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The Effect of Variation in Mass Flow Rate and Solar Irradiance on Temperature Uniformity and Thermal Performance of Photovoltaic Thermal: A Simulated CFD Study

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ABSTRACT

Although, the effect of mass flow rate and solar irradiance variation is present in literature, it is still of significant interest to investigate the extent of the effect especially when utilizing a custom absorber design. In this paper, the effect of changing the mass flow rate and solar irradiance on the performance and temperature uniformity of a PVT using a custom spiral absorber design is simulated using ANSYS CFD software. By increasing the mass flow rate, the temperature uniformity and the performance parameters such as the average PV temperature, water outlet temperature, thermal and electrical efficiency all increase. By increasing the irradiance level, performance and temperature uniformity drop albeit at a smaller degree compared to change observed in mass flow rate variation. Amongst the tested range, the optimum mass flow rate and solar irradiance levels for best performance are 40 kg/h and 800 – 1000 W/m^2, respectively.

1. Introduction

Due to the ever-increasing energy demand because of factors such as increasing population and rapid advancement of technology, renewable energy resources (solar energy, wind energy, hydro energy, biomass, geothermal energy etc.) are put in the spotlight to increase the energy supply [1-3]. In addition to that, energy production by conventional (non-renewable resources such as fossil fuels, natural gas, coal, etc.) means also contributes to global greenhouse gas emissions [3]. Besides, the consumption rate of non-renewable energy resources is high enough as it is today which has led to some depletion concerns in the future. Increasing the consumption rate will only make things worse. Therefore, relying on conventional non-renewable resources to meet the increased supply-demand is not feasible.

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One of the renewable energy resources with substantial energy generation potential is solar energy [4]. Solar energy is available across the globe albeit at varying degrees of intensity. Solar photovoltaic (PV) cell systems are energy generators that utilize solar energy to produce electricity and thermal energy. Due to inefficient technology, it is still considered an expensive source of electrical energy generation. Most PV systems have an electrical efficiency in the range of 4-17% as a major portion of the solar energy utilized by the PV systems is converted into thermal energy instead [5]. This raises the operating temperature of the PV cells. The operating temperature of the PV cell has a direct correlation to energy generation. With an increase in the operating temperature, the efficiency of the PV cell electricity generation decreases [6-8]. Researchers have been hard at work, trying to improve the efficiency of PV systems. One of the most prominent approaches to improve the efficiency of PV cells is to minimize or take away the thermal energy generated by the PV cells away. This can be achieved by introducing a cooling component to the PV systems [6,7,9-13]. The modified system is known as the solar photovoltaic thermal (PVT) system. PVT system achieves this by extracting the heat from the PV panel into a working fluid flowing through an absorber. PVT systems can have different types of absorber or collector configurations such as parabolic trough, parabolic dish, linear Fresnel and flat plate collectors (FPC) [14-16]. The most common of these is the FPC configuration which is the configuration addressed in this study.

In addition to PV cell operating temperature, the efficiency of the PVT systems also depends on various factors such as PVT design, working fluid used, temperature distribution on the PV cell plate and operating conditions such as mass flow rate of the working fluid, incident solar irradiance, working fluid inlet temperature, ambient wind speed, ambient air temperature etc. [6,17]. Various studies have worked on improving the electrical efficiency of PVT systems by altering the PVT design components such as the PV cells, absorber type, and working fluid type etc.). For example, Cappelletti mentions that mono-crystalline PV cells have higher efficiency compared to poly-crystalline PV cells [18]. In terms of the working fluid, air is considered to be less efficient than water which itself is less efficient compared to various nanofluids [5,19-25]. In terms of absorber configurations, the most common absorbers are serpentine, parallel, spiral, cross-fined absorbers amongst which, the spiral absorber is found to be the most efficient [2,26-32]. It was also found out that the absorber configuration consisting of round tubes instead of square tubes were more efficient [2,27]. Even temperature distribution on the PV cell plate leads to better overall performance and protects from hotspots, preserving the intended lifetime of the PV cells [6,33,34]. The temperature uniformity is most influenced by tube spacing and the absorber type. Small tube spacing and spiral absorber configurations lead to better temperature uniformity and therefore, better performance [33,35].

