Performance Study of a Double Pass, Hybrid -Type Solar Air Heater with Slats

Mokalla. Srinivas* and Simon. Jayaraj

Department of Mechanical Engineering, National Institute of Technology
Calicut-673601, India

msrinivas@nitc.ac.in

Abstract- A solar hybrid energy system having photovoltaic and thermal (PV/T) devices, which produces both thermal and electrical energies simultaneously is considered for analysis. A double pass hybrid solar air (PV/T) heater with slats is designed and fabricated to study its thermal and electrical performance. Air as a heat removing fluid is made to flow through upper and lower channels of the collector. The collector is designed in such way that the absorber plate is partially covered by solar cells. The raise in temperature of the solar cell is expected to decrease its electrical performance. Thin metallic strips called slats are attached longitudinally at the bottom side of the absorber plate to improve the system performance by increasing the cooling rate of the absorber plate. Thermal and electrical performances of the whole system at varying cooling conditions are also presented.

Keywords- Double Pass; Energy; Photovoltaic; Solar Air Heater; Slats

NOMENCLATURE

A_c	area of absorber plate (m^2)
A_{cells}	solar cells area (m^2)
c	specific heat (kJ/kg K)
I_L	current (ampere)
m	mass flow rate of air (kg/s)
S	solar insolation (W/ m^2)
T_i	ambient air température (^{0}C)
T_o	air temperature at the outlet of collector (^{0}C)
V_L	voltage (volt)

Greek letters

η_{el}	electrical efficiency
η_{th}	thermal efficiency
$(\eta_{th})_o$	overall thermal efficiency of the system

Abbreviations

ARC	anti-reflective coating
CPC	compound parabolic concentrator
DPHSAH	double pass hybrid solar air heater
EAHE	earth air heat exchanger
EPBT	energy payback time
EVA	ethylene vinyl acetate
IMD	Indian Metrological Department
PV/T	photovoltaic thermal

I. INTRODUCTION

Solar energy is one of the most important sources of clean energy. Solar thermal energy systems convert solar energy into heat and solar photovoltaic systems convert solar energy into electrical energy. In solar thermal energy systems electrical energy is one of the inputs for extracting the useful energy. A single unit which is obtained by combining the solar thermal energy system with photovoltaic panels or solar cells pasted on the absorber plate is known as a hybrid collector or photovoltaic thermal collector (PV/T). A hybrid PV/T collector produces both thermal and electrical energy simultaneously. This concept increases the electrical efficiency of photovoltaic systems by increased cooling rate and overall efficiency of the hybrid unit. Hybrid PV/T collector can significantly reduce overall energy use that might be required to circulate working fluid in thermal collector and to cool the PV panels, thereby improving their performance and life. As electrical energy is also one of the outcomes, the greenhouse gases that are emitted from conventional thermal power plants are reduced and the environmental impact by greenhouse gases is reduced. A number of theoretical, numerical and experimental studies have been reported on the solar hybrid PV/T air collector using air or water as the working fluid. Kern and Russel [1] discovered the concept of integrated PV/T collector based energy system. Solanki et al. [2] conducted simulation and testing of a hybrid collector of 0.45 m in width and 1.2 m in length, under controlled conditions, mounted on a wooden duct. It was reported that, the thermal and electrical efficiencies of the system were 42% and 8.4%, respectively. Joshi et al. [3] communicated study on a hybrid photovoltaic thermal (PV/T) air collector with two kinds of photovoltaic panels. The panels differed in the structural layers. It was observed that the hybrid collector with PV module of glass to glass gave better performance in terms of the overall thermal efficiency. Dubey et al. [4] established a mathematical model for the electrical performance parameter by considering four different configurations of PV modules. It was reported that glass to glass PV module with duct shows better overall performance. Toni and Tripanagnostopoulos [5] performed experiments to evaluate the efficiency of three types PV/T solar collectors. It was reported that for forced convection with flow rate of 60 m^3/h and 15 cm channel depth, collector with fins yielded higher efficiency (30%).The system with thin metallic sheet (TMS) yielded efficiency of 28%.The reference configuration gave an efficiency of 25%. Tripanagnostopoulos et al. [6] developed a new type of PV/T collector with dual mode heat extraction operation, both with water and air as the working fluids. Collector with water as working fluid resulted in better performance; however leakage of water reduced the life of the system. Dubey et al. [7] submitted a mathematical model for 'N' hybrid photovoltaic thermal (PV/T) air collectors connected in series. They reported that collectors fully covered by PV modules and air flowing below the absorber plate gave better performance in terms of thermal energy, electrical energy and exergy gain. Joshi and Tiwari [8] attempted exergy analysis of hybrid photovoltaic thermal collector for cold climatic conditions of India (Srinagar) by obtaining the climatic data of Srinagar from the Indian Metrological Department (IMD) Pune, for a period of four years (1998-2001). Tiwari et al. [9] analyzed the energy metrics of hybrid photovoltaic system for the climatic conditions of New Delhi. It was observed that energy payback time (EPBT) got significantly reduced by utilizing thermal energy in addition to electrical energy. Nayak and Tiwari [10] introduced a simplified mathematical model to study "round the year effectiveness" of a photovoltaic / thermal (PV/T) and earth air heat exchanger (EAHE) integrated with a green house located at IIT Delhi, India. The annual thermal and exergy performance of a PV/T and EAHE system, integrated with the green house was evaluated [11]. A comparison of various energy metrics of the system, considering the four weather conditions of five climatic zones was also presented. Tiwari et al. [12] introduced an analytical expression for the water temperature of the integrated PV/T solar water heater under constant flow rate. It was shown that the daily overall thermal efficiency of an integrated PV/T solar system increases with increase in constant flow rate and decreases with increase in constant collection temperature. Kostic et al. [13] had communicated the study on the influence of reflectance from the flat plate solar radiation concentrators on energy efficiency of PV/T collector using water as the energy carrier. Othaman et al. [14] developed a new design for a double pass photovoltaic thermal air collector with compound parabolic concentrator (CPC) and with fins attached in second channel of the collector. According to their experimental studies, the thermal and electrical output of the photovoltaic thermal (PV/T) system increases with increase in air mass flow rate. Another paper by Othaman et al. [15] illustrates the theoretical and experimental study on a double pass photovoltaic thermal solar collector with fins. There seems to be a good agreement between theoretical and experimental results. The paper also indicates the utility of fins as an integral part of absorber plate to achieve a significant efficiency enhancement of the collector. Charalambous et al. [16] conducted a review of the available literature on PV/T collectors in a thematic way in order to enable an easier comparison of findings obtained by various researchers especially on parameters affecting the (PV/T) performance. It has been highlighted that substantial steps need to be taken towards reducing the cost to make them more competitive. Touni and Tripanagnostopoulos [17] submitted economical performance improvement methods. Theoretical modeling and experimental validation for modified methods were also presented. These systems were studied with and without glazing. The collector with fins and glazing yielded the highest thermal and electrical efficiencies out of all the considered cases. Matrawy [18] reported that the efficiency of a solar collector could be enhanced by using metal slats between the absorber plate and bottom plate of a solar air heater. This collector was called a box frame absorber, which has a better performance than the finned plate absorber. Ho et al. [19] communicated a study on the influence of baffled double pass flat plate solar air heaters with internal fins attached. They concluded that, the presence of baffles created higher turbulence, which increased the heat transfer rate to the working fluid. It is observed that the present researchers tried to improve the efficiency of box type collector [1-14]. Very few works were attempted to extract accumulated heat in the absorber plate (PV panel) with fins; [15-19] and it was concluded that there is still scope for performance improvement by heat extraction. No work has been reported with slats attached to the absorber plate and bottom plate for increasing rate of cooling.

