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Performance Evaluation of Solar Photovoltaic / Thermal (PV/T) System

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Abstract: ***Solar photovoltaic/thermal (PV/T) system consists of PV module coupled with heat extracting media such as water. Solar (PV/T) collector at the same time produces both thermal energy and electricity. The electrical output of a photovoltaic module drops as its surface temperature increases. Solar PV/T system's design aims to reduce the operating temperature of PV modules and to keep the electrical output at adequate level. When there is temperature change in any process, there is a loss of exergy. In comparison, exergy efficiency is lower for electricity generation using the considered PV module, ranging from 8% to 10%. It is observed that photovoltaic module temperature has a considerable effect on the various efficiencies of the system such as thermal, electrical or exergy efficiency. The increase in operating temperature of the system also affects the properties of material used in manufacturing of PV module. The electrical efficiency can be improved if the heat can be removed from the surface of photovoltaic module and at the same time it also improves other efficiencies. In this paper the performance analysis including all aspects i.e. electrical, thermal and exergy efficiency are discussed. Mass flow rate of coolant fluid also plays an important role in heat extraction from photovoltaic module. In this paper the analysis of performance of solar (PV/T) system is done by varying mass flow rate of coolant fluid.***

Keywords: Energy, Exergy, Hybrid Solar PV/T Collector, PV/T System, Solar Energy

1. Introduction

Energy is one of an important and significant factor in the economic development of any country. With increase in economic development of any country also increases the energy consumption. Today the world daily oil consumption is 85 million barrels of crude oil and it is expected that this will increase to 123 million barrels per day by the year 2025 [1]. As fossil fuels are well known for their environmental impact and this increase in demand of crude oil will be the main reason for pollution. Solar energy is the primary source of energy and also having advantages of non-polluting, easily available and environment friendly. Solar energy is one of the most important source of renewable energy at earth's surface and that what world needs. The applications of solar energy can be divided into two categories, Solar Thermal system (T) and Solar Photovoltaic system (PV). When we combine solar photovoltaic system (PV) and solar thermal system (T) in one system, it results in formation of solar photovoltaic thermal (PV/T), which is a hybrid system that converts solar energy into electricity and heat at the same time from one integrated system. The designing of solar photovoltaic thermal (PV/T) system have different approaches. The design parameters are based on type of collector used for collecting the solar radiation, thermal output, electrical output, solar fraction and the temperature at which the system operates. There can be selections among mono-crystalline solar cell, poly-crystalline solar cell, a-Si solar cell or thin-film solar cell, glazed or unglazed solar module, circulation of coolant either natural or forced or combination of both, type of coolant either air, water or both etc. In conventional photovoltaic system, high incident solar radiation on (PV) panel should give high electrical efficiency. However, high incident will increase the temperature of the solar cells and that will decrease the efficiency of the panel. A solar photovoltaic cell converts solar radiation into electrical energy with peak photoelectric conversion efficiency in the range of 6–15%, depending on type solar-cell at standard temperature and pressure. In conventional photovoltaic system, higher incident solar radiation on solar photovoltaic panel should give high electrical output. However, high incident radiation will also increase the surface temperature of the solar cell and that will decrease the photoelectric conversion efficiency of the solar cell. As there is increase in operating temperature of PV module by 1 ^{0}C there is reduction of the photoelectric conversion efficiency by 0.5%. In addition to decrease in temperature of photovoltaic module and increase in performance efficiency, the design of hybrid system gives other advantages also such as a lower thermal stresses and hence an increase in life of the photovoltaic module, optimum performance and reliability, less maintenance and a smooth solar cell current–voltage characteristics. Lot of research has been done in the field of solar photovoltaic thermal (PV/T) hybrid systems in past 25 years. Wei He et. al.[2] designed a hybrid photovoltaic/thermal system for natural circulation of water and aluminium-alloy as thermal absorber. They found thermal efficiency was around 40%, electrical efficiency was around 9.87%. Boddaert and Caccavelli [3] have designed and developed hybrid solar panels that consist of polycrystalline silicon cells and heat exchanger. The cheap roll-bond technology using aluminium is specially designed with a hollow tube in the middle of it act as the heat exchanger system underneath the PV module. Tiwari and Sodha [4] have developed an integrated photovoltaic and thermal solar system (IPVTS) which is a combination of water and air type of PV/T collector system. They deployed and configured four systems, which are; the unglazed with tedlar, glazed with tedlar, unglazed without tedlar and glazed without tedlar. The data shows that the overall thermal efficiency of the system during summer and winter conditions is approximately 65% and 77%. Zondag

