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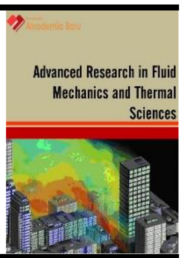

A Simulation Study on Temperature Uniformity of Photovoltaic Thermal Using Computational Fluid Dynamics

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ABSTRACT

The temperature distribution across the photovoltaic (PV) module in most cases is not uniform, leading to regions of hotspots. The cells in these regions perform less efficiently, leading to an overall lower PV module efficiency. They can also be permanently damaged due to high thermal stresses. To enable the high-efficiency operation and a longer lifetime of the PV module, the temperatures must not fluctuate wildly across the PV module. In this study, a custom absorber is designed based on literature to provide a more even temperature distribution across the PV module. This design is two standard sets of spiral absorbers connected. This design is relatively less complicated for this reason and it allows room for adjusting the pipe spacing without much complication. The absorber design is tested via computational fluid dynamics (CFD) simulation using ANSYS Fluent 19.2, and the simulation model is validated by an experimental study with the highest percentage error of 9.44%. The custom and the serpentine absorber utilized in the experiment are simulated under the same operating conditions having water as the working fluid. The custom absorber design is found to have a more uniform temperature distribution on more areas of the PV module as compared to the absorber design utilized in the experiment, which leads to a lower average surface temperature of the PV module. This results in an increase in thermal and electrical efficiency of the PV module by 3.21% and 0.65%, respectively.

1. Introduction

The energy demand has seen a sudden increase in recent years due to the increase in population and the rapid advancement of technology [1]. According to the International Energy Agency, global energy consumption rates are expected to rise by up to 37% by 2040 [2]. In recent years, to match this increase in demand and to decrease the depletion rate of natural resources while avoiding greenhouse gas emissions in energy generation, renewable energy resources such as wind, solar,

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hydro, biomass, and geothermal energy are being used for energy generation [3]. Solar energy is one of the best options due to its high potential and availability across many regions worldwide. However, it is still considered an expensive source for electrical energy generation due to inefficient technology. Even though it is inefficient, solar power still possesses the most potential for power generation [4]. Therefore, a lot of research work is being done to improve the technology in recent years. Abdullah *et al.,* [5] does a useful review of the recent advancements made in solar photovoltaic thermal (PVT) technology. While Sachit *et al.,* [6] focuses on the flat plate type photovoltaic (PV) systems. Photovoltaic (PV) cells are used to convert solar energy into electrical energy, and thermal energy is produced as well. PV panels typically have electrical efficiency in the range of 4-17%, depending on the operating conditions [7]. Most solar irradiance is converted into thermal energy instead. This thermal energy raises the temperature of PV cells, which causes a decline in the electricity generation and efficiency and can also lead to permanent damage due to high thermal stress levels [8,9].

To solve this problem, solar photovoltaic thermal (PVT) systems are used, which take the thermal energy away from the PV cells allowing them to work under lower temperatures, thus increasing their efficiency [9,11]. Solar PVTs use various cooling fluids to extract thermal energy. Various techniques are used to improve the heat transfer between the cooling fluid and the PV module, which influences the efficiency of the system. Some studies focus on the working fluid, which normally is either air (less efficient) or water [12]. But it can be changed to achieve better thermal efficiency using various nanofluids [7,13-16].

Another approach for improving efficiency is by changing the absorber configuration. Absorbers can be configured in many shapes such as serpentine, parallel, spiral, or other custom shapes like Misha designs as shown in Figure 1 [17,18]. When compared with each other, the spiral arrangement is found to be most efficient [2,19,20]. Studies have also compared different tube shapes for the absorbers. Round tubes are found to be more efficient as they allow for better flow even though square tubes have better contact area with the absorber plate [2,20].

Table 1 shows the thermal and electrical efficiencies obtained by various studies present in literature. Where ‘T_a’ is the ambient temperature, ‘W_s’ is the wind speed, ‘I_r’ is the solar radiation, ‘T_s’ is the temperature of the sky and ‘T_i’ is the inlet temperature.

The performance of the PVT system depends heavily on operating conditions. This is explored to a high degree in literature. However, temperature uniformity also affects the performance of a PVT system—non-uniform temperature distribution results in regions of hotspots (areas of high temperatures). The cells in these regions perform poorly compared to other cells due to high temperature, resulting in decreased efficiency due to lower power generation. These temperature hotspots can also cause permanent damage to the PV cells due to high thermal stresses. Therefore, temperature uniformity is an essential factor in increasing the performance and PV panels' lifetime [9]. The temperature uniformity is extensively studied by Bahaidarah *et al.,* [9] for both concentrating and non-concentrating PV systems. The importance of uniform cooling is signified by the mention of adverse effects on performance due to non-uniform temperatures across the PV due to shading and inconsistent irradiance levels across the PV system. In a series combination of PV cells, the overall current produced by the module is restricted to the minimum current produced by a cell in a hotspot [9]. Because of this, the performance of PV panels is usually determined by the hotspots [31].

Table 1
Efficiency studies in recent years on PVT systems

Reference	Thermal Collector	Operating Conditions	Thermal Efficiency	Electrical Efficiency	Type of Study
Wang *et al.,* [21]	Fresnel	T_a = 30°C, W_s = 3 m/s, I_r = 960 W/m^2,	79%	8.7%	Theoretical
Valizadeh *et al.,* [22]	Parabolic Trough	T_a = 25°C, T_s = 19°C, W_s = 5 m/s, I_r = 1000 W/m^2, T_i = 70°C,	67%	22%	Theoretical
Yu *et al.,* [23]	Flat Plate	T_a = 23.6°C, W_s = 3 m/s, I_r = 940 W/m^2,	25.2%	11.8%	Theoretical & Experimental
Abd El-Samie *et al.,* [24]	Compound Parabolic	T_i = 25.1°C,	50.6%	7.3%	Theoretical
Bellos and Tzivanidis [25]	Parabolic Trough	T_i = 25°C, I_r = 1000 W/m^2,	46.84%	6.6%	Theoretical
Adam *et al.,* [26]	Fresnel, Parabolic Trough	T_a = 25°C, T_i = 20°C, I_r = 1000 W/m^2,	55%, 70%	5%, 18%	Theoretical
Jaaz *et al.,* [27,28]	Compound Parabolic	T_a = 33°C, I_r = 800 W/m^2,	81%	13.75%	Experimental
Proell *et al.,* [29]	Compound Parabolic, Flat Plate	T_a = 17 - 29°C, I_r = 1000 W/m^2,	34%	9%	Experimental
Yazdanifard *et al.,* [30]	Parabolic Trough, Flat Plate	T_a = 25°C, T_i = 25°C, W_s = 1.5 m/s, I_r = 700 W/m^2,	52.58% - 56.37%	7.12 % - 7.94%	Theoretical
Hosseinzadeh *et al.,* [7]	Flat Plate	T_a = 30°C, T_i = 40°C, I_r = 900 W/m^2,	56%	14.4%	Theoretical & Experimental
Misha *et al.,* [16]	Flat Plate	W_s = 1 m/s, T_i = 26°C, I_r = 600 – 1000 W/m^2,	59.6%	11.71%	Theoretical & Experimental

