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Numerical Analysis of Solar Hybrid Photovoltaic Thermal Air Collector Simulation by ANSYS

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ABSTRACT

Solar energy is one of the renewable energy sources which have potential for future energy applications. The current technology converts solar energy into electricity and heat respectively. The aim from the paper to increases the PV efficiency by using duct of air under the PV panels to help reduce the temperature of the PV cells, an effort was made to simulate and evaluate the overall performance of a hybrid photovoltaic thermal (PVT) air collector using computational fluid dynamics (CFD) software. The numerical analysis of the flow and heat transfer in hybrid PVT systems is computationally complicated. Based on numerical analysis, the performance of a solar hybrid PVT air collector was studied. The numerical simulation was performed using a commercial software ANSYS FLUENT 19.1. The electrical energy conversion from the solar cells was calculated with a user defined function. The numerical results were validated with the experimental results from the literature. The results showed a good agreement between the experimental and simulated results for outlet air temperature and PV cell temperature. Using a validated model, the effects of mass flow rate and duct depth on the performance of solar hybrid PVT collector were studied and optimum values were identified. The results indicated that the reduction in the depth of air channel increases the thermal efficiency, but it has no considerable effect on the electrical efficiency. The increase of the mass flow rate of air increases the thermal efficiency, but a slight enhancement is required for the generation of electrical power by PVT.

1. Introduction

Photovoltaic Hybrid PVT Collector is used in the conversion of solar energy. The technology involves the process of solar thermal conversion and solar photovoltaic conversion making it possible to produce electricity and heat simultaneously from solar radiation as well as generate real.

Energy system to utilize the electricity and heat produced. The high rate of solar radiation with the absence of cooling sources increases the temperature of solar cells significantly due to

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interactions of photonic matter. High temperature affects the movement of electrons and lead to the reinstallation of the electron-hole resulting in a decrease in electrical efficiency [1]. Based on the literature, a study was conducted to investigate energy and exergy efficiencies for Hong Kong climates. Due to high electricity consumption, high operating cost, and environmental pollution from conventional electricity, researchers have begun working on power production system and solar photovoltaic technology to improve electricity generation from renewable energy [2].

In another paper, a comparative study of three configurations of hybrid PVT air solar collector was conducted which included unglazed hybrid photovoltaic thermal tiles, glazed hybrid photovoltaic thermal tiles, and conventional hybrid photovoltaic thermal air collectors. The study performed four configurations of the optical thermal air collector theoretically [3]. Furthermore, a comprehensive assessment of four different solar cells was conducted which involved single crystals, polycrystalline, arsenide, gal day, and super solar cells [4]. The behavior of the PVT complex consisting of the adhesion of single crystalline silicon cells to a black plastic solar heat absorber (non-glazed PVT system) was studied. The built-in PVT concept for low-temperature thermal applications was recommended to increase the electrical efficiency of the photoelectric system, for example, heating the spaces in the building [5]. Different refrigerated PV photovoltaic cells were used, and the thermal absorption configurations were placed on the back of the cell. Based on the water flow rate, a spiral design of 0.01 kg/s was proved to be the best design with the highest thermal and electrical efficiency of 50.12 % and 11.98% respectively [6]. The electric and thermal performance of the PVT system using a water tube was numerically investigated. Three different types of absorbers were studied which achieved a maximum thermal and electrical efficiency of 66.8% and 12.1% respectively for the PV module with an absorber covering 50 % of its surface.

A hybrid PVT solar system was designed and studied by Teo *et al*., [7]. The PV cells were actively cooled by a parallel array of ducts with inlet/outlet manifold to allow for a uniformed air flow. The efficiency of the uncooled PV module was compared with the cooled module. The uncooled PV efficiency ranged between 8% and 9 %, while with active cooling, the solar cell efficiency ranged between 12% and 14 %. The daily average thermal and electrical efficiency was about 50.5% and 10.5% respectively [8]. The results showed that the electrical efficiency increases when the wind speed increases but decreases when the space between the tubes increases. Contrary to this, the thermal efficiency increases when the wind speed and the space between the tubes decreases. The effect of optical and meteorological parameters on the heat transfer in a PVT water system for different geometric configurations of the cooling system was numerically studied [9]. In the last decade, many studies have been implemented to improve the efficiency of these systems and evaluate their economic and environmental parts [10].