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et al. [5] conducted a comparative study and observed that all channel concepts have slightly higher efficiency when compared to the sheet and tube due to better heat transfer characteristics of channel. Fraisse et al. [6] has been studied a energy performance of water hybrid PV/T collectors applied to the combisystems. The combisystem, has been installed in Macon area in France, without PV glass cover, produced efficiency of 10% which is 6% better than a standard module. Sandnes and Rekstad [7] have performed the experimental and analytical model for PV/T collector. In this experimental, a polymer absorber collector is combined with single-crystal silicon PV cell and assembled it as a hybrid energy generating system. Ji et al. [8] studied a facade integrated PV/T collector for residential building in Hong Kong. The annual thermal efficiencies were found to be around 48% for the thin film silicon and 43% for the crystalline silicon case respectively.

2. Methodology

The experiments were carried out under the following conditions:

Location	Bhopal, Madhya Pradesh, India
Meteorological Conditions	Latitude of 23.16ºN; Longitude of 77.24ºE
Month	April 2014 and May 2014
Time	10.00 a.m. to 5.00 p.m.

2.1 Solar PV/T Water Collector Construction

The solar PV/T is constructed using polycrystalline silicon solar panel. Behind the panel copper sheet and copper tube is attached. Copper sheet acts as an absorber, which absorbs heat from the panel and transfers it to coolant fluid flowing in copper tubes. A pump is used to circulate the coolant in the system. Water is used as a coolant in the system with a varying mass flow rate. Solar intensity, wind velocity, ambient temperatures, relative humidity, open circuit voltage, short circuit current, maximum power, front side and back side temperature of module, fill factor, voltage and current at maximum power, initial and final temperature of water were measured every one hour from 10.00 a.m. in the morning to 5.00 p.m. in the evening for both solar PV and solar PV/T systems.



Figure 1: Experimental setup of PV and PV/T system

2.2 Measurements

Table 2: Instruments Used In Experiment

S.No.	*Instrument*	*Range*	*Model make*
1	Solar Module Analyser	0-10 V, 0.01-10A	MECO 9009
2	Solar Power Meter	0-1999 W/m^2	Tenmars TM-207
3	Humidity/Temperature meter	R.H. – 0 – 80% & 0-50 ^{0}C	Lutron HT-3006A
4	IR Thermometer	-18 to 400 ^{o}C	Raytec MT4
5	Mercury Thermometer	-10 ^{0}C to 110 ^{o}C	Elite

2.3 Performance Evaluation

Combination of efficiency terms describes the performance of PVT collector. Thermal efficiency and electrical efficiency are the basic ones. Thermal efficiency and electrical efficiency are respectively the ratio of useful thermal gain and electrical gain of the system to the incident solar irradiation on the collector's aperture within a given period. The sum of thermal and electrical efficiency is known as overall efficiency and is commonly used to assess the overall performance.

Photo Electric conversion efficiency,

$$\eta e = \frac{I_m V_m}{GA} \quad (1)$$

Thermal Efficiency,

$$\eta th = \frac{mc_p (T_f - T_i)}{GA} \quad (2)$$

Where, m is mass flow rate of water, cp specific heat of water (4200 J/KgK), G is the daily global solar radiation on the collector surface, T_i is initial temperature and T_f is the final temperature of the water at the storage tank.

Overall Efficiency, $\eta_o = \eta_{th} + \eta_e$ (3)

Considered electrical energy as a high grade form of energy gain, the energy saving efficiency η_f is also used [9]: it is defined as:

$$\eta_f = \eta_e / \eta_{power} + \eta_{th} \quad (4)$$

Where η_{power} is the electric power generation efficiency of the conventional power plants; its value can be taken as 38%.

