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Energy and exergy analysis of a two pass photovoltaic – thermal (PV/T) air heater

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Abstract
A double pass hybrid solar air (PV/T) heater with slats is designed and fabricated to study elaborately its thermal and electrical performance corresponding to the warm and humid environment. 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. Thin metallic strips (called slats) are attached longitudinally at the bottom side of the absorber plate to improve the overall system performance (by increasing the cooling rate of the absorber plate). Thermal and electrical performances of the whole system at different cooling rates are presented. The exergy analysis of double pass hybrid solar air (PV/T) heater with slats has also been carried out. The instantaneous overall energy and overall exergy efficiency of the double pass hybrid (PV/T) solar air heater varies between 29 – 37% and 14-17% respectively. These obtained values are comparable with that of published results.

Keywords: Double pass; Exergy; Photovoltaic thermal; Solar air heater; Slats.

1. Introduction
Electrical energy has became one of the most important life supporting system in this modern electronic era. The growth of a nation's economy directly gets effected on the development of its power sector. Increase in population with higher living standards enhances the pressure on conventional energy sources. Renewable energy sources are predominantly environmental friendly as well as have potential to provide sustainable solutions to the energy related problems of international community. Solar energy is considered as one of the most important sources of renewable energy. In general solar energy systems are classified as solar - thermal and solar - photovoltaic systems. Solar thermal energy systems convert solar energy into heat and photovoltaic systems convert solar energy directly into electrical energy. In solar thermal energy systems often some electrical energy is required for extracting the useful energy more effectively. A single unit obtained by combining the solar thermal energy system with photovoltaic panels fitted on the absorber plate is known as a hybrid collector or photovoltaic- thermal (PV/T) collector. A hybrid PV/T collector generates 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. Exergy analysis gives completeness to the performance evaluation of the energy producing device. Hybrid PV/T collector has potential to reduce the overall energy usage and its adverse environmental impact. A number of theoretical, numerical and experimental studies have been reported particularly during the last decade, about the solar hybrid PV/T collector using air or water as the working fluid.

Presently hybrid (PV/T) energy systems continue to be one of the very important area of research with respect to renewable energy systems. Hybrid energy system is a sort of cogeneration system which produces both thermal energy and electrical energy by using a single or multiple energy sources. Kern and Russell [1] have first put forth the concept of integrated PV/T collector based energy system. Optimized design of flat plate air collector to increase the solar absorptance is discussed by Cox and Raghuraman [2]. Agarwal and Tiwari [3] performed experiments on a building integrated photovoltaic thermal (BIPV) system fitted on the rooftop of an experimental laboratory for analyzing the energy, exergy and electrical energy under different weather conditions. The monthly energy and exergy values for Indian climates are detailed by Joshi and Tiwari [4]. It is vivid that monthly total energy was varying from 35 – 60 kWh and monthly total exergy from 7–16 kWh for different months and cities for a 1.2 m^2 PV/T collector with air as the working substance. The monthly variation of exergy has a similar behavior as monthly thermal energy for all weather conditions. Ozturk H.H [5] conducted theoretical and experimental study by developing energy and exergy model for predicting the solar cooker performance and the same is used for predicting the thermal efficiency of two models, such as box type and parabolic type. Naphon [6] conducted the numerical study on performance and entropy generation of the double pass flat plate solar air heater with longitudinal fins and the numerical predictions are done at air mass flow rate ranging between 0.02 – 0.1 kg/s. It is understood that the thermal efficiency is increasing with increase in height and number of fins, whereas the entropy generation is inversely proportional to the height and number of fins. Dubey and Tiwari [7] evaluated overall thermal energy and exergy provided in the form of heat and electricity from hybrid photovoltaic thermal (PV/T) solar water heating system considering five different cases with and without withdrawal and found that annual maximum heat and electricity are obtained in the case of continuous withdrawal. Tiwari et al. [8] introduced an analytical expression for the water temperature of the integrated PV/T solar water heater under constant flow rate. 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.

Nayak and Tiwari [9] evaluated annual thermal and exergy performance of a PV/T and Earth Air Heat Exchanger (EAHE) system, integrated with the green house. A comparison of various energy metrics of the system, considering the four weather conditions of five climatic zones was also presented. Joshi and Tiwari [10] studied the exergy analysis of hybrid photovoltaic thermal collector for cold climatic conditions of a cold region in India by obtaining the climatic data of Srinagar from the Indian Metrological Department (IMD) for a period of four years (1998-2001). Dubey et al. [11] authored a mathematical model for 'N' hybrid photovoltaic thermal (PV/T) air collectors connected in series and it is reported that 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. Ucar and Inalli [12] conducted experimentals on solar air collectors with staggered absorber sheets and attached fins on absorber plate. It is understood that the largest irreversibility is occurring at the conventional solar collectors in which collector efficiency is lowest. The experimental results also reveal 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. Wang et al. [13] simulated the influence of a building's integrated photovoltaic on heating and cooling loads for four different cases that the photovoltaic roof with ventilated air gap is suitable for the application in summer because this integration leads to low cooling loads and high photovoltaic conversion efficiency. Charalambous et al. [14] 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 performance. It is highlighted that substantial steps need to be taken towards reducing the cost to make them more competitive. Assoa et al. [15] developed mathematical model of a PV/T dual fluid collector with metal absorber. The results of numerical study and results obtained in indoor testing are compared. It was reported that the thermal efficiency obtained is nearly 80%, and electrical performance of the system is satisfactory, and still there is scope for further improvement of cooling the photovoltaic panels. Sopian et al. [16] presented the study on theoretical and experimental investigation of double pass solar air heater with porous media in the lower channel of the collector. It is reported that the presence of porous media had improved the thermal efficiency of the collector. There is a good agreement between the theoretical and experimental results of the system. Gan [17] presented a numerical study on effect of air gap on ventilation cooling of photovoltaic panels integrated on roof top of a building. It is reported that photovoltaic panel temperature decreases with increase in air gap between panels and roof of building.

