INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 4, Issue 4, 2013 pp.687-698

Journal homepage: www.IJEE.IEEFoundation.org

Investigations on the performance of a double pass, hybrid - type (PV/T) solar air heater

M. Srinivas, S. Jayaraj

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

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 a 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 presented. An artificial neural network model is used for forecasting the system performance at any desired conditions. The proposed model can be successfully used for evaluating the effect of different operating parameters under different ambient conditions for predicting the overall performance of the system.

Keywords: Artificial neural network; Double pass; Photovoltaic; Solar air heater; Slats.

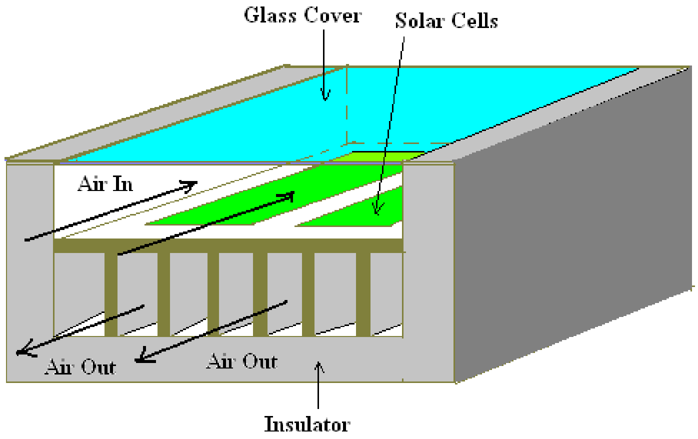
1. Introduction
Solar energy is one of the most important sources of clean energy. Solar thermal energy systems convert solar energy into heat and solar photovoltaic systems convert solar energy into electrical energy. In solar thermal energy systems electrical energy is one of the inputs for extracting 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 and environmental impact. 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. Integrated PV/T collector based energy system produce both thermal energy and electrical energy, Kern and Russel [1]. Hybrid energy systems (PV/T) can be integrated to rooftops of any building to produce electrical energy, hot fluid for lighting, space heating and drying purposes, Agarwal and Tiwari [2]. For different months and cities, for a 1.2 m^2 PV/T, monthly total energy was varying from 35-60 kWh and monthly total exergy from 7–16 kWh with air as the working substance for Indian climates. The monthly variation of exergy has a similar behavior like monthly thermal energy for all weather conditions, Joshi and Tiwari [3]. In

various types of solar cookers, the performance and exergy analysis offers an alternative method for evaluation and comparison, Huseyin [4]. The thermal efficiency increases with increase in height and number of fins of a double pass flat plate solar air heater with longitudinal fins, whereas the entropy generation was inversely proportional to the height and number of fins, Naphon [5]. The annual maximum heat and electricity were obtained in the case of continuous withdrawal from hybrid photovoltaic thermal (PV/T) solar water heating system, Dubey and Tiwari [6]. As per the analytical expression, overall thermal efficiency of integrated PV/T solar system increases with increase in constant flow rate and decreases with increase in constant collection temperature, Tiwari et. al [7]. Integration of a PV/T and Earth Air Heat Exchanger (EAHE) system, with the green house would save overall energy consumption of green house Nayak and Tiwari [8].The instantaneous energy and exergy efficiency values of PV/T air heaters varies from 55% to 65% and 12% to13% respectively, Joshi and Tiwari [9].The collectors fully covered by PV modules and air flowing below the absorber plate give better performance in terms of thermal energy, electrical energy and exergy gain in the analysis of 'N' hybrid photovoltaic thermal (PV/T) air collectors connected in series, Dubey et. al [10]. The largest irreversibility was occurring at the conventional solar collectors in which collector efficiency was lowest. The experimental results also revealed the use of passive techniques such as staggered sheets and fins. The efficiency of solar collector has been increased approximately up to 30% in comparison with the conventional solar collector, Ucar and Inalli [11]. The photovoltaic roof with ventilated air gap was suitable for the application in summer, because this integration could leads to low cooling loads and high photovoltaic conversion efficiency (Wang et. al [12]. Substantial steps need to be taken towards reducing the cost to make PV/T collectors more competitive, Charalambous et. al [13]. The thermal efficiency of a PV/T dual fluid collector with metal absorber obtained was nearly 80%, and electrical performance of the system was satisfactory, and still scope for further improvement of cooling the photovoltaic panels was noted, Assoa et al. [14]. The presence of porous media had improved the thermal efficiency (theoretical and experimental) of the double pass solar air heater, Sopian et. al [15]. The photovoltaic panel temperature decreases with increase in air gap between panels and roof of building, Gan [16]. It is observed that the present researchers tried to improve the efficiency of box type collector.Very few works were attempted to extract accumulated heat in the absorber plate (PV panel) with fins, and concluded that there is still scope for performance improvement by heat extraction. Almost 90% of above reported works were on single pass PV/T collectors.

