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Hybrid photovoltaic-thermic system with enhanced cell energy efficiency

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Abstract. Interest towards green energy has been increasing over the past decades, due to the increasing effect climate change and unsustainable energy sources pose to the planet. Among the renewable energy sources only solar, hydropower and wind provide substantial potential, while geothermal, wave energy, and biomass provide a local solution.

Solar energy has the potential of being one of the world’s largest energy providers, due to the fact it is present in every corner of the earth and can be converted with ease in the electric energy and thermal energy using photovoltaic (PV) and solar panels.

Hybrid systems generate significant quantities of electricity and also generate heat. Photovoltaic-Thermal (PVT) systems have the potential to reduce the energy consumption in buildings, reducing both thermal and electrical energy, thus reducing the operation costs.

This study aims to design, model, and test the energy efficiency of a PVT system in order to overcome the main drawbacks of photovoltaic panels.

The main challenge photovoltaic panels face is overheating that leads to a reduction in the cells efficiency and energy production, a method of overcoming this is through cooling, recovering the excess heat with the cooling agent. At the same time using the recovered thermal energy to supply the needs of the building in terms of heating and hot water, either directly or as a preheated primary agent, a further reduction in terms of the building energy requirements is achieved.

This study analyses the performance and efficiency of three original design hybrid photovoltaic systems by cooling a photovoltaic panel using water as a cooling agent.

By cooling a photovoltaic panel with a cooling agent with various flow rates, the efficiency of the photovoltaic cells is maximized, and by keeping their temperature as close to the nominal operating cell temperature (NOCT), the study aims to prevent degradation through overheating and cooling cycles during the day and night.

By cooling a PV panel with water as a coolant, the efficiency of the photovoltaic cells is increasing from 17.85 in the case of the uncooled panel to over 19% in the case of the water-cooled systems at a flow rate of v = 3 l / min and v = 5 l / min.

Keywords. Photovoltaic Cooling, Photovoltaic Cell Efficiency, Energy Efficiency, Cooling Methods, Computational Fluid Dynamics.
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1. Introduction

Based on the Global Energy review made by the International Energy Agency global energy consumption has increased over the past decades, the only year when this was not the case was the year 2020 which marked the debut of the SARS-CoV-2 viral pandemic, the energy consumption of 2021 surpassing both the values of 2020 and 2019. Moreover, even though the demand for renewable energy sources has been increasing yearly due to an omnipresent energy crisis, the demand for fossil fuel increased significantly, following the decline in 2020 the demand for coal in the year 2021 rising upwards to 60% in comparison to all renewable sources combined (1).

In terms of energy consumption, the buildings sector is responsible for over 40% of the global energy consumption, and regarding emissions, the buildings are responsible for 30% of the global CO2 emissions. This is a result of the development of the world and factors such as an increase in indoor residence time, rapid urbanization coupled with significant deforestation (2).

Recently the development of the energy sector was centered on sustainability and green energy. Among all clean and sustainable sources of energy, the sun is one of the most important sources because it is responsible directly or indirectly for the majority of the renewable energy sources, furthermore, it is a direct progenitor of the conventional fuels as well, considering a significant portion of these fuels are a result of the photosynthesis process. Solar energy in comparison to other types of renewable energy sources presents the potential of being not only one of the largest suppliers of energy among renewable sources but one of the largest suppliers of energy among all sources, through its accessibility, being implementable on every continent. Furthermore, solar radiation can be converted directly to thermal energy or electrical energy with the use of thermal or photovoltaic (PV) modules (3,4).

Through the implementation of PV systems, the energetic vulnerability of the European Union is reduced, through the production of energy locally without the use of fossil fuels that originate outside the European community. At the same time taking into consideration that with the current technology, PV systems have an increased service life and their CO_2 emissions are reduced and the potential to stabilize the energy market and prevent future shortages in terms of energy supply or energy crises (5,6,7).

According to the literature, if the cell temperature of a polycrystalline silicon, monocrystalline, and amorphous silicon photovoltaic cell increases by 1 °C, the electrical efficiency of the photovoltaic unit will decrease by 0.45%, 0.45%, and 0.25% (8,9).