The effect of operating conditions on the performance of the PVT systems is also studied extensively [36]. It is observed that a higher mass flow rate of the working fluid, Lower inlet temperature, moderate solar irradiance, high wind speed, and lower ambient air temperature leads to better performance [5,37].

This paper is a continuation of previous work by Rosli *et al.,* [38], where a new absorber design for solar PVT was suggested to improve efficiency and to achieve a more uniform temperature distribution. The performance and the temperature uniformity of the new PVT system are simulated and validated. In this paper, the effect of two operating conditions namely mass flow rate, and solar irradiance on the performance and temperature uniformity of the PVT system fashioning the custom spiral absorber design is investigated using the same computational fluid dynamics (CFD) simulation model used in the previous work [38]. The effect of mass flow rate and solar irradiance on the performance and temperature uniformity are well documented in literature. However, the new design has a unique pipe arrangement. Therefore, the extent of their influence has not been tested for the custom absorber design introduced in previous work [38].

2. Methodology

The simulation is carried out in ANSYS using the same model utilized in the previous study. The simulation model is verified with the experimental data taken from a study by Hosseinzadeh *et al.,* [5]. The methodology is the same as in the study by Rosli *et al.,* [38]. The custom absorber designed is shown in Figure 1. The custom absorber has an approximate pipe length of 12.85m. The collector pipe is made of copper which has an inner diameter of 0.01m and an outer diameter of 0.012m. The material properties and PVT layer dimensions are shown in Table 1 and Table 2. More details can be seen in the study by Rosli *et al.,* [38].

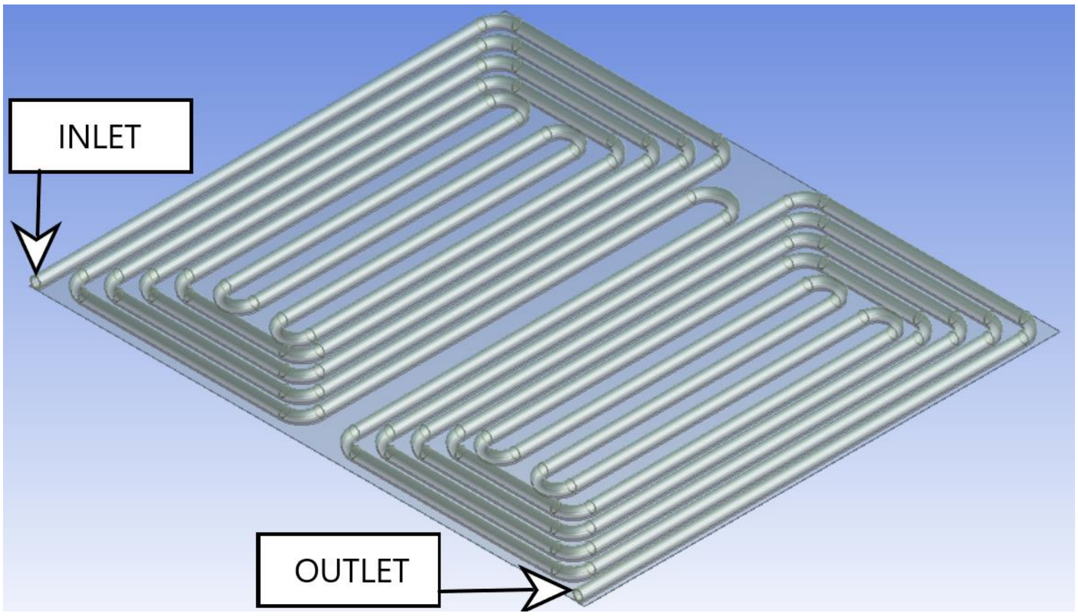

Fig. 1. The Custom Absorber Design [38]

Table 1
Material properties [38]

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 2
PVT layer dimensions [38]

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

The effect of mass flow rate and solar irradiance on the performance and the temperature uniformity of the PVT system is studied by observing key parameters such as the PV plate temperature, water outlet temperature, thermal efficiency and electrical efficiency at different mass flow rates and solar irradiance levels while keeping other operating parameters constant as shown in Table 3.