It is observed that the above reported works are predominantly on single pass collectors. There is a scope for energy and exergy performance improvement of a hybrid PV/T system with improved cooling rate by providing a double pass flow, where air enters in to upper channel and leaves through the lower channel. 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 an appropriate blend of solar thermal energy system for extracting thermal energy (double pass solar air heater with slats) and solar photovoltaic system, for extracting electrical energy. It is expected that the provision of slats will improve the cooling rate and there by DPHSAH overall performance. Mono-crystalline silicon solar cells were used in the present device. The system performance is studied both in terms of energy and exergy calculations.

2. Hybrid PV/T system

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 Figure 1 (b).

Table 1. Dimensions of the 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

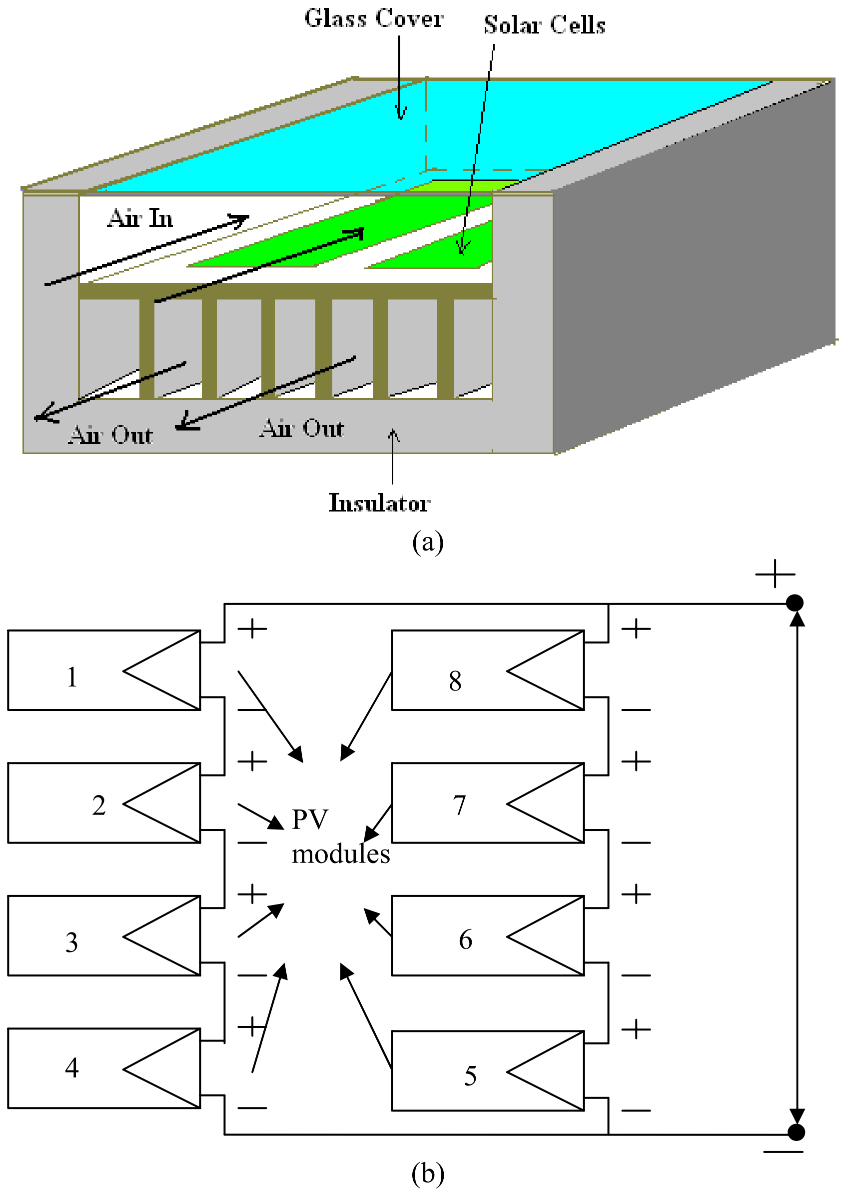

Figure 1. (a) Schematic diagram of DPHSAH with slats; (b) Schematic representation of PV module connections

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. 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 (Figure 2).