A study was conducted to investigate glazed photovoltaic thermal air PVT system for single and double pass air heater for space heating and drying purposes. A thermal model for each system was developed [11]. The findings indicated that thermal energy for glazed PVT system increased with low electrical efficiency due to high operating temperature. The performance of a concentrating photovoltaic thermal solar collector was also studied and concluded that the overall thermal and electrical efficiency of PVT concentrating systems were 58% and 11 %, respectively. This gave a total efficiency system of 69 % [12].

A recent study investigated the thermodynamic characteristics of solar photovoltaic PV cells in terms of exergy. It was found that the energy efficiency of the solar cells varied between 7 % and 12% and the exergy efficiency which incorporated the second law of thermodynamics and accounted for solar irradiation exergy, varied between 2% and 8%. The aim of this paper is to study the performance of unglazed hybrid photovoltaic thermal PVT glass-to-glass system for the composite climate of New Delhi and its comparison with the glass-to-tedlar PVT system. An experimental validation [13] was also conducted in terms of various temperatures such as back surface temperature, cell temperature, and outlet air temperature. The comparison of both systems was done based on various temperatures which are back surface temperature, cell temperature, and outlet air temperature as well as the overall thermal and electrical efficiency. Furthermore, the variation of overall thermal efficiency with the length of collector and different duct air velocity was studied for both models [14]. the solar radiation was increased, which resulted in the decrease in the PV efficiency of the PV panel. An energy analysis was conducted for the different mass flow rates of water that ranged from 0.03332 to 0.16666 kg/s. The average PV, thermal and PVT energy efficiencies were 11%, 81% and 92% at the solar radiation of 500W/m^2 and mass flow rate of 0.16666 kg/s, respectively. The average PV, thermal and combined efficiencies of the PVT system were 11.3 %, 81 % and 92.3% at the average solar radiation of 1000 W/m^2 and mass flow rate of 0.16666 kg/s respectively [15].

A model for predicting the performance of serpentine tube water cooled PVT collector is established by combining experimental and CFD simulations method. From the Simulation and experimental results show that reducing the tube spacing is the most effective way to make the plate temperature distribution uniform. The use of absorber materials with better thermal conductivity can also reduce the temperature non-uniformity [16] . This field study explored the viability of a recently developed PVT system as a self-powered, off-grid, solar collector. This constitutes the first time that such a device has been tested experimentally, and it has demonstrated the capability to provide hot water of approximately 80 °C for a family of four, as well as providing excess electricity towards household applications, assuming an average daily solar irradiance of >4.5 kWh/m^2. Electrical and thermal efficiencies of 13.4 % and 53.4 % are reported, which compete well with the traditional PVT system the mean PV temperature decreased and the PV efficiency significantly increased when the mass flow rate of water was increased [17].The current study aim to increases the PV efficiency by using duct of air under the PV panels to help reduce the temperature of the PV cells and analyze the thermal performance of PVT air collector with a single pass of air and the effect of parameters such as mass flow rate and wind speed on the thermal and electrical efficiency by using the ANSYS software.

2. Methodology

The aim of this study is to evaluate the thermal performance of a hybrid photovoltaic thermal air collector system. A numerical model was developed to determine the overall performance of the solar hybrid PVT air collector. Parametric studies have been conducted to study the effects of operating and design parameters of the hybrid PVT air collector on its overall energy efficiency. Finally, a design of the hybrid solar collectors for air heating and electrical production was proposed to produce good thermal and electrical conventional hybrid collectors.

2.1. Energy Analysis

To write down the energy balance equation for each section of the PVT air collector system, the following assumptions were made:

- The system is in quasi-steady state condition.
- Transitivity of EVA is almost 100%.
- The temperature deviation along the thickness is negligible.
- The air flow between tedlar and insulation is homogeneous for forced manner of operation.

