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A Case Study on Effect of Inclination Angle on Performance of Photovoltaic Solar Thermal Collector in Forced Fluid Mode

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Abstract

A case study is conducted to evaluate the photovoltaic (PV) performance in a horizontal and in an inclined PV solar thermal collector (PVT) for two different PVT geometries, the series flow and the parallel series flow. It is shown that the series flow gives a better photovoltaic performance at a horizontal PVT surface as compared to the parallel series flow. At a mass flow rate of 0.03 kg/s and a zero inclination angle (horizontal PVT surface), the PV efficiencies are 14.32% and 14.25% for series and parallel series flow, respectively. However, for an inclined PVT surface, the parallel series performs better than the series flow. At a mass flow rate of 0.03 kg/s and an inclination angle of 45 °C, the PV efficiencies are 13.76% and 13.87% for the series and parallel series flow, respectively. It can be concluded that the inclination angle is one of the essential parameters that can be used to evaluate any PVT design and make better comparisons between different designs. It is also beneficial for the researchers and PVT product designers to know the effectiveness of their collector designs for cooling the PV panel at the early product design stage and to base on the optimum inclination angle of the region.

Keywords: *Solar energy, photovoltaic solar thermal collector, inclination angle, photovoltaic efficiency.*

1. Introduction

Due to the harmful impact of fossil fuel consumption on the environment, the scientists are investigating alternative and clean energy resources such as solar energy, which has recently attracted more attention for the purpose of electricity and heat generation [1-8].

A photovoltaic solar thermal collector (PVT) is a combination of a photovoltaic (PV) module and a solar thermal collector technology. The major advantages of a PVT system are as follow [9]:

1. It is used for electricity and heat generation.
2. It is flexible and efficient; the efficiency of the combined PVT is always greater than that for the two separate modules.
3. It is inexpensive and practical; PVT can be installed in buildings without any major modification.

Due to the rotation of the earth around its axis and around the sun, an optimum inclined angle is to be set where an optimum yearly solar radiation can be obtained. However, most of the time, the practical orientation for PVT is to be in an inclined position, and the amount of the pumping requirement will be increased as the inclination angle increases, and thus the increment of the power depends on the PVT design specifications. The literature shows that the studies on PVT in forced fluid mode conducted are based on a horizontal PVT surface, as shown in table 1, and normally, the pressure drop and the pumping requirement are considered negligible, making the analysis and comparison in term of PV performance among PVT with different designs incomplete. The reason behind not considering the inclination angle effects in the PV performance evaluation is the lack of guideline on PVT testing [11-17].

In this paper, the effect of inclination angle on the PV performance of PVT in forced fluid mode and its importance are studied. In order to address the situation, a case study is conducted for two different PVT designs to determine the PV performance at low and high inclination angles. It will be shown that the inclination angle is an important parameter, and should be taken into consideration during the PVT design stage.

2. A Comparison between Two Collector Designs

There are two common PVT types available, water- and air-based PVT. The main components of a PVT are a photovoltaic panel and a solar collector (to circulate water using a water pump for water type and a fan for air type to cool the PV panel). Therefore, an insulation material should be included to limit the heat losses from the system, as shown in figure 1.

Table 1. Some current literature on the study of PVT with different geometries.

Reference	PVT with different designs in forced fluid mode	Inclination angle study
[18]	Heat exchanger using baffles	No
[19]	Multiple serpentine flow design.	No
[20], [22], [30]	Direct flow design	No
[21]	Serpentine design	No
[23]	Sheet and tube Modified serpentine design	No
[24], [25]	Roll-bond aluminium absorber	No
[26]	Roll-bond flat plate	No
[27]	Ellipse flow design	No
[28]	Water heater	No
[29]	Rectangular tubes design	No
[30], [34], [35]	Spiral flow design	No
[31]	Water heater	No
[32]	Duct channel	No
[33]	Parallel plate channels	N/A

