Heat Transfer Analysis and Waste Heat Recovery of Specially Designed Heat Exchanger used in Hybrid Solar Water System

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Abstract- The amount of heat extracted from bottom surface of PV module of hybrid solar water system is strongly influenced by air gap between bottom surface of module and top surface of heat exchanger. The heat transfer analysis between these two surfaces and waste heat recovery of specially designed heat exchanger used in hybrid solar water system are studied in this research work for latitude of Mumbai. For this configuration, outside heat transfer coefficient of stagnant air was calculated and found to be 50 $W/m^2\,{}^0k$. By using desired equations and correlations, air gap between these surfaces was found to be 0.53 mm. For this air gap at highest electrical power point condition, with solar radiation of 918 W/m^2 and mass flow rate of 0.035 kg/sec, the system was able to generate a combined power with PV/T efficiency of 53.7 % and PV efficiency of 11.7 %. Experimental results showed that increase in heat transfer from these surfaces was strongly influenced by the air gap.

Keywords- Hybrid PV/T solar water system; overall heat transfer coefficient; heat transfer coefficient of stagnation air; combined PV/T efficiency.

1. Introduction

An absorbed solar radiation by PV module results in generation of electricity and it’s heating. The cooling of PV module improves its electrical efficiency at a reasonable level. Generally PV module is cooled by circulating cold water through a heat exchanger called as PV absorber surface, fitted at its bottom surface. In hybrid PV/T solar water system, simple flat plate PV module and heat exchanger fitted at the bottom surface, extracts heat from module and cools it at desired temperature. Both devices are mounted together converting solar energy to electrical and thermal energy from one integrated system. This system generates higher combined energy output per square meter of a conventional PV module and could be used as a cost effective method if additional cost of thermal unit is kept minimum.

Normally in hybrid solar water systems, heat exchanger with different geometries and materials have been fabricated and fitted at bottom surface of module. The performance of hybrid system depends mainly on heat transfer rate from module to working fluid of heat exchanger. For small or negligible air gap between these surfaces, performance of hybrid solar water systems enhances drastically. Such modified hybrid systems will be financially viable in near future for domestic, swimming and other low temperature applications.

Simple review was conducted on research, development and selection of various PV absorber designs, materials and use of concentrators for higher energy output of hybrid solar systems [1].Overall system performance of PV module could be improved by applying these augmentation techniques to existing simple hybrid solar systems.

Critical review was carried on enhancement in system performance of a hybrid PV/T water collector system for various heat absorbing fluids and configurations of heat exchanger with different materials [2]. Spiral flow heat exchanger with copper material fitted with reflectors could produce highest combined power PV/T efficiency compare to simple hybrid solar water system and this system could be commercially viable in future.

Different experiments were performed at the University of Patras and Rome on hybrid PV/T system with & without Glazing, and with & without reflectors with system operating at temperatures of 25 ^{0}C, 35 ^{0}C and 45 ^{0}C respectively [3]. The PV/T system with Glazing and flat reflectors at system operation at 25 ^{0}C was found generating maximum annual electrical energy of 167.98 kWh/m^2 y with electrical efficiency of 10.21% and maximum annual thermal energy of 831.75 kWh/m^2 y with efficiency of 50.57 % as compared to other operating temperatures.

An experimental study was conducted on hybrid PV/T water collector system by using two heat exchanger surfaces i.e. sheet and tube type absorber and fully wetted surface absorber [4]. During the experiment, it was observed that, the wetted collector surface and sheet-and-tube surface could produce 65% and 60.6% combined PV/T efficiency respectively. The performances of above two absorber surface were also compared by considering unglazed and glazed designs. The results of this work showed that unglazed system fitted with heat exchanger produces more electrical energy than conventional PV module. It was also noted that the glazed system could generate more thermal energy than unglazed system.