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Figure 1 (a) shows the cross sectional view of the PVT air collector and (b) shows its corresponding thermal resistant circuit. The energy balance equation for each part of the PVT air collector, the thermal parameters, and the thermal, electrical, and overall efficiency of the PVT air collector are as follows [15]:

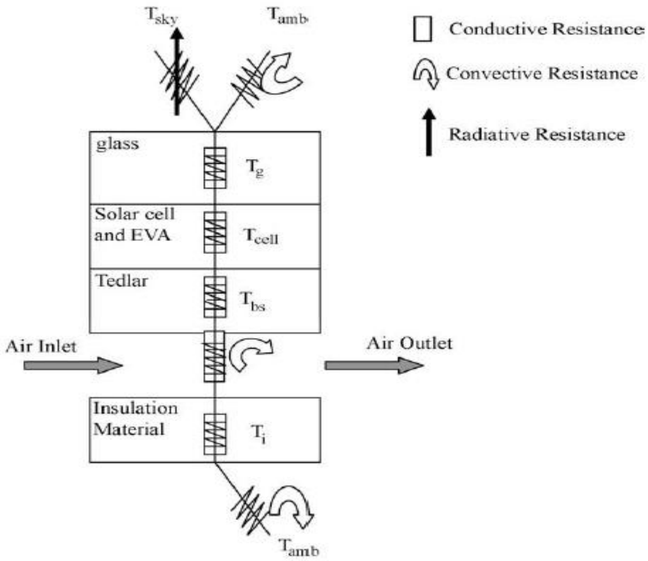


Fig. 1 (a) Cross sectional view of the PVT air collector[18]

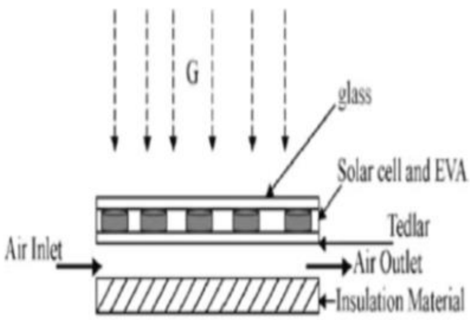


Fig. 1 (b) The thermal resistance circuit diagram [18]

2.1.1. For the PV module

$$\tau_g[\alpha_c\,\beta+\alpha_T\,(1-\beta\,)]G\,(t)\,bdx=[U_t\,\,(T_c-T_a)+U_T\,(T_c-T_{bs})]bdx+\eta_c\,\tau_g BG(t) \quad (1)$$

[Rate of solar energy available on PV module] = [Rate of overall heat transfer from the top surface of the cell to ambient temperature] + [Rate of overall heat transfer from the cell to the back surface of tedlar] + [Rate of electrical energy produced].

2.1.2. For the back surface

$$U_T\,(T_c-T_{bs})\text{bdx} = h_T(T_{bs}-T_f)\text{bdx} \quad (2)$$

[Rate of heat transfer from the cell to the back surface of tedlar] = [Rate of heat transfer from the back surface of tedlar to flowing fluid].

2.1.3. For air flowing below the tedlar

$$\dot{m}\, C_p \frac{dT_f}{dx} dx + U_b\left(T_f - T_a\right) b dx \tag{3}$$

[Rate of heat gained by flowing fluid in the duct] + [The overall heat transfer from flowing fluid to ambient temperature] = [Rate of heat transfer from the back surface of tedler to flowing fluid]

The rate of useful thermal energy can be calculated for the PVT air system as follows [19, 20]:

$$Q=\dot{m}C_p(T_{air,out} - T_{air,in}) \tag{4}$$

Thermal efficiency of PVT collector is:

$$\eta_{th} = \frac{Q}{A \times G} \tag{5}$$

Where Q is the rate of usual energy in watts. The electrical efficiency of the PV module was calculated from following equation [21, 22]:

$$\eta_E = \frac{P_{mp}}{A_{PV} \times G} \times 100 \tag{6}$$

The maximum output power was obtained by multiplying the corresponding value of current and voltage which was calculated from following equation [23].