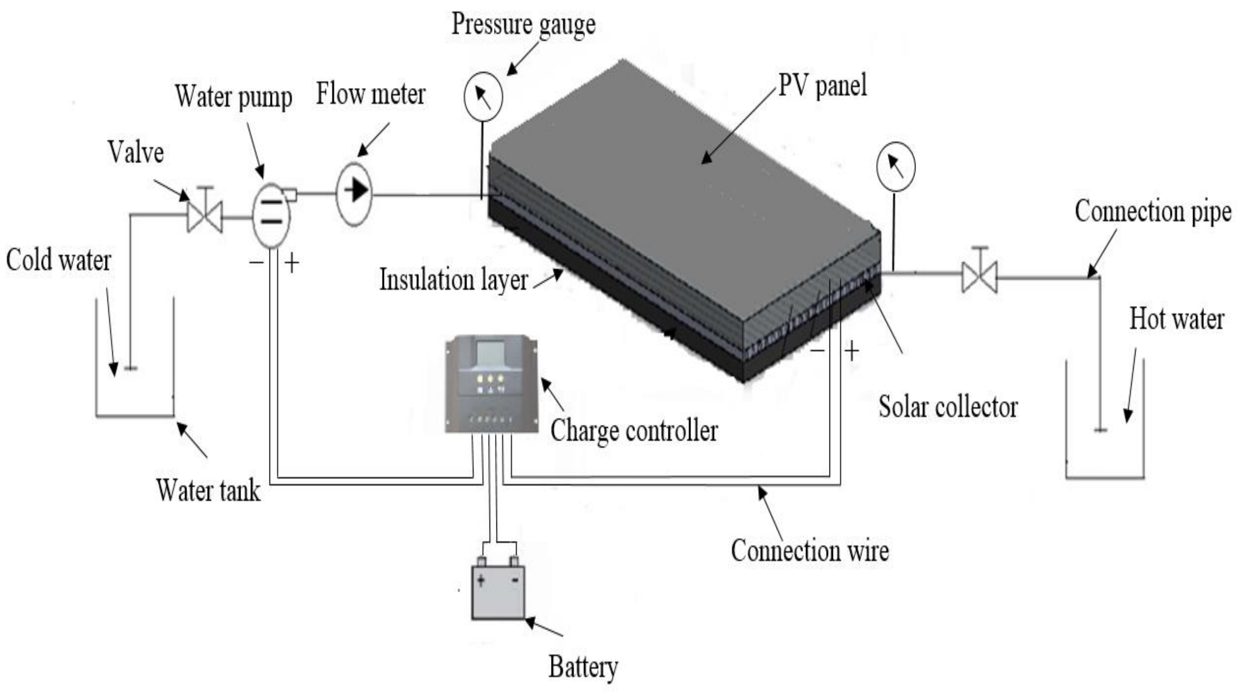

Figure 1. A line diagram of PVT.

A PVT utilizes a collector for absorbing heat and transferring it to the circulated fluid. Therefore, the fluid will be heated and will withdraw the excessive heat from the PV panel, and hence, the PV performance can be enhanced [35]. In this section, two different collector designs are compared to study the effect of the inclination angle on the pressure drop and the pumping requirement, and thus on the PV performance. Figure 2 illustrates two different collector designs. Figure 2a shows the parallel series flow absorber, while figure 2b presents the series flow absorber. Each absorber consists of 32 parallel copper circular tubes. The piping fitting with the equivalent loss coefficient for each design is shown in figure 3. The pipes are attached underneath a transparent PV module. The PV panel and the PVT specifications are listed in tables 2 and 3, respectively. Therefore, the insulation material is designed to be located under the collector to reduce the heat leakage to the surroundings. Both absorber designs have one inlet channel to allow the water to enter the collector, and one outlet channel where hot water can exit. In the present work, the solar radiation is set to be perpendicular to the PVT surface for any PVT inclination angle. The inclination angle is the angle of the PVT surface with respect to the horizontal surface. PVT was exposed to different PVT inclination angles to explore their effects on the PV performance for both designs (series flow and parallel series flow).

Table 2. Mono-crystalline silicon PV specifications.

Parameters	Values
Solar cell size	0.125 m x 0.125 m
Isc	5.96 A
Voc	43 V
Imax	5.27 A
Vmax	36 V
PV area	1.27 m2
Number of cells	72
Power	190 W