The investigational study was performed on conventional flat plate PV module by running thin film of water over its top surface to determine the effect of direct cooling on overall performance of PV module [5]. Experimental studies showed that working temperature of PV module for combined system was found lower as compared to un-cooled PV module as heat exchanger was continuously engaged in cooling of PV module. Heat removed from PV module by water film was utilized for low temperature applications, increasing overall efficiency of combined PV/T system. The experimental work revealed that the electrical performance of the combined system was 33% higher than un-cooled module.

Three PV/T water collector systems i.e. direct flow, Parallel flow and Split flow were designed and their thermal performances had been compared experimentally at various tilt of hybrid PV/T system [6]. During these experiments, it was found that split flow PV/T system produced 51.4 % more thermal power as compared to other two PV/T systems.

The investigational study was performed on PV/T water collector system using a stainless steel spiral flow absorber collector as a heat exchanger surface fitted at bottom surface of module [7]. During this study, the performance outcomes on photovoltaic, thermal and combined PV/ water collector system over range of operating conditions were discussed and analyzed. At solar irradiance of 1321 W/m^2 and mass flow rate of 0.041 kg/s, hybrid PV/T system was able to produce combined PV/T efficiency of 65 % with electrical efficiency of 12%.

The various experiments had been conducted on sheet and tube heat exchanger PV/T water collector systems with flat concentrators fitted to both sides of module [8]. Two flat Aluminum sheet concentrators were mounted on both sides of PV module at an angle 10^0 and 56^0 to the vertical plane of PV/T water collector. These concentrators were effective in producing 8.6% and 39 % of more PV electrical and thermal energy respectively than simple PV module. It was also found that the addition of Aluminum foil concentrators to the module could increase production of electrical and thermal energy by 17.1% and 55% respectively as compared to simple PV module.

The different experiments were performed on seven new configurations of heat exchangers namely Direct flow, Oscillatory flow, Serpentine flow, Web flow, Spiral flow, Parallel-Serpentine flow and Modified Serpentine-Parallel used in hybrid PV/T collectors and their performances had been investigated and compared by simulation techniques [9]. From simulation results it was found that spiral flow design of heat exchanger could produce highest thermal efficiency of 50.12% with cell efficiency of 14.98%.

The analytical model was developed for behavior analysis of PVT collector at stagnation and with flow of water [10]. By this analysis, the average thermal and electrical efficiency obtained were 49.68 % and 3.57 % at mass flow rate of 235 ml/h. With mass flow rate of 173 ml/h, the average thermal and electrical efficiency were found increasing to 51.27% and 2.54% respectively.

Present research work determines effect of air gap between top surface of heat exchanger and bottom surface of module on the performance of hybrid solar water system. For this investigation the air gap and its effect on heat transfer analysis has been carried out at the mass flow rate which generates highest electrical power. Outside heat transfer coefficient of stagnant air between these two surfaces has been calculated and analysed. Using desired correlations, air gap between two surfaces was found out. From these calculations and results it can be concluded that, the performance of hybrid system is strongly influenced by the air gap and this gap can be minimized by applying thermal grease between these two surfaces. For calculated air gap, various technical parameters of hybrid system such as PV power, thermal power, PV efficiency, thermal efficiency, combined PV/T efficiency and performance ratio has been tabulated and analyzed.

2. Experimental

2.1. Commercial PV module with stand

A commercial Tata Bp Mono Crystalline PV module was selected for this research work. The electrical specifications of the module are given in Table 1 at standard test conditions (STC). The manual tracking was used to track PV module to South direction at different slopes during experimental process. The PV module fitted on stand is placed on roof of institute’s main building at I.C.T. Mumbai.