Table 3
Operating parameters

Parameter	Value
Ambient Wind Speed (m/s)	5
Water Inlet Temperature (°C)	30
Ambient Air Temperature (°C)	30

When testing the effect of mass flow rate, the solar irradiance level is kept constant at 1000 W/m^2. The mass flow rate is changed at increments of 10 kg/h from 10 to 40 kg/h which is the laminar flow region. Conversely, when checking the solar irradiance, the mass flow rate is kept constant at 30 kg/h while the irradiance levels vary from 600 to 1200 W/m^2 at 200 W/m^2 increments.

For temperature uniformity, the temperature readings at various points (the locations of which are shown in Figure 2) on top of the PV plate are taken and compared. The temperature along a line located at the centre of the top surface of the PV plate on the x-axis is also shown to observe temperature variation across the x-axis.

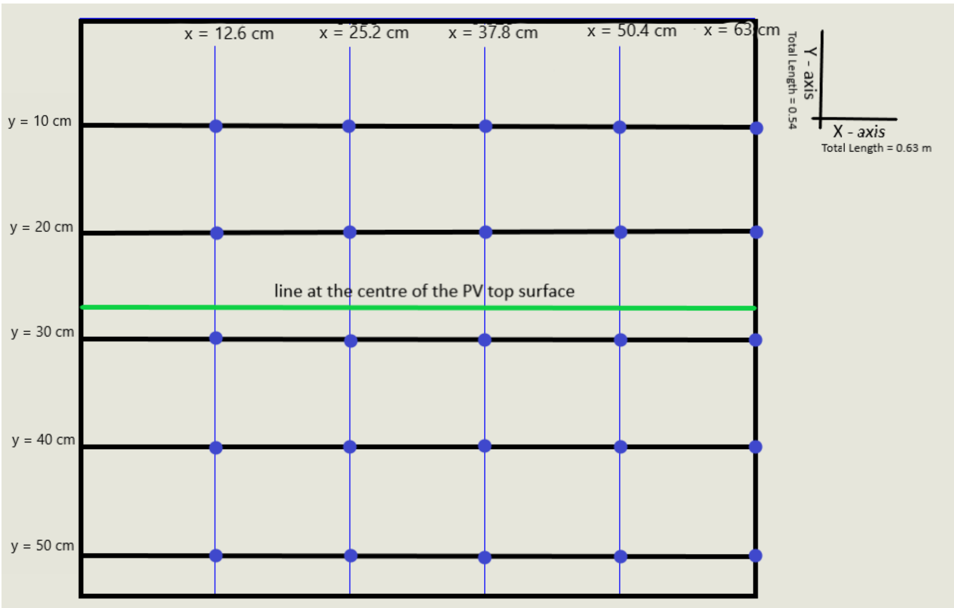

Fig. 2. Locations for temperature readings were taken to investigate temperature uniformity

2.1 Model Discretization

Computational fluid dynamics (CFD) is used to conduct the research. The following governing equations for continuity, momentum, and energy are employed when viewing the PVT system as a control volume [5,39]:

Continuity equation: $$\nabla \cdot (\rho_f V_f) = 0 \quad (1)$$

Momentum equation: $$\nabla . (\rho_f \, V_f \, V_f) = -\nabla P + \nabla . (\mu_f \, \nabla \, V_f) \quad (2)$$

Flow Energy equation: $$\nabla \cdot (V_f \, \rho_f \, C_{p,f} \, T_f) = \nabla . (k_f \, \nabla T_f) \quad (3)$$