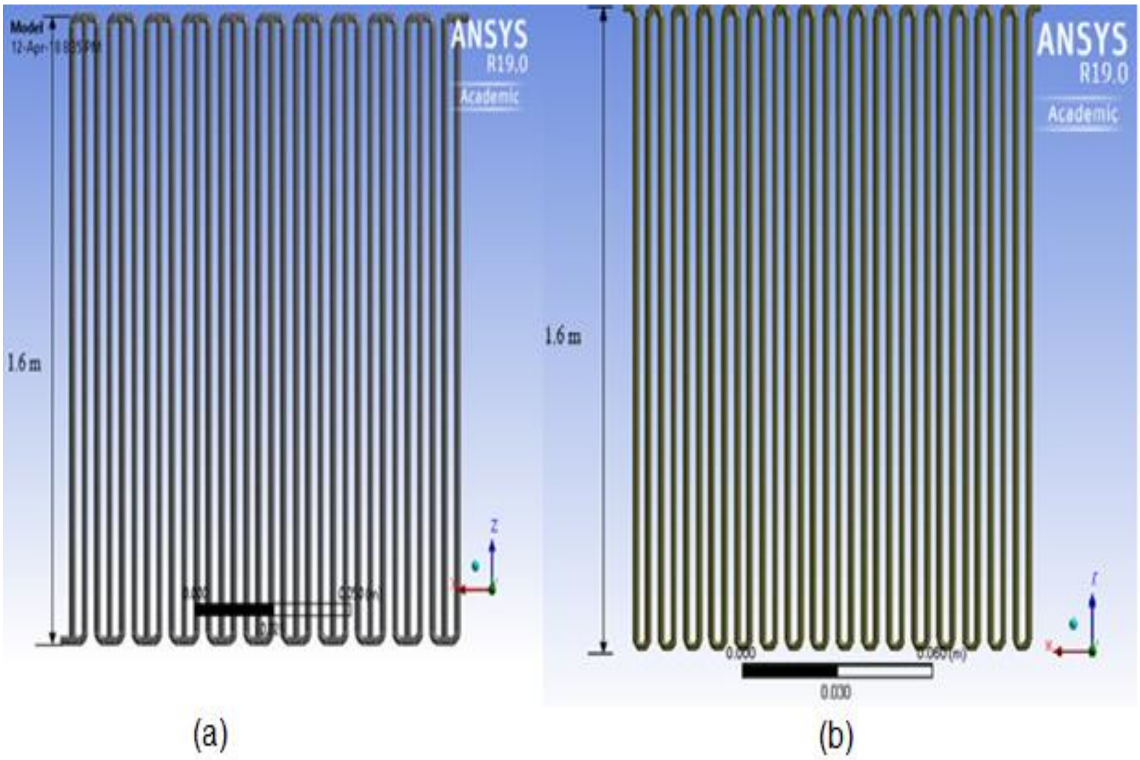

Figure 2. Parallel series flow design. (b) Series flow design.

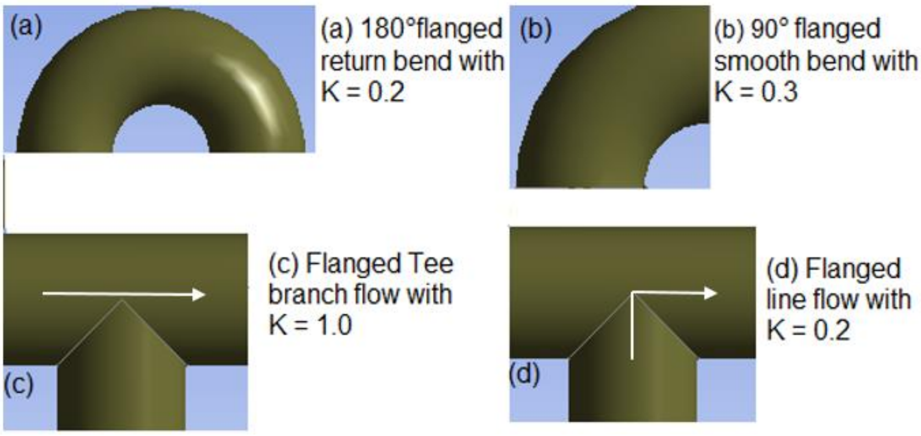

Figure 3. Different pipe fittings with equivalent loss coefficients.

Table 3. PVT specification.

Parameter	Values
Ambient temperature	27 ºC
Collector area	1.27 m2
Emittance of glass plate	0.88
Water fluid thermal conductivity	0.613 W/m ºC
Specific heat of water	4180 J/kg ºC
Back insulation thermal conductivity	0.045 W/m ºC
Back insulation thickness	0.05 m
Absorber thermal conductivity	51 W/m ºC
Absorber thickness	0.0025 m
Fin thermal conductivity	84 W/m ºC
Loss coefficient for series flow	6.8
Loss coefficient for parallel series flow	23.6
Fin thickness	0.0005 m
Transmitivity	0.88
Absorptivity	0.95

