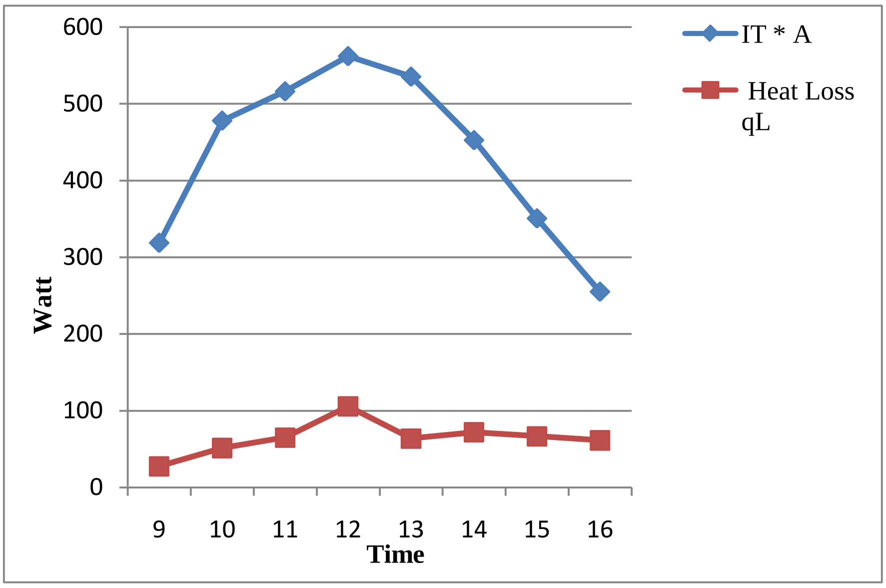

Fig. 10. Incident solar radiation and heat loss from the collector

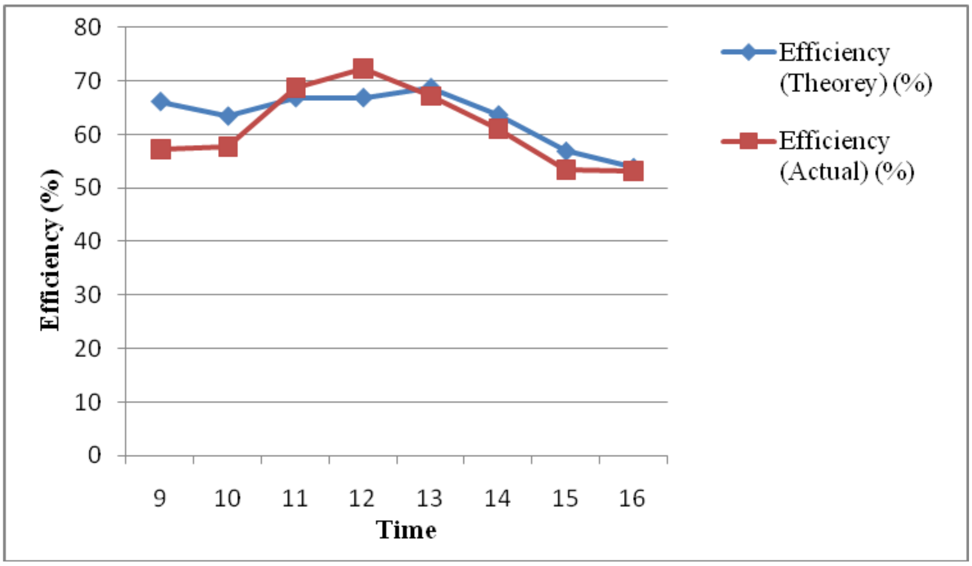

Fig. 11. Theoretical and Actual efficiency of DPSC

The important parameters in the analysis of DPSC are: solar radiation, air and water inlet temperature, mass flow rate of air & water, heat transfer coefficient between fluids, water tubes and air channel.

Table 2 shows comparisons between experimental and numerical result of water and air. Actual heat gain for time 11 pm & 12 pm is maximum than the theoretical it is because more increase in absorber plate temperature and decrease in losses. Losses decrease due to increase in ambient temperature.

The variation of inlet, outlet, absorber plate average and difference between inlet and outlet fluid temperatures are shown in figure 5 & 6. As it is clear, an increase in radiation, increases absorbed heat. The difference between the inlet and outlet water temperature is increased up to 12 noon. In the afternoon, the difference is decreased because of a decrease in radiation, decrease in mean plate temperature and increase water inlet temperature. In case of air, in the afternoon the ambient air temperature is increased so the difference between the absorber plate and inlet air temperature is decreased.