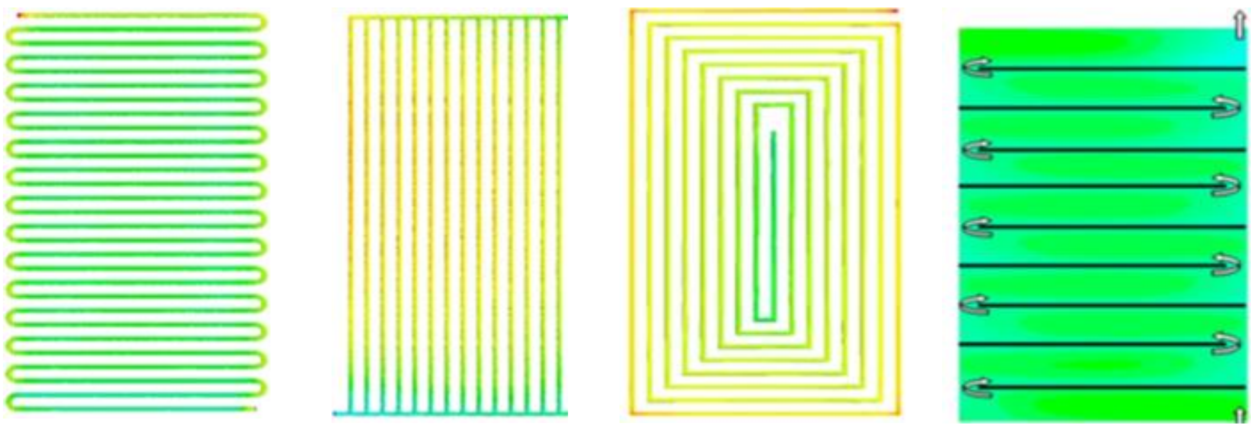

(a) (b) (c) (d)

Fig. 1. (a) Serpentine absorber, (b) Parallel absorber, (c) Spiral Absorber, (d) Cross fined absorber (for air) [2]

Not many studies focus primarily on temperature uniformity on the PV module. That is because temperature uniformity is more prevalent in the concentration PV systems [32]. However, it should not be neglected for flat-plate PV systems [33]. The limited studies that mention the effects of temperature uniformity point towards performance gains due to better uniformity. Mohammad highlights the bypass diode effect, which hurts performance due to uneven temperatures across the PV induced by partial shading [34]. When using air, a better temperature distribution is observed across the PV. Nevertheless, at the same time, the air is not a good conductor of heat as compared to water. Nevertheless, when using liquid cooling techniques, the temperature distribution becomes uneven.

Many parameters affect the temperature uniformity and efficiency of PV panels, such as ambient wind speed, incident solar irradiation, ambient air temperature, coolant inlet temperature, coolant mass flow rate, absorber tube spacing, absorber tube length, and absorber configuration, etc. The effect of tube spacing on temperature uniformity is highlighted by Zhou *et al.,* [33]. They concluded that with a small tube spacing, better uniformity of temperature distribution is observed. High ambient wind speed results in high convection on the top glass surface resulting in lower temperatures, i.e., high electrical efficiency. However, this results in lower thermal efficiency due to more heat loss to ambient. The effect of wind speed on temperature uniformity is not significant [7]. High solar irradiation causes high temperatures on the cells. This results in lower electrical efficiency. However, if the PVT system has good thermal efficiency, PV cells can operate at higher irradiation levels with good electrical efficiencies. Low coolant inlet temperatures lead to better thermal and electrical efficiency [7]. A high mass flow rate leads to better electrical and thermal efficiency [7]. However, for uniformity, the inlet velocity/flow rate does not play a significant role [33]. The spiral absorber can lead to better thermal efficiency due to increased pipe length and the surface contact area between tubes and the module.

In summary, for best uniformity of temperature on PV panels, a spiral absorber (because it gives a better contact area between pipe and module) with low values of tube spacing, aluminium/copper as the absorber plate material, and an optimum flow rate based on the absorber pipe dimensions is recommended. Usually, a high flow rate results in better heat transfer [33].

In this article, a PVT system with a custom absorber configuration is designed and tested which will ensure an improved and more uniform temperature distribution across the PV plate. This custom absorber will be optimized based on the previous literature. This new absorber design should give better temperature distribution across the PV plate surface, which will help with prolonging the lifetime of the panel and its overall efficiency. A simulation model is prepared and validated by an experimental study [7]. The new absorber is then tested in terms of performance and temperature uniformity in this simulation model and its performance is compared with that of the absorber used in the experimental study [7]. There have been studies that explore temperature uniformity. Figure 2 shows the research gap found in these studies which is contributed towards by this article.