Table 1. Electrical data of the PV module

Rated Power (W)	180
I_{SC} (A)	5.4
V_{OC} (V)	44.8
I_{MP} (A)	4.99
V_{MP} (V)	36.6
η_{mod} (%)	14.5
PV module area (m^2)	1.25

2.2. An Oscillatory heat exchanger surface

The combined efficiency of hybrid system depends on different materials and configurations of heat exchanger which absorb heat of module and cools it at desired temperature. To ensure desirable results, Aluminium tubes were used to manufacter heat exchanger considering its high thermal conductivity and lower weight. The hollow square tubes were used to fabricate heat exchanger to enhance surface contact between bottom surface of PV module and top surface of heat exchanger. Various configurations of PV absorber surfaces had been designed and tested by simulation to predict highest combined hybrid PV/T efficiency under certain range of weather conditions [9]. In this research the result obtained experimenally by oscillatory flow heat exchanger for latitude of Mumbai were tabulated and compared with results obtained by simulation under certain range of weather conditions [9].

For hybrid system to generate highest combined PV/T efficiency, oscillatory flow PV absorber design was preferred with hollow tubes of square cross section. The hollow square aluminium tubes with 12 x 12 mm cross section with 1 mm thickness and 34 mm pitch were used for fabrication of heat exchanger. The heat exchanger was fabricated using argon welding technique. Complete fabricated oscillatory flow PV absorber surface was installed at bottom surface of PV module as shown in Fig.1. The entire path followed by tubes from cold water inlet to hot water outlet was 36 meters in length. The heat exchanger covered 37% of area of module from its bottom side. The top surface of heat exchanger absorbed heat of PV module surface cooling it at satisfactory temperature level.

2.3. Fibre Glass Wool

Fibre Glass wool insulation with thermal conductivity of 0.04 W/m ^{0}k was fitted at bottom side of PV absorber surface. The glass wool was used to thermally insulate the heat exchanger for reducing overall temperature loss from bottom and sides . Glass wool with density of 24 Kg/ m^3 and 50 mm thick were used in blanket form for this application.

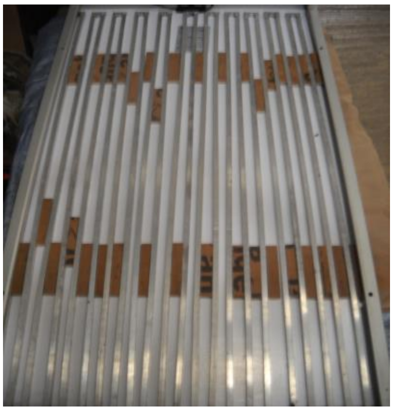

Fig.1. Installation of an oscillatory flow PV absorber surface at rear side of PV module.

2.4. Measuring Instruments

A Dynalab Radiation Pyranometer was used to measure global solar radiations mounted parallel to PV module surface. K-type thermocouples were used to measure ambient temperature and temperatures at top and bottom surface of module. During experiments the different temperature redings were recorded using a sixteen channel temperature data logger. A DC voltmeter and ammeter were used to measure voltage and current at various loading conditions. A DC load bank of 36-Volt with 180 Watts capacity was used to measure voltage and current across load applied to PV module. A 500 LPH Rota meter was used to measure water flow rate at inlet to oscillatory flow PV absorber surface. The dial type temperature gauges were used to measure inlet and exit water temperatures of heat exchanger. The water pump was used to circulate cold water through PV absorber surface absorbing heat and cooling PV module at desire temperature level. Figure 2 shows the experimental set up with accessories.

2.5. Experimental Observations

The main aim of this research study was to predict the effect of air gap between bottom surface of module and top surface of heat exchanger on performance of hybrid (PV/T) water system for Mumbai latitude. All experiments were conducted during months of April 2013. For this month, 5^0 tilt towards south was selected for the experiments. The solar systems were proposed to run for 5 to 6 hrs per day daily during the experimental process.

Fig. 2. Experimental set up of hybrid (PV/T) solar water system with accessories.

To determine performance of hybrid PV/T solar water system over a day, all experiments were started at 9:30 am in morning and were continued till 4:30 pm. The different readings such as global radiation;voltage and current at various loading conditions were recorded with 30 minutes of time interval. K-type thermocouples were fitted to data logger to record ambient temperature and temperatures of PV module at various points at top and bottom side and there reading were recorded for 30 second time interval. Inlet and exit water temperatures of heat exchanger were recorded for 30 minutes of time interval to calculate thermal power.

