Tuijin Jishu/Journal of Propulsion Technology
ISSN: 1001-4055
Vol. 44 No. 6 (2023)

Experimental Study of the Effect of Submerged Cooling on the Performance of Photovoltaic Panels

[1]Salar Setorg, [2]Ali Akbar Alemrajabi, [3]Mohsen Saghafian
[1]Research Scholar, Isfahan University of Technology;
[2]Prof. Isfahan University of Technology Department of Mechanical Engineering
[3]Associate Prof. Isfahan University of Technology Department of Mechanical Engineering

Abstract: Day by day increase in demand for different forms of energy, especially electricity, is caused by increase in population and increase in the use of technologies in various aspects of human life. One way to overcome this problem is to increase the efficiency and power of photovoltaic systems and at the same time, to reduce the cost of electricity production. Solar radiation intensity and photovoltaic panel temperature, are the two effective parameters in the efficiency and power of photovoltaic panels. As the radiation intensity increases, so does the panel output and its temperature. If the panel's tempetarue increases to high level, the panel may be damaged. Also, increase in panel's temperature leads to reduction in its efficiency. Therefore, some kind of panel cooling is necessary, especially if concentrated radiation is to be used. One way of cooling the panels is to immerse them in a liquid. On the other hand, the coolant light transmittance characteristics, and its thermos-physical properties, affect the performance of the PV panel. In this research, properties of different liquid coolants are considered and methanol has been selected for further investigation. The effects of covering glass, air gap thickness, and the thickness of liquid coolant on the performance of the PV panel is investigated experimentally. Filling the gap between the glass cover and the panel leads to 6.6% increase in the panel's efficiency whereas wen the glass cover is removed, the enhancement in efficiency for the submerged panel reaches 14.8%.

Keywords: *photovoltaic (PV) panels, efficiency of PV panels, immersion cooling of PV panels, performance of PV panels.*

1. Introduction

The sun is the biggest source of energy, and it can also be said that all terrestrial forms of energy sources originate from the sun. It is estimated that the sun can be considered as an important and large source of clean energy for the next 5 billion years. Due to the fact that solar energy is clean, inexhaustible and available almost everywhere on the earth, mankind has been trying to replace this energy with other non-renewable energies during last few decades, and has been able to convert solar energy into other forms of energy such as heat and electricity through direct and indirect methods. One of the most widely used methods of harvesting solar energy is the direct production of electricity from the sun's rays by photovoltaic systems [1]. Photovoltaic (PV) is based on the photoelectric phenomenon. This phenomenon was observed for the first time by Edmond Becquerel in 1839 [2].

Since then, research on materials that show photovoltaic effect has continued, and finally in 1954, the first semiconductor solar cell by Chabin, Fuller and Persson was made using silicon in Bell Laboratories. This cell had an efficiency of about 6%. After that, advancement were constantly made to increase the cell's efficiency and reduce its production costs. In the 70s, the price for each watt of PV power decreased from 100 to 20 dollars, and this significant reduction, as well as the crisis of non-renewable energy resources, attracted more public attention towards these products. During this period, these products received great attention and the strategy of producing cheaper and more efficient PV devices were on the agenda of many countries [3].

In 1985, the first silicon cell with 20% efficiency was made. In the last decade of the 20th century, the gallium indium phosphide and gallium arsenide cells reached 30% efficiency, and polysilicones were also used for ground applications. With the increase in photovoltaic production, their price also decreased. Since then, the use of renewable energies and, as a result, the use of photovoltaics in all aspects and conditions became possible and expanded day by day [4]. In general, PV cells, are often produced from silicon semiconductor materials with monocrystalline and polycrystalline structures in various ways. Some information about the structure of PV cells are presented in [5].

Fossil fuels are finite and limited. In addition, their use has negative effect on the environment [6]. Therefore, in line with control of the deteriorating situation of environment, solar energy, which is one of the most abundant, and accessible clean energy, and in line with that, the use of PV will play a very important role in the future. Having said that, it is very important to pay attention to the efficiency and performance of PV systems [7]. One of the most common ways to increase the efficiency and reduce the costs of PV cells is to use cells under intensified radiation; i.e. the goal is to reduce the area of the solar cell and replace it with lenses and mirrors, which have a much lower manufacturing costs. One drawback of using concentrated solar beam is that though it increases the power out per unit area, it leads to elevated temperature in the PV cells which in turn it tends to reduce their efficiency. To deal with this problem, some cooling mechanisms may be devised [8].

The dependence of cell efficiency on temperature depends on the cell type and quality. Some cooling methods include using fans and cooling currents, air flow drift channels, etc. [9, 10]. Dobi et al. [11] have proposed air-based cooling and evaluated it analytically with two different collector designs. In the first design, the PV module was completely covered the air collector and air flowed on top of its surface. In the second design, the photovoltaic module completely covered the air collector and air flowed under the surface of the absorber. Increase in the air velocity led to a higher efficiency increase in the first design as compared with the second one. Kim et al. [12] investigated the performance of a PV panel by connecting an air collector to its back, through which, on average, it increased the thermal and electrical efficiency of of the PV panel by 15% and 22%, respectively. Crowther [13] conducted an experimental study in which water was flown on the front surface of a PV panel, and was able to reduce the panel temperature by 22 °C. The increase in electricity production was up to 10.3% and finally, even by considering the required power consumption to run the water pump, an increase of 8 to 9% in the net power was obtained. Dorubanto et al. [14] investigated the cooling effects of a water film placed on the front of a PV panel. The temperature of the back surface of the panel decreased from 48 °C to 35.5 °C, but the temperature difference between the front and back surfaces of the panel remained at about 7-8 °C.