2. Photovoltaic panels

Photovoltaic (PV) panels are made of PV cell arrays that directly convert the energy radiated by the sun into electric energy. The conversion of solar energy into electrical energy in comparison to other types of energy production presents several advantages: apart from the initial cost, the energy is free, due to the fact that the electricity production is done without any moving parts the maintenance costs are reduced and it is fully renewable and in terms of emissions, PV panels do not produce greenhouse gasses, waste or noise.

In terms of environmental parameters that influence the lifetime and efficiency of a PV panel, the most notable ones are solar radiation, the wind direction and velocity, ambient temperature, dust, humidity, shading, and cell temperature (10,11). A majority of these parameters are meteorological parameters, which cannot be controlled. Moreover, there are parameters that even though in comparison with the environmental parameters, which seem random, can be controlled, such as orientation, tilt angle, and positioning, in a vast majority of cases these parameters are not managed, especially in the case of typical PV systems. However, a parameter that can be controlled and one that has a significant impact on the efficiency of the PV cells is their operating temperature, and keeping the cell temperature as close to the nominal operating cell temperature (NOCT) is a way to maximize the cell temperature (12,13,14).

Unfortunately, through the energy generation process a portion of the solar radiation is not converted into electrical power, thus increasing the temperature of the PV cells, which translated to a reduction of the efficiency of the energy conversion through a reduction of the current intensity and voltage inversely proportional with the temperature of the cells. This phenomenon was studied by Fesharaki et al and Qiang et al in their respective researches, highlighted in Fig. 1 and Fig. 2. (15,16).

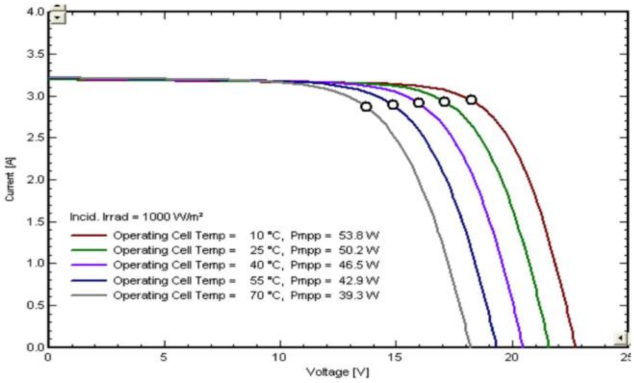


Fig. 1 - Photovoltaic Cell current intensity and voltage variation based on cell temperature

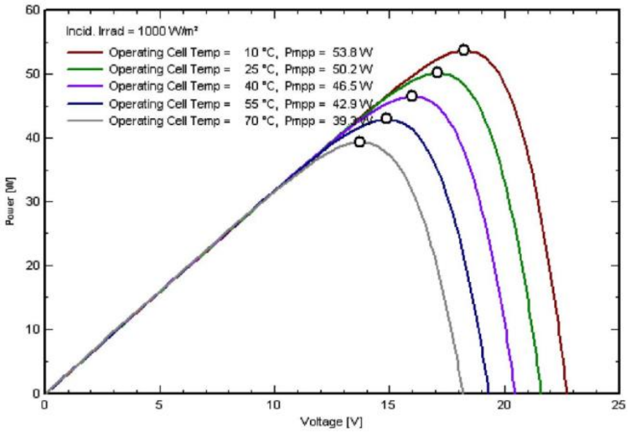


Fig. 2 - Photovoltaic Cell power output and voltage variation based on cell temperature

Taking into consideration the effect temperature has on the performance of the photovoltaic cell, it can be said that cooling is a requirement in some cases in order to maximize the efficiency of the electrical conversion (15).

In terms of energy production and efficiency, the current efficiency of the solar cells in a majority of commercial photovoltaic systems is below 20% (17).

Through scientific research and the evolution of technology, the production cost of advanced solar cells is decreasing, these cells provide higher efficiency in comparison to commercial cells, with an advanced cell, in a single p-n junction, in theory, the achievable efficiency is 29.4% (18).