Energy equation for solids: $$k_s \, \nabla \, (T_s) = 0 \quad (4)$$

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

ANSYS is used to discretize the equations and solve them using the pressure-based finite volume approach. The SIMPLE technique is used to link pressure and velocity. Convective terms are interpolated using a second-order upwind method. The wall condition is present on the top of the glass surface, with a heat generation rate equal to the absorbed solar irradiation. The glass is expected to absorb about 10% of it, while the PV module absorbs the rest. Convection also happens in the surrounding air. It is projected that the ambient wind speed is less than 5 m/s. The following equation can be used to determine convective heat transfer [40]:

$$h_w = 5.7 + 3.8 \, V_w \quad for \, V_w < 5 \, m/s \quad (5)$$

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:

$$E_{sun} + E_{mass,in} = E_{el} + E_{mass,out} + E_{loss} \quad (6)$$

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:

$$E_{sun} = G \cdot Ac \cdot \tau_g \cdot \alpha_{cell} \quad (7)$$

'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:

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

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

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

The electrical energy efficiency of the PVT system is calculated from the equation [41]:

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

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 [42]:

$$\eta_{el} = \frac{E_{el}}{E_{sun}} = \frac{V_{OC} \cdot I_{SC} \cdot FF}{G \cdot Ac \cdot \tau_g \cdot \alpha_{cell}} \tag{11}$$

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 [43]:

$$FF = \frac{V_{max} \cdot I_{max}}{V_{OC} \cdot I_{SC}} \tag{12}$$

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 [44]. The temperature distribution uniformity is checked by plotting the temperature across a line in the middle of the PV module's top surface.

3. Results

3.1 An Overview of Results from Previous Work

For validation, the simulation model is used to replicate the experiment from the study by Hosseinzadeh *et al.,* [5]. The PVT design was recreated and simulated in the model with the same boundary conditions. The average percentage error between the simulated and the experimental average PV temperature and water outlet temperature is found to be 7.8% and 6.67%, respectively. Whereas the error for electrical efficiency and thermal efficiency between the simulation and the experimental data is 0.28% and 33.62%, respectively. as the error is high, the results are compensated based on average error.

As demonstrated in Figure 3, meshing is done in ANSYS using polyhedral volume meshing. Mesh counts of 2.9M, 3.4M, 3.98M, and 4.78M were used to test the mesh parameters. Table 4 shows the outcomes of the simulations utilising these various mesh counts.

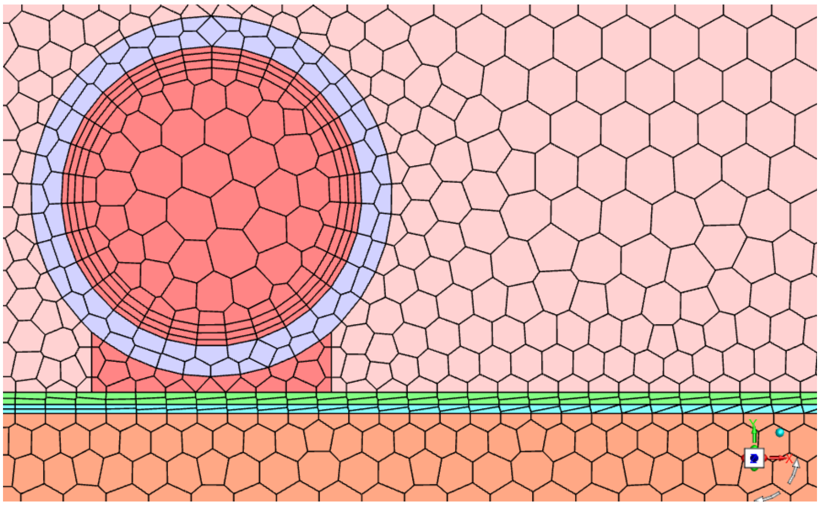

Fig. 3. A view of the mesh used for simulation [38]

Table 4
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

Despite the fact that the results vary with mesh size, due to hardware limitations and the small magnitude of change, the mesh size is not adjusted further to increase the mesh count. A minimum orthogonal quality of 0.2, a maximum aspect ratio of 27, and a maximum skewness of 0.78 are all features of the mesh.