The experiments were conducted on three separate days for different water flow rates through heat exchanger. The readings were recorded for water flow rates of 0.028, 0.035 and 0.042 kg/sec respectively. With this method, it was possible to determine the flow rate of hybrid system generating highest PV, thermal, combined PV/T efficiency and performance ratio. The water pump was used to circulate cooling water through heat exchanger of hybrid system and the flow rate of the water was controlled with the adjustable non return valve fitted at tap water line.

3. Equations Used to Calculate Various Parameters

Different equations as shown in Table 2 were used to calculate photovoltaic power, thermal power, input solar power, photovoltaic, thermal and combined PV/T efficiency at ATC conditions [11,12].The overall heat transfer coefficient and heat transfer coefficient were calculated as shown in Table 2 [13,14].

Table 2. Equations used to calculate various parameters

$P_{PV} = V * I$	(1)
$P_T = \dot{m} * Cp * (T_{we} - T_{wi})$	(2)
$I_G = I_{Gn} * A_{PV}$	(3)
$P_R = P_{PV}/P_{STC}$	(4)
$\eta_{PV} = (V * I)/ I_G$	(5)
$\eta_T = P_{T} / I_G$	(6)
$\eta_{PV/T} = \eta_{PV} + \eta_T$	(7)
$U = P_T / [A_{tube} * (\Delta T)_{lm}]$	(8)
$1/h_o = (1/U) - (1/h_i) - (b_{tube}/k_{tube})$	(9)

4. Nomenclature and Greek Symbols

V	:	Voltage produced by PV module at ATC conditions (V)
I	:	Current produced by PV module at ATC conditions (A)
A_{PV}	:	Area of PV module (m^2)
P_{PV}	:	Electrical power produced by PV module (W) at ATC conditions
P_{STC}	:	Electrical power produced by PV module (W) at STC conditions
P_R	:	Performance ratio of PV module (%)
η_{PV}	:	Electrical efficiency of PV module (%)
I_{Gn}	:	Total or Global Solar radiation measured by Pyranometer (W/m^2)
$\dot{m}$	:	Mass flow rate of water (kg/sec)
Cp	:	Specific heat of water (J/kg ^{0}K)
T_{wi}	:	Water inlet temperature (^{0}K)
T_{we}	:	Water exit temperature (^{0}K)
P_T	:	Useful thermal power produced by hybrid (PV/T) solar water system (W)
η_T	:	Thermal efficiency hybrid (PV/T) solar water system (%)
$\eta_{PV/T}$	:	Combined PV/T efficiency (%)
U	:	Overall heat transfer coefficient (W/m^2 ^{0}K)
A_{tube}	:	Top surface area of heat exchanger (m^2)
$(\Delta T)_m$	:	Log mean temperature difference (^{o}C)
h_i	:	Local heat transfer coefficient of turbulent flow of circulating water ((W/m^2 ^{0}K))
h_o	:	Outside heat transfer coefficient of stagnation air between back side of module and top surface of heat exchanger (W/m^2 ^{0}K)
b_{tube}	:	Thickness of tube surface of heat exchanger (m)
k_{tube}	:	Thermal conductivity of heat exchanger material (W/m ^{0}K)

5. Results and Discussion

5.1. Performance of Hybrid PV/T Solar Water System

The performance comparison of un-cooled and cooled PV module or hybrid PV/T system for highest PV power at ATC condition for Mumbai latitude is shown in Table. 3. As a result of cooling by heat exchanger, PV output power was found increased by 16 % and performance ratio was increased by 17%. The highest PV efficiency was also found improved marginally from 10.2% to 11.7 % as shown in Fig.3. Additional thermal power of 482 W with efficiency of 42% was obtained from hybrid system as a result of absorbing heat from module at mass flow rate of 0.035 Kg/sec. The temperature of exit water from heat exchanger was found at 38 ^{0}C. This hot water is suitable for low temperature applications such as domestic, swimming, and preheating etc.