2.1. Photovoltaic cooling

Taking into consideration the significant impact the environmental parameters pose on the photovoltaic cell efficiency; the research community has studied various cooling methods in order to ensure the optimal cell temperature and the cell operation at optimal parameters.

All types of cooling techniques can be characterized into two categories:

Active photovoltaic cells cooling, which employs a cooling agent in order to reduce the temperature of the cells. The most commonly used coolants are air and water but scientists analyzed the use of specially designed cooling agents such as refrigeration agents or nanofluids, but these have the major drawback of being very expensive to produce (19). The main advantage of active cooling methods is the increased effectiveness caused by the possibility to control the flow rate of the agent with a fan or a pump and the main disadvantage of these types of cooling is the operating cost (20,21,22,23).

The second type of cooling method is passive cooling. This type of cooling focuses on adding extra components on the rear of the photovoltaic panel with the aim of better natural convection. The added components function as heat exchangers, extracting the heat from the PV cells and dispersing it into the surrounding air. During their research scientists analyzed the use of heat sinks, heat pipes, and even phase change materials (PCMs). The use of heat pipes, in particular, is intensely studied, their field of applications ranging from the buildings sector to the IT sector (24,25,26). Passive cooling techniques present the advantage of being cheaper to install and operate, the only cost being the initial cost of the added components but their main drawback is the fact that it is impossible to control the heat transfer and their efficiency is thus reduced in comparison to active cooling techniques (27,28).

In terms of active cooling, cooling the photovoltaic panel using fluid is more efficient in comparison to air cooling methods because fluids present increased heat-carrying capacity in comparison to air (29).

Boumaarafa et al. studied a hybrid photovoltaic/ thermal (PVT) system with a serpentine heat exchanger and revealed that through the combination offers a significant cumulative efficiency, the overall thermal efficiency reaching 79.43% (30).

3. Research Methodology

In order to improve the electrical efficiency of a photovoltaic panel and reduce the energy waste, as is the case for most passive cooling systems, hybrid systems called photovoltaic-thermal systems (PVTs) were conceptualized through adding a heat recovery system to the rear of the PV panel, absorbing the excess heat generated by the sun and using it to produce thermal energy, decreasing the temperature of the PV cells which translates to a better electrical output. PVTs function as cogeneration systems and their use in domestic applications has a significant effect on the environment (31).

Even though the interest towards PVT systems is great and a large number of research papers have been published on the subject, there is little research that treats the enhancement of flow parameters such as inlet flowrate on multiple designs of PVT simultaneously.

The paper addresses multiple numerical simulations on three types of transient PVT models, employing the use of CFD numerical simulations with the Autodesk CFD Software in order to study the thermal distribution of all the systems during operation. This was made to demonstrate the most effective design for the cooling system in increasing the performance and the electrical production efficiency of the photovoltaic cells.