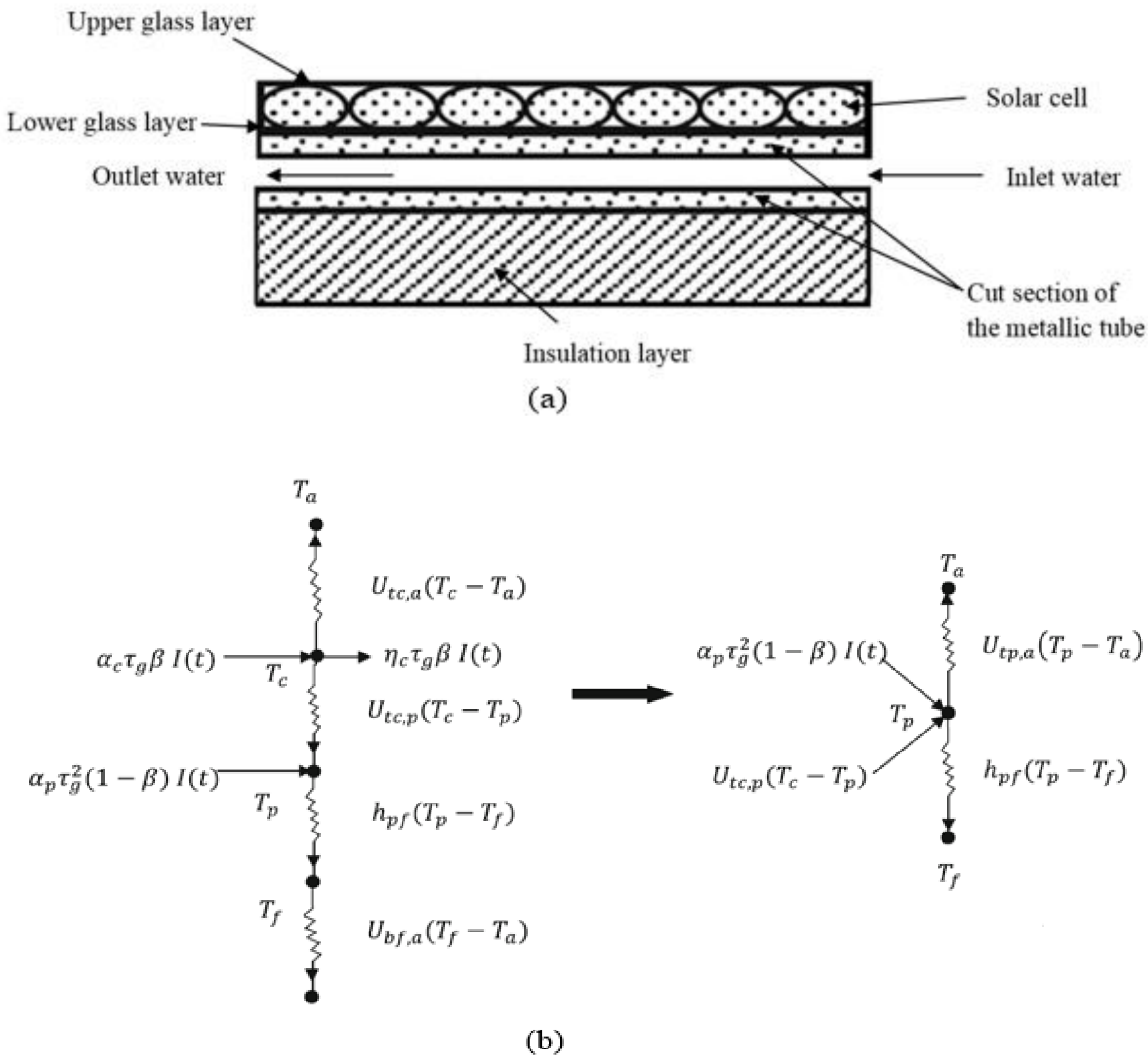

Figure 4. (a) The different layers of the water based semi-transparent PVT. (b) The associated thermal network of the semi-transparent PVT [39]