In the present work, a new design of double pass hybrid (PV/T) solar air heater with slats (DPHSAH) was studied experimentally. This design is a beautiful blend of solar thermal energy system (double pass solar air heater with slats) and solar photovoltaic system. PV panels of monocrystalline silicon solar cells (10 % module efficiency) were used in the device. It is proposed that the attachment of slats on the absorber plate will increase the rate of cooling by conducting the heat through the slats and transferring the same to working fluid. Thus the accumulated heat in different layers of PV module is removed; there by both thermal and electrical performance of the present system is increased.

II. HYBRID (PV/T) SYSTEM DESIGN

The double pass hybrid photovoltaic thermal (PV/T) solar air heater (DPHSAH) consisted of aluminum absorber plate of dimensions 1 m x 2 m (W x L) and thickness 2 mm. The height of the upper and lower channels was 5 cm (each). The sides and bottom of the collector were insulated with a 5 cm thick layer of thermocol. Nine slats of 5cm in height, 2m in length and

2mm in thickness (each) were fixed longitudinally at equal distance at the bottom side of the absorber plate. Top surface of the absorber plate and lower channels were coated with black paint for increasing the absorptivity of the system. A toughened or tempered glass of dimensions 1 m x 2 m (W x L) and thickness 2 mm was provided as front cover for reducing convection heat losses from the collector. The PV modules (mono-crystalline silicon solar cells) of glass to tedlar type each rated at 25Wp having dimensions of 545 mm x 445 mm, were fixed over an absorber plate. Each PV module consisted of 36 solar cells, connected in series. Two rows, with four panels in each were connected in series and finally these two arrays are connected in parallel for obtaining rated (200 Wp) nominal peak power as shown in Fig1 (b). Series connection of solar cells or PV modules enhanced voltage and parallel connection of solar cells or PV modules enhanced current. The total area covered by solar cells was 1.054 m^2. And the packing factor or the fraction of the total collector area covered by the solar cells is 0.527. Specifications of DPHSAH are given in Table I and Table II.The double pass PV/T solar collector is shown schematically in Fig. 1(a), and schematic representation of PV modules connections is shown in Fig.1 (b).

TABLE I SPECIFICATIONS OF DOUBLE PASS SOLAR AIR HEATER WITH SLATS

Element of system	Sizes of element
Absorber plate : Aluminium absorber Bottom	(1 m X 2 m), (thickness 2mm)
Plate : Aluminium plate	(1 m X 2.1 m), (thickness 2mm)
Slats : Aluminium	(9 per 1 meter width), (length = 2 m each)
Top Glazing : Toughened glass	(1 m X 2 m), (thickness 2 mm)
Insulation : Thermocol	5 cm thick

TABLE II SPECIFICATIONS OF DOUBLE PASS SOLAR AIR HEATER WITH SLATS

Parameter	Value
Nominal peak power (W_p)	25 Wp
Maximum power voltage V_{mpp})	16.8 V
Maximum power current (I_{mpp})	1.49 A
Open circuit voltage (V_{oc})	21.2 V
Short circuit current (I_{sc})	1.79 A
Solar cell efficiency (η_c)	13%
Module efficiency (η_m)	10%
Length of a PV module (l)	545 mm
Width of a PV module (w)	445 mm