2.3.1 Energy Efficiency of Solar Panel

According to first law of thermodynamics, the exergy equation for an open system under steady state assumption, can be written as

$$E_{in} = E_{out} \quad (5)$$

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General equation for the exergy balance:

$$EX_{in} - E_{out} = E_{loss} \quad (6)$$

Energy efficiency of the solar PV can be defined as the ratio of power output to energy input of the solar PV. The output power and energy efficiency of the PV system, however, fluctuates depending on solar insolation and surface temperature.

The electric power output of PV is:

$P_{el} = I \times V$ (7)

The maximum power output is given by:

$P_{max} = V_{OC} \times I_{SC} \times FF$ (8)

$P_{max} = V_{mp} \times I_{mp}$ (9)

The solar energy absorbed by the PV modules is converted to electric energy and thermal energy, which is dissipated, by convection, conductive, and radiation. The rate of the heat transfer process depends on the design of the PV system. To achieve the efficiency of a PV module its operating temperature T_C must be determined which is for simplicity could be assumed homogenous on the plate and it is depends on the ambient conditions. The higher surface temperature could cause reduction in PV efficiency. Therefore, the cells may be cooled artificially by passing air or water on the backside of the module especially in the hot region. A dynamic thermal model proposed by Duffie and Beekman, included a lump overall loss coefficient UL for a unit area [10].

2.3.2 Exergy Efficiency of Solar Panel

Exergy analysis includes a consideration of energy quality or capability, which permits evaluation of the most effective, not just most efficient, use of energy potential. For the steady-state flow process during a finite time interval, the overall exergy balance of the solar PV can be written as follows [3].

Exergy Input = Exergy Output + Exergy Loss + Irreversibility

This degradation in the quality of energy is called exergy loss (availability loss). The exergy loss is also called irreversibility [12]. Exergy efficiency of the photovoltaic module is also defined as the ratio of total output exergy to total input exergy [11, 13, 14]. An exergy efficiency of the solar PV can be defined as the ratio of the exergy gained by the solar PV (exergy output) to the exergy of the solar radiation (exergy input) [15].

$$\eta_{ex} = \frac{E_{x_output}}{E_{x\ input}} \quad (10)$$

Table 3: Input parameter used for analysis

Input parameter	*Value*
Nominal operating cell temperature (NOCT)	41 °C
Stefan Boltzmann constant (σ)	5.67×10^{-8} W/m^2-K
Emissivity of the panel (ε)	0.9
Sun temperature	5800 K

3. Results and Discussion

In the present study, a commercial 37W polycrystalline PV module is used to build an PV/T water collector system. The present test results show that the energy saving efficiency of a hybrid PV/T system for various mass flow rates exceeds 0.70, which is larger than the efficiency of conventional solar water heating system. The overall performance of PV/T system including electrical and thermal conversion is affected by various factors like Mass flow rate, inlet & outlet water temperature, intensity of solar radiation, ambient temperature, wind speed, orientation of system.

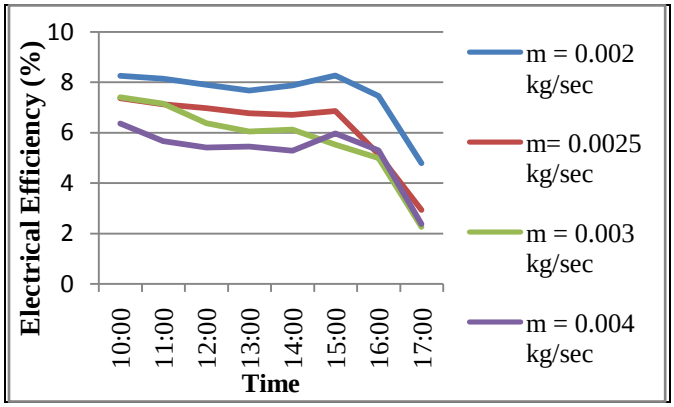


Figure 2: Variation of Electrical Efficiency for various mass flow rate for PV/T

The electrical efficiency of solar module decreases by 0.5% with rise of 1 ^{0}C in temperature. The maximum electrical conversion efficiency is obtained at 25 ^{0}C and 1000 W/m^2. Figure 2 shows the variation of electrical efficiency of PV/T system for various mass flow rates. The electrical efficiency of PV/T varies between 5 - 8% for different flow rate. For flow rate of 0.002 kg/sec the efficiency of the system is between 7 – 8 %.