3. Analytical Model of PV Performance

The steady state energy balance equations were applied to determine the temperatures of the different PVT layers. From the thermal network (figure 4), the cell temperature of PV and T_c can be written as below [38, 39]:

$$T_c = \frac{(\alpha\tau)_{1,eff} I + U_{tc,a} T_a + U_{tc,p} T_p}{U_{tc,a} + U_{tc,p}} \quad (1)$$

where $(\alpha\tau)_{1,eff}$ can be denoted as:

$$(\alpha\tau)_{1,eff} = \tau_g(\alpha_c - \eta_c)\,\beta c \quad (1a)$$

Therefore, the plate temperature T_p of PVT can be expressed as follows [38, 39]:

$$T_p = \frac{(\alpha\tau)_{2,eff} I + PF_1(\alpha\tau)_{1,eff} I + U_{L2} T_a + F' h_{pf} T_f}{U_{L2} + F' h_{pf}} \quad (2)$$

where $(\alpha\tau)_{2,eff}$ can be expressed as:

$$(\alpha\tau)_{2,eff} = \alpha_p(1 - \beta c){\tau_g}^2 \quad (2a)$$

and PF_1 becomes as:

$$PF_1 = \frac{U_{tc,p}}{U_{tc,a} + U_{tc,p}} \quad (2b)$$

Therefore, U_{L1} can be written as:

$$U_{L1} = \frac{U_{tc,p} U_{tc,a}}{U_{tc,a} + U_{tc,p}} \quad (2c)$$

and U_{L2} can be denoted as:

$$U_{L2} = U_{L1} + U_{tp,a} \quad (2d)$$

The average fluid temperature, $\overline{T}_f$, will be as below [38, 39]:

$$\overline{T}_f = \left[\frac{PF_2(\alpha\tau)_{m,eff} I}{U_{L,m}} + T_a\right] \times \left[1 - \frac{1 - \exp\left(-\frac{A_m U_{L,m}\, F'}{\dot{m} C_f}\right)}{\frac{A_m U_{L,m}\, F'}{\dot{m} C_f}}\right] + T_i \left[\frac{1 - \exp\left(-\frac{A_m U_{L,m}\, F'}{\dot{m} C_f}\right)}{\frac{A_m U_{L,m}\, F'}{\dot{m} C_f}}\right] \quad (3)$$

where PF_2 can be expressed as:

$$PF_2 = \frac{h_{p,f}}{U_{L2} + h_{p,f}} \quad (3a)$$

and $(\alpha\tau)_{m,eff}$ can be denoted as:

$$(\alpha\tau)_{m,eff} = PF_1(\alpha\tau)_{1,eff} + (\alpha\tau)_{2,eff} \quad (3b)$$

Since the PV performance is related to the pumping requirement and thus on the pressure drop, the pressure drop, ΔP, equation should be written as [36]:

$$\frac{\Delta P}{\rho g} = \frac{V^2}{2g}\left[\frac{Lf}{D} + K\right] + L \sin\theta \quad (4)$$

After obtaining the pressure drop, the pumping requirement, P_{Pump}, for the pump to circulate the fluid inside the PVT pipes can be easily determined from the equation below [36]:

$$P_{Pump} = \frac{\dot{m}\Delta P}{\rho \eta_{pump}} \quad (5)$$

The PV performance for the photovoltaic solar thermal collector depends on the cell temperature, T_c, and given by Florschuetz [37]:

$$\eta_{PV} = \eta_r[1 - \beta r(T_c - T_r)] \quad (6)$$

The above equation can be modified by including the pumping requirement, and can be written as:

$$\eta_{PV} = \eta_r[1 - \beta r(T_c - T_r)] - \frac{P_{Pump}}{(I \times A_{PV})} \quad (7)$$

4. Results and Discussion

The study of the different inclination angles for various PVT geometries on the pressure drop and thus on the pumping requirement has been conducted. Therefore, the influence of the inclined PVT surfaces on the PV performance has been investigated as well. The importance of including the inclination angle in the PV performance is illustrated.

4.1. Analytical model validation

In the present work, the PVT analytical model analysis used has been validated with the experimental measurements by the previous researchers [35-39]. Therefore, the analysis of the pumping requirements (that has also been validated earlier [36]) was taken into account for the evaluation of the PV performance of PVT.