$$P_{mp}=I_{mp} \times V_{mp} \tag{7}$$

The overall efficiency of the system was calculated using the following equation [24]:

$$\eta_{ov} = \eta_{th} + \frac{\eta_{el}}{\eta_{cp}} \tag{8}$$

Value of η_{cp} vary between 0.30 and 0.40 in the literature. It was recorded as 0.40 in this simulation. The calculation of convective heat transfer coefficient is based on the following equation [25]:

$$h=5.82+4.07V_w \tag{9}$$

The equivalent temperature of the sky is given by the following relation [26]:

$$\mathrm{T_{sky}} = 0.05T_a^{1.5} \tag{10}$$

3. Numerical Analysis

Figure 2 shows the geometric model of the hybrid PVT air collector. The domain was created using ANSYS Design Modeler 19.1 where the PV Module, duct, and insulation are fully modeled. The design parameters corresponded to the experimental system described [27] to validate the simulated outcome. The operation and design parameters of the PVT air collector required during validation procedure were described in Table 1. Further information regarding the experimental set up, method, and its conditions are explained by Kasaeian *et al.,* [27].

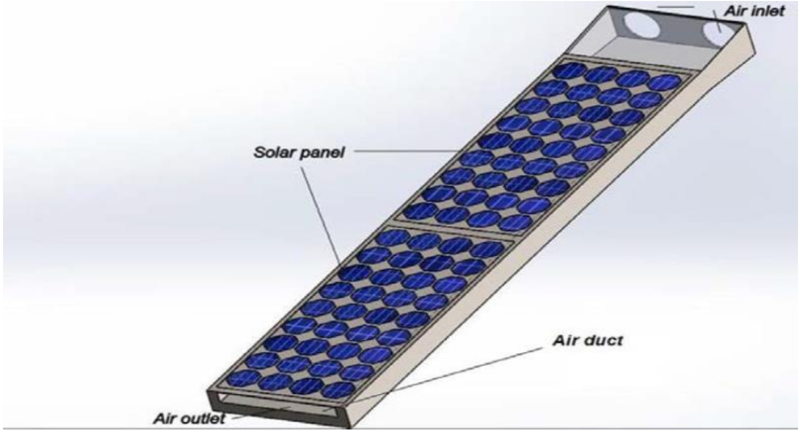


Fig. 2. Geometric model of hybrid PVT air collector

An unstructured tetrahedral mesh was employed in this simulation. The mesh was refined to attain an optimum value of aspect ratio and skewness. To resolve the flow parameters, a very fine mesh is required near the inner surface of the duct wall. In ANSYS Meshing, this was achieved with an inflation layer for computation efficiency. The mesh became coarser towards the center of the duct to save computation time. A mesh independence test was conducted to attain a statically accurate and converged solution. The fluid flow and heat transfer characteristics in PVT collector was studied using computational fluid dynamics (CFD) calculations through the FLUENT 19.1 software. A simplified meshed model which was previously built was imported to the FLUENT software for analysis.

Table 1
Operating and design parameters of hybrid PVT air collector system

Components	Parameters	Value	Unit	Ref
Glass cover	Thickness	0.003	m	[29]
	Thermal conductivity, kg	2	W/mk	[29]
	Emissivity, β_g	0.85	---	[30]
	Absorptivity, αg	0.04	---	[30]
	Transmissivity, τg	0.92	---	[30]
Silicon Solar cell layer	Thickness, δsc	0.0002	m	[30]
	Transmissivity, τ_{sc}	0.02	---	[30]
	Thermal conductivity, ksc	148	W/mk	[29]
	Absorptivity, αc	0.9	---	[30]
TPT (tedlar) back Sheet	Thickness	0.0003	m	[30]
	Thermal conductivity, kT	0.2	W/mk	[30]
	Absorptivity, α_t	0.128	---	[30]
	Duct depth	0.05	m	

