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Analysis of Solar Photovoltaic-Thermal System using an Experimental and Simulation Approach

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Abstract

One potential solution for overcoming the use of fossil fuels involves harnessing photovoltaic (PV) power. Nonetheless, the efficiency of PV systems tends to decline as the temperature of the cells rises. A promising approach to enhance both the electrical performance of PV and the acquisition of beneficial heat energy is through the implementation of photovoltaic thermal (PVT) systems. This technology aims to increase overall system efficiency. This research undertook the development and examination of a PVT water system employing a serpentine-type tube configuration. To analyze outlet and cell temperatures, ANSYS software was utilized. The investigation encompassed a range of mass flow rates, spanning from 0.001kg/sec to 0.005kg/sec, and three heat flux rates (600, 800, and 1000 W/m^2). The study also encompassed real-world testing under Nepal's weather conditions, mirroring the parameters set in the simulation. Computational fluid dynamics (CFD) results unveiled peak thermal and electrical efficiencies of the system at 59.3% and 11.6%, respectively. Experimental testing yielded slightly lower figures, with thermal and electrical efficiencies measuring 53.5% and 10.4% correspondingly. Notably, the PV system's electrical efficiency was gauged at 9.6%, while the PVT system reached 10.4%, underscoring the PVT system's enhanced efficiency due to its cooling impact and lower cell temperatures compared to standalone PV systems. The study highlighted that thermal efficiency exhibited a direct correlation with mass flow rate, whereas cell temperature exhibited an inverse relationship with increasing mass flow rates.

Keywords

PV, PVT system, CFD, mass flow-rate, heat flux

1. Introduction

The need for food and energy is rising along with the global population. The continued rise in energy demand, which is largely met by burning fossil fuels, has been a global worry in many ways. (IEA, 2021) estimates that 81% of the world's energy consumption is met by fossil fuels, but these sources also provide 89% of the world's CO_2 emissions and 70% of its greenhouse gas emissions, which are the primary contributors to global warming and climate change (IPCC, 2022).With the huge CO_2 and greenhouse gas (GHG) emissions from these sources, it's critical to investigate alternative energy sources including solar, hydro, biomass, and geothermal energy as a way to both meet demand for energy and dramatically cut emissions [1].

Everywhere on Earth can receive energy from solar, which is a plentiful carbon-free energy source. In fact, the 4.3×109 TJ of solar energy that reaches Earth's surface in a single day is more than enough to meet the planet's 4.1×109 TJ annual energy needs [2]. Fundamentally, the two main types of energy obtained from the sun are electricity and heat. The greatest benefit of solar energy is that it can be used at any production scale, from small-scale homes to large-scale factories connecting to the grid or operated off-grid, using a variety of technologies including photovoltaic, CSPs, or integrating system with other forms of energy sources. The solar technologies also require very little maintenance because, unless tracking devices are added, they don't have any moving parts. With an average power loss of just 0.5% per year, the technology has a longer lifespan of over 20 years [3]. Most crucially, the levelized cost of energy (LCOE) averaged across the globe in 2021 was $0.048/kWh, a reduction of 88% in just the previous ten years [4]. Solar energy is expanding more than other renewable energy sources due to technological improvement, increased efficiency, and lower investment costs, and it can be projected that it will rule the market in the future decades. Combining electrical and thermal energy would be a revolutionary strategy that might simultaneously have a wide range of applications and require less space. The hybrid photo voltaic thermal (PVT) modules could be the considerable solution because this cutting-edge technology can give three times as much energy as a PV system of equal size and around 1.1 times as much thermal energy as a thermal system of comparable scale [5]. Although having lower electrical and thermal efficiency than individual PV and thermal systems, the PVT system offers a higher efficiency usage of space covered. The other benefit is an extension of system lifespan since the heat is optimally utilized and the fluid that passes past the panel lessens thermal stress on the PV panel. Given all these benefits, PVT installations can be the most beneficial solutions for household hot water and electric space heating.Arslan et al., designed, manufactured and tested the finned type air fluid photovoltaic-thermal collector where both experimental and numerical analysis were performed under various flow rates of mass. ANSYS was used for the numerical analysis for predicting the PV module surface temperature before conducting the experiment and under the similar meteorological conditions experiment was performed for 0.031087 kg/sec and 0.04553 kg/sec mass flow rates. The findings showed that the electrical efficiency was improved by 0.42%. Thermal and electrical efficiencies of

PV/T collector for 0.031087 kg/sec flow rate were 37.10% and 13.56% and for 0.04553 kg/sec flow rates they were 49.5% and 13.98% respectively[6].