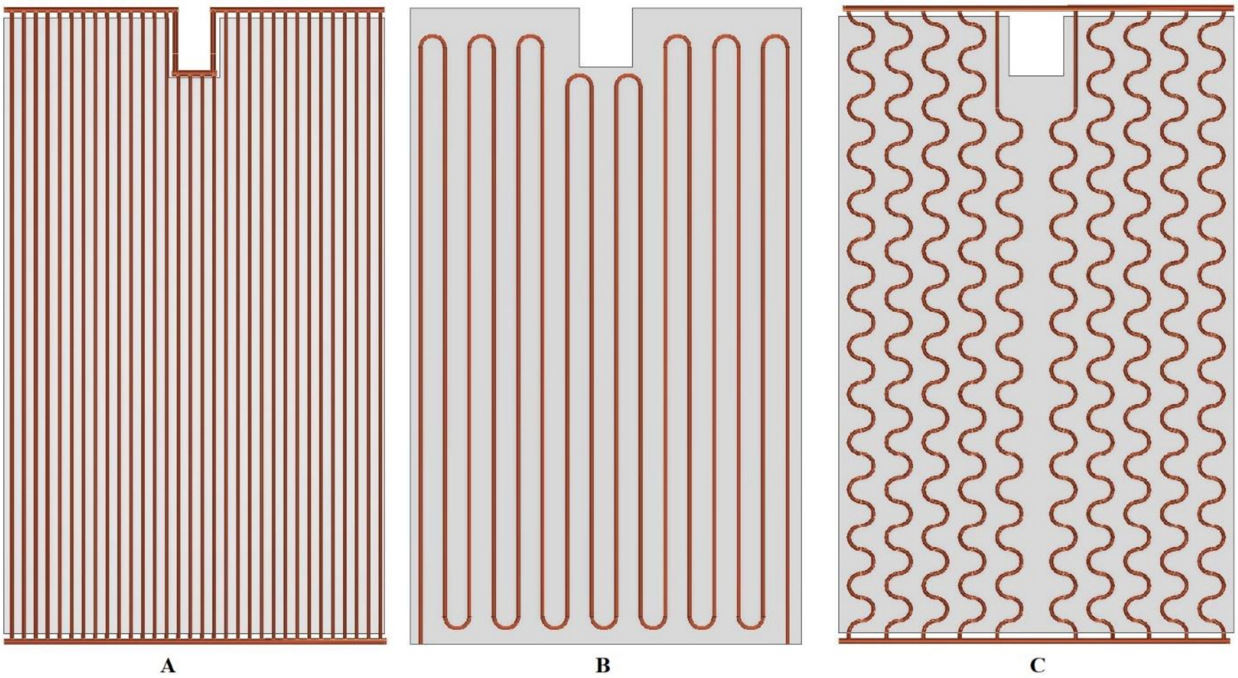
For the study, a common monocrystalline Si-based PV panel (Jinko Eagle PERC JKM315M-60-V) was analyzed because of the advantageous position of the junction box with the main parameters presented in (Table 1) (32).

Tab. 1 - PV module technical characteristics.

	STC	NOCT
Maximum Power (Pmax)	315Wp	235Wp
Maximum Power Voltage (Vmp)	33.2V	31.2V
Maximum Power Current (Imp)	9.49A	7.56A
Open-circuit Voltage (Voc)	40.7V	37.6V
Short-circuit Current (Isc)	10.04A	8.33A
Module Efficiency (%)	19.24%	
Temperature coefficients of Pmax	-0.37%/°C	
Temperature	-0.28%/°C	

coefficients of Voc	
Temperature coefficients of Isc	0.048%/°C
NOCT	45±2°C

The heat recovery systems were designed in three constructive methods, a cooling system comprised of vertical pipes through which water flows from a distributor towards a collector (Fig. 4 – A), a cooling system comprised of a serpentine through which flows water (Fig. 4 – B) and a cooling system made of multiple serpentines connected by a distributor and a colector at the top and bottom (Fig. 4 – C).



The photovoltaic panel consists of 60 photovoltaic cells of 156x156 mm with a thickness of 5 mm made of monocrystalline silicon. The efficiency of the photovoltaic cells is 19.24% at the nominal operating cell temperature of, T_{NOCT} = 45°C. The decrease in the efficiency of the photovoltaic cells is 0.37% /ºC.

In the first phase, it was necessary to model each part using the Auto-desk Inventor Professional 2021 software.

The panel is comprised of a metallic frame (3) L = 1650 mm, w = 992 mm, d = 35 mm, 60 photovoltaic cells (5), L = 156 mm, w = 156 mm, d = 5 mm, enclosed in a glass protective layer (4), L = 1650 mm, w = 992 mm, d = 5 mm and cooled with a heat recovery system (6), through which water flows from an intel (1) to an outlet (2). The components of the models can be viewed in Fig. 3.

Fig. 4 – Heat recovery plates designs

For the water in order to have a pertinent comparison between the three cooling designs, four values for the velocity were considered: a lower flow rate of 1 l/min, a higher flow rate of 10 l/min, and two intermediary flow rates of 3 and 5 l/min.

The next step consisted in assigning the simulation parameters by setting each component the material it is made of, followed by the meshing process and afterwards imposing the boundary conditions.