Figure 3 shows the variation of thermal efficiency of PV/T for various mass flow rates. Thermal efficiency of PV/T varies from 40% to 74% for different mass flow rates. For mass flow rate of 0.003%, thermal efficiency exceeding 74% and the average thermal efficiency was found to be 61.43%. The minimum average thermal efficiency of the system was found to be 52.30% for the mass flow rate of 0.002 kg/sec.

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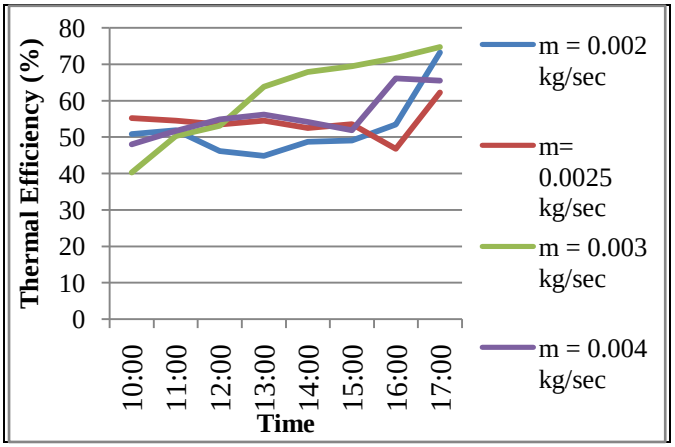


Figure 3: Variation of Thermal Efficiency for various mass flow rate for PV/T

Overall efficiency is the sum of thermal efficiency and electrical efficiency. Figure 4 shows the variation of overall performance of the PV/T system. Overall efficiency of the PV/T system varies from 51% to 77% for different flow rates. Maximum average overall efficiency was found to be exceeding 67% for mass flow rate of 0.003 kg/sec and minimum average overall efficiency was found to be 59.84%.

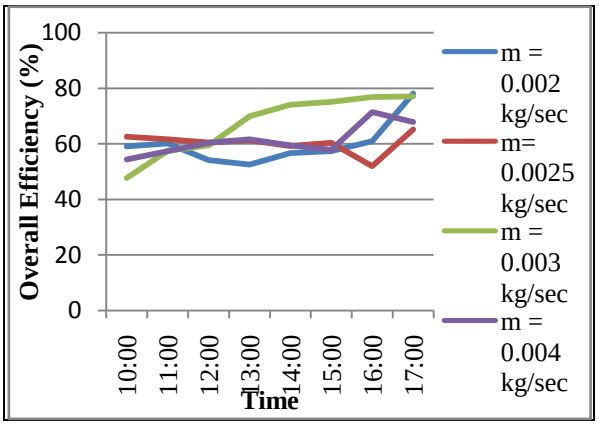


Figure 4: Variation of Overall Efficiency for various mass flow rate for PV/T

Figure 5 shows the variation of exergy efficiency of PV/T for different mass flow rate of water. The exergy of a system is the part of low grade energy which is available for conversion to high grade energy. Exergy efficiency of the PV/T varies from 2% to 13% for various mass flow rates. The maximum exergy efficiency was found to 13.10% for the mass flow rate of 0.002 kg/sec.

