SIMULATION OF THE TEMPERATURE DISTRIBUTION INSIDE A SOLAR PHOTOVOLTAIC THERMAL COLLECTOR

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ABSTRACT

New technologies are being invented everyday to improve the quality of human life. The rapid development in solar energy technologies together with the fast depleting fossil fuel sources have led to the high dissemination of solar photovoltaic and thermal systems. The self-independency with low payback time and reduced carbon footprint has made several Governments to offer customer-friendly policies and incentives. However, there is reluctance in implementing these technologies due to the low efficiency, high initial cost and large area requirement. These drawbacks can be sorted to certain extent by the use of solar PV/T technology. In a solar PV/T air collector, the flow of air beneath the photovoltaic module, cools the silicon cells and transfers the heat to the thermal application. The flow velocity of air can be controlled by a blower powered by the photovoltaic module itself. Thus, the system could be installed independently in cold rural areas for drying applications or in cold urban areas for space heating and lighting applications. Different PV/T air designs were developed for uniform cooling of the PV cells and improve the overall efficiency. However, the cooling distribution inside the PV/T collector due to the movement of air was not studied till now. In this paper, the cooling air distribution in a PV/T system was simulated using ANSYS FLUENT software, and compared using experimental results.

INTRODUCTION

Generation of energy from sun using solar energy technologies, has started from one of the renewable energy technologies to the level of one among the fastest growing industries today. This change is attributed to the over-exploitation of fossil fuels and rising global warming. Solar PV and Solar thermal technologies were recognized worldwide as promising options to counter fuel scarcity and power shortage. Among solar thermal technologies, tap water heating and solar air heating have 39% and 45% respectively followed by solar cooling (7%), industrial heating (6%), drying (3%) and pool heating (0.2%) [1], mainly in the residential sector with low energy high solar fraction houses,

where PV/T may be combined with a heat pump and multi-family buildings, with limited available roof area [2]. Also, in solar PV technologies, the rise in temperature of the PV cell is linearly proportional to the incident photons and ambient temperature, but it has a negative impact on the electrical efficiency, but higher solar radiation values produce more current output. So to reduce the temperature, the commonly used cooling techniques are the less expensive air cooling and the more effective water cooling. But this increases the complexity and cost of the completed component. Nevertheless, the energy payback period and the annual energy output per unit area have substantial improvement [3]. Also, installing photovoltaic (PV) modules may use only 10 to 15% of the incident solar energy and reduces the possibility of using solar thermal collectors in the limited roof-space of buildings [4]. PV/T collectors of unit area annually produced 1.1×10^3 kWh/m^{2}year of heat and 55 to 83 kWh/m^{2}year of electricity respectively [5]. PV/T air collectors are similar to solar air collectors, except the black thermal absorber sheet is replaced by a solar PV module underneath which air as heat transfer fluid circulates through channels and the thermal efficiency is dependent upon the channel depth, design of air flow and its flow rate [6]. Air based PV/T arrangement is the simplest, low cost and widely used structure in which air is allowed to pass behind the PV rear surface, so that the heat is removed effectively and used for space heating or drying applications such as de-humidification of air in cabins, garages, allotment houses and mobile homes [7], and various industrial and agricultural processes such as drying, curing, regeneration of dehumidifying agents, timber seasoning, leather tanning, etc. [8]. PV/T air based systems have no leakage problems, no fluid freezing problems and commercial PV modules may be used without any modification, but bulky and wide air channels are required that creates noise if forced air circulation is used [9]. An optimum number of fans for achieving maximum electrical efficiency were found since increasing the inlet air velocity increases the electrical power consumed [10] and hence natural convection is most beneficial for PV/T systems [11] and setting glass cover on photovoltaic panel leads to increase in thermal efficiency [12]. Around 10% higher electrical efficiency was obtained owing

to air ventilation of PV module [13]. The electricity produced by the PV module is used to run a DC fan that circulates the air through the collector and drying chamber. The heat generated in the collector is used for drying the agricultural products [14]. Similarly, a double pass PV/T system where air was circulated on the back surface and top surface of the PV module gave the best compromise between the electrical and thermal performance compared with a single pass PV/T system [15].