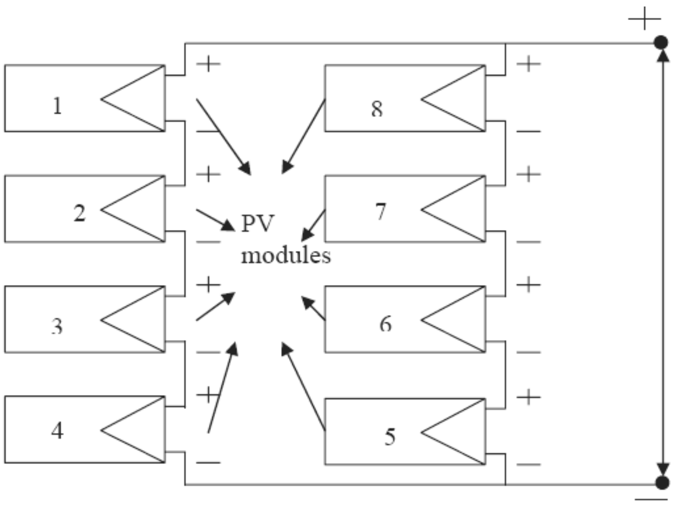
In the present work, a new design of double pass hybrid (PV/T) solar air heater with slats (DPHSAH) was studied experimentally. This design is a beautiful blend of solar thermal energy system (double pass solar air heater with slats) and solar photovoltaic system. To the best of author's knowledge no work had been reported with slats attached to absorber plate. Monocrystalline silicon solar cells were used in the device.

2. 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 size 5 cm height, 2 m long and thickness of 2 mm (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 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 Figure 1. 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 1 and Table 2. The double pass PV/T solar collector is shown schematically in Figure 1 (a), and schematic representation of PV modules connections is shown in Figure1 (b).



(a)



(b)

Figure 1. (a) Schematic diagram of DPHSAH with slats; (b) Schematic representation of PV module connections

Table 1. Specifications of double pass solar air heater with slats

Element of system	Sizes of element
Absorber plate: Aluminium absorber	(1 m X 2 m), (thickness 2mm)
Bottom 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 2. 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

ISSN 2076-2895 (Print), ISSN 2076-2909 (Online)

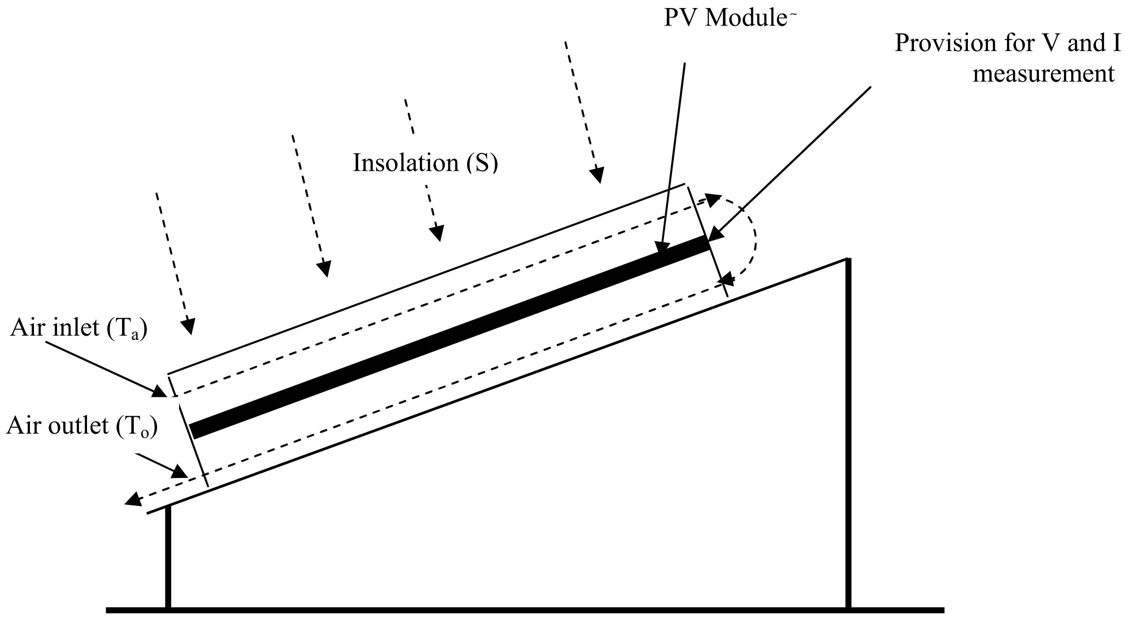


Figure 2. Schematic representation indicating locations of parameters measured

3. Experimental setup

Phovoltaic panels made of mono-crystalline silicon solar cells are pasted on the absorber plate of a box framed solar air heater to obtain the DPHSAH (Figure 2). An air blower for circulating the air is fitted at the ground end of the system. Air enters through the upper channel formed by the glass cover and the photovoltaic panels and is heated directly by the sun and the channel walls. After that air 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 increases the heat transfer rate to the air and by conducting heat to bottom plate thus enhances the efficiency of the system. The setup is situated under the direct sunlight avoiding nearby shading effect which will reduce the solar insolation effect on the system. The DPHSAH is kept 11^0 facing south at the Solar Energy Center located in National Institute of Technology Calicut.