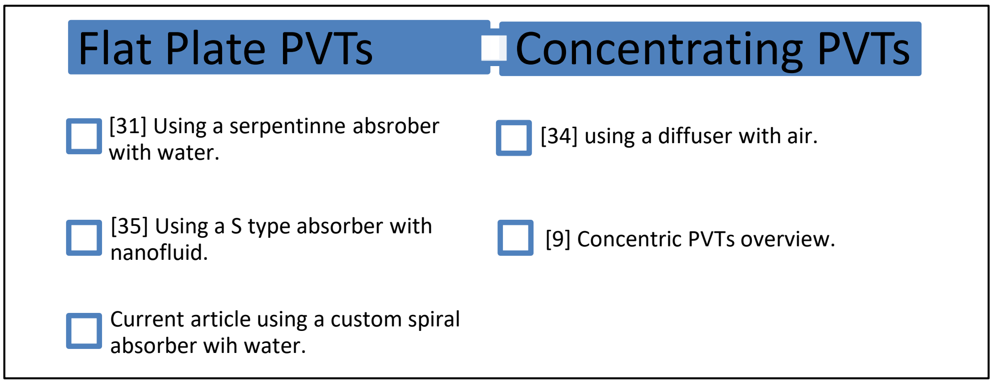


Fig. 2. Research gap demonstration for temperature uniformity

2. Methodology

The model consists of a typical monocrystalline silicon PV module. The module is coupled with an absorber made of copper, having water as its working fluid. The geometric model for the simulation is made in Design Modeler and consists of a glass, PV module, absorber plate, thermal contact paste, absorber pipe, and insulation body as shown in Figure 3. Layers such as the ARC protective layer and the tedlar are excluded from the model due to their very small size (0.0001m). At the same time, EVA layers are considered to be 100% transparent and therefore also excluded from the model for further simplification [31].

The properties of the different materials and the dimensions of layers used in the model are borrowed from the studies of Hosseinzadeh *et al.,* [7], Fayaz *et al.,* [35], and Filipović *et al.,* [36] are shown in Table 2 and Table 3, respectively. The properties of insulation material are absent from the study. These properties are estimated as wood.

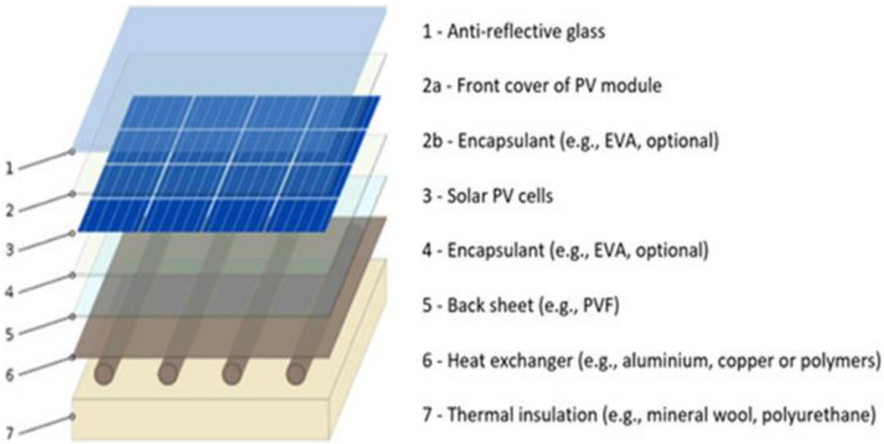


Fig. 3. A general PVT module diagram

Table 2
Material properties [7,25,26]

Material	Thermal Conductivity (k) $\frac{W}{m^1\,K^1}$	Specific Heat (Cp) $\frac{J}{Kg^1K^1}$	Density $\frac{Kg}{m^3}$
Glass	1.3	749	2200
PV	148	700	2330
Copper	387.6	381	8978
Thermal Paste	1	650	2400
Insulation	0.173	700	2310
Water	0.6	4182	998.2

Table 3
PVT layer dimensions [7]

Layer	Dimensions (L x W x H)
Glass	0.63m x 0.54m x 0.003m
PV	0.63m x 0.54m x 0.0003m
Absorber Plate	0.63m x 0.54m x 0.0004m
Insulator	0.63m x 0.54m x 0.013m

2.1 Model Discretization

The study is conducted using the Computational fluid dynamics (CFD) method. By considering the PVT system as a control volume, the following governing equations for continuity, momentum, and energy are used [7,27]

Continuity equation

$$\nabla \cdot (\rho_f V_f) = 0 \tag{1}$$

Momentum equation

$$\nabla . (\rho_f V_f V_f) = -\nabla P + \nabla . (\mu_f \nabla V_f) \tag{2}$$

Flow Energy equation

$$\nabla \cdot (V_f \rho_f C_{p,f} T_f) = \nabla . (k_f \nabla T_f) \tag{3}$$

Energy equation for solids

$$k_s \nabla (T_s) = 0 \tag{4}$$

where 'V_f' is the fluid velocity, and 'P' is pressure. Subscript 'f' indicates fluid, where 's' indicates solid.

The equations are discretized and solved using the pressure-based finite volume method using ANSYS Fluent 19.2. For the mass flow rate of 40 kg/h, the Reynolds number is near but under the critical Reynolds number of 2300. Therefore, the flow is considered laminar for a flow rate under 40 Kg/h and turbulent over 40 Kg/h. Furthermore, the flow is considered steady, fully developed, and incompressible. The pressure and velocity are coupled using the SIMPLE scheme. The second-order upwind interpolation scheme is used for convective terms. The top of the glass surface has the wall condition with the heat generation rate equal to the absorbed solar irradiation. About 10% of it is assumed to be absorbed by the glass, while the PV module absorbs the rest. In addition, convection occurs in the ambient air. The ambient wind speed is assumed to be less than 5 m/s. For which the convective heat transfer can be calculated using the following equation [28]

$$h_w = 5.7 + 3.8\, V_w \; for \; V_w < 5\, m/s \tag{5}$$

where 'h_w' is the convective heat transfer co-efficient, and 'V_w' is the wind speed.