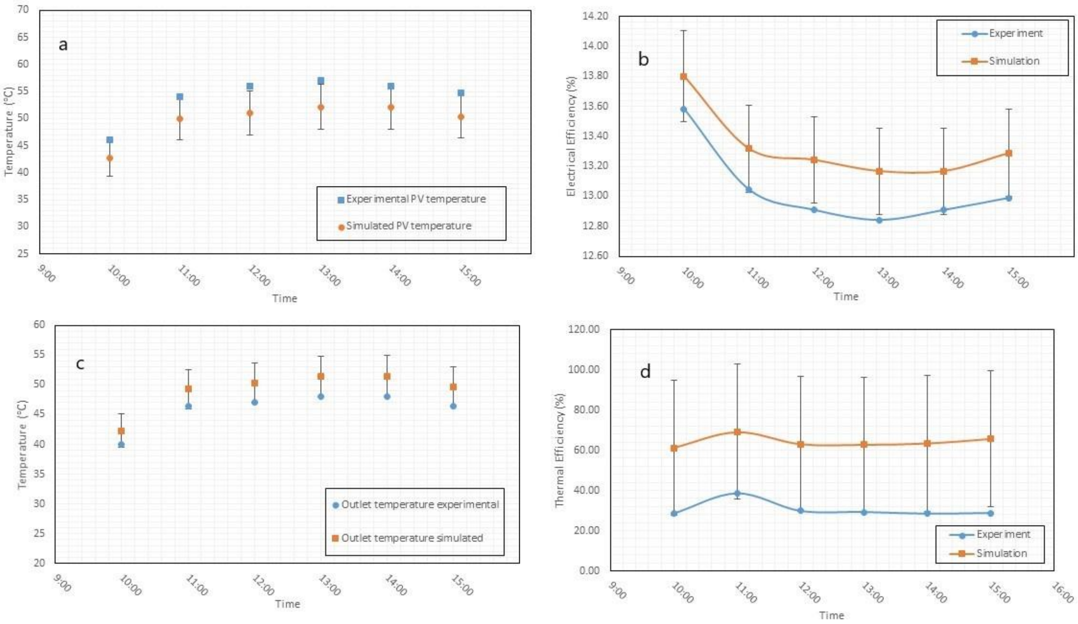

Fig. 4. (a) PV temperature error, (b) Electrical efficiency error, (c) Coolant outlet temperature error, (d) Thermal efficiency error [38]

After error compensation, the average thermal efficiency obtained for the custom absorber is 49.46% and the custom absorber has an average electrical efficiency of 13.87%. The improved absorber design results in an average PV temperature of 37.63°C and a coolant outlet temperature of 38.11°C. When evaluated under the same operating conditions, the bespoke absorber design improves the thermal and electrical efficiency of the PV by 3.21% and 0.65%, respectively, over the serpentine absorber utilized in a study by Hosseinzadeh *et al.,* [5].

In terms of temperature uniformity, the new absorber allowed better temperature distribution across the PV plate. Further details can be found in the previous paper by Rosli *et al.,* [38]. It should be noted that the results presented in this study are without any error compensation, which is not needed here because the main focus is to check the effect of changing mass flow rate and solar irradiance on the performance. This can be studied by observing the trend even if the values are inaccurate.

3.2 Effect of Mass Flow Rate on Performance

CFD simulations at various mass flow rates are used to determine efficiency and temperature distribution. The mass flow rates that were tested are 10, 20, 30, and 40 kg/h. The incident sun irradiation is maintained at 1000 W/m^2.

In terms of performance, as shown in Table 5, a higher flow rate results in better performance. Both efficiency ratings are observed to be improving with an increase in mass flow rate.

Table 5
Temperature and efficiency of PVT at different mass flow rates

Mass Flow Rate (Kg/h)	PV Temperature (°C)	Outlet Temperature (°C)	Thermal Efficiency (%)	Electrical Efficiency (%)
10	45.43	49.04	64.99	13.62
20	39.76	41.39	77.85	14.01
30	37.63	38.11	83.07	14.15
40	36.5	36.29	85.89	14.22

3.3 Effect of Mass Flow Rate on Temperature Uniformity

It can be observed from Table 6 and Figure 5 that not only is the overall temperature decreased when increasing mass flow rate, the temperature uniformity is also improved. As a result, it stands to reason that a larger flow rate will result in not only improved performance due to lower temperatures, but also better temperature uniformity for the custom absorber.