In context of Nepal the average global horizontal irradiation (GHI) reaches up to 5.5 kWh/m^{2}day in northwest part of country while it is in the range of 4.4 to 4.9 kWh/m^{2}day in the southern part of the country. The specific solar PV electricity output capacity of the country lies between 1400 kWh/kWp and 1600 kWh/kWp (= average daily total between 3.8 and 4.4 kWh/kWp) as per the report published by the Nepal government in 2022.

1.1 Objective

The main objective of this study is to analyse the performance of the solar photovoltaic-thermal system in the context of Nepal using simulation and experimental approach.

The specific objectives of this study are to develop the 3D model of the solar photovoltaic-thermal system with serpentine type thermal collector,to determine the outlet temperature of the water and cell temperature of solar PV based on the different mass-flow rate and heat flux using CFD approach and to construct the solar photovoltaic-thermal system and test its performance.

2. Methods

2.1 Design and modelling

The designed 3D model has PV panel of size 450mm × 340mm with same size of thermal absorber plate. The thermal collector has 10mm as the outer diameter and 9 mm as the inner diameter with 20 mm thickness of insulation. The designed has 7 loops of pipes with 60mm distance between the each pipe.

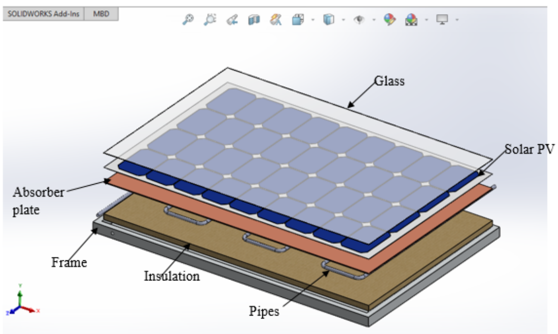

Figure 1: Exploded view of different parts of developed system

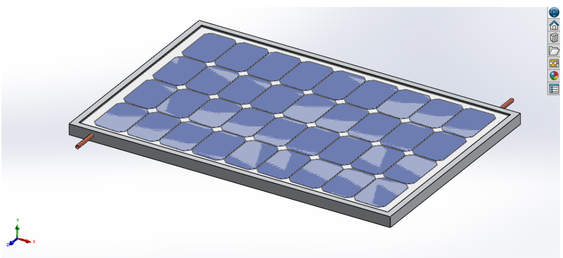

Figure 2: Isometric drawing of develpoed model

Unity packing factor is assumed and module is made of pure silicon where heat received by the absorber is equal to the irradiation incident on PV module per square meter. Similarly for modelling overall process is considered to be in steady state where water is used as working fluid and ambient temperature is considered constant with neglecting the shading effect and losses from dust.

The following table 1, shows the material properties used during the study where depth, density, specific heat capacity and thermal conductivity has units mm, kg/m^3, J/kg.K and W/m.K respectively.

Table 1: Material properties

Parts	Depth	Density	Sp.heat capacity	Conductivity
Glass	2	2200	480	1.1
PV cell	1	2330	700	148
Plate	2	8960	385	401
Pipes	-	8960	385	401
Fluid	-	998.2	4182	0.8
Insulation	20	1.127	1000	0.03

Electrical efficiency of PV module is greatly affected by the cell temperature of the module and can be expressed as ration of electrical power output to the solar insolation on the module which is given by Duffie & Beckman [7];

$$\eta_{ele} = \frac{I_m \times V_m}{G \times A} = \text{Fill factor} \times \frac{I_{SC} \times V_{OC}}{G \times A}$$

where, V_m and I_m are the voltage and current at maximum power conditions, I_{SC} and V_{OC} are short circuit current and open circuit voltage respectively. G and A are total solar irradiation and area of the PV module respectively. There is only slight increase in short circuit current while fill factor and open circuit voltage both decreases with the temperature. Therefore, the net effect is linear equation given by Dubey et al. [8] is;

$$\eta_{ele} = \eta_{Tref} + \beta(T_{out} - T_{ref})$$

Where, η_{Tref} is the electrical efficiency of the PV module at the reference temperature (T_{ref}) and solar radiation of STC conditions i.e., 1000/m^2 at 25° C with air mass ratio of 1.5, β is the coefficient of temperature of open circuit voltage which is normally given by the PV manufacturer and its values varies with the material and T_{out} is the outlet temperature.