Because photovoltaic panels are under the influence of solar radiation, they can heat up significantly, the temperature of 65 ºC was used for the temperature of solar cells as an initial condition during operation.

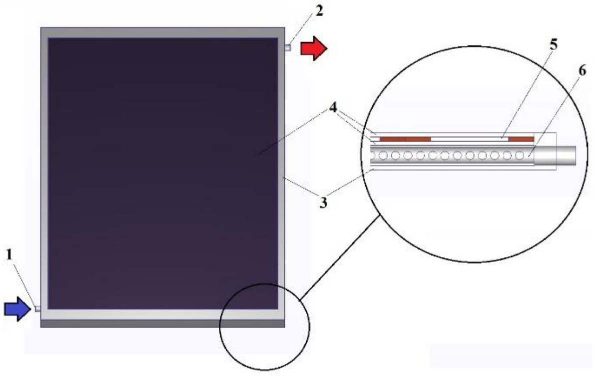
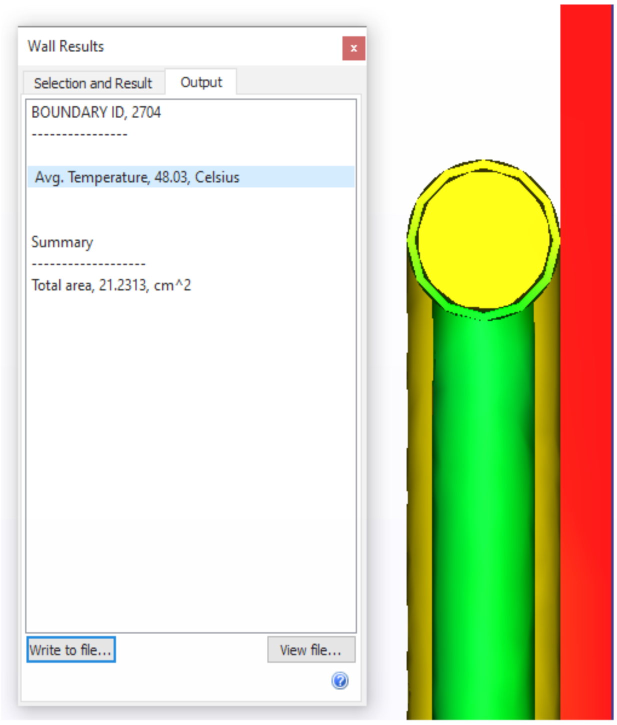


Fig. 3 – PVT model elements.

4. Results and discussion

After running the simulations, the average temperature of the water outlet was recorded for each case as well as the average temperature for the photovoltaic cells, as exemplified in Fig. 5.

In figure 6 it can be observed the backside of the panel for every type of cooling system analysed as well as the temperature distribution.



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BOUNDARY ID, 2704
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Avg. Temperature, 48.03, Celsius


Summary
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Total area, 21.2313, cm^2
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Fig. 5 – Water outlet temperature

Tab. 2 – Simulation Results

	Water flowrate [l/min]	Cell temperature [˚C]	Water temperature [˚C]
PV	0	64.53	12
Vertical tubes	1	57.19	59.07
	3	50.34	48.03
	5	43.5	36.98
	10	35.36	28.62
Serpentine	1	56.83	64.08
	3	47.32	54.63
	5	37.81	45.19
	10	29.85	32.55
Multiple Serpentines	1	56.55	64.16
	3	46.91	54.74
	5	37.27	45.33
	10	29.48	34.07