The governing equations including energy equation, radiation model, and k- ε turbulence model was chosen to test the suitability and the applicability of the model regarding movements that flow through the duct. The suitable conditions were applied on computational domain as per physics of the problem. Longitudinal uniformed velocity was introduced in the inlet. The outer boundary was an average static reference pressure of 0 pa. Top surface of the PV panel was subjected to solar flux as well as convective and radiative losses which were implemented in FLUENT by user defined functions. The bottom surface of the PVT collector was defined by convective boundary conditions. The rest of the outer boundaries were defined by adiabatic boundary conditions. The inner wall of the duct has a no slip boundary conditions whereby velocity increases from zero at the wall surface to maximum at the center of the duct. Due to the presence of electrical efficiency of the PV module in Eq. (1) and dependency of electrical efficiency with solar intensity in Eq. (6), the thermal analysis of the hybrid PVT air collector and its electrical analysis were dependent. The calculation precision of thermal parameters of the PVT air collector will improve if the electrical efficiency of PV module is precisely calculated. The simulation was performed in steady state conditions [28] whereby the length of photovoltaic module is 1.053 m, the width of photovoltaic module is 0.554 m, and the thickness of insulation is 0.003m.

4. Result and discussion

4.1. Experimental Validation

The experimental results by Kasaeian *et al.,* [27] on the performance of the air PVT system involved the following parameters: Channel depth of 5 cm, tilt angle of 35°, and mass flow rate of 0.06 kg/s. The values of the solar intensity and the temperature of the ambient, the inlet air, and outlet air were recorded and monitored. The average temperature of the absorber plate, the back surface of the panel, the top surface of the panel was measured. In this work were obtained the maximum error for out temperature value between "exp" and "sim" ΔTout equal (-1.95 %) and solar cell temperature value ΔTsc equal (-0.48 %).

Other than the obtained results from the thermal section, the electrical data such as the short circuit current, the open circuit voltage, and the current and voltage in maximum power was used to validate the results obtained by the simulation model. The computer–generated values of the outlet air temperature, solar cell temperature, thermal efficiency, electrical efficiency, and overall efficiency in the current study were validated by their equivalent experimental values as reported by Kasaeian *et al.,* [27]. The comparison between the simulated value of solar cell temperature, outlet air temperature, and the corresponding experimental data by Kasaeian *et al.,* [27] are shown in Figure 3. The subscript 'sim' indicates the simulated value of parameters in the current study and the subscript 'exp' indicates the experimental value.

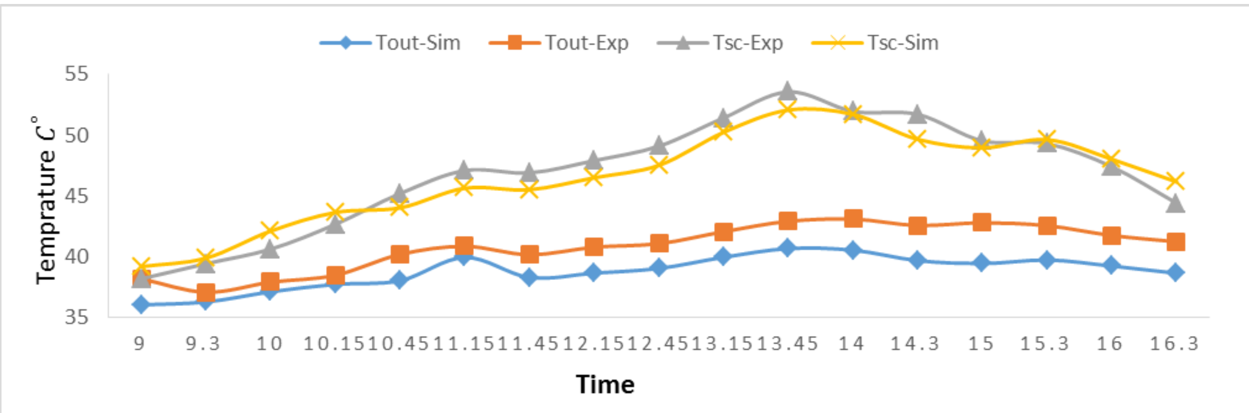


Fig. 3. Comparison of experimental and simulation of solar cell temperature and outlet air temperature of hybrid PVT air collector

According to the Figure 3, it is observed that there is a good agreement between the experimental and simulated value of these parameters. However, the agreement in the simulated and experimental values for solar cell temperature is closer in low ambient temperatures whereby the fired is about the same and the value difference is acceptable.