4.2. Effect of inclination angle on pressure drop and thus on pumping requirement

From figures. 5 and 6, it can be noticed that the pressure drop for the series flow design is greater than that for the parallel series flow because of the difference in the collector's loss coefficient due to pipe fitting, length of the pipes, friction factor, distribution of the mass flow rate in the pipes, and PVT surface inclination angle. It can also be noticed that the increment in the inclination angle will have a proportional relation with the pressure drop and thus on the pumping requirement to push the fluid into the collector's tubes of the water-based PVT. It can be observed that the pressure drop of the parallel series flow is 2.3 kPa, which is approximately half of the series flow design pressure drop that is 5.2 kPa at a horizontal PVT surface $\theta = 0°$ and a mass flow rate of 0.03 kg/s. Besides, the pumping requirement for the series flow design is 0.2 W, which is almost double than the pumping requirement of the parallel series flow design (0.093 W). Now, increasing the inclination angle to 15 °C and maintaining the mass flow rate at 0.03 kg/s will have an influence on the pressure drop and pumping requirements for both designs. The pressure drop values are 70 kPa and 47 kPa for the series flow and parallel series flow designs, respectively. The pumping requirements are 2.9 W and 1.9 W for the series flow and parallel series flow, respectively. Therefore, if the inclination angle increases to 25° and the pressure drop of the parallel series will be 111 kPa for the series flow design, whereas the pumping requirement is 3.01 W and it is 4.45 W for the series flow design. Thus if the inclination angle increases to 45° at the same mass flow rate that is 0.03 kg/s, the pressure drop will be increased for both designs. It is 124 kPa for the parallel series flow, while it is 182.2 kPa for the series flow. Therefore, the pumping requirement for the parallel series and the series flow will be 4.97 W and 7.3 W, respectively.

From results of this section, it is shown that both designs have a negligible pressure drop and pumping power requirement at horizontal PVT surface ($\theta = 0°$). However, at high inclination angles, the effect becomes noticeable. In this case, the parallel series flow has a lower pressure drop and pumping power requirement as compared to the series flow design.

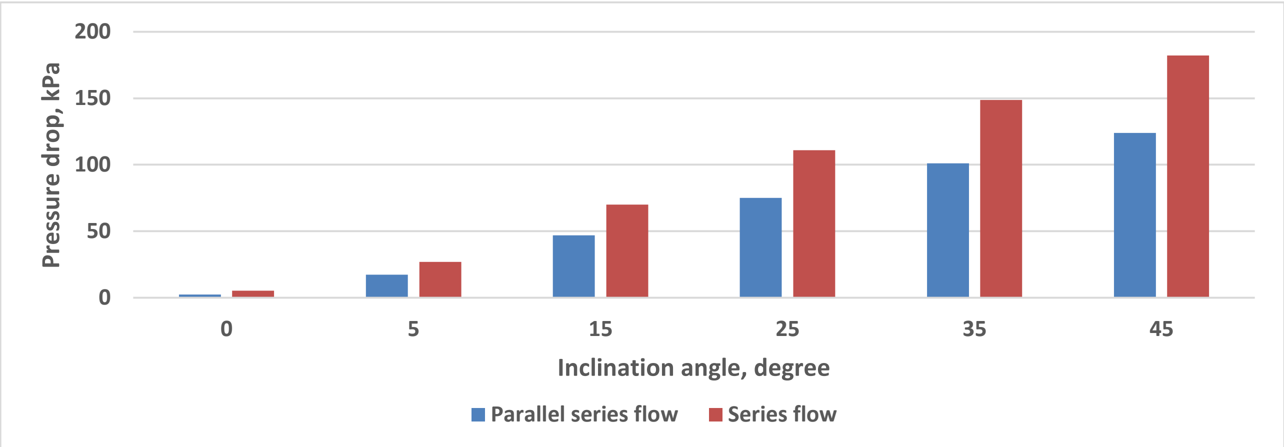

Figure 5. Effect of inclination angle on pressure drop at a mass flow rate of 0.03 kg/s.