3.1 Instrumentation

The following parameters were measured during experimentation:

(i) Inlet air temperature
(ii) Outlet air temperature
(iii) Absorber plate temperature (PV panel)
(iv) Slat temperature
(v) Bottom plate temperature
(vi) Solar insolation
(vii) Air velocity
(viii) Load current
(ix) Load voltage

3.2 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 at the collector plane. An electrical air blower was used to augment air flow in the collector and it was controlled through an auto-transformer for different mass flow rates. The air mass flow rate was determined by an orifice meter which was connected at the outlet pipe of the collector. The air flow rate of the DPHSAH is 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. 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 on a day under clear blue sky conditions. All the measurable parameters are recorded at every 1 hour time interval. Data collected was 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. Photographs of the DPHSAH set up used for the experimentation are given in Figure 3 and Figure 4.

Figure 3. Photograph of the experimental setup

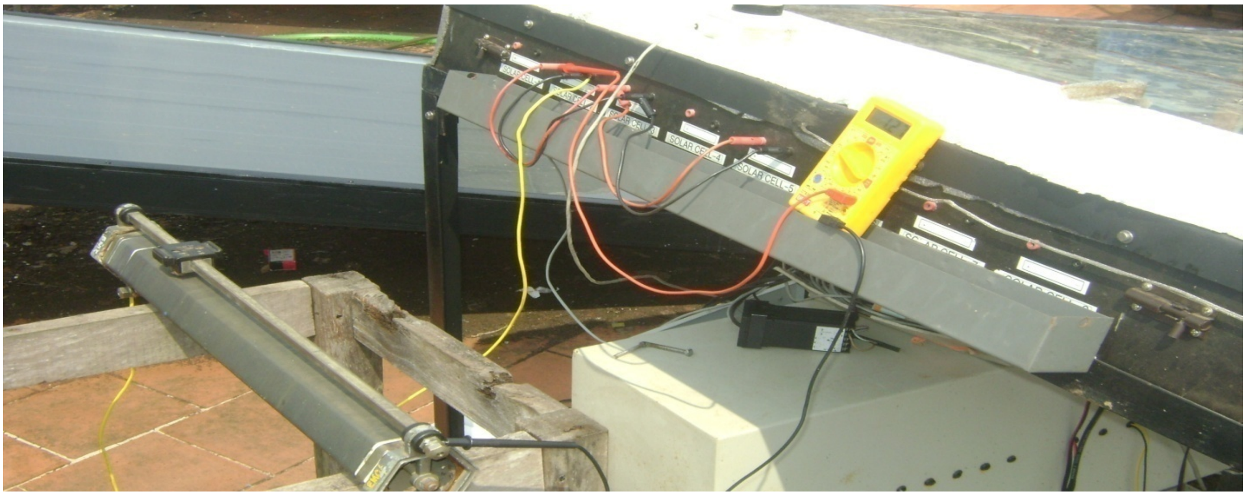


Figure 4. Instrumentation used for the experimentation in the DPHSAH

4. Performance analysis

Performance of DPHSAH with slats is studied by applying the first and second laws of thermodynamics.

4.1 The energy analysis

The energy balance of DPHSAH is based on the first law of thermodynamics. The following expressions are applicable with respect to this.

$$\eta_{th} = \frac{\dot{m} c (T_o - T_i)}{SA_c} \times 100 \tag{1}$$

$$\eta_{el} = \frac{I_L V_L}{SA_{cell}} \times 100 \tag{2}$$

The overall thermal efficiency of a double pass hybrid (PV/T) solar air heater is defined

$$\eta_{oth} = \eta_{th} + \frac{\eta_{el}}{0.38} \tag{3}$$

Overall thermal efficiency of the PV/T system is equal to the sum of thermal efficiency of the PV/T system and the ratio of electrical efficiency to ç power, Huang et. al [17]. Here ç power is the electric power generation efficiency of a conventional power plant.