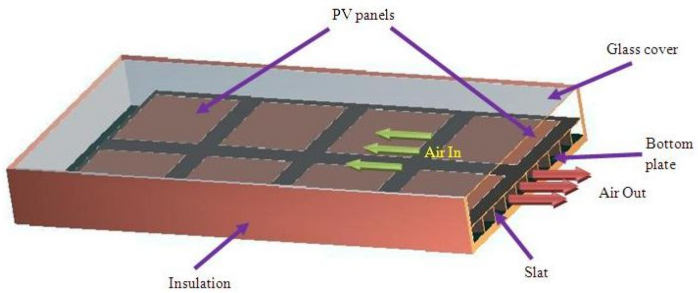

Fig.1 (a) Schematic diagram of DPHSAH with slats

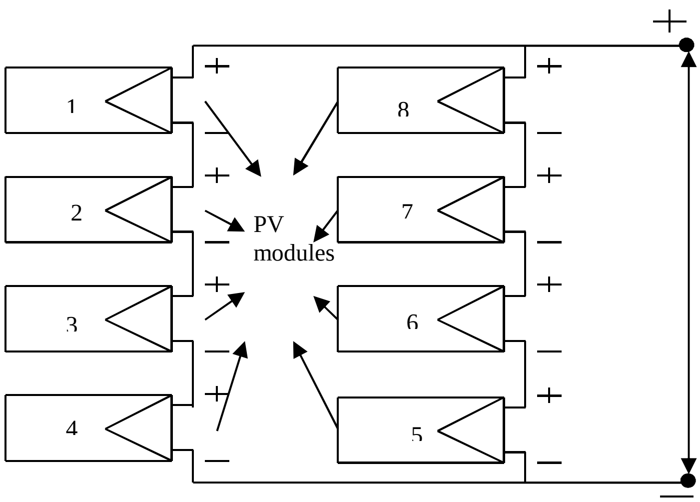

Fig.1 (b) Schematic representation indicating locations of parameters measured

Modules 1 to 4 and 5 to 8 are connected in series for enhancing the voltage i.e. 67.2 V, the two resultant arrays are finally connected for enhancing the current i.e. 2.98 A and thus the rated power 200 Wp is obtained.

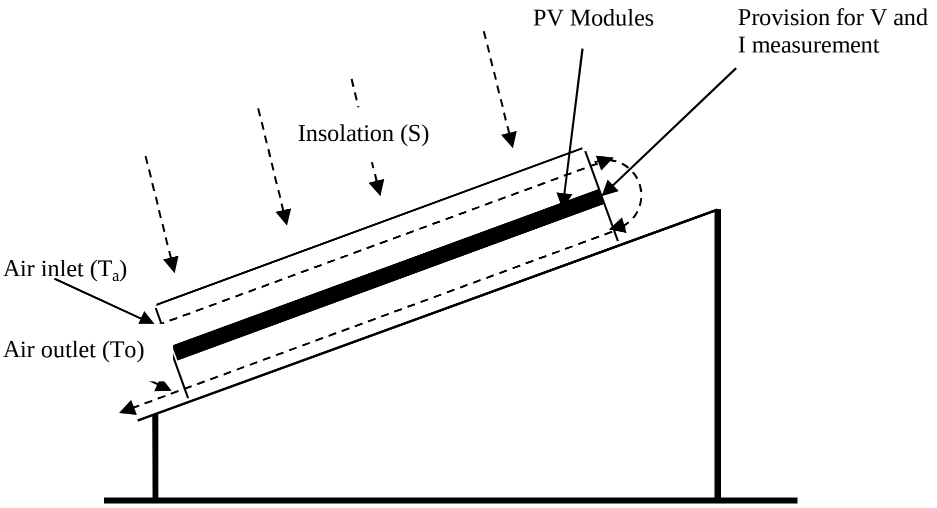

Fig.2 Schematic representation indicating locations of important parameters measured

III. EXPERIMENTAL SETUP

PV panels made of mono-crystalline silicon solar cells were pasted on the absorber plate of a box framed solar air heater to obtain the hybrid (PV/T) solar air heater. An air blower for circulating the air was fitted at the ground end of the system. Air entered through the upper channel formed by the glass cover and the photovoltaic panels and was heated directly by the sun and the channel walls. After that it flows through the lower channel formed by the back plate with slats and the absorber plate. The slats fixed at the back of the absorber plate (photovoltaic panel) increase the heat transfer rate to the air and by conducting heat to bottom plate thus enhance the efficiency of the system by introducing sufficient turbulence in the lower channel. The setup is situated in open sky avoiding nearby shading effect which will reduce the solar insolation effect on the system. The double pass hybrid photovoltaic thermal (PV/T) solar air heater (DPHSAH) is kept 11^0 facing south at the Solar Energy Center located in National Institute of Technology, Calicut.

A. Instrumentation

The following parameters were measured during experimentation:

(1) Inlet air temperature
(2) Outlet air temperature
(3) Absorber plate temperature (PV panel)
(4) Slat temperature
(5) Bottom plate temperature
(6) Solar insolation

B. Experimental Procedure

The PV/T collector was tested at nominal operating conditions in order to study the electrical, thermal and overall performance of the system. The solar radiation was measured using a digital pyranometer installed parallel to the collector plane. Electrical air blower was used to produce air flow in the collector and it was controlled through an autotransformer for different mass flow rates. The air mass flow rate was determined by the orifice meter which was connected at the outlet pipe of the collector. The flow rate was varied from 0.005 to 0.0123 kg/s. The minimum flow rate corresponds to 1 cm head and maximum flow rate corresponds to 6 cm head of water column in U tube differential manometer of orifice meter. Calibrated Chromel – Alumel (K type) thermocouples with digital temperature indicator are used to measure temperatures at several locations of the system. Ambient air temperature and collector outlet air temperatures are measured by digital thermometers provided at suitable locations. Load was connected to the PV cells through a 50 Ω, 5A rheostat for measuring the load voltage and load current multimeters were used separately. The PV/T solar collector was operated at a fixed mass flow rate from sunrise to sunset under clear blue sky. All the measurable parameters are recorded at every 1 hour time interval. Data collected were used to determine the thermal, electrical and overall efficiency of the system. The system was operated for different mass flow rates to study the performance variation of the PV/T solar collector.