1. Inlet air temperature
2. Outlet air temperature
3. Absorber plate temperature (PV panel)

4. Slat temperature
5. Bottom plate temperature
6. Solar insolation
7. Air velocity

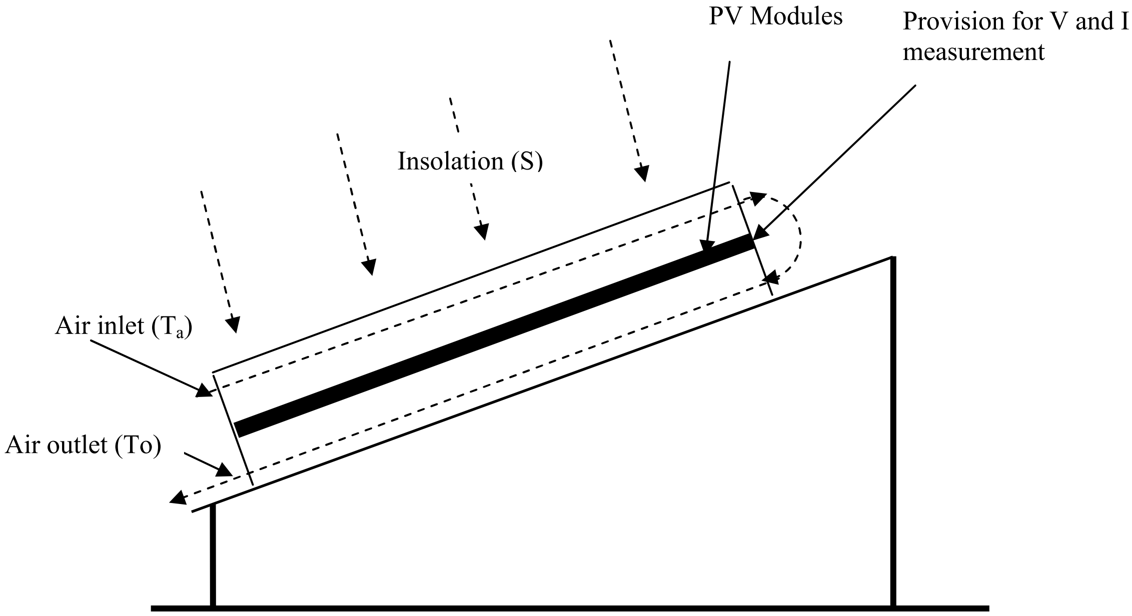

Figure 2. Schematic representation indicating locations of parameters measured

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 Figures 3 and 4.

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

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

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

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. [18]). Here ç power is the electric power generation efficiency of a conventional power plant.

Figure 3. Photograph of the experimental setup

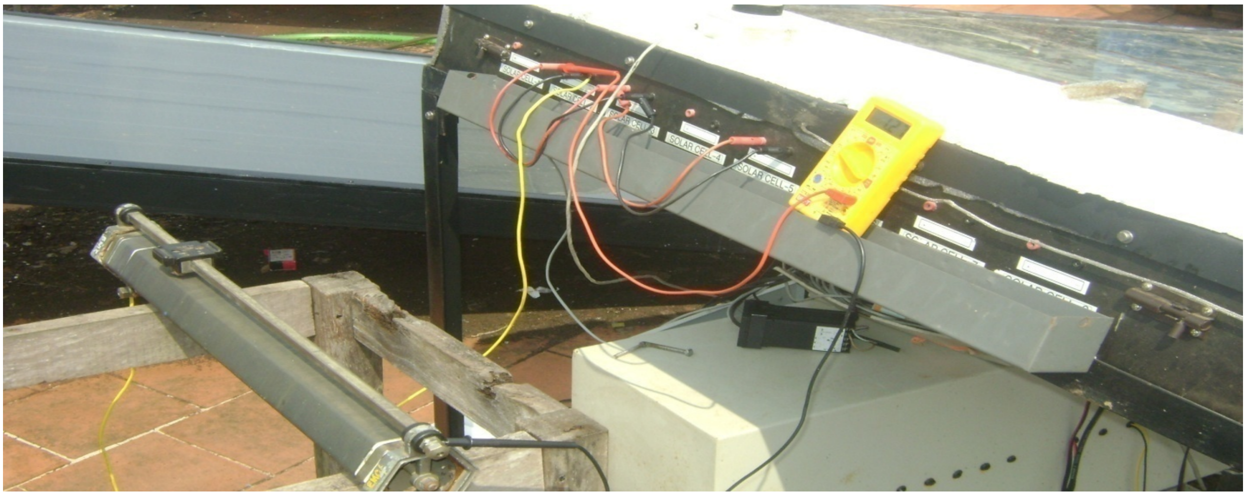

Figure 4. Instrumentation used for the experimentation in the DPHSAH

4.2 The exergy analysis

The exergy balance is based on the second law of thermodynamics which stated that the exergy inflow and exergy outflow is equal to the exergy destructed in the system.

$$\dot{E}x_{in} = \dot{E}x_{out} = \dot{E}x_{des} \tag{4}$$

$$\dot{E}x_{in} = A_c S\left[1 - \frac{4}{3}\left(\frac{T_a}{T_c}\right) + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4\right] \tag{5}$$

$$\dot{E}x_{out} = \dot{E}x_{th} = \dot{E}x_{el} \tag{6}$$

$$\dot{E}x_{th} = \dot{Q}u\left(1 - \frac{T_a}{T_o}\right) \tag{7}$$

$$\dot{E}_{x_{el}} = \eta_{cell} S A_{cell} \tag{8}$$

$$\eta_{cell} = \eta_r\left[1 - 0.0045\left(T_p - T_r\right)\right] \tag{9}$$

η_r is the reference efficiency of the module, the present value of reference efficiency of the module is 0.12 at standard test conditions, which corresponds to the ambient air temperature of 25^0C, solar intensity at 1000 W/m^2 and air mass ratio of 1.5 (Dubey and Tiwari [7]).