4.2 Uncertainity analysis
Determination Uncertainty in the measured results of experimentation is important (Table 3).

Table 3. Uncertainties associated with the individual elements of the DPHSAH

Equipment	Measurement	Error
Thermocouples	PV/T air temperature	$\pm 1^0$C
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 Root sum Square method to the result R is a given function of independent variables $x_{1,}$ $x_{2,}$ $x_{3\ldots}$ $x_{n.}$
Thus

$$R = R(X_1, X_2, X_3.....X_n) \tag{4}$$

Let w_R be the uncertainty in the result and $w_{1,}$ $w_{2,}$ w_3 ....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 [18] as

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

Percentage of uncertainty in the performance parameters (energy and exergy) obtained is given below:
Thermal efficiency = 4.3
Electrical efficiency = 0.2
Overall thermal efficiency = 5.6

5. ANN modeling
The performance of the DPHSAH is influenced by ambient parameters (such as, ambient temperature and solar radiation) and operating parameters (such as mass flow rate of air and time of the day). When the system is operating at fixed mass flow rate of air the ambient air temperature and solar radiation are taken as constant. Hence the effect of ambient parameters is controlled by mass flow rate of air. Therefore the performance of a DPHSAH can be evaluated with respect to mass flow rate of air in a particular day of the month. The experimental data of different days and of different operating conditions was used to train the Artificial Neural Network (ANN) model for forecasting the thermal, electrical and overall performance of the PV/T air heater. In the present study back propagation algorithm (the most widely used method in ANN) with two hidden layers is found to be suitable (Figure 5). A total of 207 sets of inputs (such as, ambient air temperature, solar radiation and mass flow rate of air) and 207outputs (such as, thermal efficiency and electrical efficiency) are used to train the network.

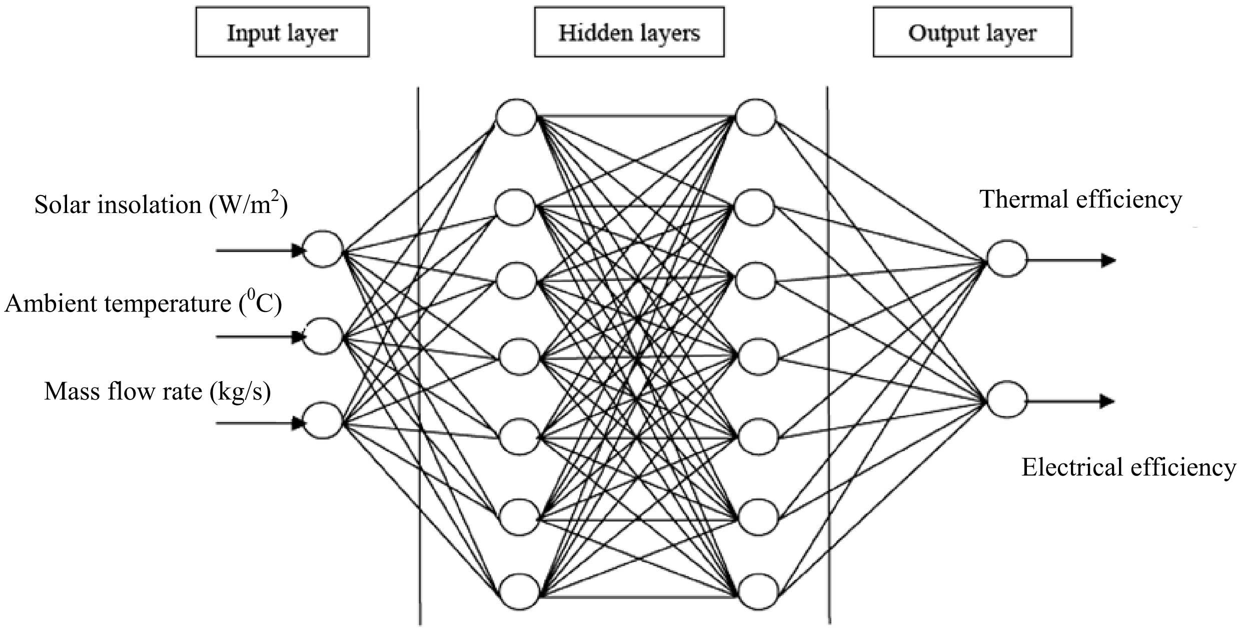


Figure 5. Architecture of ANN used for the performance prediction

6. Results and discussion

Figure 6 show the important elements temperature of the double pass hybrid (PV/T) solar air heater is increasing from morning to noon and decreasing from noon to evening, 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.