Fig.3 Photograph of the experimental setup

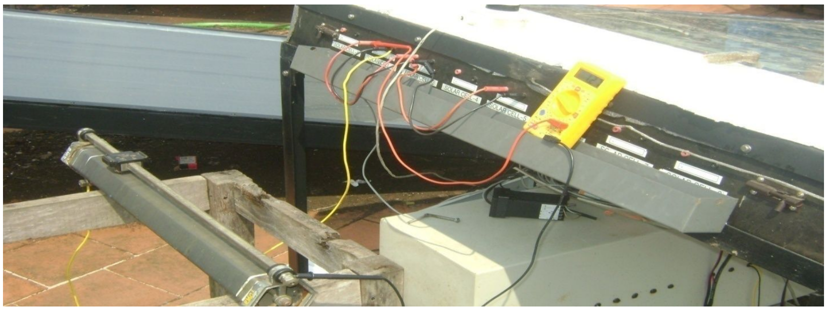

Fig. 4 Instrumentation used for the experimentation in the DPHSAH

IV. PERFORMANCE ANALYSIS

The performance of a photovoltaic thermal (PV/T) solar collector can be described by a combination of efficiency terms.

$$\eta_{th} = \left(\dot{m} c \Delta T / S A_{cell} \right) \times 100 \quad (1)$$

$$\eta_{el} = \left(I_L V_L / S A_{cell} \right) \times 100 \quad (2)$$

$$(\eta_{th})_o = \eta_{th} + \eta_{el} / 0.38 \quad (3)$$

Overall thermal efficiency (Eq.3) from a PV/T system is given by the combination of thermal efficiency from the PV/T system and electrical efficiency from the PV/T system divided by electrical power generation efficiency (0.38) of a conventional power plant [20]. Since thermal energy is low grade energy and electrical energy is high grade energy, electrical power generation efficiency is used to express electrical energy in terms of low grade energy.

A. Uncertainty Analysis

Determination uncertainty in the measured results of experimentation is important.

TABLE III UNCERTAINTIES ASSOCIATED WITH THE INDIVIDUAL ELEMENTS OF THE DPHSAH

Equipment	Measurement	Error
Thermocouples	PV/T air temperature	± 1^0C
Pyranometer	Irradiance	± 5%
Multimeter	PV current	± 1%
Multimeter	PV voltage	± 1.4%

Root Sum Square method can be used to determine the combined effect of random measurement errors. According to Root Sum Square method the result R is a given function of independent variables

$$x_1, x_2, x_{3\ldots} x_n. \text{ Thus } \quad R = R\,(x_1, x_2, x_{3\ldots} x_n) \quad (4)$$

Let w_R be the uncertainty in the result and $w_1, w_2, w_3 \ldots w_n$ be the uncertainties in the independent variables. If the uncertainties in the independent variables are all given with the same odds, then the uncertainty in the result having these odds is given by Holman [21] as

$$w_R = \sqrt{\left(\frac{\partial R}{\partial x_1} \times w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} \times w_2 \right)^2 + \left(\frac{\partial R}{\partial x_3} \times w_3 \right)^2 + \ldots\ldots + \left(\frac{\partial R}{\partial x_n} \times w_n \right)^2} \quad (5)$$

The uncertainity in the results of calculations of thermal efficiency was obtained as ± 4.2%.

Similarly, the uncertainty in the calculation of electrical efficiency is ± 0.2% and the uncertainty in the calculation of overall thermal efficiency is ± 5.6%.

V. RESULTS AND DISCUSSION

Figure 5 shows the important element temperature of the double pass hybrid (PV/T) solar air heater is increasing from morning to noon and decreasing from noon to evening, and this is because of solar insolation which is less at morning and evening but more at afternoon. The outlet air temperature is below the absorber plate (PV Panel), due to less volumetric heat capacity of air compared to aluminium metal. Increase in volume flow rate of air significantly reduces the absorber plate (PV panel) temperature. Hourly variation of solar radiation, ambient air and collector outlet air temperatures on 1st February 2011 are presented in Fig.6. Solar radiation, ambient air and collector outlet air temperature are gradually increasing from 9AM to 12 Noon and decreasing from 12 Noon to 5PM. It has been observed that there is a gradual rise in the absorber plate temperature from sunrise to noon with increase in solar insolation and then gradual fall in absorber plate (PV panel) temperature from noon to sunset with decrease in solar insolation. This trend is causing variation in the outlet air temperature. Since air is flowing in contact with absorber plate (PV panel), outlet air temperature is always more than the ambient air temperature, as represented.

