

Investigations on the Performance of a Two Pass, Hybrid -Type Solar Air Heater with Slats

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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 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: *Photovoltaic; Solar air heater; Slats; Double pass; Artificial neural networks*

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 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, 1978). 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, 2011). For different months and cities, for a 1.2 m² 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, 2007). In various types of solar cookers, the performance and exergy analysis offers an alternative method for evaluation and comparison (Huseyin, 2004). 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, 2005).

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)
\dot{m}	Mass flow rate of air (kg/s)
S	solar insolation (W/ m ²)
T_i	ambient air temperature (°C)
T_o	air temperature at the outlet of collector (°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

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, 2010). 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., 2009). 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, 2009). The instantaneous energy and exergy efficiency values of PV/T air heaters varies from 55% to 65% and 12% to 13% respectively (Joshi and Tiwari, 2007). 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., 2009). 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, 2006). The photovoltaic roof with ventilated air gap was suitable for the application in summer, because this integration could lead to low cooling loads and high photovoltaic conversion efficiency (Wang et al, 2006). Substantial steps need to be taken towards reducing the cost to make PV/T collectors more competitive (Charalambous et al. 2007). 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., 2007). The presence of porous media had improved the thermal efficiency (theoretical and experimental) of the double pass solar air heater (Sopian et al., 2009). The photovoltaic panel temperature decreases with increase in air gap between panels and roof of building. (Gan, 2009). It is observed that the recent 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.

II. HYBRID (PV/T) SYSTEM DESIGN

The double pass hybrid photovoltaic thermal (PV/T) solar air heater (DPHSAH) consist of aluminum absorber plate of dimensions 1 m x 2 m ($W \times L$) and thickness 2 mm. The height of the upper and lower channels is 5 cm (each). The sides and bottom of the collector are 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) are fixed longitudinally at equal distance at the bottom side of the absorber plate. Top surface of the absorber plate and lower channels are coated with black paint for increasing the absorptivity of the system. A toughened or tempered glass of dimensions 1 m x 2 m ($W \times L$) and thickness 2 mm is 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, are fixed over an absorber plate. The total area covered by solar cells is 1.054 m². Therefore, the packing factor or the fraction of the total collector area covered by the photovoltaic cells is 0.527. The double pass PV/T solar collector is shown schematically in Fig. 1(a) and (b).

III. EXPERIMENTAL SETUP

PV panels made of mono-crystalline silicon solar cells are 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 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 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) increases the heat transfer rate to the air and by conducting heat to bottom plate thus enhances 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° facing south at the Solar Energy Center located in National Institute of Technology Calicut is shown in Fig. 2 (a) and (b).

1.1 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

Data acquisition system is used to record parameters under consideration for the performance study of DPHSAH. Data acquisition systems used typically converts the analog waveforms into digital values for processing. The components of data acquisition systems include

(i) Sensors (such as, solar radiation sensors, temperature sensors etc.) that convert physical parameters to electrical signals.

(ii) Signal conditioning circuitry to convert sensor signals into a form that can be converted to digital values (such as, mV into V).

(iii) Analog-to-digital converters, which convert conditioned sensor signals to digital values (such as, numerical values of temperature, solar insolation etc.) stored with help of a computer.

Agilent VEE PRO (graphical programming language) software is used for recording the data with the help of computer.

1.2 Experimental procedure

The PV/T collector was tested at nominal operating conditions with insolation 620 W/m^2 , ambient temperature equal to 31°C and wind speed equal to 1 m/s 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 50Ω , 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 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.

IV. PERFORMANCE ANALYSIS

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

$$\eta_{th} = \frac{\dot{m} c \Delta T}{SA_c} \times 100 \quad (1)$$

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

(2)

$$(\eta_{th})_o = \eta_{th} + (\eta_{ei})/0.38$$

(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 for India. Huang et al. (2001). 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.

V. 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 (Fig 3). A total of 207 sets of inputs (such as, ambient air temperature, solar radiation and mass flow rate of air) and 207 outputs (such as, thermal efficiency and electrical efficiency) are used to train the network.

VI. RESULTS AND DISCUSSION

Figure 5 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. Hourly variation of solar radiation, ambient air and collector outlet air temperatures on 1st February 2011 is 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. Figures 6 and 7 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 Fig.8) however, at higher air mass flow rates, electrical performance of the system is better (as represented in Fig.7). 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. Figures 8 and 9 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 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 11 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 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 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. Figures 11 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.

VII. 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.

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