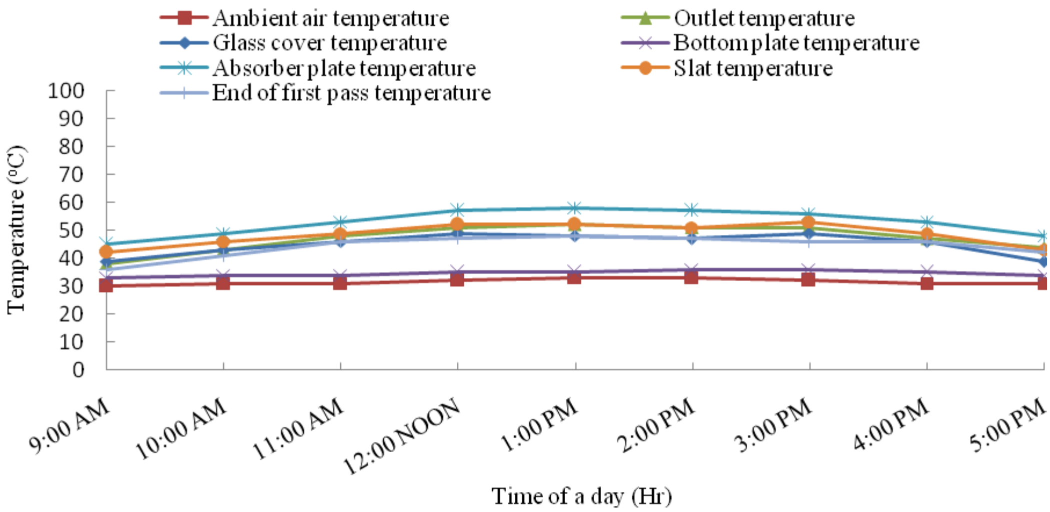


Figure 6. Hourly temperature variation of double pass hybrid (PV/T) air heater with respect to time of the day

Hourly variation of solar radiation, ambient air and collector outlet air temperatures on 1st February 2011 is presented in Figures 7. 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.

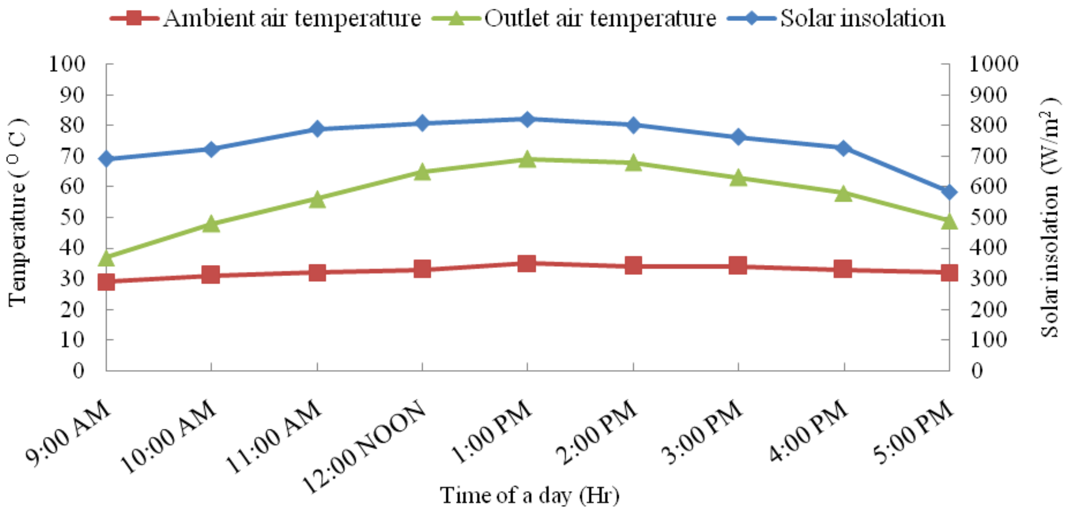


Figure 7. Hourly variations of solar radiation, ambient air and outlet air temperatures (1st February 2011)

Figures 8 and 9 show the variation of cell temperature and electrical efficiency 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 to decrease the electrical efficiency of the PV cell, as high kinetic energy electrons due to higher solar insolation prevents 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 in Figures, 24 January and 28 February) however, at higher air mass flow rates, electrical performance of the system is better (as represented in Figures, 25 January and 16 February). 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.

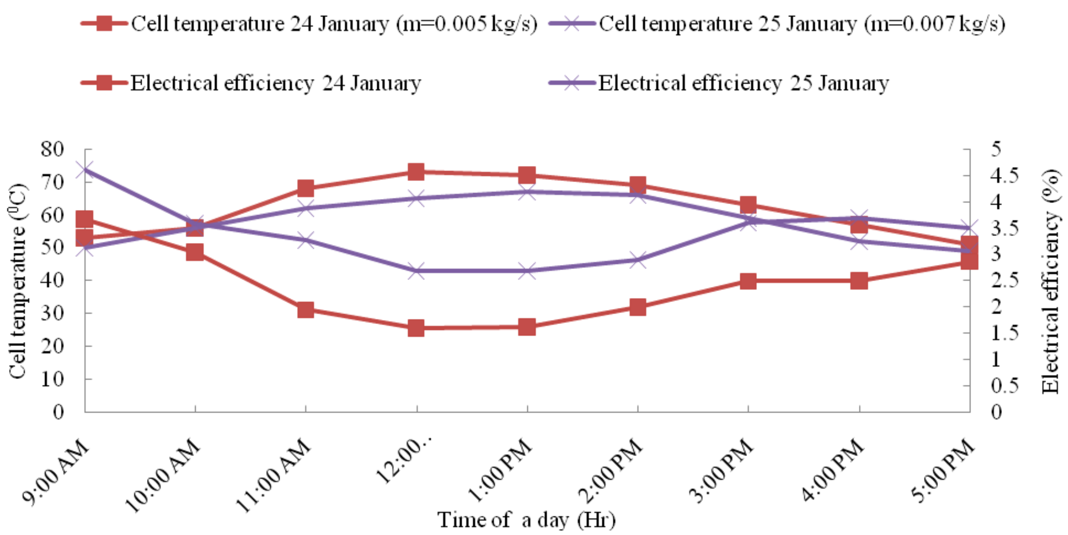


Figure 8. Hourly variation of cell temperature and electrical efficiency for the month of January, 2011