Few designs of PV/T collectors tested such as UV stabilized polyethylene greenhouse dryer was fabricated to reduce the moisture content in mint leaves from 80% to 11% for preservation [16]. Also, c-Si PV module was found best suited based on the annual thermal and exergy performance of PV/T greenhouse dryer compared to different PV modules and weather conditions of New Delhi [17]. The effect of transmittance of beam and diffuse radiation through the atmosphere was mathematically found for different climatic conditions of New Delhi using simple regression analysis and the obtained data were used to evaluate the performance of PV/T air collector [18].

A more advanced software specially dealing with PV/T design, and optimization of electrical and thermal requirements for a given area, combined with its meteorological data, would prove useful. The performance, environmental impact and economic analysis of a building integrated PV/T air system were studied using a SimaPro 5.1 simulation software [19]. TRNSYS simulation software was used largely to measure and compare the performance of PV/T collectors. The performance of a PV/T collector was found to be advantageous compared with a conventional solar thermal collector and a PV module from the energy, exergy and primary energy saving point of view [20]. The economic performance was also found to be favourable for BIPV/T air system compared to a PV module and a solar thermal collector for Canadian climatic conditions [21]. Similar electrical and thermal advantages of the air type BIPV/T system, was found compared to those of the BIPV and BIPV/T models [22]. Few simulations were done using MATLAB such as a thermodynamic model of a hybrid solar PV/T system was designed, and the parametric studies and annual transient simulations carried out proved that the most important variable to improve thermal performance is the photovoltaic module emittance [23]. Also, a thermo-electrical model was derived for design and operating conditions of a single pass hybrid PV/T air collector and solved for two cities of Iraq [24]. Lastly, a coupled multiphysics model to analyse the thermal, structural and electrical response to different operating conditions of a PV module with and without cooling was developed using ANSYS CFX, ANSYS Mechanical and MATLAB respectively [25].

As discussed above, most research on PV/T collector are focused on the design and performance evaluation. Only limited research has been carried out using simulation softwares. The benefits of PV/T collector as a competitive solution to solar PV module and solar thermal collector has been underestimated by this limited research. In this paper, the temperature distribution in a air based PV/T collector was found using ANSYS simulation software and validated with experimental results.
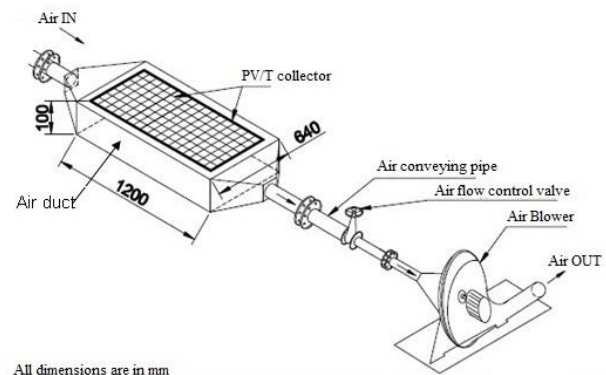
METHODOLOGY

The photovoltaic thermal collector was experimentally tested for three different flow rates and simulated for the same flow rates and the results were compared.

Experimental Investigation

The solar photovoltaic thermal air collector was tested on the roof-top for three different flow rates (0.134 and kg/s, 0.224 kg/s and 0.288 kg/s).

Figure 1 Schematic diagram and picture of the PV/T collector

The solar PV module used in this study is of 37 W mono-crystalline with V_{mp} = 17 V, I_{mp} = 2.05 A, which is tilted corresponding to the latitude of the location (Chennai latitude = 13˚) and facing South direction. The current and voltage were measured using DC digital ammeter and DC digital voltmeter respectively. The temperature measurements were taken using T-type thermocouples from the top & bottom layers of the solar PV module and entry & exit ports of the solar PV/T collector. The solar radiation was measured using a solar power meter [Tenmars TM-207], ambient temperature was measured using a weather station [Spectrum Technlogies, WeatherDog 2000]. An air blower was used for forced air circulation and an anemometer [Starmeter Instruments, AM 802]. The readings were manually taken from 10:00 am to

03:00 pm. In Figure 1, the different components with their dimensions and position are given.