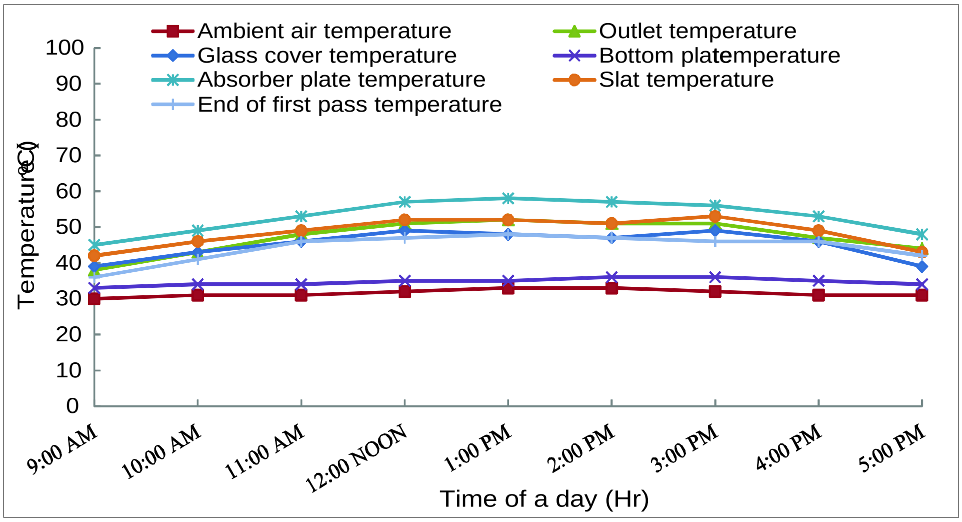

Fig.5. Hourly temperature variation of double pass hybrid (PV/T) air heater with respect to time of the day

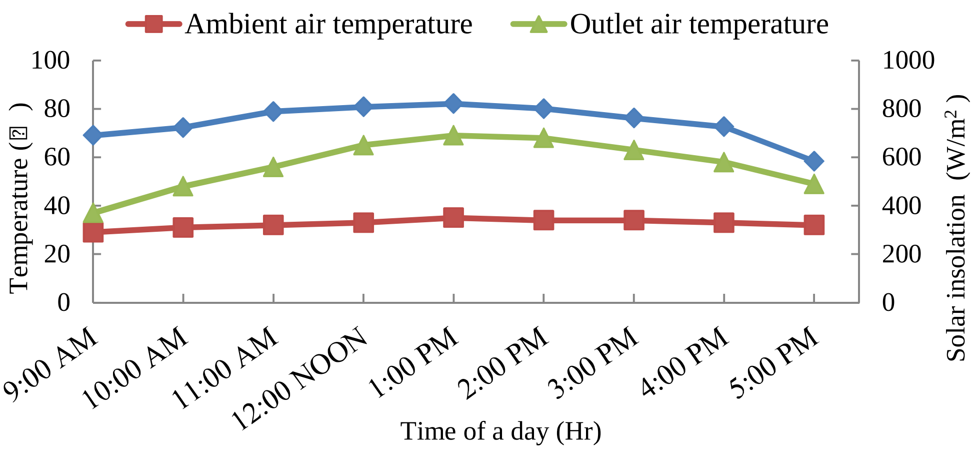

Fig.6 Hourly variation of solar radiation, ambient air and outlet air temperatures (01.02.2011).

Figures 7 and 8 show the variation of cell temperature and electrical efficiency for various days in the month of January and February. The temperature of PV cell was lower at morning and evening, corresponding electrical efficiencies are higher. The temperature of PV cell is high at noon so that it causes decrement of the electrical efficiency of the PV cell, as high kinetic energy electrons due to higher solar insolation prevent the motion of their neighboring electrons and that is how increases resistance to electricity generation by the PV panels. When the air mass flow rates are lower PV panels are getting over - heated quickly but when air mass flow rates are higher, PV panels are getting over - cooled. When the air mass flow rate is lower, electricity yield is small due to lower volumetric heat capacity of air (as represented when m = 0.05 kg/s), however, at higher air mass flow rates, electrical performance of the system is better (as represented when m = 0.07 kg/s). In this case the PV panels are cooled to lower temperatures. PV panels should not be cooled below their optimum operating temperature. That is why during morning hours in order to maintain the PV panels at their best operating temperature, higher air mass flow rates are not recommended. If the air mass flow rate of the system is raised, especially at mid-day as solar insolation and ambient air temperature are at higher values, the PV panel temperature can be sufficiently reduced to their operating temperatures and electrical performance can be increased. Again during evening hours in order to reduce the over cooling effect, air mass flow rates of the system should be reduced. Thus DPHSAH should be operated at smaller air mass flow rates during morning and evening hours and larger air mass flow rates are recommended during mid-day.