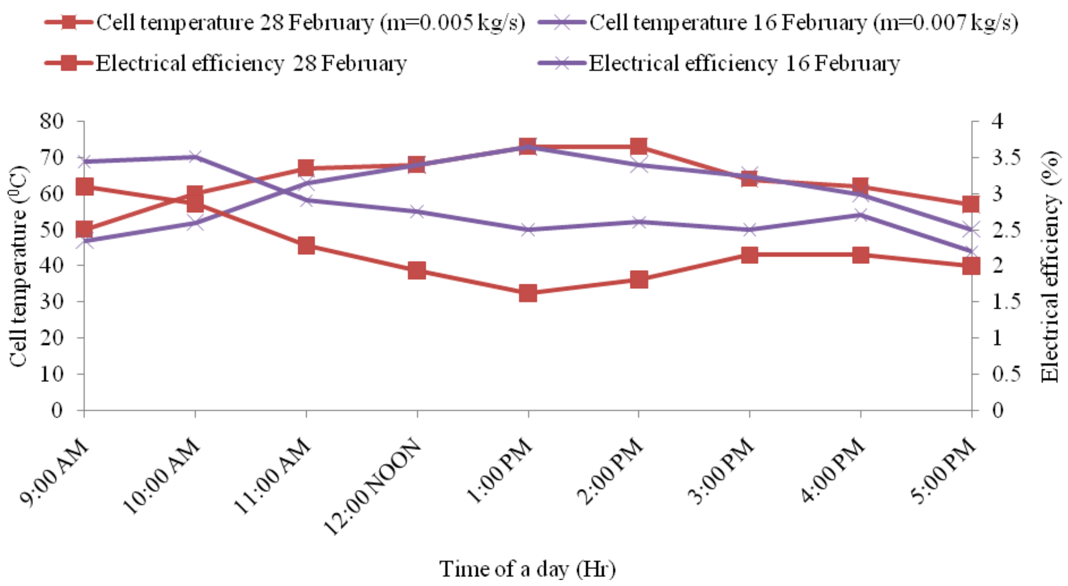


Figure 9. Hourly variation of cell temperature and electrical efficiency for the month of February, 2011

Figures 10 and 11 shows 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. It is observed that, always there is 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 draw back 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.

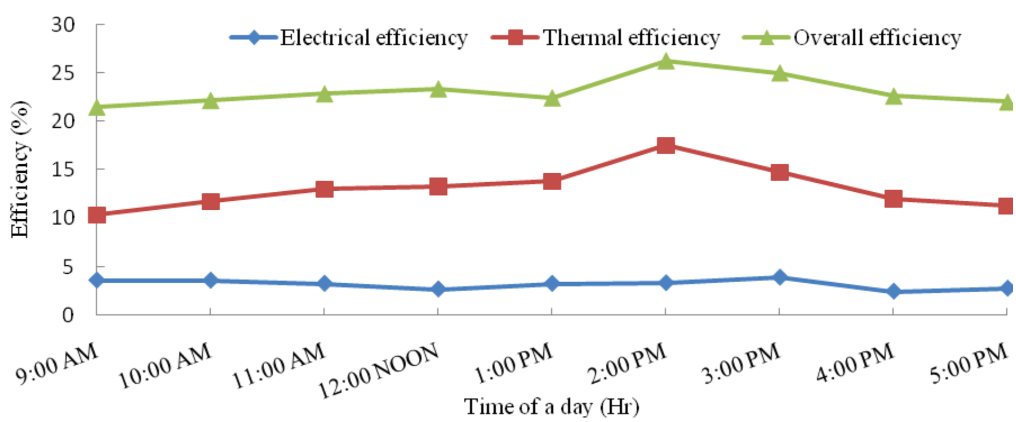


Figure 10. Variation of electrical, thermal and overall efficiencies (21 January 2011)