Taking the PVT system as a control volume and assuming steady-state conditions applied, the energy balance for the PVT system can be expressed as

$$E_{sun} + E_{mass,in} = E_{el} + E_{mass,out} + E_{loss} \tag{6}$$

Where, '$E_{mass,in}$', '$E_{mass,out}$', and 'E_{loss}' refers to input, output, and lost energy. 'E_{sun}' is equal to the absorbed solar irradiation, and it can be expressed as

$$E_{sun} = G \cdot Ac \cdot \tau_g \cdot \alpha_{cell} \tag{7}$$

'G' is the rate of total solar irradiation, 'Ac' is the surface area of the collector, 'τ_g' is the transmissivity of the glass cover, while 'α_{cell}' is the absorptivity of the PV cells. The energy relating to mass flow is calculated as

$$E_{mass,out} - E_{mass,in} = E_{th} = m_f \, C_{p,f} \cdot (T_{f,out} - T_{f,in}) \tag{8}$$

where 'm_f' is the mass flow rate and '$T_{f,in}$' the fluid temperature. The thermal efficiency of the system is calculated by

$$\eta_{th} = \frac{E_{th}}{E_{sun}} = m_f \, C_{p,f} \cdot \frac{T_{f,out} - T_{f,in}}{G \cdot Ac \cdot \tau_g \cdot \alpha_{cell}} \tag{9}$$

The electrical energy efficiency of the PVT system is calculated from the equation [29]

$$\eta_{el} = \frac{E_{el}}{E_{sun}} = \eta_r \,.\, [1 - 0.0045 \,.\, (T_{cell} - 298.15)] \tag{10}$$

where 'η_r' is the PV module efficiency, and 'T_{cell}' is the temperature of the PV cell. This equation is used for numerical analysis. For experimental analysis, the electrical energy efficiency of PVT system is found by Yazdanifard *et al.,* [30]

$$\eta_{el} = \frac{E_{el}}{E_{sun}} = \frac{V_{oc} \,.\, I_{sc} \,.\, FF}{G \cdot Ac \cdot \tau_g \cdot \alpha_{cell}} \tag{11}$$

where 'V_{oc}' and 'I_{sc}' stand for open-circuit voltage and short circuit current of the PV module, respectively. 'FF' is the fill factor, which is calculated by Yazdanifard *et al.,* [30]

$$FF = \frac{V_{max} \,.\, I_{max}}{V_{oc} \,.\, I_{sc}} \tag{12}$$

The overall efficiency is the sum of thermal efficiency and electrical efficiency. The heat transfer in the PVT system due to the incident solar irradiation is simulated by the heat flux method [26]. The temperature distribution uniformity is checked by plotting the temperature across a line in the middle of the PV module's top surface.

2.2 Simulation Assumptions

Following assumptions are made for the model.

- Steady-state conditions are assumed.
- Perfect contact between all components is assumed.
- EVA layer is assumed not to affect the model thermally (100% transparency) [31,41].
- The thermophysical properties of various materials in the model are assumed to be constant.
- Solar Irradiance is assumed to be incident on the PV panel normally for maximum performance.
- Some space on the PV panel will be left for the junction box.

Table 4 shows the values of the input parameters to the equations.

Table 4
Input parameters for the equations

Parameter	Value
Specific Heat ($\boldsymbol{Cp}$) $\frac{J}{Kg^1K^1}$	4182
Surface Area of The Collector ($\boldsymbol{Ac}$) $\boldsymbol{m^2}$	0.54 x 0.63
Rate of Total solar Irradiation ($\boldsymbol{G}$) W/m^2	1000
Transmissivity of the glass cover (τ_g)	0.9
Absorptivity of the PV cells (α_{cell})	0.9

2.3 Custom Absorber Design

From the literature review, it is found that the spiral absorber is most efficient. However, a simple spiral absorber cannot be housed in the PVT system without making flow design changes to accommodate the junction box. Instead of fashioning a single spiral absorber to leave some space for the junction box, two spiral absorbers connected, as shown in Figure 4, are proposed. This way, ample space is left for the junction box, and the absorber itself provides a decent flow design without the use of complicated machining techniques. On top of that, the overall pipe length is increased which will lead to more heat transfer to the working fluid. The custom absorber has an approximate pipe length of 12.85m where the serpentine design used by Hosseinzadeh *et al.,* [7] has an approximate pipe length of 7.53m.

The collector pipe is made of copper which has an inner diameter of 0.01m and an outer diameter of 0.012m. The custom absorber design is shown in Figure 4. The pipe spacing is kept at 0.002m to ensure more contact area between the pipe and the plate. The pipe spacing is a bit extended in areas like the centre of each spiral loop and the middle region where the loops are connected, where the pipe spacing is 0.032m and 0.04m, respectively. This is done for model design simplification and to allow simulation with a relatively small mesh count. If the pipe spacing is to be kept consistent throughout, there will be more tight spaces in geometry which will require a much finer mesh to avoid invalid dihedral angles.

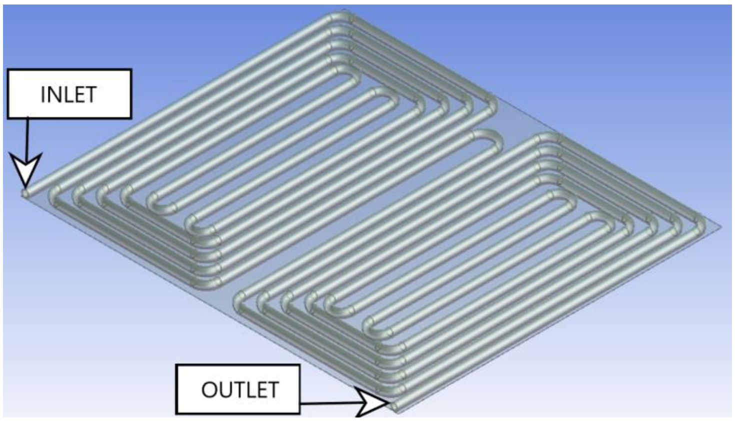


Fig. 4. The Custom Absorber Design

Many custom designs have been proposed in the literature, the novelty of this design is its simplistic geometry. In most cases, to accommodate for the junction box usually, major changes in the flow design are made which brings up complications especially if the pipe spacing is to be kept small for temperature uniformity. This design is two standard sets of spiral absorbers connected. This design is relatively less complicated for this reason and it allows room for adjusting the pipe spacing without much complication.

3. Results

3.1 Model Validation

The simulation model is verified with the experimental data taken from a study by Hosseinzadeh *et al.,* [7]. The experiment takes place in Mashhad, Iran. The specifications under standard testing conditions of the monocrystalline PV module used in the experiment are detailed in Table 5.