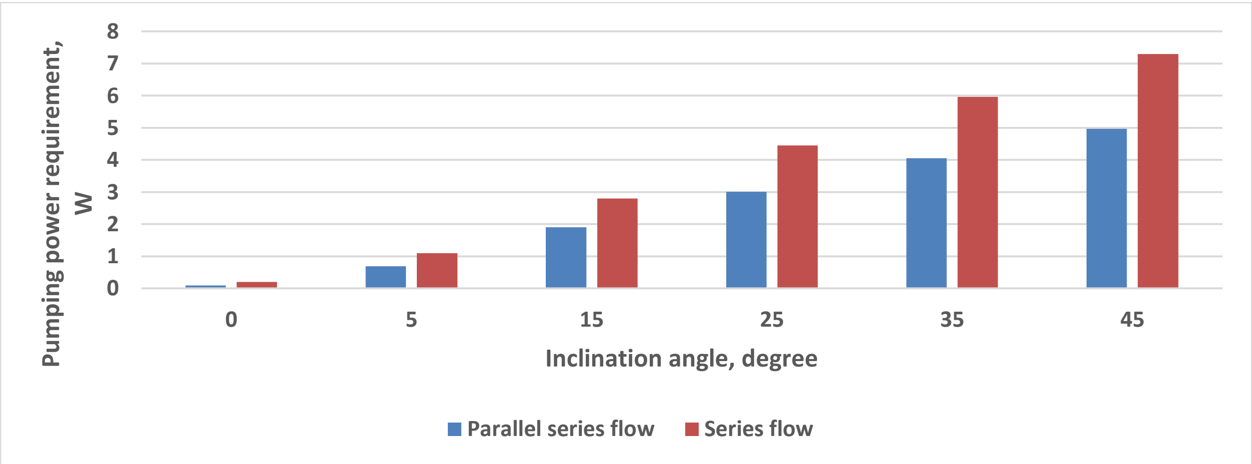

Figure 6. Effect of inclination angle on the pumping power requirement at a mass flow rate of 0.03 kg/s.

4.3. Effect of inclination angle on PV performance of PVT

The effect of the inclination angle on the PV performance for different PVT geometries are illustrated in figure 7.

It is shown that there is an inverse proportional relation between the photovoltaic efficiency and the inclination angle. As the inclination angle increases, the photovoltaic efficiency will be decreased eventually. The amount of decrement depends on the PVT design specification and thus on the pressure drop and the pumping power required to circulate the fluid into the PVT tubes. Therefore, when the mass flow rate is 0.03 kg/s and the inclination angle is set to be 0°, the photovoltaic efficiency is 14.25% for the parallel series flow, and it is 14.32% for the series flow design. Increasing the inclination angle to 15 ˚, the PV efficiencies are 14.13% and 14.12% for the series and parallel series flow, respectively. Then if the inclination angle is increased to 25°, the photovoltaic efficiency for both design will be dropped due to the increment of the pressure drop and the corresponding pumping power requirement. Hence, for the parallel series flow, it is 14.02%, while it is 13.99% for the series flow. At $\theta = 45°$, the PV efficiencies are 13.87% and 13.76% for the parallel series flow and the series flow, respectively. It is noticeable that the photovoltaic efficiency for parallel series becomes higher than that of the series flow at higher inclination angles.

It is shown that at the horizontal PVT surface ($\theta = 0°$), the series flow shows a better PV performance response as compared to the parallel series flow. On the other hand, at an inclined PVT surface, the parallel flow design performs better as compared to the series flow. The reason for this result is that at a horizontal PVT surface, the pressure drop and the pumping requirement are negligible for both designs. Therefore, the series flow design allows more water to cool the PV panel as compared to the parallel flow design, and thus a maximum heat can be extracted from the solar cell. On the other hand, at an inclined PVT surface, the parallel series flow has shorter tubes as compared to the series flow, and thus the pressure drop and the pumping requirement will be less. Therefore, the PV efficiency will not be affected much.