For the designed model, all these mentioned values has been referenced from Luminous Polycrystalline solar panels where, η_{Tref} is 13.072%, β is $-0.27\%/K$ at STC conditions and T_{ref} is 25° C.

Thermal efficiency is the function of temperature difference between inlet and outlet temperature of the working fluid i.e., water here in this case. The inlet temperature in case of simulation is constant i.e., 300K while the outlet temperature is determined through the simulation. On the experimental side, the inlet and outlet temperature were measured using the k-type thermo-couple using clamp meter for various flow rate. Thermal efficiency is defined as the ratio of useful energy to the input energy and is given by Duffie & Beckman [7];

$$\eta_{th} = \frac{Q_{use}}{Q_{in}} = \frac{\dot{m}_w \times C_P \times (T_{in} - T_{out})}{G \times A}$$

Overall efficiency of PVT system is the sum of electrical and thermal efficiency which given as;

$$\eta_o = \eta_{ele} + \eta_{th}$$

2.2 ANSYS geometry

The 3D model was analyzed in ANSYS software to determine the outlet and cell temperature. During this process, meshing was done with 4 mm as the element size where it was found that the average and maximum skewness were 0.1444 and 0.71269 respectively in less than 1% elements with 296920 and 212359 as nodes and elements number respectively. The following figure 3 shows the meshed model of the system.

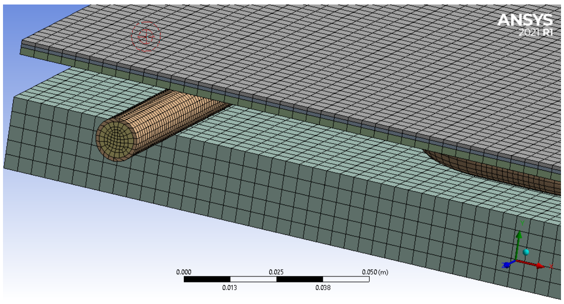

Figure 3: Meshed model

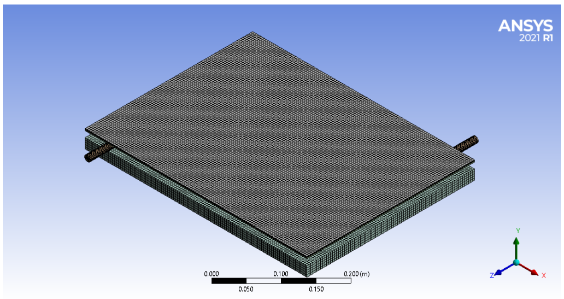

Figure 4: Isometric view of meshed model

Based on the governing equation, literature review and assumptions, boundary conditions were set. The boundary conditions that were used during the simulation were mention in table 2.

Table 2: Boundary conditions

Boundary conditions	Description
Mass flow rate	0.001 to 0.005 kg/sec
Inlet temperature	300K
Heat flux	On top surface 600, 800 and 1000 W/m^2
Outlet condition	Pressure outlet

2.3 Experimental setup

Experimental setup was prepared for investigating the both thermal and electrical performance of the solar PVT water system with serpentine type pipe collector. The setup was constructed by using luminous polycrystalline solar PV of 20W. To prepare the PVT water system copper plate of thickness of 1mm was used as the thermal absorber which was brazed with the copper pipe having 10 mm and 9 mm as the outer and inner diameter respectively. The pipe was bend in such a way that it forms the serpentine type with 60 mm as the distance between the each pipe. There was 7 loops of pipe. Below the pipe insulation of 20mm thickness was used and all the components were frame together.