Table 5
Parameter specification

Parameter	Specification
Maximum power (W)	40
Number of cells	36
Fill factor	0.726
Open-circuit voltage (V)	21.6
Short-circuit current (A)	2.57
Optimum operating voltage (V)	17.6
Optimum operating current (A)	2.29
Cell efficiency (%)	16
Module efficiency (%)	15

In the experiment, the PV module is attached to a copper plate, which is soldered to a serpentine copper absorber and an insulating body around it. The working fluid is circulated at a flow rate of 30 kg/h. The experiment takes place in Mashhad, Iran. The readings are taken on selected days in August and September [7]. The experiment results are compared to the results of a simulation model. For validation, the same model was recreated with the same boundary conditions. The ambient temperature, incident solar irradiance, and the water inlet temperature are shown in Figure 5.

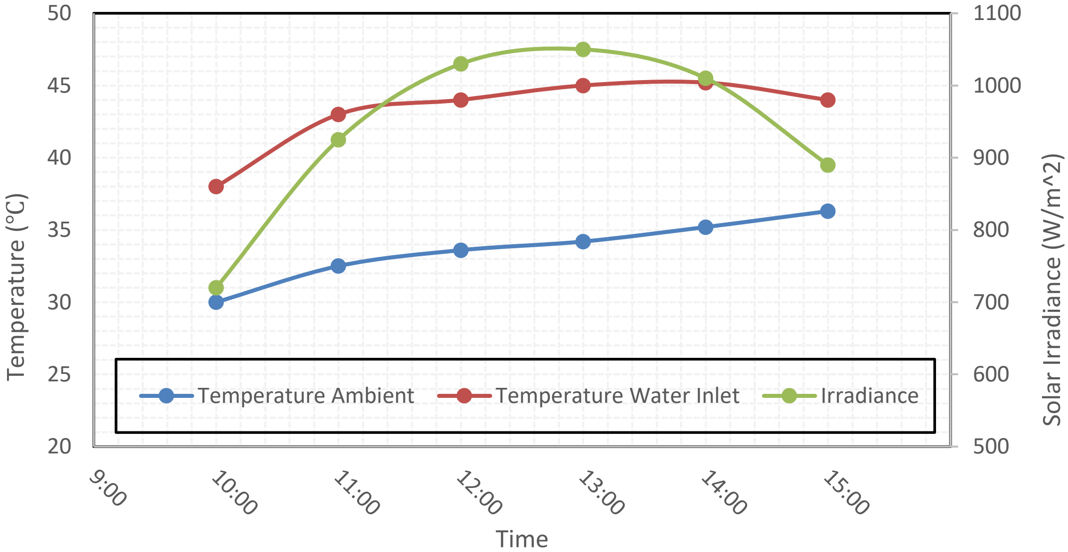


Fig. 5. Initial ambient, coolant inlet temperatures and incident solar irradiance with respect to time [7]

Using the data from the experiment, the simulation model is verified by recreating the absorber design shown in Figure 6. Under the same conditions as the experiment, the simulation is carried out. The results of the simulation and the experiment are compared and validated. The comparison is shown in Figure 7 and Figure 8.

The percentage error between the experimental data and simulation result is found to be 7.8% and 7% for PV temperature and outlet temperature, respectively. The highest percentage error is 9.44%, where the lowest is 3.17%. The mean squared deviation is 18.2 and 11.4 for PV and water outlets, respectively. This higher percentage of error is present due to model simplification undertaken due to hardware limitations. It should be noted that this high percentage of error will lead to errors in the efficiency calculation of the PVT system as well. The variation of thermal and electrical efficiency between simulated and experimental data is shown in Figure 9 and Figure 10.

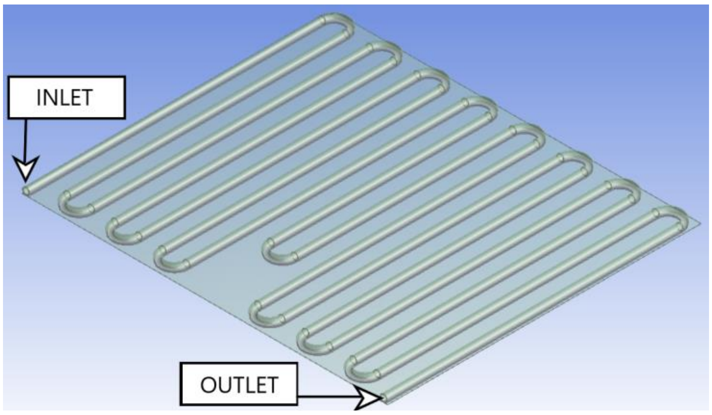


Fig. 6. Serpentine absorber design [7]