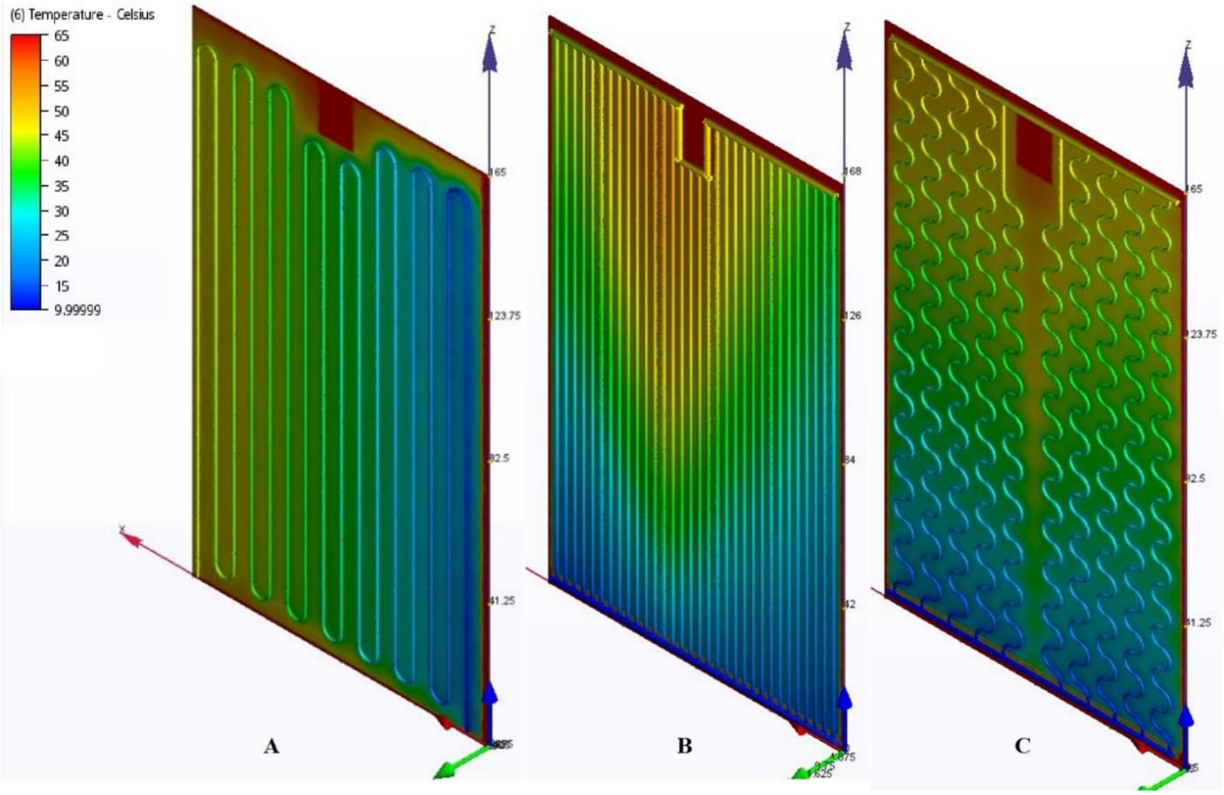

Fig. 6 – The temperature distribution of each cooling system

The pronounced effect that PV operating temperature has upon PV electrical efficiency (η_c) is well documented (10)

$$\eta_c = \eta_{ref} - [\beta_{ref} \times \eta_{ref} \times (T_c - T_{ref})] \qquad (1)$$

β_{ref} = solar radiation coefficient ≈ 0.004 K

T_{ref} = reference temperature (°C)

The values of T_{ref} and η_{ref} are normally provided by the module's manufacturer.

The energy conversion efficiency was determined and displayed in Tab.3.

Tab. 3 – Cell Efficiency

	Water flowrate [l/min]	Cell temperature [˚C]	Cell efficiency [%]
PV	0	64.53	17.85
Vertical tubes	1	57.19	18.37
	3	50.34	18.86
	5	43.5	19.13
	10	35.36	18.55
Serpentine	1	56.83	18.40
	3	47.32	19.07
	5	37.81	18.73
	10	29.85	18.16
Multiple Serpentines	1	56.55	18.42
	3	46.91	19.10
	5	37.27	18.69
	10	29.48	18.14

For an easier visualization of the efficiency of each cooling system at every flowrate, all the data was introduced in the graphs presented in Fig. 7. and Fig.8.