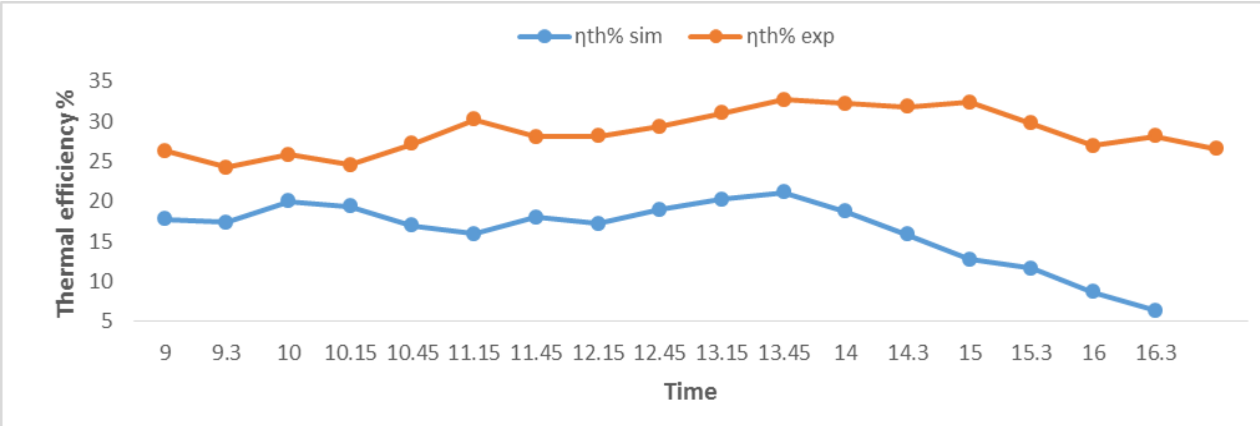
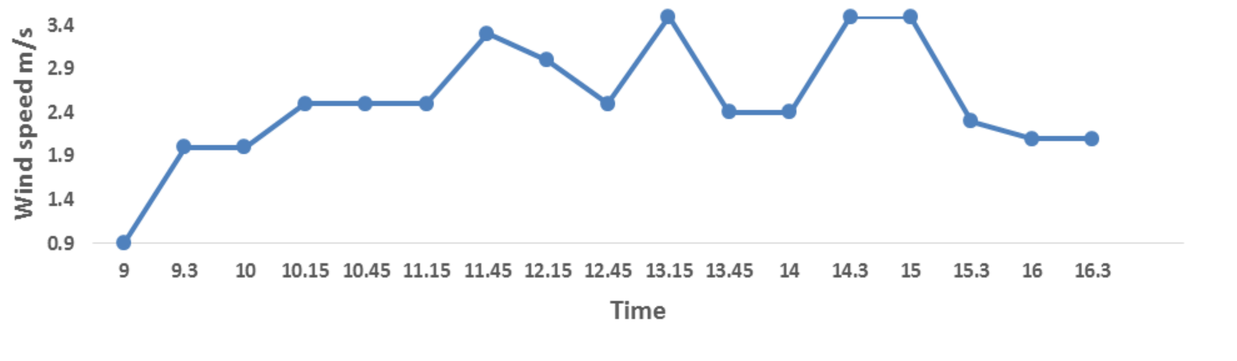
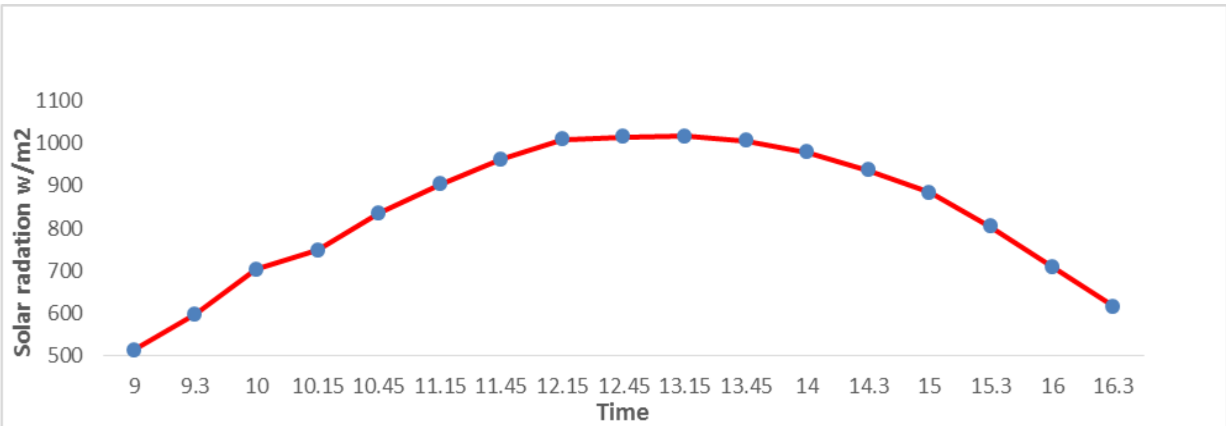