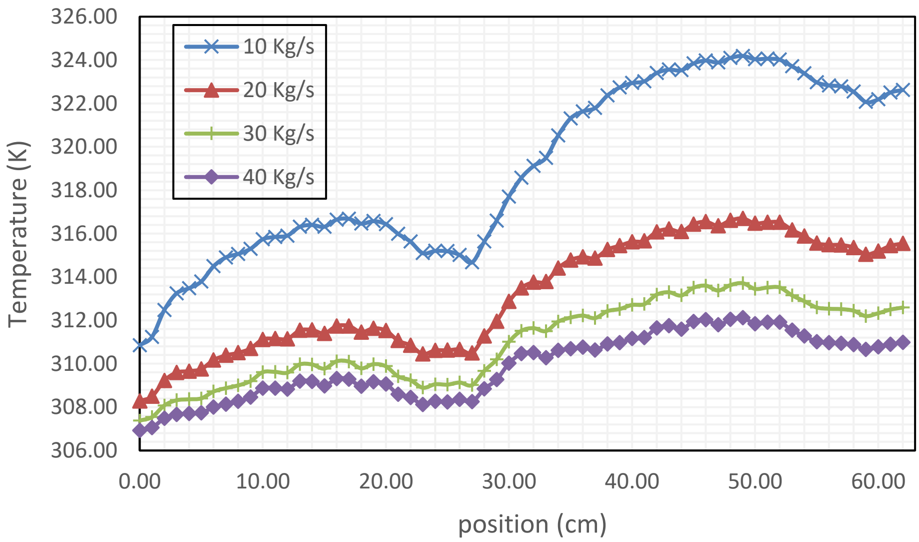

Fig. 5. Temperature distribution on a line at the centre of the PV top surface at different mass flow rates

Table 6
The temperature at various points on the PV surface at different Mass Flow Rates

Mass Flow Rate = 10 kg/h; Irradiance = 1000 W/m^2					
Locations (x,y) cm	12.6	25.2	37.8	50.4	63
	Temperature (°C)				
10	37.07	42.32	45.46	50.26	49.17
20	37.51	43.26	45.48	50.77	49.40
30	37.78	43.36	45.38	50.78	49.49
40	37.96	43.07	45.12	50.47	49.52
50	37.44	40.74	46.42	49.22	49.79
Mass Flow Rate = 20 kg/h ; Irradiance = 1000 W/m^2					
Locations (x,y) cm	12.6	25.2	37.8	50.4	63
	Temperature (°C)				
10	34.76	37.49	40.31	42.72	42.21
20	35.02	38.35	40.37	43.30	42.36
30	35.16	38.45	40.32	43.31	42.40
40	35.22	38.17	40.13	42.97	42.37
50	34.96	36.63	41.78	41.98	42.62
Mass Flow Rate = 30 kg/h ; Irradiance = 1000 W/m^2					
Locations (x,y) cm	12.6	25.2	37.8	50.4	63
	Temperature (°C)				
10	33.95	35.93	38.31	39.73	39.30
20	34.15	36.73	38.38	40.33	39.42
30	34.25	36.83	38.35	40.34	39.44
40	34.28	36.56	38.19	40.00	39.38
50	34.14	35.23	39.97	39.07	39.60
Mass Flow Rate = 40 kg/h ; Irradiance = 1000 W/m^2					
Locations (x,y) cm	12.6	25.2	37.8	50.4	63
	Temperature (°C)				
10	33.53	35.17	37.25	38.15	37.72
20	33.71	35.94	37.31	38.75	37.81
30	33.79	36.03	37.29	38.76	37.82
40	33.80	35.78	37.16	38.44	37.75
50	33.73	34.53	39.01	37.51	37.95

3.4 Effect of Solar Irradiance on Performance

CFD simulations at various levels of solar irradiation are used to determine efficiency and temperature distribution. 600, 800, 1000, and 1200 W/m^2 were the tested levels. The mass flow rate is kept constant at 30 kg/h in this case. Lowering solar irradiation results in higher electrical efficiency since less thermal energy is created, as evident from the data in Table 7. But lower irradiance also leads to low power generation. Whereas thermal efficiency is influenced significantly by solar irradiation.