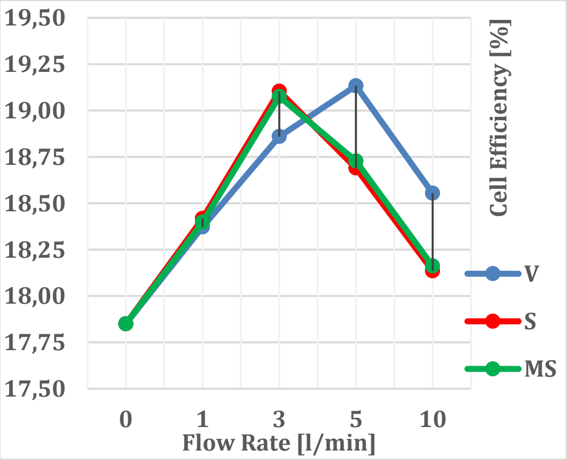

Fig. 7 – Cell efficiency graph

The maximum efficiency was obtained for the vertical tube cooling system (V), with a value of 19.13% with a water flow rate of 5 l/min.

Through cooling, the PV panel the efficiency of the electric production increased by almost 7% in the case of cooling it using the single serpentine (S) and multiple serpentines (MS) at a flow rate of 3 l/min and for the vertical tube cooling system (V) at a flow rate of 3 l/min.

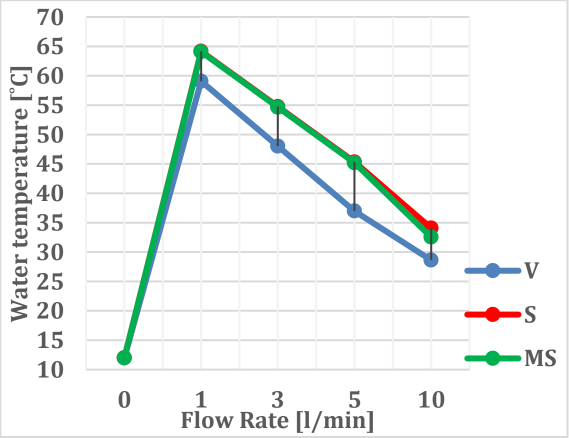

Fig. 8 – Water temperature graph

The cooling system comprised of a single serpentine (S) and the cooling system comprised of multiple serpentine (MS) present comparable results and similar trends but among these two the system comprised of multiple serpentines presents a better temperature distribution.

In terms of thermal performance, the maximum value for the outlet water temperature was 64.16 ˚C at a flowrate of 1 l/min and the water temperature for the flowrate of 3 l/min, which corresponds to a cell temperature close to the NOCT value, the water temperature reached 54.74 ˚C in the case of the multiple serpentines (MS) system.

Among these 3 systems, the most suitable one for cooling a PV panel is the multiple serpentines (MS) system, due to the fact it provides a comparable increase in cell efficiency at a lower flow rate in comparison to the vertical tube cooling system (V) and provides a more uniform temperature distribution than the single serpentine (S) cooling system.

5. Conclusions

Hybrid systems generate significant quantities of electricity and also generate heat. Photovoltaic-Thermal (PVT) systems have the potential to reduce the energy consumption in buildings, reducing both thermal and electrical energy, thus reducing the operation costs.

This study analyses the performance and efficiency of three original design hybrid photovoltaic systems by cooling a photovoltaic panel using water as a cooling agent.

Through cooling a PV panel with water as a coolant, the efficiency of the photovoltaic cells is increasing from 17.85 in the case of the uncooled panel to over 19% in the case of the water-cooled systems at a flow rate of v = 3 l / min and v = 5 l / min.

The water reached a temperature ranging from 28.62 to 64.16 ˚C, and the water temperature for the bestcase scenario, the multiple serpentines (MS) at a flow rate of v = 3 l / min reached a temperature of 54.74 ˚C, an ideal temperature for the water to be used as domestic hot water or even as a heating agent.

Among these 3 systems, the most suitable one for cooling a PV panel is the multiple serpentines (MS) system, due to the fact it provides a comparable increase in cell efficiency at a lower flow rate in comparison to the vertical tube cooling system (V) and provides a more uniform temperature distribution than the single serpentine (S) cooling system.

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