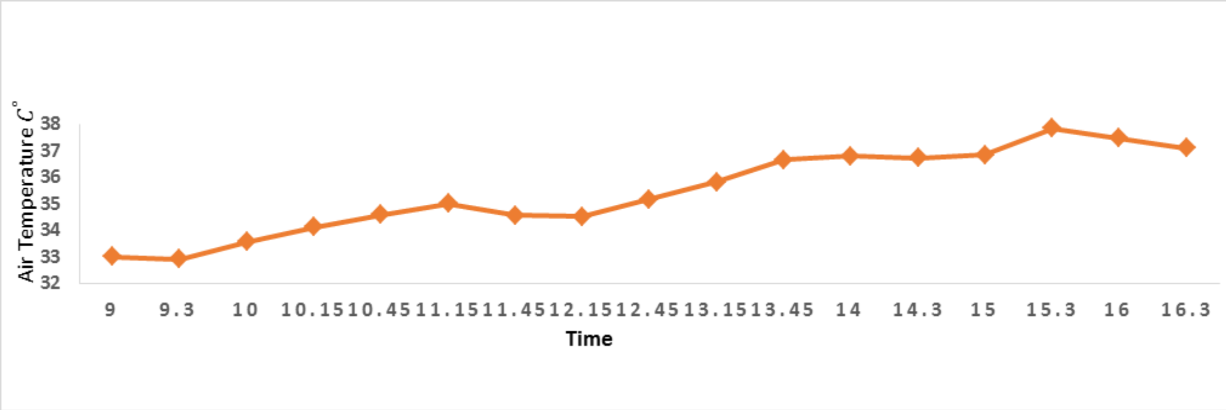
Fig. 4. Comparison of experimental and simulation thermal efficiency of hybrid PVT air collector



(a)



(b)



(c)

Fig. 5. Experimental weather data used in validation setup [27]

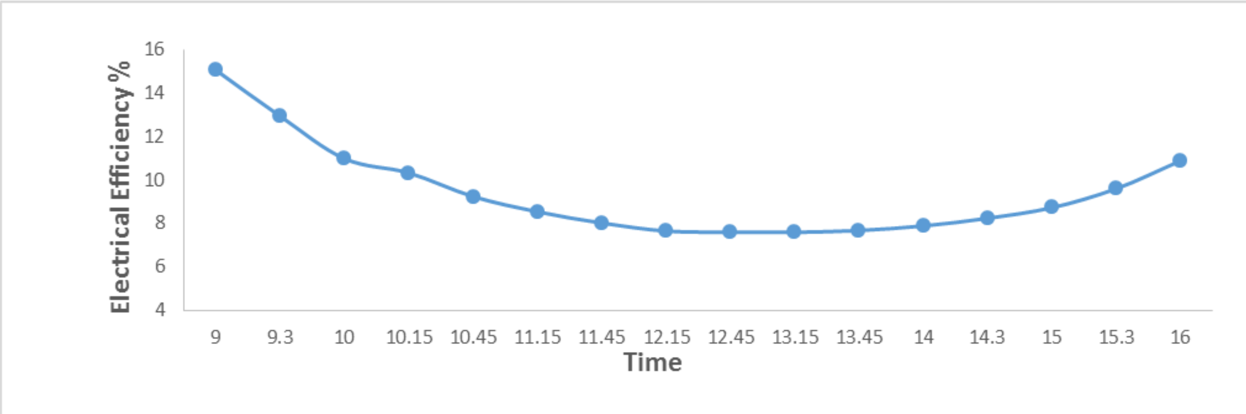


Fig. 6. Simulation validation on the hourly variation of electrical efficiency of hybrid PVT air collector