For circulating the water through the pipes, 15W DC pump was used which was attached to storage tank. To control the flow of the water manual valve was connected after the pump at the inlet side and the flow rate was measured by noting the time to fill the calibrated mug and volume of water collected per minute. To measure the inlet and outlet temperature of the water clamp meter was used by connecting the k-type thermo-couple probe in the clamp meter. Similarly for measuring the current and voltage of the solar pv and pvt water system DT830D digital multimeter was used. The data obtained during the experiment was manually noted down by observing the reading shown by the different instruments used during the experiment. For measuring the global irradiation manual pyranometer was used where the reading ranges from 0 to 1200 W/m^2. All the instrument that were used during the experiment has different uncertainty values. The experiment was carried out at Khashi Bazar, Kalanki, and Kathmandu for seven days.

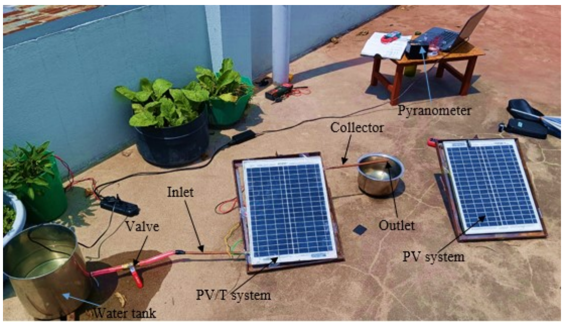

Figure 5: Experimental setup

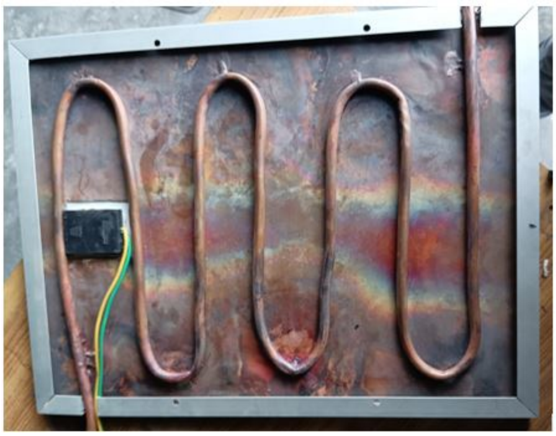

Figure 6: Serpentine type pipe configuration

3. Results and discussion

3.1 Thermal efficiency

Thermal efficiency is the function of temperature difference between the inlet and outlet. During the simulation, the inlet temperature was kept constant to 300K while the outlet temperature of water was measured which passes through the collector. On the experimental side both inlet and outlet temperature are varying with respect to time and solar radiance.

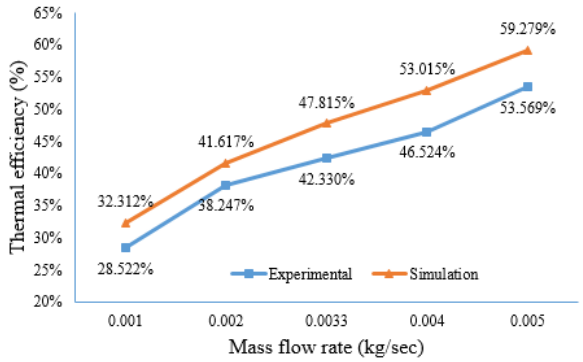

Figure 7: Comparison of thermal efficiency-simulation and experiment with mass flow rate

From figure 7,it was observed that the both approach has similar trend of thermal efficiency i.e., in both cases thermal efficiency was increasing with increase in the flow rate. From the simulation it was found that the thermal efficiency vary from 32.212% to 59.279% while it ranges from 28.522% to 53.569% for experiment. When analyzing the result from simulation and experiment, it was observed that the deviation was in between 8% to 14%. This deviation may be due to varying meteorological data, geographical conditions, variation in assumption made for CFD, losses to surroundings and instrument inaccuracy. It was also observed that when the mass flow rate increases from 0.001 kg/sec to 0.002 kg/sec then the increase in thermal efficiency was maximum in both cases compared to other flow rate.

3.2 Electrical efficiency

Electrical power is considered more valuable in solar PV compared to the thermal power and the electrical efficiency is determined based on the outlet temperature and temperature coefficient of open circuit voltage as mention in the earlier section.The figure 8 shows the relation between the electrical efficiency with mass flow-rate obtained from simulation and experiment.