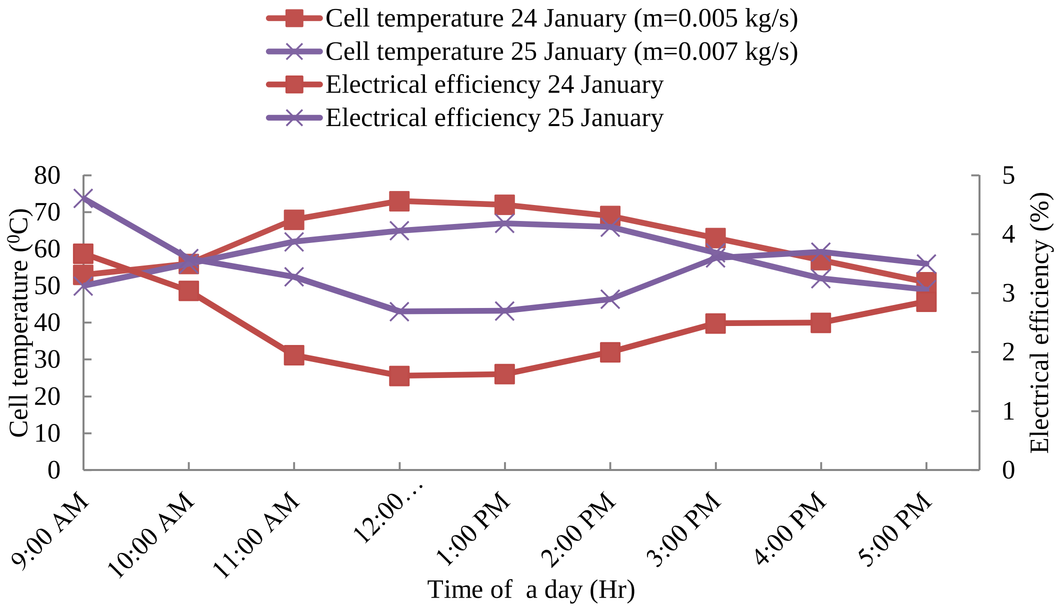

Fig.7. Hourly variation of cell temperature and electrical efficiency for two particular days. (24.01.2011 & 25.01.2011).

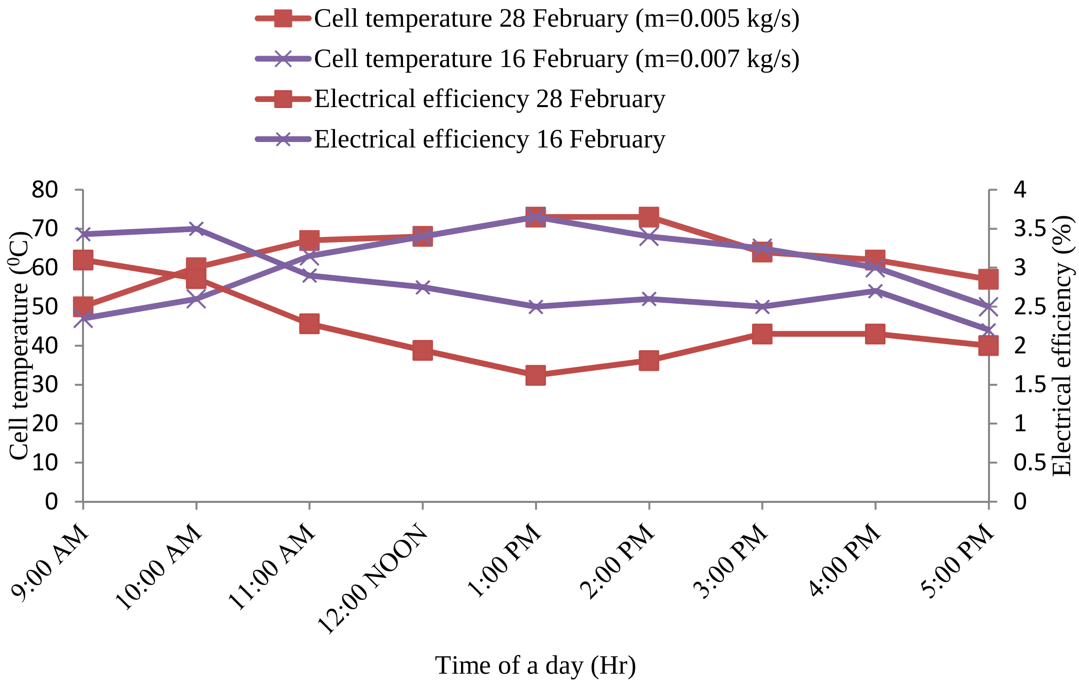

Fig.8. Hourly variation of cell temperature and electrical efficiency for two particular days. (16.02.2011 & 28.02.2011)

Figures 9 and 10 show the variation of thermal, electrical and overall efficiencies on two days (one each in the month of January and February 2011, respectively). During the course of a day, thermal and overall efficiencies were initially increased and decreased later. Simultaneously the electrical efficiency has a reverse impact i.e., initially decreased and increased later. This is because of higher cell temperature at noon than early and later hours of the day which results in smaller efficiency of the PV cell.

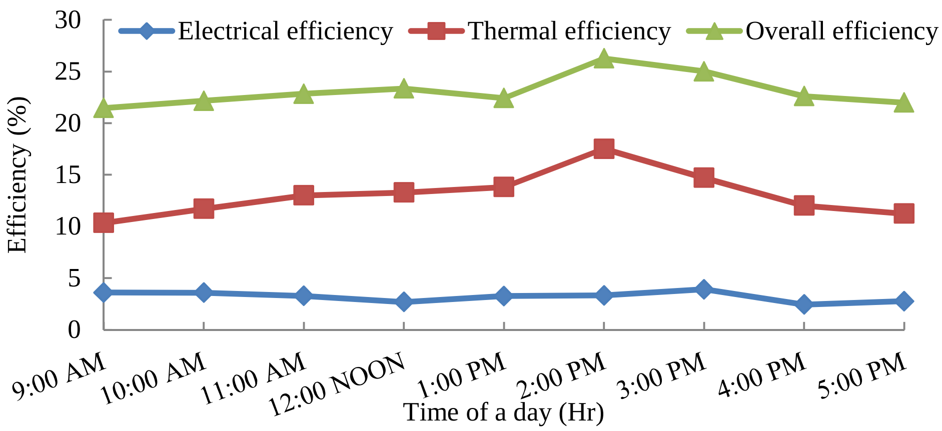

Fig. 9. Variation of electrical, thermal and overall efficiencies (21.01. 2011).