The exergy efficiency of a DPHSAH is defined as

$$\eta_{ex} = 1 - \frac{\dot{E}_{x_{des}}}{\dot{E}_{x_{in}}} \tag{10}$$

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

$$\eta_{oex} = \eta_{el} + \eta_{th}\left[1 - \frac{T_a + 273}{T_o + 273}\right] \tag{11}$$

4.3 Uncertainty 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	± 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 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

$$R = R\left(x_1, x_2, x_3 \ldots\ldots x_n\right) \tag{12}$$

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 [19] as

$$w_R = \sqrt{\left(\frac{\partial R}{\partial x_1} \times w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} \times w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} \times w_3\right)^2 + \ldots\ldots + \left(\frac{\partial R}{\partial x_n} \times w_n\right)^2} \tag{13}$$

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
Overall exergy efficiency = 6.1

5. Results and discussion

5.1 Experimental analysis

Hourly variation of solar radiation, ambient air and collector outlet air temperatures is presented in Figure 5. Solar radiation, ambient air and collector outlet air temperature are gradually increasing from sunrise to noon and decreasing from noon to sunset. 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, which is causing variation in the outlet air temperature. Since air is flowing over absorber plate (PV panel), it gets heated up as indicated by the outlet air temperature which is always more than the ambient air temperature (see Figure 5).

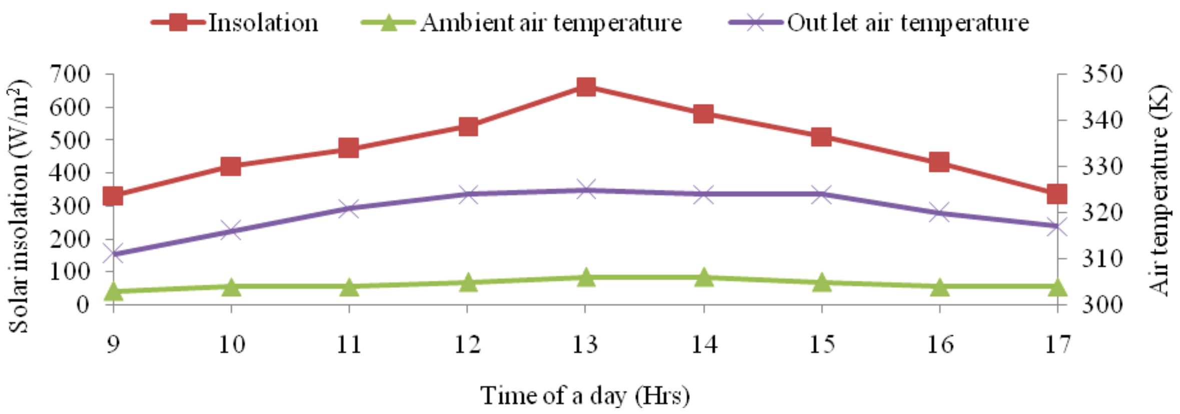

Figure 5. Hourly variation of solar insolation and fluid temperatures

Hourly variation of thermal, electrical and overall thermal efficiencies is presented in Figure 6. Lower insolation during sun rise, resulted in lower PV panel (absorber plate) temperature caused lower thermal performance (both thermal and overall thermal) and higher electrical performance. Whereas, lower absorber plate temperature (PV panels) due to lower insolation during sunrise and sunset caused lower overall thermal efficiency. On the other hand, higher insolation at mid day, raised the absorber plate and PV panel temperature resulting higher thermal, overall thermal and lower electrical efficiencies.
Figure 7 shows that thermal, electrical and overall performance of the system is increasing with increase in air mass flow rate, as air mass flow rate extracts heat which is collected by double pass hybrid collector resulting in increased thermal performance of the system. Air mass flow rate as it extracts accumulated heat of the collector, providing the better cooling of the DPHSAH, thus causing the better electrical performance of the system. Overall thermal performance is higher than both thermal and electrical individual performance of the system for any air mass flow rate. Hence, merging of solar thermal energy system and solar photovoltaic energy systems as a single hybrid photovoltaic thermal (PV/T) system can always prove to be economical. At higher air mass flow rates, better overall performance of the system noticed.