Here in figure 8,it was seen that the simulation has higher electrical efficiency in comparison to experimental results. The simulation result shows that the electrical efficiency vary from 10.019% to 11.636% whereas the experimental efficiency vary from 8.781% to 10.430%. It was also observed that the efficiency was increasing with increase in flow rate. However there was deviation in the electrical efficiency between simulation and experimental. The deviation vary from 10% to 16% which was observed due to varying meteorological data, geographical conditions such as varying global irradiance with

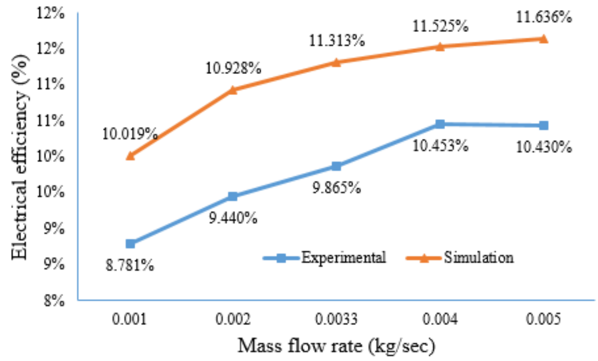

Figure 8: Comparison of electrical efficiency- simulation and experiment with mass flow-rate

respect to time, variation in assumptions made for CFD and losses to surroundings. Moreover both simulation and experimental results shows the similar trend and has similar pattern of electrical efficiency with respect to mass flow rate.

3.3 Temperature difference between inlet and outlet

The following figure 9 shows how the temperature difference between inlet and outlet vary with the mass flow rate for simulation and experiment result. During the experiment, average temperature was taken as the temperature vary with the time. Therefore the temperature was noted for 1 minute and then average value was taken for the calculation in both inlet and outlet for the experiment data.

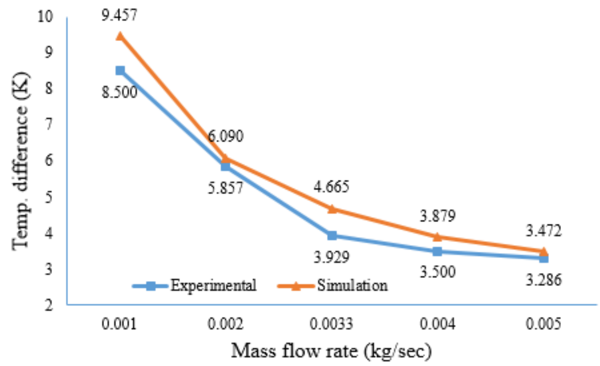

Figure 9: Comparison of temperature difference- simulation and experiment with mass flow-rate

From figure 9, it was found that the temperature difference for simulation data was more compared to the experimental result. This was because during the simulation, the inlet temperature and heat flux was kept constant for certain flow rate but during the experiment the solar irradiance vary with the time and the inlet temperature and outlet temperature of water also vary with the time. Further there may be the losses to the surrounding during the experiment. For flow rate 0.003kg/sec the deviation of temperature difference was higher compared to other flow rate. However, it was also analyzed that the temperature difference between the inlet and outlet decreases with increase in the flow rate and has similar trend in both cases.

3.4 Variation of cell temperature of PV and PVT system

The following figure 10 shows the relationship between the average cell temperature of the PV system and PVT system measured during seven days experiment.

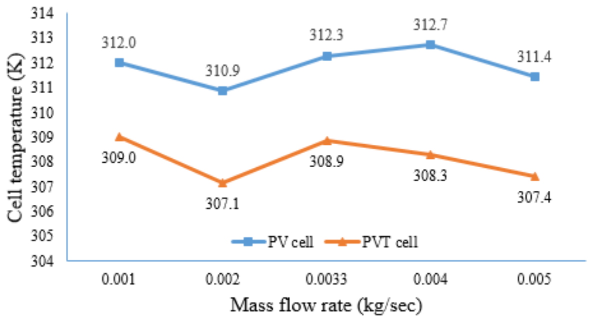

Figure 10: Variation of cell temperature for PV and PVT system

From the figure 10,it was observed that the cell temperature for PV system was higher than that of the PVT system. It was also analyzed that for PVT system the cell temperature decreases when the flow rate increase from 0.001kg/sec to 0.002kg/sec and then increases upto 0.003kg/sec. Afterward the cell temperature decreases with the flow rate. However the trend was slightly different in case of PV system where it can be seen that the cell temperature first decreases and then increases upto 0.004kg/sec flow rate and then again decreases afterward. It was also analyzed that the deviation of the cell temperature between PV and PVT system varies from 0.9% to 1.4% which indicates that the flowing fluid gets heated thus decreasing the cell temperature of the PVT system compared to the PV system.