The efficiency of the solar PV module depends on the temperature of the silicon PV cells. In order to cool the PV cells, a PV/T collector using air as the heat transfer medium was fabricated.

Theoretical Investigation

A small part of the PV/T collector consisting of a single PV cell and the corresponding cross-section view was modeled in CATIA software (Mechanical Product Design) and analysed in ANSYS Fluent. The generated mesh using hexahedron as shown in Figure 2, had an average aspect ratio of 1.736 and zero skewness, suggesting the mesh is of high quality. The accuracy of the simulated results were also tested for different mesh elements. The grid independence test conducted from 1936 elements to 523224 elements, and there was very negligible variation (0.1 %) in the obtained results.
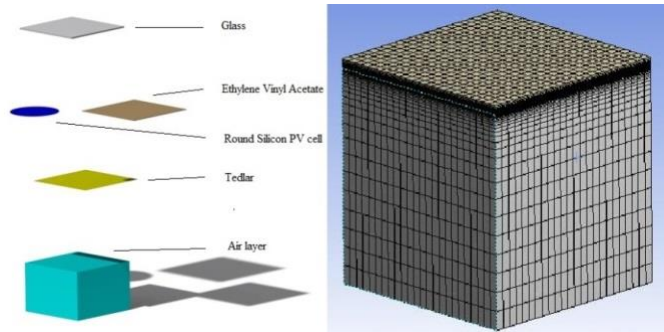

Figure 2 Exploded CATIA view of the PV/T collector and the pictorial diagram of mesh in ANSYS.

The properties of the different layers of the PV module used in CAD modeling using CATIA software and flow analysis using ANSYS Fluent software are given in Table 1.

Table 1. Properties of the different layers in the PV/T collector

Material	Thickness (m)	Density (kg/m³)	Specific heat (J/kgK)	Thermal conductivity (W/mK)	Refractive index	Calculated	
						Thermal resistance (K/W)	Thermal capacitance (J/K)
Glass	0.003	2800	840	1.2	1.47	0.0032	5419
EVA	0.0005	925	1400	0.34	1.48	0.0038	994.56
PV cell	0.0002	2328	710	149	3.44	0.0047	93.45
Tedlar	0.0001	1370	1760	0.2	1.46	0.0006	185.18
Air	0.1	1	1005	0.02	1	**0.0123**	**6692.19**

Different correlations were developed to find the temperature of the PV cell [25], and in this paper, the temperature of the PV cell was calculated using the following formula [26]

$$T_{cell} = T_{back} + \frac{E}{1000}\,\Delta T \qquad (1)$$

where T_{cell} is the PV cell temperature in ˚C, T_{back} is the measured bottom surface of module temperature in ˚C, E is the measured solar irradiance incident on the module in W/m², ΔT is the temperature difference between the PV cell and the module bottom surface.

Uncertainty analysis

The accuracy of the anemometer, T-type thermocouple temperature sensors, the solar power meter, voltmeter and ammeter were ±3%, ±0.1˚C, ±2%, ±0.5% and ±0.5% respectively. The overall uncertainty equation for the electrical and thermal efficiencies of the solar PV/T air collector can be calculated from the following equations.

$$(\eta_i)_{elec} = f(V, I, G) \qquad (2)$$

$$(\eta_i)_{therm} = f(\dot{m}, G, \Delta T) \qquad (3)$$

Therefore the overall uncertainty equations can be expressed as:

$$\left[\left(\frac{U_{\eta_i}}{\eta_i}\right)^2\right]_{elec} = \left(\frac{U_v}{V}\right)^2 + \left(\frac{U_I}{I}\right)^2 + \left(\frac{U_G}{G}\right)^2 \qquad (4)$$