The combined PV/T efficiency of 53.7 % was obtained from hybrid system at mass flow rate of 0.035 Kg/sec as shown in Fig. 4. By attaching heat exchanger to PV module and utilizing available heat energy, module operating temperature decreased to 46.7 ^{0}C. The Photovoltaic, thermal and combined efficiency for hybrid system for various mass flow rates are shown in Fig.5

This hybrid PV/T solar system could generate combined electrical power and heat power at efficiency of 53.7 % experimentally as compared to efficiency of 54.85% found by simulation technique [9]. The above results showed that experimental observations were fairly close to the results of theoretical calculations. This hybrid PV/T solar water system harnessed solar energy of 53.7% of total solar radiation falling on earth and converted 42 % heat energy to hot water utilizing the waste heat energy, which increases temperature of module and nearby surroundings. Combined efficiency of PV/T system may be increased by reducing inlet water temperature of the heat exchanger, Use of thermal grease between module and heat exchanger and by fitting reflectors to this system, enhance its overall system performance by

20% to 25% [3, 4, 8]. Replacing oscillatory flow heat exchanger with spiral flow PV absorber surface of same material, the overall performance may augment by 10% to 15% at highest electrical power point condition [7]. Heat exchanger fabricated with high conductive material such as Copper [2, 8] and with same configuration, may improve overall system performance by 5% to 10%.

Table 3. Performance comparison of un cooled PV module and hybrid PV/T system at highest PV power point condition

Sr. No	Technical parameters	Un cooled PV module	Combined PV/T system
1	Open circuit voltage (V)	37.4	39.80
2	Voltage (V)	27.5	30.30
3	Current (A)	4.2	4.43
4	PV power (W)	115.2	134.2
5	PV efficiency (%)	10.2	11.7
6	Thermal power (W)	----	482
7	Thermal efficiency (%)	----	42
8	Combined PV/T efficiency (%)	----	53.7
9	Top side module temperature (^{0}C)	64	46.7
10	Performance ratio	64	75

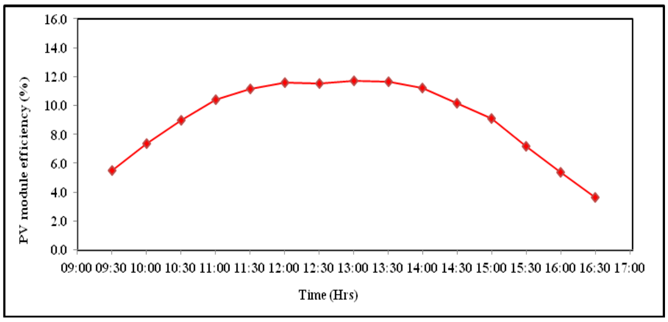

Fig. 3. Photovoltaic efficiency of cooled PV module.

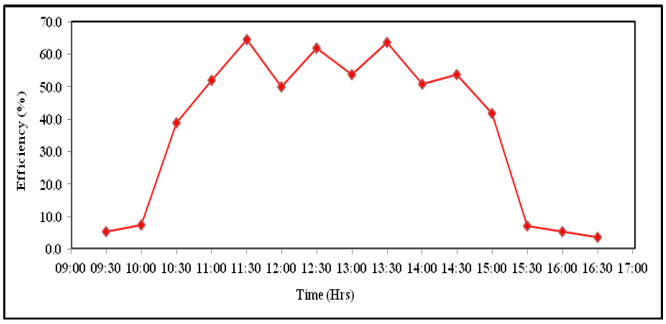

Fig. 4. The combined PV/T efficiency of cooled PV module.