Table 7
Temperature and efficiency of PVT at different irradiance levels

Solar Irradiance (W/m^2)	PV Temperature (°C)	Outlet Temperature (°C)	Thermal Efficiency (%)	Electrical Efficiency (%)
600	34.58	34.86	83.04	14.35
800	36.10	36.49	83.05	14.25
1000	37.63	38.11	83.07	14.15
1200	39.15	39.73	83.05	14.04

3.5 Effect of Solar Irradiance on Temperature Uniformity

In terms of temperature distribution, as shown in Figure 6 and Table 8, the irradiance level has a small impact on the temperature distribution across the PV. Lower irradiance levels, on the other hand, produce a little better temperature distribution accompanied by lower overall PV temperatures.

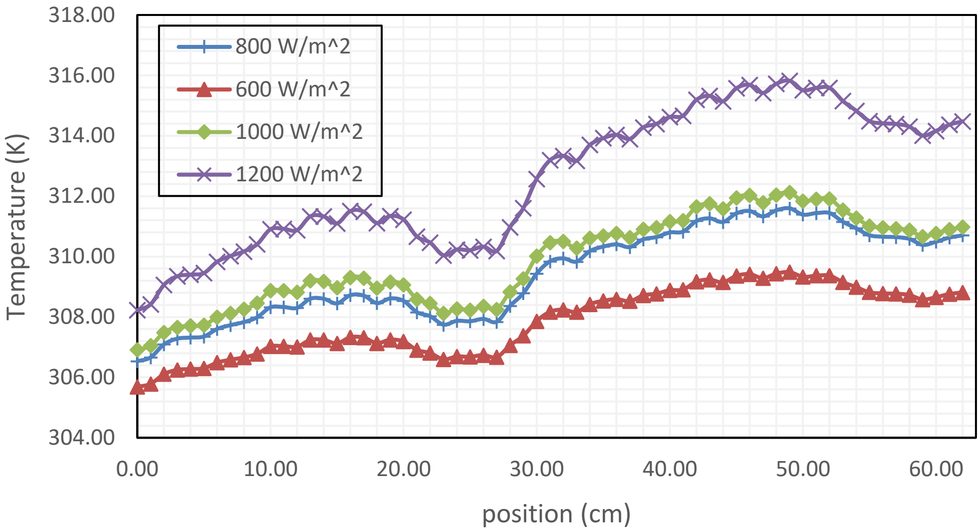

Fig. 6. Temperature distribution on a line at the centre of the PV top surface at different solar irradiance levels

Table 8
The temperature at various points on the PV surface at different irradiance levels

Irradiance = 600 W/m^2 ; Mass Flow Rate = 30 kg/h					
Locations (x,y) cm	12.6	25.2	37.8	50.4	63
	Temperature (°C)				
10	32.37	33.56	34.99	35.84	35.58
20	32.49	34.04	35.03	36.20	35.65
30	32.55	34.10	35.01	36.20	35.66
40	32.57	33.94	34.91	36.00	35.63
50	32.48	33.14	35.98	35.44	35.76
Irradiance = 800 W/m^2 ; Mass Flow Rate = 30 kg/h					
Locations (x,y) cm	12.6	25.2	37.8	50.4	63
	Temperature (°C)				
10	33.16	34.74	36.65	37.78	37.44
20	33.32	35.38	36.70	38.26	37.53
30	33.40	35.46	36.68	38.27	37.55
40	33.43	35.25	36.55	38.00	37.51
50	33.31	34.18	37.98	37.25	37.68
Irradiance = 1000 W/m^2 ; Mass Flow Rate = 30 kg/h					
Locations (x,y) cm	12.6	25.2	37.8	50.4	63
	Temperature (°C)				
10	33.95	35.93	38.31	39.73	39.30
20	34.15	36.73	38.38	40.33	39.42
30	34.25	36.83	38.35	40.34	39.44
40	34.28	36.56	38.19	40.00	39.38
50	34.14	35.23	39.97	39.07	39.60