$$\left[\left(\frac{U_{\eta_i}}{\eta_i}\right)^2\right]_{therm} = \left(\frac{U_{\dot{m}}}{\dot{m}}\right)^2 + \left(\frac{U_G}{G}\right)^2 + \left(\frac{U_{\Delta T}}{\Delta T}\right)^2 \qquad (5)$$

where U denotes uncertainty and the variables such as $\dot{m}$, ΔT, G, V, I are the mass flow rate of water (kg/s), the temperature difference between the outlet and inlet fluid of the solar collector (˚C), global solar radiation incident on the solar collector plane (W/m²), voltage (V) and current (A) respectively. The maximum uncertainty in the mass flow rate, temperature difference, solar radiation, voltage and current were calculated as 0.03%, 1.18%, 0.01%, 0.008% and 0.0004% respectively. Therefore, the maximum uncertainties in electrical efficiency and thermal efficiency, thus calculated were 0.02% and 1.18% respectively.

RESULTS AND DISCUSSION

The three flow rates considered were in the turbulent region (Re > 2300)

Table 2. The heat transfer coefficient calculated at the different flow rates

Mass Flow rate (kg/s)	Velocity (m/s)	Reynolds number	Nusselt Number	Heat Transfer coefficient (W/m²K)
0.0134	0.21	2479.87	8.21	1.64
0.0224	0.35	4133.12	12.35	2.47
0.0288	0.45	5314.01	15.10	3.02

Top surface (Glass) temperature of the PV/T collector

The glass layer is the thickest top layer of a PV module, which protects the PV cells from physical damage and different weather conditions. This reflects up to 30% of the incoming solar radiation, thereby reducing the electrical efficiency.
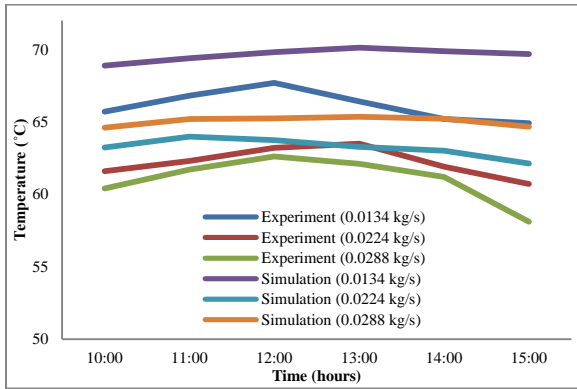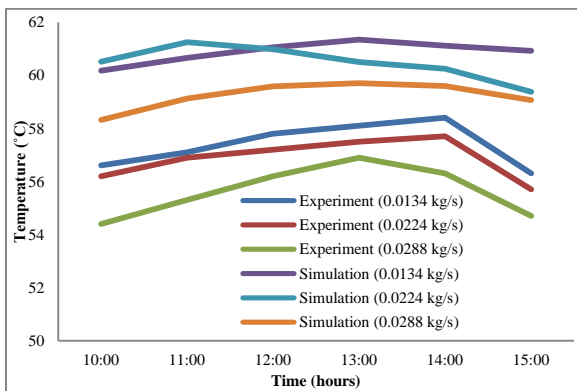
Figure 3 Top glass surface temperature of the PV/T collector

The temperature of the glass reveals the actual health of the solar PV module. Using infrared imaging camera, the presence of hotspots or damaged cells in the PV module is analysed. Similarly, the temperature of the PV module is generally measured as the temperature of the top glazing. From Figure 3 it is observed that the temperature of the top layer decreases with increase in air flow rate. The simulated temperature were higher compared to the obtained experimental results.

Bottom surface (Tedlar) temperature of the PV/T collector

To reduce the weight of the PV module, the bottom glass layer is replaced with a Tedlar layer. It protects the PV cells from atmospheric elements such as rain due to its low moisture absorption. It also helps to increase the electrical efficiency of the PV module, by reflecting the incoming radiation which has surpassed the PV cells back to the PV cells.


Figure 4 Bottom Tedlar surface temperature of the PV/T collector

The bottom surface is normally few degree Celsius temperature lower compared to the top glass surface. This is due to the thermal resistance of the different layers of the PV module. The temperature of the bottom Tedlar layer is shown in Figure 4. It was found that the temperature of the Tedlar layer was few degree Celsius lower than the top glass layer.