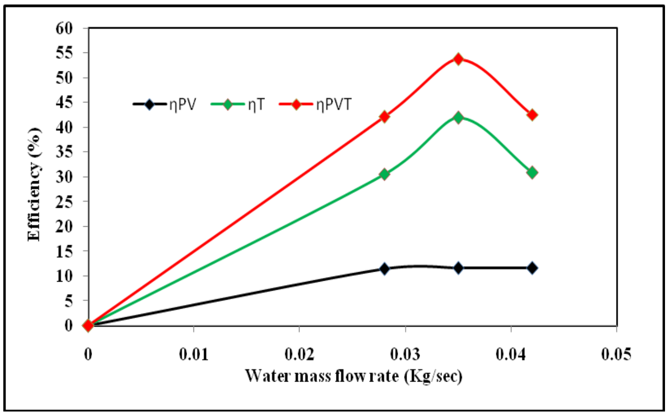

Fig. 5. Maximum Photovoltaic, Thermal and Combined efficiency for various mass flow rates.

5.2. Heat Transfer Analysis of Oscillatory Flow PV Absorber Surface

At global solar radiation of 918 W/m^2 and mass flow rate of 0.035 kg/sec at 1 pm, hybrid system was able to generate maximum photovoltaic power at 11.7 %, thermal at 42% and combined PV/T efficiency at 53.7 % respectively. The above results showed that 53.7% of solar power was converted to useful work. Heat transfer analysis of heat exchanger was found helpful to determine factors affecting heat flow from bottom surface of module and top surface of heat exchanger tube. The hollow square section of the heat exchanger surface helped to enhance surface contact with module surface to achieve optimum heat transfer rate which improvs the overall performance of the system.

Overall heat transfer coefficient found for this configuration, was 49.93 W/m^2 ^{0}K . The outside heat transfer coefficient of stagnant air between bottom surface of module and top surface of heat exchanger was determined using equation no:9 of Table 2, was found to 51.10 W/m^2 ^{0}K. Value of this overall heat transfer coefficient of stagnation air was compared to standard value for same medium [13]. After comparison, it was found that both values were approximately same and equal to 50 W/m^2 ^{0}K.

5.3. Effect of Air Gap Between Top Side of Heat Exchanger and Bottom Side of Mod Ule on Performance of Hybrid System

By using equation no: 9 of Table 2, air gap between bottom surface of module and top surface of heat exchanger was calculated. The above result showed that heat transfer from bottom surface of module and top side of heat exchanger was strongly influenced by this air gap. Filling this air gap with thermal compound or grease may enhance electrical and thermal efficiency of hybrid system significantly. By achieving minimum or nigligible air gap between these surfaces, operating temperature of module will come down drastically increasing its life. Such hybrid systems will be financially viable in near future for domestic, swimming and other low temperature applications.

6. Conclusions

This experimental analysis determines the heat transfer rate of oscillatory flow PV absorber surface and effect of air gap between heat exchanger and bottom surface of module on performance of hybrid PV/T solar system at ATC conditions for Mumbai latitude.

During analysis, outside heat transfer coefficient of stagnant air between bottom surface of module and top surface of heat exchanger was found to be 50 $W/m^2\ ^0k$. By using desired correlation, air gap between module and top surface of heat exchanger was found to be 0.53 mm. By considering this air gap with solar irradiance of 918 W/m^2 and water mass flow rate at 0.035 kg/sec, hybrid system was able to generate a combined PV/T efficiency of 53.7 % and PV efficiency of 11.7 % with performance ratio of 75 %. It was found that PV module temperature had been decreased by 37 % by supplying cold water in heat exchanger at flow rate of 0.035 kg/sec, at average inlet water temperature of 32^0C, improving the overall performance of the system.

From the above results it can be concluded that, the performance of hybrid system is strongly influenced by the air gap between these two surfaces. By using thermal grease, the heat transfer rate between these surfaces may be increased. The rise in heat transfer rate between these surfaces, will enhance performance of hybrid system drastically and operating temperature of module will be come down significantly.

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