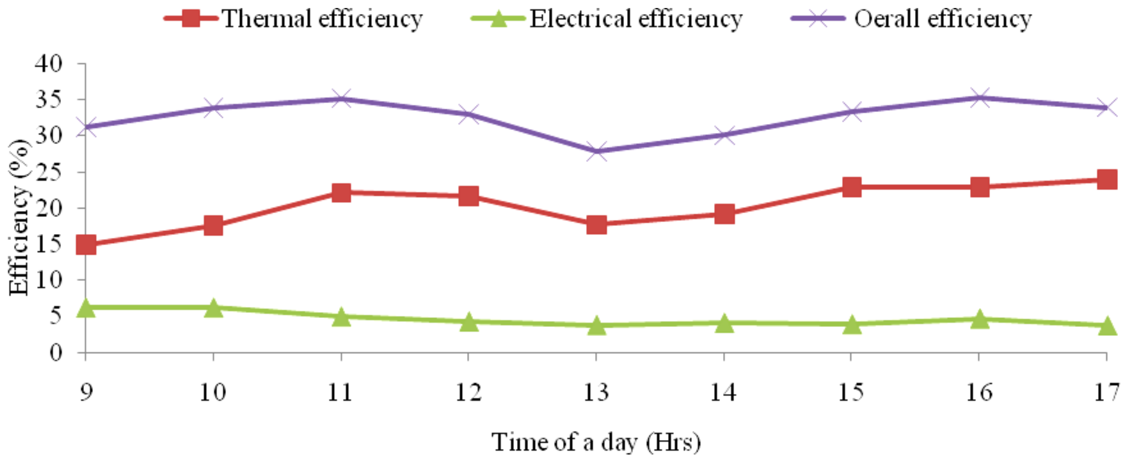

Figure 6. Hourly variation of thermal, electrical and overall thermal efficiencies

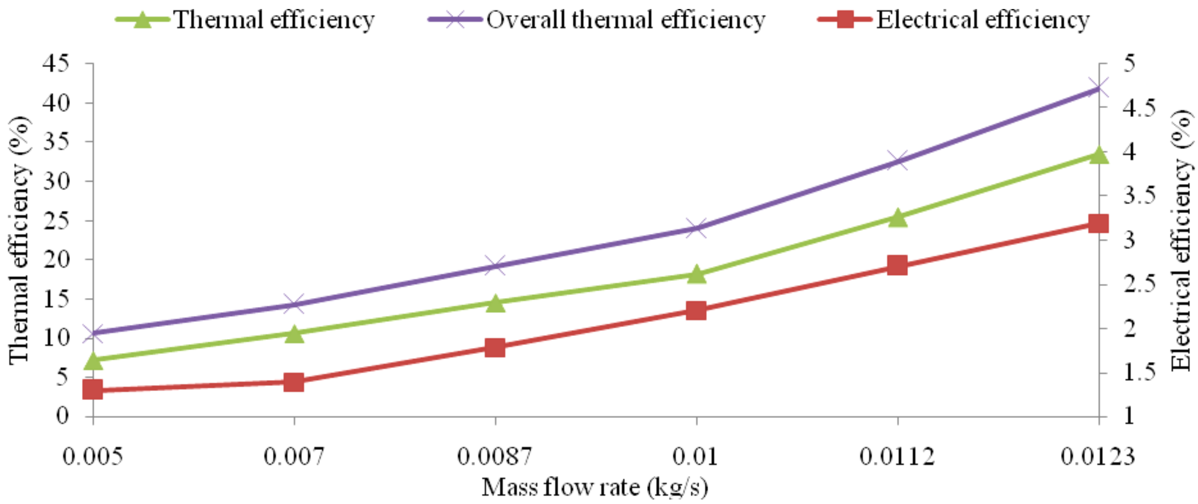

Figure7. Thermal, electrical and overall thermal efficiencies variation with air mass flow rate

Thermal exergy is increasing from morning to noon and then decreasing from noon to evening, due to lower solar insolation at morning and evening (Figure 8). Thermal exergy value is directly proportional to the solar insolation and area of the solar collector. Electrical exergy is also depends on the solar insolation however, but higher the PV panel temperature poorer will be the electrical exergy. In Figure 8 it is seen that the electrical exergy is slightly increasing for few hours of morning. However, at mid day because of higher PV panel temperature there is a minor loss in electrical exergy. Towards the evening time as insolation decreases, electrical exergy is also decreasing. Total exergy is always higher than individual thermal and electrical exergy, which is just following the trend of thermal exergy of a particular day.

Figure 9 shows system thermal exergy, electrical exergy and overall exergy. All these exergy values are increasing with respect to increase in air mass flow rate. Total exergy indicates the conversions of low grade energy form into equivalent high grade energy form. Air mass flow rate extracts heat which is collected by double pass hybrid collector resulting in increased thermal exergy of the system. Air flow extracts accumulated heat of the collector, providing the better cooling to the DPHSAH. Thus better electrical exergy of the system is obtained. Total exergy obtained is higher than both thermal exergy and electrical exergy of the system for any mass flow rate of air at higher mass flow rates, higher are the total exergies of the system. The electrical exergy is always greater than thermal exergy for any mass flow rate this is because of more losses from system while using the thermal energy than the electrical energy.