Irradiance = 1200 $\boldsymbol{W/m^2}$; Mass Flow Rate = 30 kg/h					
Locations (x,y) cm	12.6	25.2	37.8	50.4	63
	Temperature (°C)				
10	34.74	37.11	39.97	41.68	41.17
20	34.98	38.08	40.05	42.39	41.30
30	35.10	38.20	40.02	42.41	41.32
40	35.14	37.88	39.83	42.00	41.26
50	34.97	36.27	41.96	40.88	41.52

3.6 Discussion

Regarding performance, it was found that when the mass flow rate was increased from 10 kg/h to 40 kg/h, the average PV plate temperature dropped by a difference of 8.93℃ from 45.43℃ to 36.5℃. the most significant drop was observed in change from 10 kg/h to 20 kg/h while the subsequent temperature drops were relatively smaller. Therefore, it can be estimated that in the laminar flow regime, the degree of the temperature drop gets smaller when reaching the laminar region. A similar trend was observed for the outlet temperature of the working fluid. The thermal efficiency increased with an increase in flow rate with a similar trend as well from 64.99% at 10 kg/h to 85.89% at 40 kg/h. The electrical efficiency change in magnitude was the least in magnitude from 13.62% to 14.22% (by 0.6%). regardless of the magnitude, the upgrade is still significant. By observing the trends, it can be estimated that an increase in flow rate will generally lead to better performance.

When changing the solar irradiance, the opposite trend was observed. The average PV plate temperature increased from 34.58℃ to 39.15℃ when changing the irradiance level from 600 to 1200 W/m^2, where the outlet temperature increased from 34.86℃ to 39.73℃. that's an increase of 4.57℃ and 4.87℃, respectively. No significant change in thermal efficiency was observed. However, the electrical efficiency dropped from 14.35% to 14.04%. it should be noted that the magnitude of change is not as significant as that of the mass flow rate for solar irradiance. Since lower irradiance levels will provide less power, it will be more preferable to ignore this drop in performance and try to attain moderate solar irradiance levels. Even though the irradiance level is not a controllable parameter, it is still important to study its effect on performance so that the other operating conditions can be calibrated accordingly to obtain the best performance.

As we already found out, a high mass flow rate leads to Better Performance. The same can be said regarding temperature uniformity as can be seen from Figure 3 and Table 3. The point-to-point temperature variation gets lower as the mass flow rate is increased. At mass flow rate of 10 kg/h, the temperature variation from (0.126 m, 0.1 m) to (0.63 m, 0.1 m) is 12.1℃. However, at 40 kg/h, this variation changes to 4.19℃. Therefore, it can be said that increasing the mass flow rate leads to better temperature distribution from cell to cell on a PV plate.

When changing the solar irradiance from 600 to 1200 W/m^2, the temperature variation from (0.126 m, 0.1 m) to (0.63 m, 0.1 m) changes from 3.21℃ at 600 W/m^2 to 5.35℃ at 1200 W/m^2. Similar to the effect on performance, the effect on temperature uniformity is there when changing the solar irradiance levels, however, it is not as significant as that of mass flow rate variation. The variation was observed to be the least when changing from 800 W/m^2 to 1200 W/m^2. This range can be given as a nice middle ground.

4. Conclusion

In this study, variation in performance and temperature uniformity at different mass flow rates and solar irradiance levels was simulated for a PVT using a custom spiral absorber design. It was found that increasing the mass flow rate increases the performance and the temperature distribution on the PV plate. On the other hand, increasing the solar irradiance level led to drops in performance and temperature distribution. It should be noted that the effect of changing the mass flow rate was far more significant compared to that of changing the irradiance level. It can be reasoned that the added benefit of potentially producing more power at higher irradiance levels with optimum operating parameters outweighs the drop in performance observed.

For the PVT system using the custom spiral absorber design, a mass flow rate of 40 kg/h and an irradiance level between 800 W/m^2 and 1000 W/m^2 can be deemed as the optimum parameter values for best performance and temperature uniformity.

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