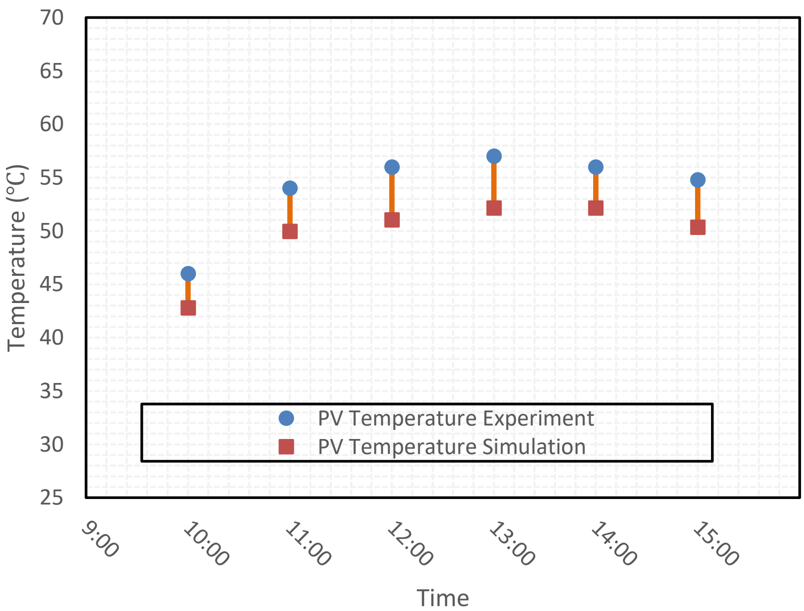


Fig. 7. PV temperature experimental and simulated with respect to time

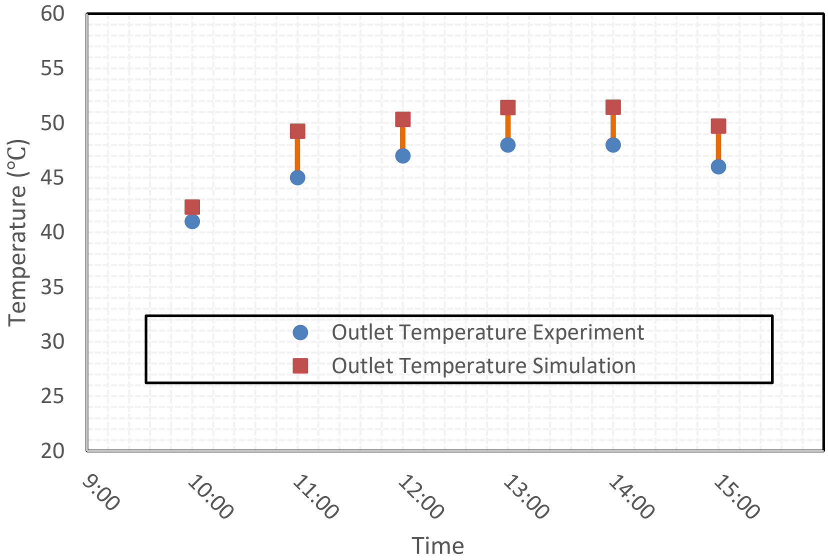


Fig. 8. Coolant outlet temperature experimental and simulated with respect to time

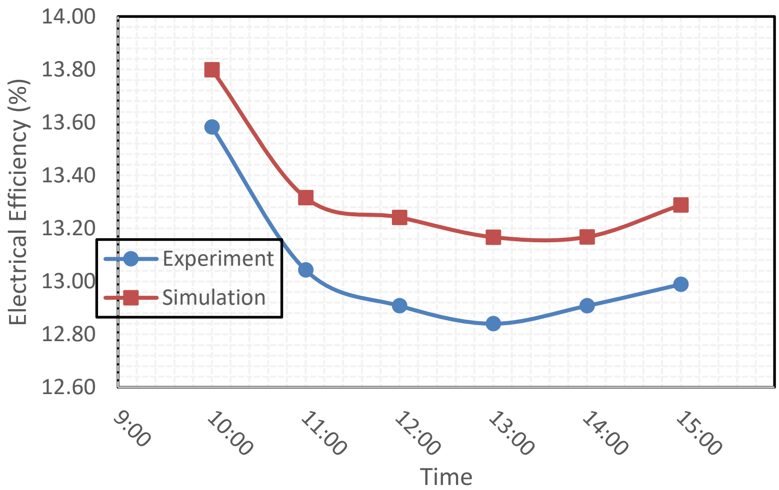


Fig. 9. Electrical efficiency comparison

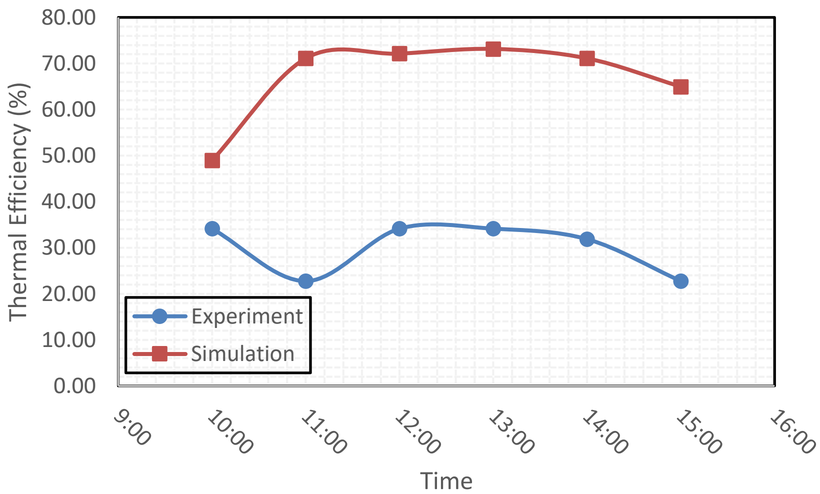


Fig. 10. Thermal efficiency comparison

As can be seen from Figure 9 and Figure 10 above, due to a relatively high percentage error, the electrical and thermal efficiencies have high margins of error, especially for thermal efficiency. On average, the electrical efficiency of the simulation is higher than the experiment data by a difference of 0.28 %. With the maximum and minimum differences being 0.33 % and 0.22 %, respectively. Whereas the thermal efficiency on average for the simulation is higher than the experiment data by a difference of 36.94 % with the maximum and minimum differences coming in at 48.92 % and 73.16 %, respectively. As the simulation setup is limited by computational power, this error cannot be reduced, but it can be accounted for in the comparison study. The unusually high margin of error can be attributed to differences in the simulation model undertaken for the sake of simplicity. These differences are as follows

- The simulation model does not utilize any radiation modelling whereas the model used by Hosseinzadeh *et al.,* [7] does utilize radiation modelling.
- The insulation material is also not simulated directly by Hosseinzadeh *et al.,* [7].
- No thermal paste is used by Hosseinzadeh *et al.,* [7].
- Mesh type and the software used for meshing are different.

3.2 Grid Independence Test

Meshing is done in ANSYS Fluent Meshing 19.2 using the polyhedral volume meshing as shown in Figure 11. Multiple mesh element sizes were tested. The mesh settings that were tested had a mesh count of 2.9M, 3.4M, 3.98M, and 4.78M. The results of the simulations using these different mesh counts are shown in Table 6.

Table 6
Coolant outlet and PV temperature with respect to mesh size

Mesh Size in Million (M)	PV Temperature (°C)	Outlet Temperature (°C)
2.9	51.05	50.34
3.4	51.07	50.35
3.98	51.05	50.35
4.78	51.03	50.35

Although the results vary with change in mesh size, due to hardware limitations and the fact that the degree of change is insignificant, the mesh size is not further refined to increase the mesh count. The mesh has a minimum orthogonal quality of 0.2, a maximum aspect ratio of 27, and a maximum skewness of 0.78.