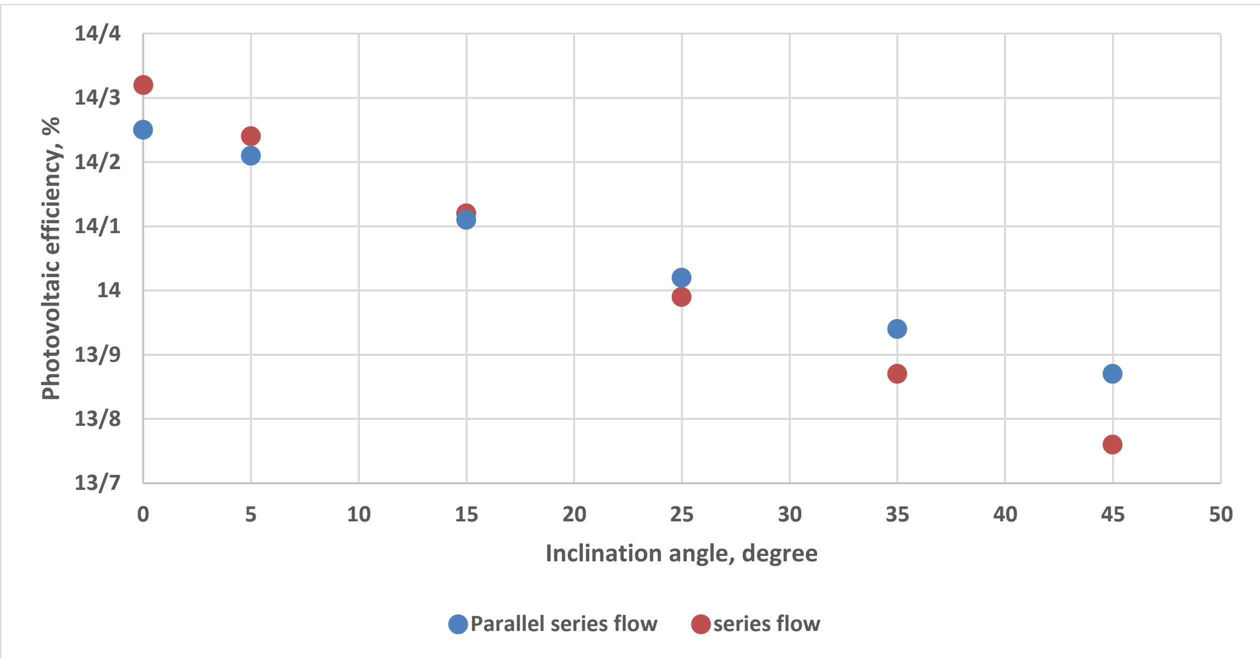

Figure 7. Effects of the inclination angle on the photovoltaic efficiency (I = 1000 W/m2, $\dot{m}$ = 0.03 kg/s, Tin = 25 ºC, Ta = 25 ºC).

4.4. Importance of considering inclination angle in PVT design

The effect of the inclination angle on the PVT's pumping requirement and thus on the PV performance are illustrated in Sections 4.2 and 4.3. It was shown that the inclination angle needs to be taken into consideration during the PVT design stage for the following reasons:

1. For every region, there is an optimum inclination angle that has the maximum solar radiation throughout the year, and thus a maximum PV performance can be obtained.
2. The PVT product designers need to know the effectiveness of their PVT designs for improving the PV performance based on the optimum inclination angle for any given region.

3. The sizing and thus the valuation of the pump of the PVT become possible by knowing the optimum inclination angle.

5. Conclusion

Usually the normal orientation of PVT is to be in an inclined position to get the optimum solar radiation throughout the year. However, the pressure drop and the pumping requirement will be increased as the inclination angle increases, whereby the amount of increment will be different from one PVT design to another depending on the design specifications. In this paper, a comparison between different PVT designs was carried out in order to investigate the influence of inclination angle on the PV performance. Two different PVT designs, the series and the parallel series flow, were considered. It was observed that at a horizontal PVT surface, the series flow performed better when compared to the parallel series flow. On the other hand, the parallel series flow had a higher PV performance as compared to the series flow design. It was shown that the inclination angle was one of the important factors that should be taken into considerations during the PVT product design process.

Nomenclature

A	Area (m^2)
Cf	Specific heat (J/kg K)
D	Diameter of the pipe (m)
f	Darcy friction factor
F′	Flat plate collector efficiency factor
hpf	Heat transfer coefficient from blackened plate to water (W/m^2 K)
I	Incident solar intensity (W/m^2)
g	Acceleration (m/s^2)
K	Loss coefficient
L	Length of pipe
$\dot{m}$	Mass flow rate (kg/s)
P	Power (W)
ΔP	Pressure drop (m)
Re	Reynolds number
T	Temperature (°C)
$\overline{T}$	Average temperature (°C)
Ubf,a	Overall heat transfer coefficient from bottom of the PVT to the ambient (W/m^2 K)
UL,m	Overall heat transfer coefficient for module, from module to the ambient (W/m^2 K)
Utc,a	Overall heat transfer coefficient from solar cell to the ambient through top surface (W/m^2 K)
Utc,p	Overall heat transfer coefficient from back surface of solar cell to the absorption plate (W/m^2 K)
Utp,a	Overall heat transfer coefficient from absorption plate to the ambient (W/m^2 K)
v	velocity of the fluid, (m/s)

Subscripts

a	Ambient
c	Solar cell
eff	Effective
f	Fluid
in	Inlet fluid
m	Module
oc	Open circuit
P	Plate
Pump	Water pump
PV	Photovoltaic
r	Reference
sc	Short circuit

Greek letters

α	Absorptivity
β	Fractional decrease in PV efficiency per unit temperature
ε	Roughness of the copper pipe
g	Gravity (m/s^2)
$\boldsymbol{\rho}$	Density of the fluid (kg/m^3)
η	Efficiency
τ	Transmissivity
θ	Inclination angle in degree

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