The variation in the trend of the cell temperature between the PV and PVT system may be due to the higher value of solar intensity with respect to time, as the solar intensity change with respect to time. This shows that the PVT system generate the thermal energy and provide the cooling effect to the system thus improving the electrical performance of the system.

3.5 Comparison with literature

On comparing the thermal efficiency obtained from simulation with the results obtained by various researcher, it was found that the thermal efficiency align with the previous literature results. As per Yang et al.[9], the thermal efficiency was 58.35% which shows that the thermal efficiency obtained from simulation was nearly 1.5% higher thus validating the result obtained from the simulation. Similarly when comparing the thermal efficiency of simulation with study conducted by Misha et al.[10], shows that the thermal efficiency align with his study where it was only 0.5% lower thus validating the result. Further as per Herrando et al.[11], the thermal efficiency vary from 65.55% to 67.45% which was nearly 13% higher than the thermal efficiency obtained from the simulation. Overall when comparing with different literature, the thermal efficiency vary from 0.5% to 13% showing the similar trend thus validating the result obtained from the simulation.

On the other side, when comparing experimental result with Yang et al., it was found that the thermal efficiency obtained from the experiment was nearly 9% lower while it was 30% higher when compared with the result obtained from (Dubey & Tay)[12]. Similarly when compared with Herrando et al., the thermal efficiency was nearly 24% lower. Overall the thermal efficiency obtained from the experiment align with the result obtained by the previous researcher. The variation when comparing with the literature was because of the materials used for the experiment, the assumptions made during the each study and the meterlgological data as the study was conducted in various parts of the world.

The electrical efficiency obtained from CFD analysis here in this study vary from 9.38% to 11.87%. When comparing this efficiency with the result obtained by Dupeyrat et al., [13] and Allan[14],whose value were 8.7% and 8% respectively, it was found that the electrical efficiency was nearly 26% and 32% higher respectively compared to Dupeyrat et al. and Allan. Similarly when comparing with the result given by Misha et al., and Herrando et al., the electrical efficiency was 3% higher and 1% lower respectively. Furthermore comparing the result with (Dubey & Tay) shows that the electrical efficiency was only 3% higher. The variation in electrical efficiency with literature review may be due to the system design and variation in assumptions made during the CFD analysis of the system.

On the experimental side, while comparing the electrical efficiency with Misha et al. result, it was analyzed that the electrical efficiency obtained was nearly 12% lower. Similarly the electrical efficiency obtained in this study was 10% lower compared to the result obtained by (Dubey & Tay). When compared with Herrando et al., it was almost 14.8% lower which indicates that the electrical efficiency determined here in this study align with the electrical efficiency determined by the previous researcher. The variation in the result may be due to the material properties used, climatic condition at which the experiment was conducted and the type of solar PV used for preparing the PVT system.

4. Conclusions

Solar photovoltaic-thermal system was developed using CAD software and analyzed using ANSYS software. Afterward Luminuous polycrystalline 20W panle was used to construct the experimental setup and the system was tested in the Nepal's climatic condition for seven days from 11:00AM to 1:30PM as considering that during this time the solar radiation was at peak. Then average value was computed from the experiment data and conclusion was drawn.

The CFD analysis revealed that the system's thermal efficiency ranged from 32.312% to 59.279%, while its electrical efficiency ranged from 10.019% to 11.636%. On the experimental side, the experimental analysis shows that the thermal efficiency was found to range from 28.522% to 53.569%, with the electrical efficiency ranging from 8.781% to 10.453%.

Further the result comparison with the previous researcher's results shows that the results obtained from this study align with those results with some deviation which may be due variation in conditions, assumptions made and material used during the study.

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