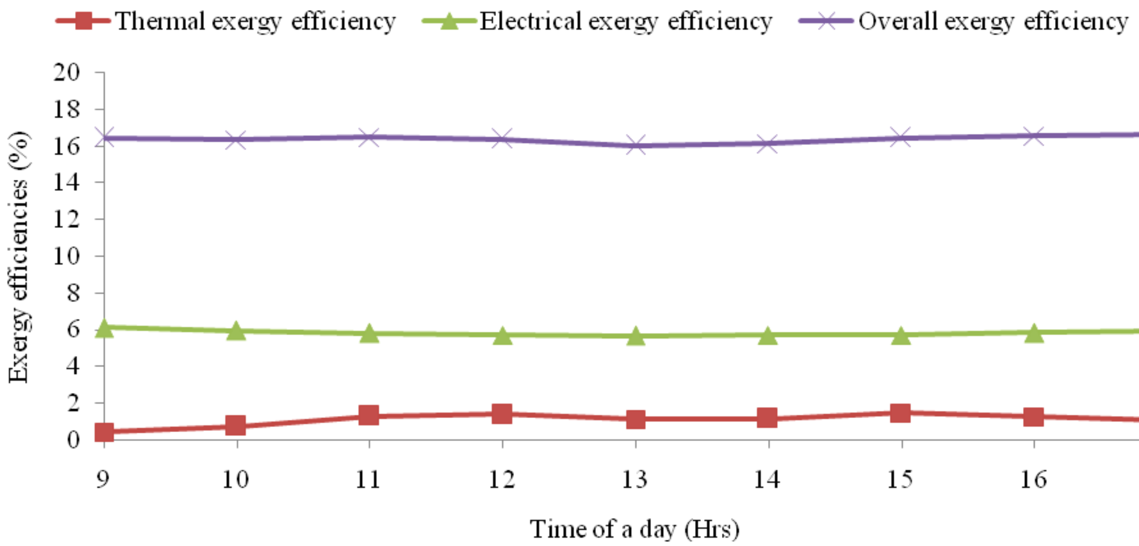

Figure 8. Hourly variation of thermal, electrical & overall exergy efficiencies

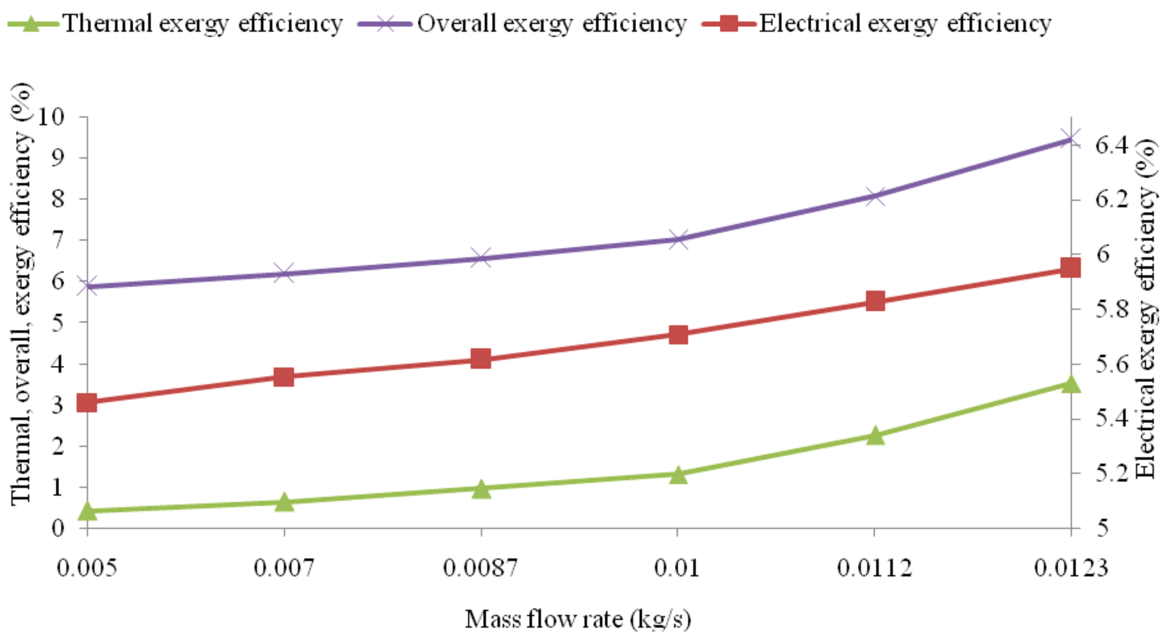

Figure 9. Thermal, electrical and overall thermal exergy efficiencies variation with air mass flow rate

The variation in overall thermal efficiency and overall exergy efficiency versus time of a day is shown in Figure 10. Overall thermal efficiency is sum of thermal efficiency and electrical efficiency, (converted in to equivalent thermal efficiency). Thermal performance increases till noon and decreases in the evening, where as electrical performance decreases till noon and increases in the evening (for a given mass flow rate of air). Unlike overall thermal performance, overall exergy efficiency is expressed by converting the thermal (low grade energy) performance in to equivalent electrical (high grade energy) performance. The sudden changes occurred in the atmosphere causes the plot appears once with sudden drops near 1PM. The overall exergy efficiency observed in Figure 10 is always less than the overall thermal (energy) efficiency as expected.

Figure 11 shows variation of overall thermal efficiency and overall exergy efficiency with air mass flow rate. Higher the air mass flow shows better performance. With increase in air mass flow rate the absorber plate cooling becomes better by extracting the accumulated heat. Hence both thermal and electrical performances get improved. The overall exergy efficiency of the DPHSAH is always less than the overall thermal energy efficiency for any mass flow rate, by an average quantity equal to 16.3%.This fact got validated in Figure 11. with η_{oex} line lying much below the η_{oth} line.