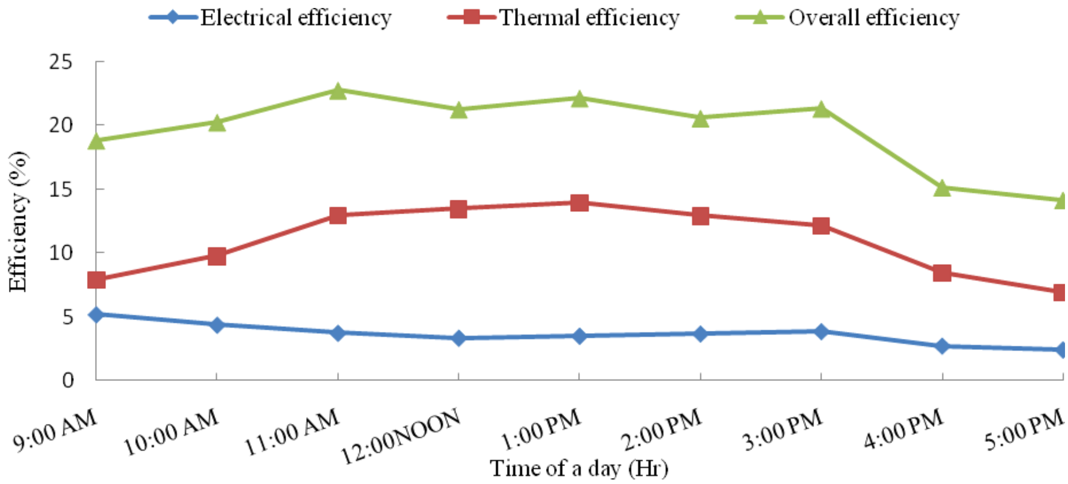


Figure 11. Variation of electrical,thermal and overall efficiencies (22 February 2011)

Figure 12 shows 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 presence of slats, for increasing the heat dissipation from the PV panels by conduction enhance the turbulence. The pressure loss due to slats is negligible since 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 and thermal and overall performance is increasing even with lower air mass flow rates.
Figure 13 show the comparison between experimental results and ANN predicted results of electrical, thermal, and overall efficiencies with mass flow rate of air. There is very good match between experimental results and ANN predicted results. The ANN results are following the trend of experimental results very closely. The ANN predicted results can be used for fore- casting the PV/T system performance.

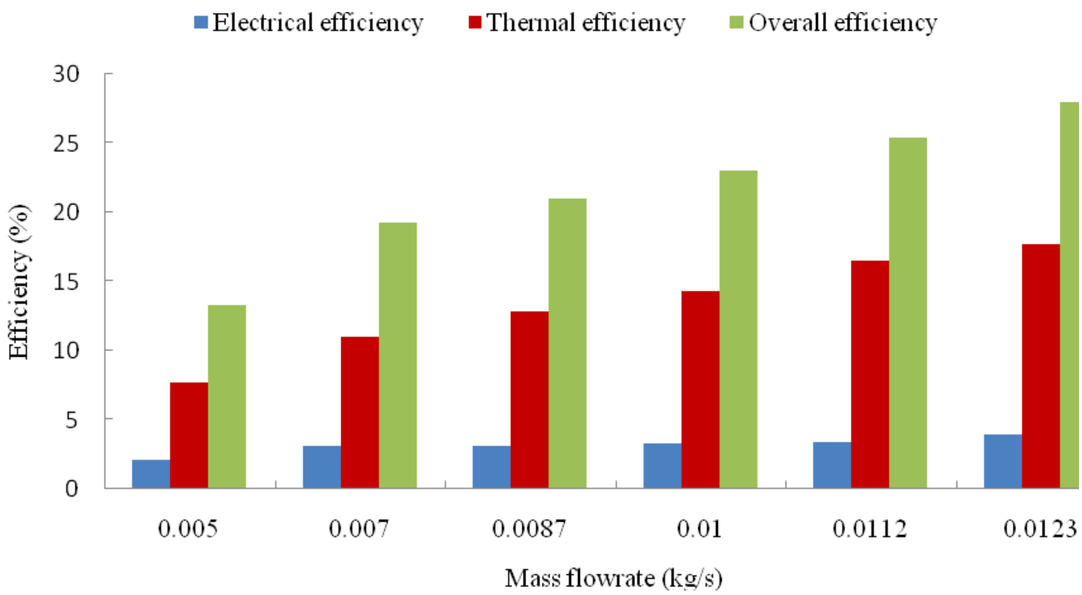


Figure 12. Typical variations of electrical, thermal and overall efficiencies with mass flow rate of air