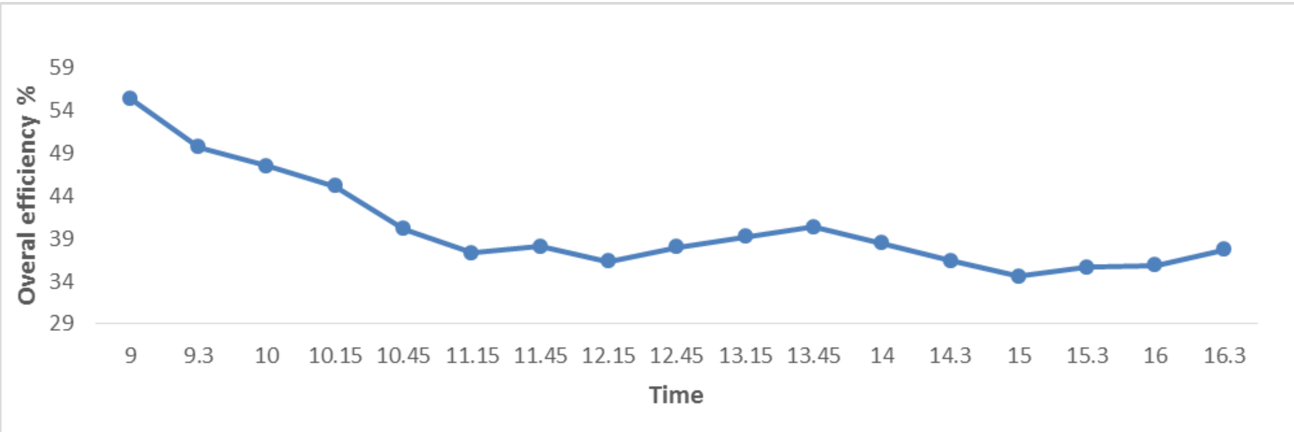


Fig. 7. Simulation validation on the hourly variation of overall efficiency of hybrid PVT air collector

Figure 4 shows the simulation validation on the hourly variation of thermal efficiency of hybrid PVT air collector and a comparison between the simulated and experimental values. For this validation setup, the climatic conditions of the experimental study shown in Figure 5 (a, b, c) were used in the numerical model of the simulation to evaluate and compare the energy performance of the system. Figure 6 shows the validation value of electrical efficiency of the hybrid PVT air collector and Figure 7 shows the validation value of the overall efficiency of the hybrid PVT air collector.

5. Conclusion

In this paper, a two-dimensional numerical model has been developed using ANSYS Fluent and was favourably compared to results available in the literature. The performance evaluation of the hybrid PVT air collector was conducted. Electrical conversion inside the panel was compensated by user-defined functions to increase the calculation precision of the PVT air collector thermal parameters. For validation, numerical simulation and parametric studies were conducted and a new design was proposed based on the studies. Based on the present study, the following conclusions were drawn:

- The numerical simulation results of this study agree with the experimental measurements noted in the previous literature. It is observed that the simulation results were as reported by Kasaeian *et al.,* [27].
- The increase in mass flow rate increased the overall efficiency initially. This is due to high rate of air that passed through the duct which extracted high thermal energy which also reached an approximate constant nature at high flow rate due to less flow residence time inside the duct.
- The increase in duct depth decreases the overall efficiency of the hybrid PVT air collectors. The change in the channel depth does not have a significant effect on the electrical efficiency. However, decreasing the channel depth increases the thermal efficiency. Electrical efficiency was affected and decreased when the value of solar radiation increased. Furthermore, increasing the temperature values of the solar cells because increases the value of solar radiation which leads to an increase in air temperature outside.

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