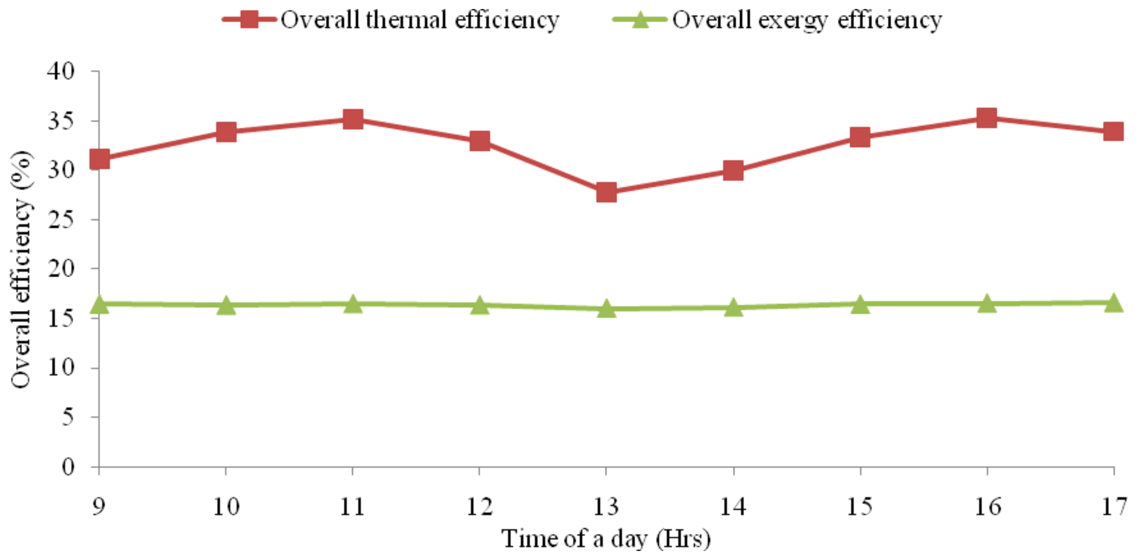

Figure 10. Hourly variation of overall energy and overall exregy efficiencies

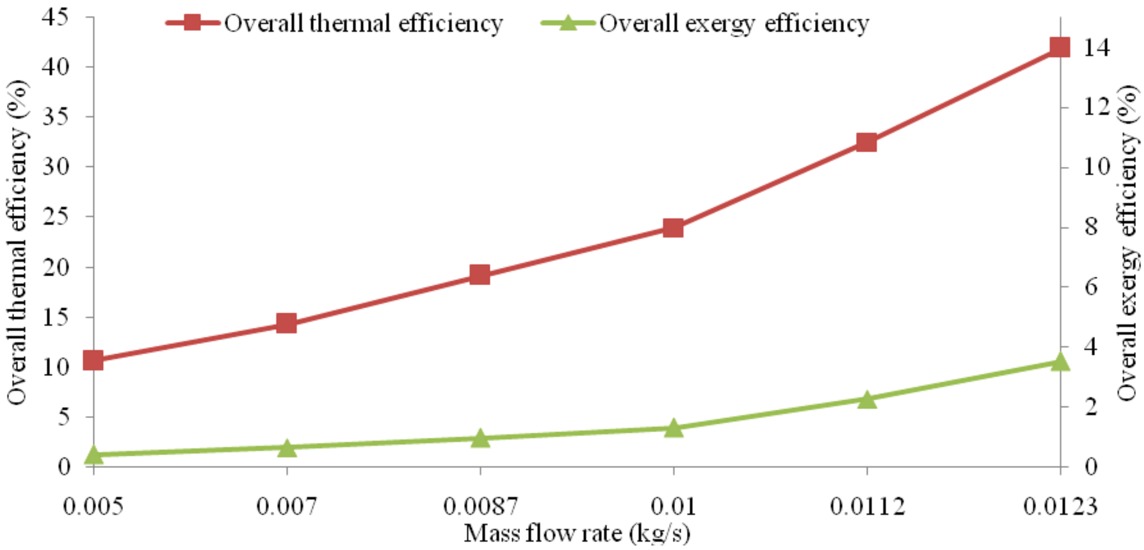

Figure 11. Overall thermal and overall exergy variation with mass flow rate

5.2 Comparison with similar results

Figure 12 shows the hourly variation of experimentally predicted overall thermal energy from present PV/T system with slats and simple box type PV/T system, Joshi and Tiwari [10] for the month of January. The present DPHSAH is operated with air mass flow rate of 0.0123 kg/s where as Joshi and Tiwari [10] has presented results corresponding to 1 kg/s. The higher air flow rate resulted in higher thermal energy values from box type PV/T system. It is concluded that for a same air mass flow rate the DPHSAH will result a higher thermal energy value than PV/T box type system.

Figure 13 shows the hourly variation of experimentally predicted overall exergy from present PV/T system with slats and simple box type PV/T system (Joshi and Tiwari [10]) for the month of January. Similar to the case of energy values the higher air flow rate resulted in higher overall exergy values. It can be concluded that for the same air mass flow rate, the DPHSAH will result in a higher overall exergy value than PV/T box type system. The variation of exergy efficiency from the referred box type system lies between 12% and 15% for the month of January, where as for the present DPHSAH lies between 16 % and 16.6%.