Simulated and theoretical cell temperature

The silicon PV cells is embedded inside the EVA layers. The EVA acts as an electrical & thermal insulator and protective buffer for the PV cells. The temperature of the PV cells cannot be measured directly using temperature sensors.
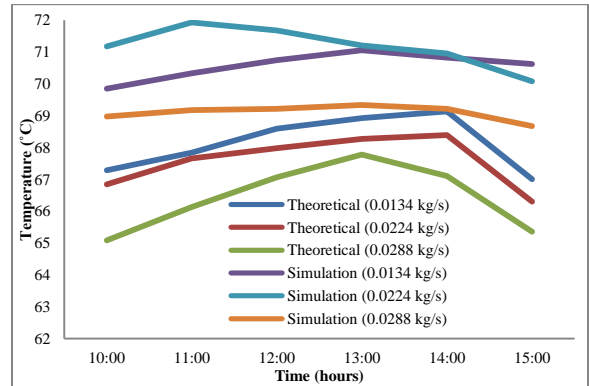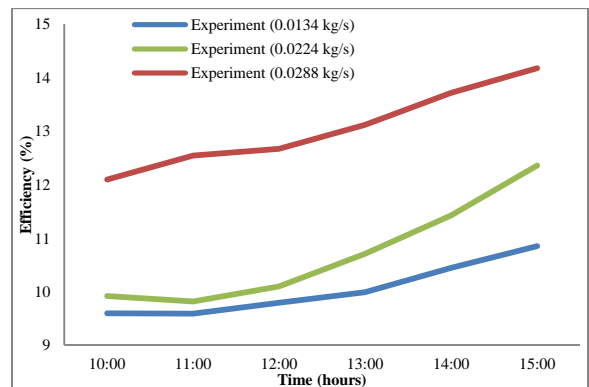

Figure 5 PV cell temperature of the PV/T collector

In Figure 5 the temperature of the PV cell using the eqn. 1 and the temperature of the PV cell obtained using the simulation results were shown. The results show that the PV cell temperature is the highest in a PV module. From the above Figure 5, it is clear that the PV cell temperature can be predicted with sufficient accuracy using the simulated software.

Electrical efficiency of the PV/T collector

The electrical efficiency is largely dependent on the incoming solar radiation and slightly dependent on the temperature of the PV cells. But reducing the temperature of the PV module using air or water based cooling removes the heat generated from the PV cells effectively.
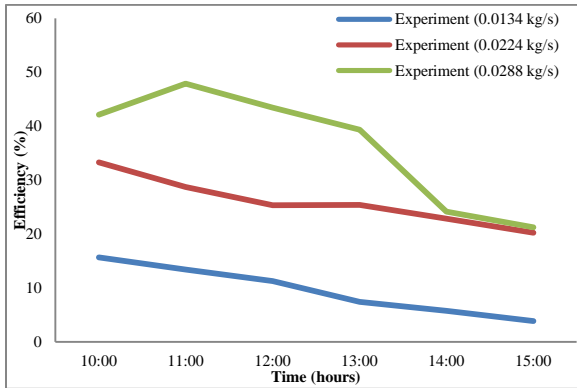

Figure 6 Electrical efficiency of the PV/T collector

Higher air flow rates causes enhanced cooling and heat dissipation, which decreases the temperature of the PV cells. The electrical efficiency was observed to be higher at higher flow rates as shown in Figure 6.

Thermal efficiency of the PV/T collector

The thermal efficiency is dependent on the ambient temperature and the temperature difference between the outlet and inlet. But, increase in temperature reduces the electrical efficiency. Hence an optimum flow rate for maximum heat transfer, thereby producing maximum electrical efficiency and maximum thermal efficiency.


Figure 7 Thermal efficiency of the PV/T collector

The advantage of PV/T collector is it produces electrical and thermal output simultaneously. As shown in Figure 6 and Figure 7 the electrical and thermal efficiencies have increases with increasing air flow rates. An average temperature difference of 5 ˚C, 8 ˚C, 9˚C were observed in the three flow rates considered in this experimental studies.