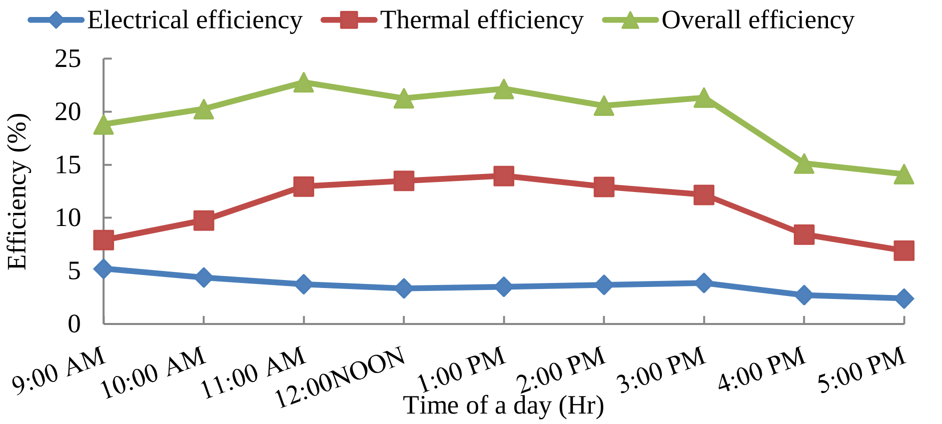

Fig. 10. Variation of electrical thermal, and overall efficiencies (22.02. 2011).

It is observed that, there is always a chance for fluctuations in outdoor conditions with respect to solar insolation and ambient air temperature, which is causing the intermediate drop and rise of the thermal, electrical and overall performance of the system. This uneven heating and cooling causes regular expansions and contractions within the layers of structure of PV panels (a glass to tedlar monocrystalline silicon solar cells are covered both sides by EVA with top cover as ARC), which is the main reason in limited life period of PV panels (25 years for mono-crystalline silicon solar cells). If the system is operated at higher air mass flow rates this drawback on life and electrical performance of the PV panel can be reduced, thus the overall performance of the system can be increased by operating at higher air mass flow rates**.** It is revealed that instances when electrical performance is lower due to higher absorber plate temperature (PV panel), thermal performance is higher, and thus loss in electrical performance is compensated in thermal performance of the system. At times when thermal performance is lower due to lower ambient temperature, electrical performance is boosting due to smaller PV panel temperature. However, electrical performance is always controlled by the solar insolation.

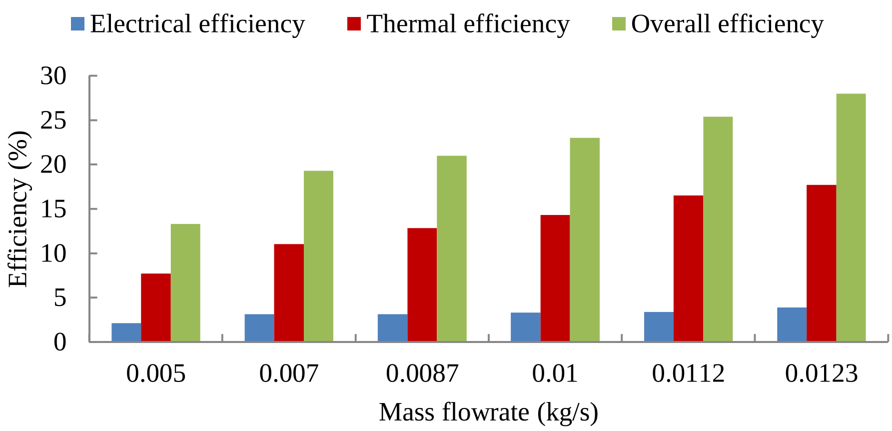

Fig.11. Typical variation of electrical, thermal and overall efficiencies with mass flow rate of air

Figure 11 shows that the electrical, thermal and overall efficiencies have a direct variation with respect to the mass flow rate. The average electrical, thermal and overall efficiencies attained maximum values of 3.9%, 18% and 28%, respectively corresponding to the mass flow rate of 0.0123 kg/s. There is a huge scope for increasing the electrical, thermal and overall efficiencies of the DPHSAH by increasing the air mass flow rate. It is observed that presences of slats, for increasing the heat dissipation from the PV panels by conduction enhance the turbulence. The pressure loss due to slats is negligible because of the increased overall performance and life of the system. Though the operating air mass flow rate is very small, because of the double pass provision of air PV panels cooling rate is enhanced. Since the PV panels are pasted on the aluminum plate with slats, the PV panel structure became glass to aluminum plate type instead of glass to tedlar type structure. There is a further improvement in heat transfer rate from tedlar sheet to aluminum plate which is gained by the circulating air mass. Thus system electrical, thermal and overall performance is increasing even with lower air mass flow rates.

VI. CONCLUSIONS

Hybrid photovoltaic-thermal solar collector with slats was experimentally studied with respect to its operating characteristics. Solar cells generate more electricity when they are exposed to higher solar insolation, their efficiency drops when temperature of the solar cells increases. Results show that electricity production in a PV/T hybrid module decreases with increasing panel temperature. At times when electrical performance of the PV panel is lower due to higher absorber plate temperature, corresponding thermal performance is higher. Thus loss in electrical energy output is compensated by thermal gain of the system, which makes hybrid system very relevant for energy conversion. It is important to use slats as an integral part of the absorber surface in order to achieve better efficiencies. In this case, both thermal and electrical output of the hybrid PV/T solar collector is expected to improve sufficiently.

REFERENCE

[1] E.C Kern Jr, M.C Russell, Combined photovoltaic and thermal hybrid collector systems, In: Proc., 13th IEEE photovoltaic specialists, Washington, USA, p p.1153–1157, 1978.