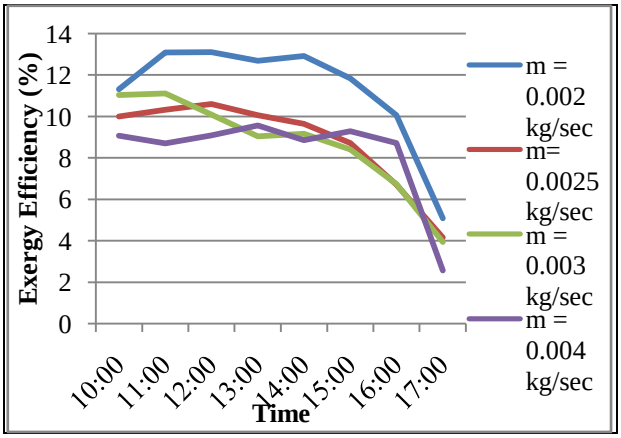


Figure 5: Variation of Exergy Efficiency for various mass flow rate for PV/T

Figure 6 shows the variation of energy saving efficiency of solar PV/T for various mass flow rates. The variation of energy saving efficiency is from 40% to 73%. The maximum average energy saving efficiency was 61.58% for the mass flow rate of 0.003kg/sec and minimum average energy saving efficiency was found to be 52.49% for the mass flow rate of 0.002 kg/sec.

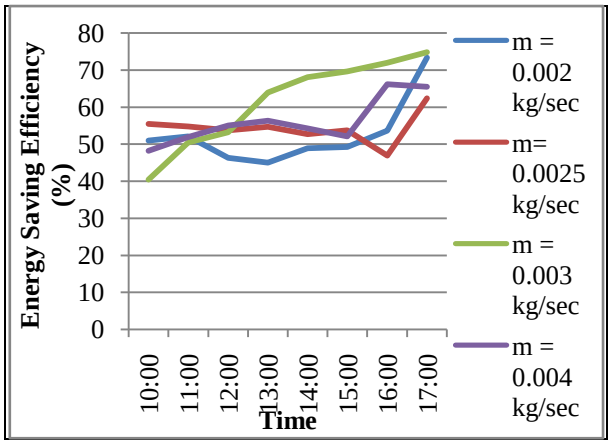


Figure 6: Variation of Energy Saving Efficiency for various mass flow rate for PV/T

4. Conclusion

This article has presented energy and exergy evaluation of the photovoltaic/thermal water collector different mass flow rates. A combined thermal and photovoltaic solar water heating system was successfully designed by using copper sheet as absorber on the back side of the polycrystalline silicon solar cells. A preliminary study of applying this technology in a university building of MANIT, Bhopal has been described. Experiments are conducted with varying water flow rate from 0.002 kg/sec to 0.004 kg/sec and with different initial water temperature in the outdoor environment. By using the PV/T technique, the experimental result has shown the significant improvement on the electrical efficiency of PV module. The results show that the electrical and thermal performance of the combined PV/T system is much more than that of employing the PV alone. The performance of PV/T system for different flow rates was analyzed in detail and an optimum flow rate is determined. The overall efficiency of PV/T varies from 47 – 77% for the mass flow

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rate of 0.003 kg/sec. The maximum average overall efficiency of PV/T was found to be 67.16% for the mass flow rate of 0.003 kg/sec. The exergy efficiency of PV/T varies from 5% to 13% for the mass flow rate of 0.002 kg/sec. The maximum average exergy efficiency of PV/T was found to be 11.26% for the mass flow rate of 0.002 kg/sec. With increase in mass flow rate of water, average electrical efficiency of solar PV/T system increases as compared with solar PV system. This is because of the increase in mass flow rate of water increases the cooling rate of panel. Exergy analysis of solar PV/T system was also carried out for different mass flow rate of water and it was found that with increase in mass flow rate of water the exergy efficiency of solar PV/T system decreases. PV/T application can offer sustainable solution for maximizing the solar energy output from building integrated photovoltaic system. This kind of PV/T system is especially suitable for low temperature applications like pre-heating of domestic water.

Nomenclature

η_f	Energy Saving Efficiency	%
η_{th}	Thermal Efficiency	%
η_e	Electrical Efficiency	%
η_o	Overall Efficiency	%
V_{oc}	Open circuit voltage	V
V	Voltage	V
V_{mp}	Voltage at maximum power point	V
I_{mp}	Current at maximum power point	A
I_{sc}	Short circuit current	A
I	Current	A
FF	Fill factor	No units
m	Mass flow rate	Kg/sec
A	Surface area of the module	m^2
G	Global irradiance	W/m^2
K	Boltzmann constant	J/K
P_{el}	Electrical power	W
P_{max}	Maximum power	W
T	Temperature	K
T_a	Ambient temperature	K
T_m	Module temperature	K
NOCT	Nominal operating cell temperature	^oC

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