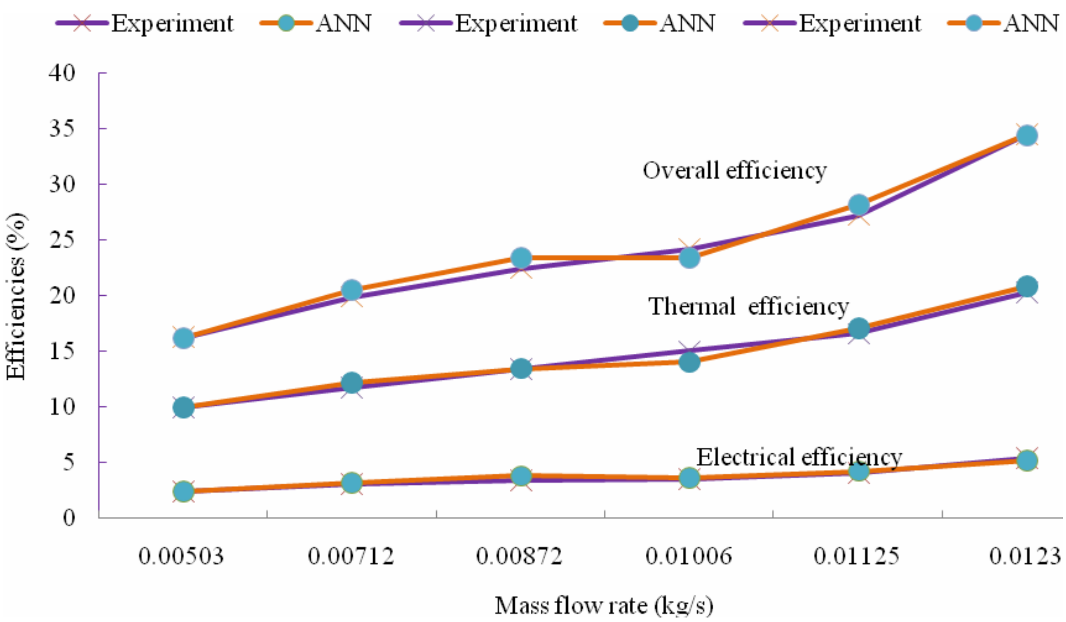


Figure 13. Comparison of electrical, thermal, and overall efficiencies (Experimental and ANN predicted)

6. Conclusions

Hybrid photovoltaic-thermal solar collector with slats was experimentally studied with respect to its operating characteristics. Solar cells generate more electricity when it is exposed to higher solar insolation, its 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 becomes very relevant for energy conversion. The ANN predicted results are matching well with the experimental results. 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.

Nomenclature

A_c	area of absorber plate (m^2)	A_{cells}	solar cells area (m^2) A
C	specific heat (kJ/kg K)	I_L	current (ampere)
$\dot{m}$	mass flow rate of air (kg/s)	S	solar insolation (W/ m^2)
T_i	ambient air temperature (^{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

References

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

[2] Agarwal, B., Tiwari, G.N. An energy and exergy analysis of building integrated photovoltaic thermal systems. Energ. Source Part A. 2011, 33, 649–664.

[3] Joshi, A.S., Tiwari, G.N.Monthly energy and exergy analysis of hybrid photovoltaic thermal (PV/T) system for Indian climate. International Journal of Ambient energy. 2007, 28(2), 99–112.

[4] Ozturk, H.H. Second law analysis for solar cookers. International Journal of green energy. 2004, 1 (2), 227–239.

[5] Naphon, P. On the performance and entropy generation of double pass solar air heater with longitudinal fins. Renewable Energy. 2005, 30, 1345–1357.

[6] Dubey, S., Tiwari, G.N. Energy and exergy analysis of hybrid photovoltaic thermal solar water heater considering with and without with drawl from tank. Journal of Renewable and Sustainable Energy. 2010, 2, 043106.

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

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

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

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

[11] Ucar, A., Inalli, M. Thermal and exergy analysis of solar air collectors with passive augmentation techniques. International communications in heat and mass transfer. 2006, 33, 1281–1290.

[12] Wang,Y., Tian, W., Ren, J., Zhu, L., Wang, Q. Influence of a building's integrated- photovoltaics on heating and cooling loads. Applied Energy. 2006, 83, 989–1003.

[13] Charalambous, P.G., Maidment, G.G., S.A. Kalogirou, S.A., and Yiakoumetti, K. Photovoltaic thermal (PV/T) collectors: A review. Applied Thermal Engineering. 2007, 27, 275–286.

[14] Assoa, Y., Menezo, C., Fraisse,G., Yezou,R., Baru,J. Study of new concept of photovoltaic thermal hybrid collector. Solar Energy. 2007, 81, 1132–1143.

[15] Sopian, K., M.A. Alghul, M.A., Alfige,E.M., M.Y. Sulaiman, M.Y., Musa, E.A. Evaluation of Thermal efficiency of double pass solar collector with porous non porous media. Renewable Energy. 2009, 34, 640–645.

[16] Gan, G. Effect of air gap on the performance of building integrated photovoltaics. Energy. 2009 34, 913–921.

[17] Huang, B.J., Lin, T.H., Hung, W.C., Sun, F.S. Performance evaluation of solar photovoltaic / thermal systems. Solar Energy. 2001, 70 (5), 443–448.

[18] Holman, J.P. Experimental Methods for Engineers. New Delhi: McGraw-Hill. 2010.

M. Srinivas is currently Assistant Professor in Mechanical Engineering Department, National Institute of Technology, Calicut, Kerala, India. He has completed engineering graduation in Mechanical Engineering 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 PhD 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.
E-mail address: sjayaraj@nitc.ac.in