[2] S.C. Solanki, S. Dubey, A. Tiwari, Indoor simulation and testing of photovoltaic thermal (PV/T) air collectors, Appl Energy. Vol. 86, pp. 2421–2428, 2009.

[3] A.S. Joshi, A. Tiwari, G.N. Tiwari, I. Dincer, B.V. Reddy, Performance evaluation of a hybrid photovoltaic thermal (PV/T) (glass-to-glass) system, International Journal of Thermal Sciences. Vol. 48, pp. 154–164, 2009.

[4] S. Dubey, G.S. Sandhu, G.N. Tiwari, Analytical expression for electrical efficiency of PV/T hybrid air collector, Appl Energy. Vol. 86 pp. 697–705, 2009.

[5] J.K. Tonui, Y. Tripanagnostopoulos, Improved PV/T solar collectors with heat extraction by forced or natural air circulation, Renewable Energy. Vol.32, pp. 623–637, 2007.

[6] Y. Tripanagnostopoulos, T.H. Nousia, M. Souliotis, P. Yinnoulis, Hybrid photovoltaic /Thermal solar systems, Solar Energy. Vol. 72 , pp. 217–234, 2002.

[7] S. Dubey, S.C. Solanki, A.Tiwari, Energy and exergy analysis of PV/T air collectors connected in series, Energy and Buildings. Vol. 41 pp. 863–870, 2009.

[8] A.S Joshi, A. Tiwari, Energy and exergy efficiencies of a hybrid Photovoltaic–thermal (PV/T) air collector, Renewable Energy. Vol. 32 pp. 2223–2241, 2007.

[9] A. Tiwari, P. Barnwal, G.S. Sandhu, M.S. Sodha, Energy metrics analysis of hybrid – photovoltaic (PV) modules, Appl Energy. Vol.86 pp .2615–2625 , 2009.

[10] S. Nayak, G.N. Tiwari, Theoretical performance assessment of an integrated photovoltaic and earth air heat exchanger greenhouse using energy and exergy analysis methods, Energy and Buildings. Vol. 41 pp. 888–896, 2009.

[11] S. Nayak, G.N. Tiwari, Energy metrics of photovoltaic/thermal and earth air heat exchanger integrated greenhouse for different climatic conditions of India, Appl Energy.

[12] A. Tiwari, S. Dubey, G.N. Sandhu, M.S. Sodha, S.I. Anwar, Exergy analysis of integrated photovoltaic thermal solar water heater under constant flow rate and constant collection temperature modes, Appl Energy. Vol. 86 pp 2592–2597, 2009.

[13] L.T. Kostic, Tomislav, T.M. Pavlovic, T. Zoran, Z.T. Pavlovic, Influence of reflectance from flat aluminum concentrators on energy efficiency of PV/Thermal collector, Appl Energy. Vol. 87

[14] M.Y. Othman, Baharudin, B.Y.K Sopian, M.N. Abu Bakar, Performance analysis of a double-pass photovoltaic/thermal (PV/T) solar collector with CPC and fins, Renewable Energy. Vol 30 pp. 2005–2017, 2005.

[15] M.Y. Othman, B.Y.K. Sopian, M.N. Abu Bakar, Performance studies on a finned double-pass photovoltaic-thermal (PV/T) solar collector, Desalination. Vol . 209 pp. 43–49, 2007.

[16] P.G. Charalambous, G.G. Maidment, S.A. Kalogirou, K. Yiakoumetti, Photovoltaic thermal (PV/T) collectors: A review, Appl Therm Eng. Vol. 27 pp. 275–286, 2007.

[17] J.K. Tonui, Y. Tripanagnostopoulos, Air-cooled PV/T solar collectors with low cost performance improvements, Solar Energy. Vol. 81 pp.498–511, 2007.

[18] K.K. Matrawy, Theoretical analysis for an air heater with a box type absorber, Solar Energy. Vol 63 pp.191–198, 1998.

[19] C.D. Ho, H.M. Yeh, T.W. Cheng, T.C. Chen, R.C. Wang, The influence of recycle on performance of double pass flat solar air heaters with internal fins attached, Appl Energy. Vol 86 pp. 1470–1478, 2009.

[20] B.J. Huang, T.H. Lin, W.C. Hung, F.S. Sun, Performance evaluation of solar photovoltaic/thermal systems, Solar Energy. Vol 70 pp. 443–448, 2001.

[21] J.P. Holman, Experimental Methods for Engineers, seventh ed., New Delhi, India, 2010.

M. Srinivas is currently Assistant Professor in Mechanical Engineering Department, National Institute of Technology, Calicut, Kerala, India. He has completed engineering graduation in MechanicalEngineering from Osmania University; Hyderabad.He has obtained his M. Tech in Thermal engineering from JNTU, Hyderabad, India in 2002. His area of research includes Renewable Energy systems, Hybrid Energy Systems. He is currently working towards his Ph.D degree. He is a ISTE member.

E-mail address: msrinivas@nitc.ac.in

S. Jayaraj is currently Professor in Mechanical Engineering Department, National Institute of Technology, Calicut, Kerala, India.

His Masters Degree From IIT Madras in Refrigeration and Air Conditioning and Ph.D From IIT Kanpur in Computational Fluid Mechanics and Heat Transfer. He was PDF scholar from Dong – A university, Republic of Korea. His area of research includes Multiphase flow, Design and analysis of energy systems, Computational methods in fluid mechanics and heat transfer, Renewable energy utilization.