Table 3. The thermal performance of the PV/T collector at different flow rates

Flow rate (kg/s)	Average Temperature difference (˚C)	Average Heat Output (W)
0.0134	5	67.40
0.0224	8	180.27
0.0288	9	260.75

PV module layer temperature

The PV module has a thickness of less than 5mm, of which 3mm is the top glass layer. The remaining layers of the PV module includes the PV cell, EVA layers and Tedlar layer. The PV cell has the highest thermal conductivity, but since it is encapsulated inside the EVA layer, the heat transfer to the surrounding ambient air is hindered.
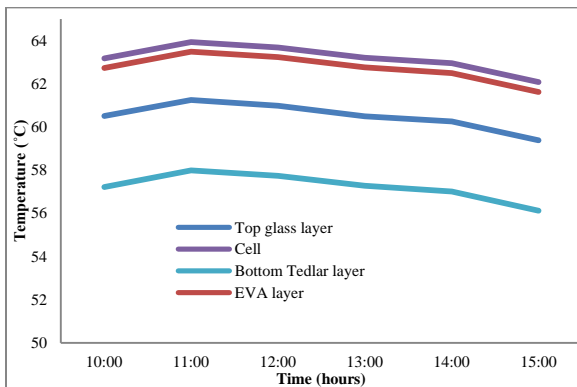

Figure 8 Temperature of the different layers of the PV module

The temperature gradient in a PV module varies between 5˚C and 8˚C in hot climatic conditions. The different layers if the PV module is at different temperatures as shown in Figure 8. This is due to the different thermal conductivities and thermal capacities of the layers. The temperature of the top glass layer is higher than the bottom Tedlar layer. This is due to the thermal resistance between the two layers. The temperature of the PV cell is the highest, with slightly lower temperature for the encapsulating EVA layers. The very low thermal conductivity of the encapsulating layers prevents the heat dissipation from the PV cells.

Contour plot of the temperature gradient in a PV/T collector

The temperature gradient inside the PV/T collector was analysed using ANSYS Fluent software. The heat released from the PV module is removed by the flow of air. With increasing flow rate of air, the outlet temperature of the PV/T collector is reduced.
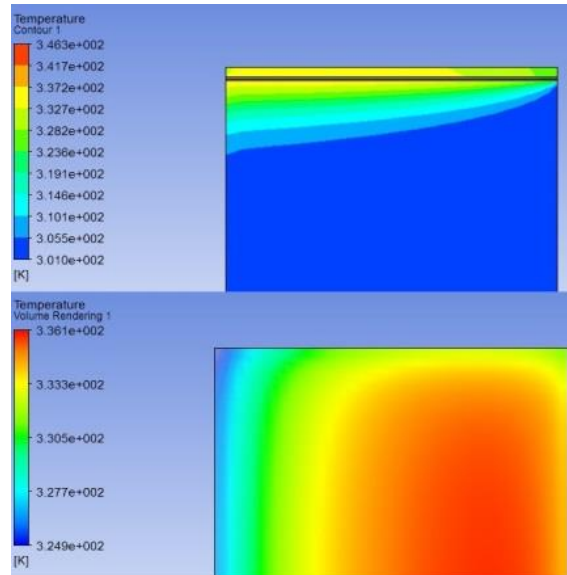
Figure 9 Contour plot of the temperature gradient in a PV/T collector

Cooling of the PV module by passing air beneath the PV module is shown as a contour plot in Figure 9. The temperature of the PV module is at a higher temperature and the air is seen removing the heat from beneath the PV module. The temperature distribution across a single solar cell is also shown. Higher flow rates reduces the temperature gradient across the solar cell and reduces the overall temperature of the PV module, thereby increasing the electrical efficiency.

CONCLUSION

The PV/T air collector has improved the electrical and thermal efficiencies of the photovoltaic unit and thermal

unit. The simulated cell temperature is the highest temperature in a PV module or PV/T collector. The complete encapsulation of the PV cells between EVA layers, hinders the effective dissipation of heat generated.

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