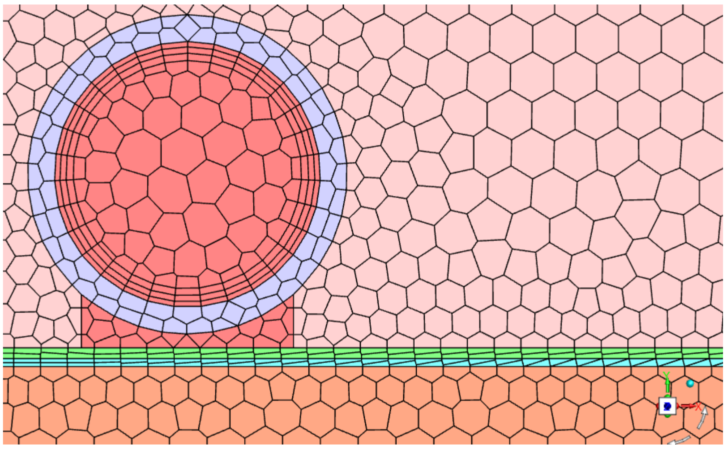


Fig. 11. A view of the mesh of the PVT system

3.3 Absorber Performance Comparison

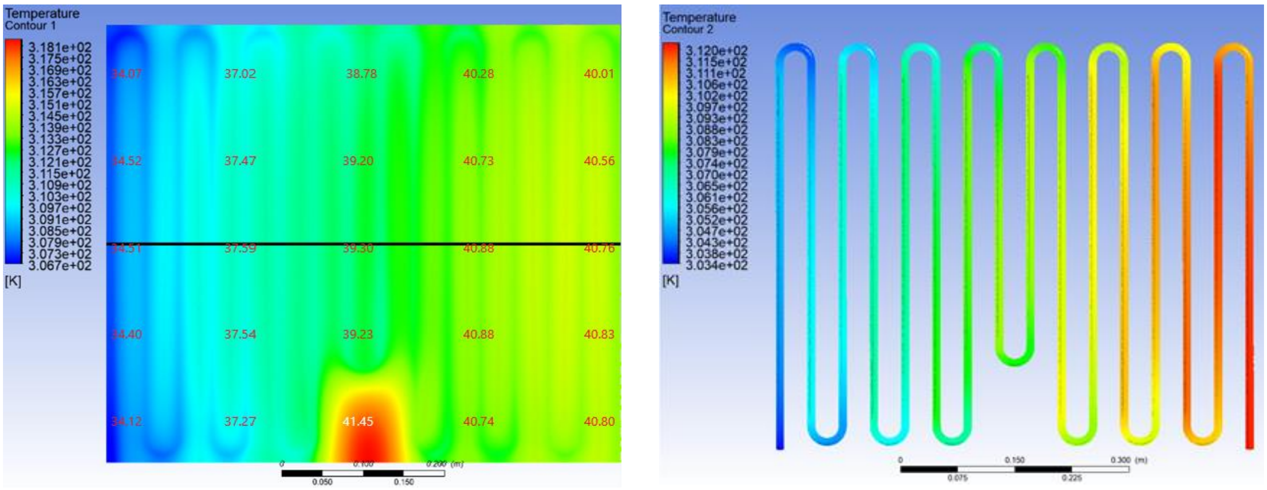
After the model verification is done, the PVT system is simulated using both absorber designs under the same conditions as shown in Table 7. The uniformity of the PVT system using the custom absorber design and the serpentine design by Hosseinzadeh *et al.,* [7] is tested. After taking the study of Hosseinzadeh *et al.,* [7] into consideration, where he found the ideal conditions for maximum efficiency, the following operating conditions are chosen as base conditions for comparison:

Table 7
Operating parameters

Parameter	Value
Wind Speed (m/s)	5
Inlet Temperature (°C)	30
Ambient Temperature (°C)	30
Coolant Mass Flow Rate (Kg/h)	30
Incident Solar Irradiance (w/m^2)	1000

3.3.1 Serpentine absorber

In the serpentine absorber configuration used by Hosseinzadeh *et al.,* [7], the average surface PV temperature and the coolant outlet temperature are found to be 38.88°C and 37.96°C, respectively. The temperature distribution across the PV module surface and the temperature contour of water are shown in Figure 12.

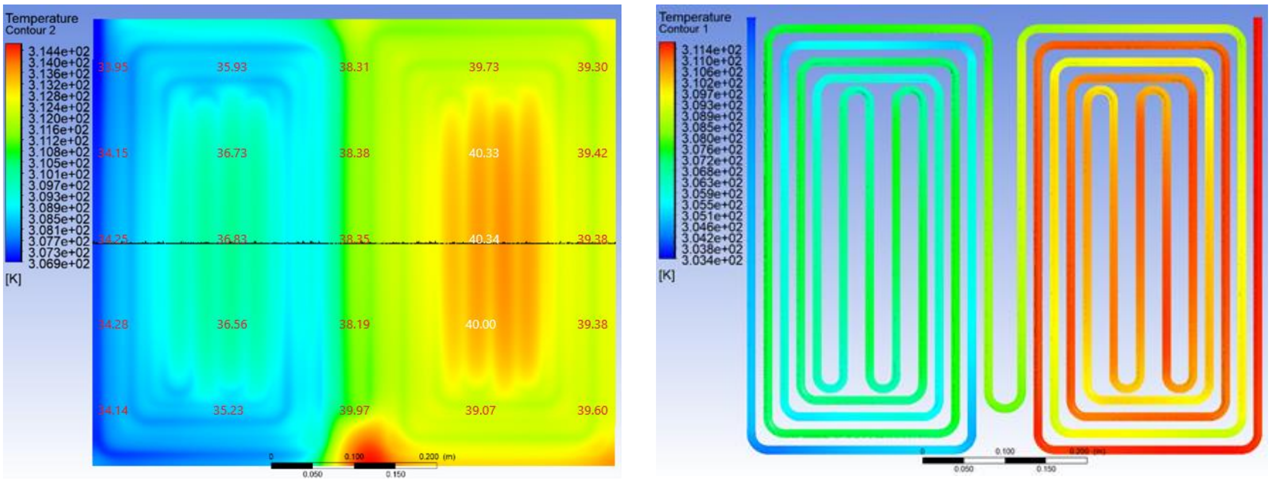


(a) (b)

Fig. 12. Serpentine absorber contour (a) Top PV surface (b) Absorber

3.3.2 Custom absorber

For the custom absorber design, the average PV surface temperature and the coolant outlet temperature are found to be 37.63°C and 38.11°C. The temperature contours of the PV surface and water are shown in Figure 13.