Figure 7 shows the variation of ambient, absorber plate and storage tank temperature with time. The storage tank temperature continues to rise from 33^0 C to 50^0 C during the day. At the end storage tank temperature and absorber plate temperature reaches to the same temperature**.** The storage tank temperature is high enough to be used for hot water supply.

Variation of effectiveness for water and air with time is plotted in figure 8.With the increase in ambient air temperature, the inlet air temperature is increased so there is a decrease in effectiveness of heat transfer of air. The same thing is happening with water. For water, the effectiveness is increased up to noon and later on it is decreasing. The effectiveness of water is more than air.

Figure 9 shows the incident radiation and theoretical & actual heat gain by water and air at different hours of the day. The result shows that, during midday radiation increases and therefore, the amount of heat absorbed by water and air increases. The radiation is maximum in between 12 noon to 13 º’ clock. At the same time heat gain is maximized. Actual & theoretical heat gain is in the same shape of incident solar radiation.

Figure 10 shows the variation of heat losses with the hours of the day. The losses are less in the morning because of there is the minimum difference in between ambient and collector temperature, the losses is increasing and it is the maximum in the solar noon due to increasing temperature difference. In the afternoon, the losses are slightly decreased, but the losses in the afternoon are more than morning. In most of the flat-plate collector, losses are about 33-50%. [7] In the DPSC, the losses are below 20%because of heat losses is recovered by using air heater.

Figure 11 shows the hourly theoretical and the actual efficiency of the collector. Approaching the midday hour’s radiation increases, so the efficiency increases and reaches maximum actual up to 72.40% at 12 noon. Late in the day, the radiation decreases, so the efficiency is decreased. There is a good agreement between the theoretical and actual efficiency. The maximum actual efficiency is 72.40% and theoretical is 68.81%. At the end of the day, the efficiency of the collector is not suddenly drop. Minimum actual efficiency is 53.22 % and theoretical is 53.8%. That means only 20% efficiency is decreased. The result shows that, the efficiency of the collector for the whole day doesn't decrease below 50%.This is because of some of the heat losses can be recovered by using air heater. So the performance of the collector is increasing.

V. CONCLUSION

A model of DPSC with horizontal water tubes and tank has been developed. Using dual purpose solar collector will reduce in cost and space of collector. The experiment was conducted, in order to characterize the overall performance of the collector. The mathematical model based on effectiveness method was developed. Numerical result shows a fair agreement with experimental measurement. Numerical result shows, efficiency up to 68.81% can be achieved in DPSC whereas in experiment it is up to 72.4%. The heat losses are only 20% in DPSC because of heat losses are recovered by using air heater. The storage tank temperature reached to 50^0C which is high enough to be used for hot water supply.

REFERENCES

[1] J. F. Kreider and F. Kreith , Solar Energy Handbook, McGraw-Hill, New York, 1978
[2] Assari, M.R., Basirat Tabrizi, H., Kavoosi, H., Moravej, M., 2011, “Experimental and theoretical investigation of dual purpose solar collector,” Science Direct. Solar energy 85 (2011) 601-608
[3] I. Jafari, A. Ershadi, E. Najafpour, and N. Hedayat, “Energy and Exergy Analysis of Dual Purpose Solar Collector” International Journal of Mechanical, Aerospace, Industrial, Mechatronic and Manufacturing Engineering Vol:5, No:9, (2011)
[4] Arun Venu, Arun P “Simulation Studies on Porous Medium Integrated Dual Purpose Solar collector” International Journal of Renewable Energy Research Arun P et al., Vol.3, No.1, (2013)
[5] Omid Nematollahi, Pourya Alamdari, Mohammad Reza Assari, “ Experimental investigation of a dual purpose solar heating system” Energy Conversion and Management 78 (2014) 359–366
[6] Alireza Mohajer, Omid Nematollahi, Mahmood Mastani Joybari, Seyed Ahmad Hashemi Mohammad Reza Assari. 2013, “Experimental investigation of a Hybrid Solar Drier and Water Heater System,” Energy Conversion and Management 76 (2013) 935–944
[7] G. N. Tiwari, Sangeeta Suneja, “Solar Thermal Engineering System” Narosa publication house, New Delhi (1997)