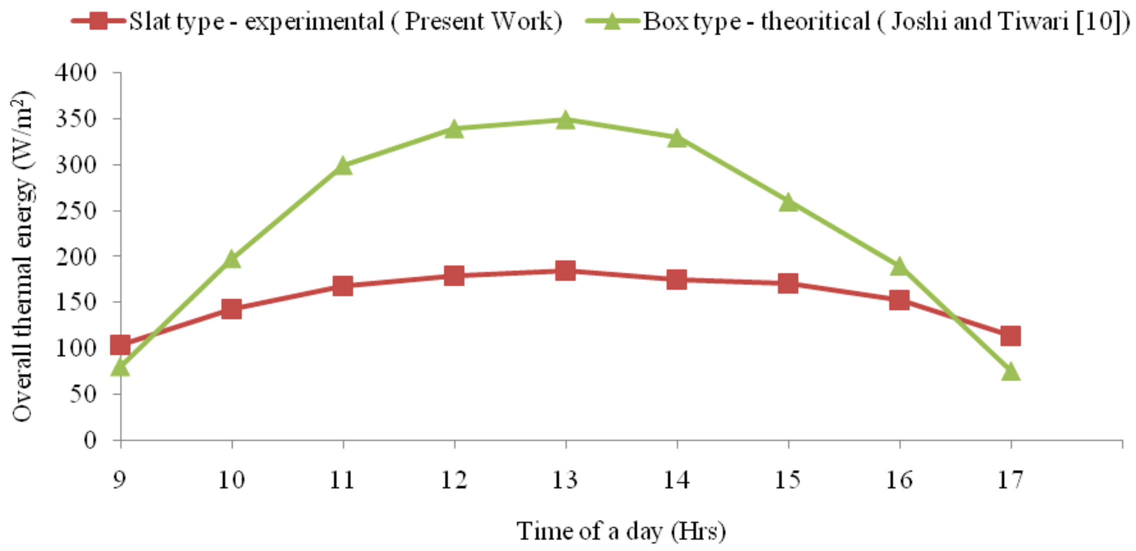

Figure 12. Hourly variation of experimental and theoretically predicted overall thermal energies

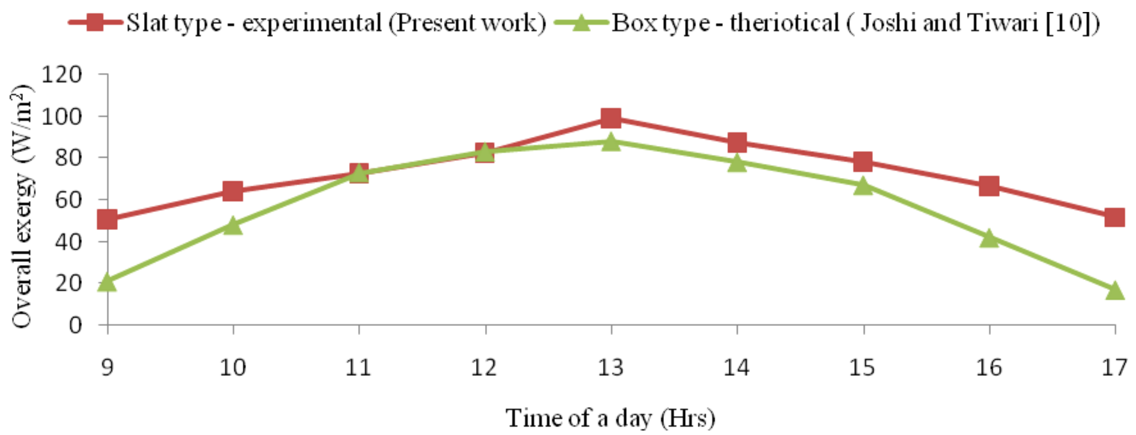

Figure 13. Hourly variation of experimental and theoretically predicted overall thermal exergy values

6. Conclusion

Hybrid photovoltaic-thermal solar collector with slats was experimentally studied with respect to its operating characteristics. Solar cells are expected to generate more electricity when it is exposed to higher solar insolation, however its efficiency drops when temperature of the solar cells increases. Results obtained indicated that the 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 found to be higher. Thus loss in electrical energy output is compensated to some extend by the thermal gain of the system and thus hybrid system becomes very relevant. It is found to be 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_{cell}	solar cells area (m^2)
C	specific heat (kJ/kg K)	$\dot{E}_x$	exergy (W/ m^2)
$m^{\cdot}$	mass flow rate of air (kg/s)	$Q^{\cdot}$	useful heat transfer (W)
S	solar insolation (W/ m^2)	T_i	ambient air température (^{0}C)
T_o	air temperature at the outlet of collector (^{0}C)		

Greek letters

η_{cell}	temperature dependent cell electrical efficiency	η_{el}	electrical efficiency
η_{elex}	electrical exergy efficiency	η_{oex}	overall exergy efficiency
η_{oth}	overall thermal efficiency of the system	η_{thex}	thermal exergy efficiency

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