(a) (b)

Fig. 13. Custom Proposed Design (a) Top PV surface (b) absorber

3.3.3 Discussion

To compare the temperature uniformity, the temperature distribution across a line located at the centre of the PV surface is shown in Figure 14. The black line shows the location of the line in Figure 12 and Figure 13.

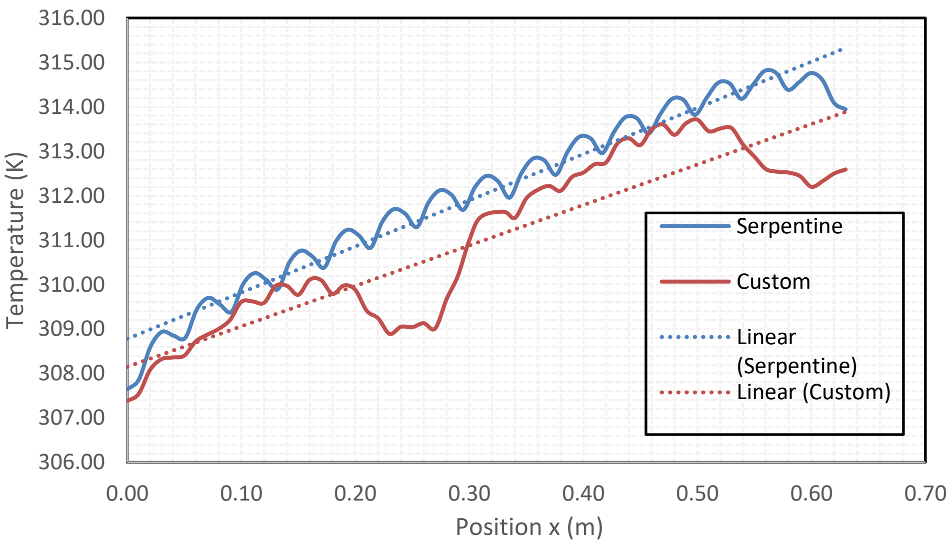


Fig. 14. Temperature distribution on a line at the centre of the PV top surface for both absorbers

When comparing the temperature on a line in the middle of the PV surface, it can be seen that the temperature of the PV when using a custom absorber varies from 34.23℃ to 39.44℃, whereas for design of Hosseinzadeh *et al.,* [7], it varies from 34.49℃ to 40.79℃. Across the PV, the highest temperature observed when using the custom absorber is 41.25℃, and for Hosseinzadeh *et al.,* [7] is 44.95℃. The difference in temperatures is due to the pipe spacing, pipe length, and absorber configuration, as evident from the literature. From Figure 14, the temperature uniformity across the PV surface when using the custom absorber can be seen as better than that of the serpentine absorber as more cells are operating at near-identical temperatures. However, the uniformity is observed to deteriorate at locations where the pipe spacing is increased due to design simplicity. The sharp decline and rise between 0.2m and 0.3m can be explained by looking at the flow design.

In the sector between 0.2m and 0.3m, the tube section is close to inlet. The water in that section is closer to the water entry point. Therefore, the water in this sector has a more prominent cooling effect because of its lower temperature. The next pipe section is further away from the water entry point. Still, when compared to the serpentine design, the temperature variation is not as fluctuant. For the custom absorber, most cells are at near-identical temperatures except for the region where pipe spacing is higher than 0.002m. For the serpentine absorber, the temperature is observed to be fluctuating periodically for almost all of the cells. The thermal efficiency obtained for the custom and the serpentine absorber is 92.31% and 90.59%, respectively.

Because of this better uniformity of temperature across the module, the custom absorber is found to be more efficient compared to the serpentine design as it results in average electrical efficiency of 14.15% as compared to 14.06% of the serpentine absorber.

3.4 Error Compensation

From the model validation, we found that the error in calculated thermal and electrical efficiency is relatively high. Using that data, the actually calculated efficiencies can be estimated. The actual calculated thermal and electrical efficiency range is shown in Table 8.

Judging by the average error, the thermal and electrical efficiency for the custom absorber is 55.37% and 13.87 %, respectively. Whereas for the serpentine absorber, the thermal and electrical efficiencies are 53.65% and 13.78%.

Table 8
Actual calculated thermal and electrical efficiency ranges after accommodating for error margins

Absorber Type	Electrical efficiency range (%)	Thermal efficiency range (%)
Custom	13.82 – 13.93	19.15 – 43.39
Serpentine [7]	13.73 – 13.84	17.43 – 41.67

4. Conclusions

The change in range for the custom absorber and the serpentine absorber and the average efficiency estimation would suggest the custom absorber will have better efficiency. The custom absorber design provides an estimated percentage improvement of 3.21% and 0.65% over the serpentine absorber to the thermal and electrical efficiency of the PV, respectively. In terms of temperature, the new absorber design helped achieve a 37.63℃ average PV temperature and 38.11℃ coolant outlet temperature. Where the serpentine absorber had an average PV temperature of 38.88℃ and 37.96℃ coolant outlet temperature. This gain in performance is attributed to lower and more uniformly distributed temperature across the PV. Many custom designs have been proposed in the literature, the novelty of this design is its simplistic geometry. In most cases, to accommodate for the junction box usually, major changes in the flow design are made which brings up complications especially if the pipe spacing is to be kept small for temperature uniformity. This design is two standard sets of spiral absorbers connected. This design is relatively less complicated for this reason and it allows room for adjusting the pipe spacing without much complication. The simulation study reaffirms the fact that better temperature uniformity on the PV module results in better performance. In the future, the absorber can be tested experimentally to verify the performance improvements. The absorber design can also be further refined to keep the pipe spacing consisting throughout the PV panel (This will require a more refined mesh to avoid invalid dihedral angles).

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