Another applied cooling methods is spraying water on the panels. As droplets evaporate, the temperature of the system is reduced to a great extent [15-17] Using phase change materials (PCM), is another effective method of preventing PV cells temperature to increase [18].

One cooling method which is worth investigating is to use the process of evaporation. If the PV panel is immersed in a liquid with a suitable phase change temperature, the heat dissipation of the panel can cause boiling and evaporation of the liquid. Since the boiling process occurs at a constant pressure and temperature, by choosing a fluid with a suitable boiling temperature, a suitable mechanism can be devised for cooling the panel. This is a rather new way to cool the PV panels which hasn't been published much about research.

Krzysztof Sorenk et al. [19] investigated the efficiency of a microscale solar concentrator system in which a monocrystalline silicon was placed in a hexagonal aluminum radiation receiver. The obtained results showed that the maximum power of the experimental solar cells increased by approximately 29%. Disadvantages of this system include high price, need for careful maintenance and continuous cleaning, sensitivity to temperature and weather conditions, shadowing and destruction of optical devices, difficulty in scaling and application in large systems.

Rosa Klat et al. [20] conducted a study using the immersion cooling method. The panel was submerged at depths of 4 cm and 40 cm in water. The photovoltaic efficiency for the panel at normal conditions was 13%, while the efficiency of the submerged panels was 14.2% and 9.5% for 4 cm and 40 cm, respectively. Sun et al. [21]

immersed a PV cell in silicon oil to investigate the panel performance using an energy intensity of 9.1 SUNS (equivalent to 9100 W/m^2). This technique has an effective cooling capacity. The cell temperature could be controlled in the range of 20–31 °C at a 910 W/m^2 DNI (direct normal irradiance). The electrical performance of the cells immersed in the silicon oil was stable and no obvious efficiency degradation was observed after 270 days.

In the present research, the goal is to investigate the effect of immersing a PV panel in a liquids other than water. This can be considered as an introduction to using it as a cooling method in concentrated sun beam radiation where dissipated heat from the panel evaporates the coolant. The effects of an extra glass cover, liquid depth, and incidence angle are investigated.

2. Research method

Characteristics of the PV panels used in this experimental investigation are listed in Table 1.

Table 1: Panel specifications

Panel dimensions (mm)	150*125
Voltage (V)	12
ampere (A)	0.167
Power (W)	2

The efficiency of the PV panel is defined as in Eq. (1), in which P_{max} is the maximum power output of the panel, and I_{max} and V_{max} are the maximum current (short circuit) and the maximum voltage (open cicuit) of the panel. The nominal performance characteristics of PV panels are usually evaluated undear the standard radiation intensity of 1000 (W/m^2) and environment temperature of 25 °C by the manufacturers. At a specific radiation intensity, the panel efficiency is adversely affected by temperature. That explains the necessity of panel cooling especially when concentrated radiation is used.

$$\eta = \frac{P_{max}}{A \times 1000 \frac{W}{m^2}} = \frac{I_{max} \times V_{max}}{A \times 1000 \frac{W}{m^2}} \quad (1)$$

2.1. Cooling fluid

To choose a cooling liquid, one shoule consider some characteristics such as boiling temperatue, electrical conductivity, color, vapor pressure, crossivity, toxicity, and light refractive index. Generally, for evaporative cooling of panels, a liquid with a boiling temperature of about 40 to 80 °C is desirable. Specifications of a few fluids are given in Table 2. Methanol was chosen as the cooling fluid for further investigation.

Table 2: Specifications of a few fluids

fluid	chemical formula	molecular mass	melting point (°C)	boiling point (°C)	Density (kg/Lit)	ignition temperature (°C)	vapor pressure (kPa)	Refractive index of light
Petroleum ether	C_4H_{10}	58.12	-130	60-35	0.66	-40	69-48	1.35

fluid	chemical formula	molecular mass	melting point (°C)	boiling point (°C)	Density (kg/Lit)	ignition temperature (°C)	vapor pressure (kPa)	Refractive index of light
Benzene	C_6H_6	78.11	5.5	80.1	0.88	-11	12.3	1.50
Carbon disulfide	CS_2	76.14	111.6	46.2	1.26	-30	48.1	1.62
Carbon tetrachloride	CCl_4	153.82	-22.9	76.7	1.59	-	11.94	1.46
chloroform	$CHCl_3$	119.38	-63.5	61.2	1.48	-	25.9	1.44
Diethyl ether	$C_4H_{10}O$	74.12	-116	34.6	0.71	-45	44	1.35
ethanol	C_2H_5OH	46.07	-114	78.4	0.79	-17	5.95	1.36
Acetone	C_3H_5OH	58.08	-95	56	0.79	-20	24	1.36
Methanol	CH_3OH	32.04	-96	65	0.79	-19	13	1.33
Water	H_2O	18.015	0	100	1	-	2.3	1.33

2.2. Measuring instruments

A solar power meter is employed to measure the solar irradiance. In addition to that, a voltmeter, and an ammeter were used to measure the potential and current output of the panel. These are essential measurements for calculation of the panel efficiency. Also a digital thermometer is used to measure the temperature of the environment and other materials.

In general, it has been tried to reduce the amount of errors by accurately calibrating the equipments.

3. Analysis of the results

All the experiments were repeated 4 times in almost the same conditions to check the reproducibility of the results. The first series of the experiments were conducted and repeated in 4 consecutive days in early February 2023. The final series of tests, which had two stages, were conducted and repeated in 4 consecutive days in the second half of February 2023. The first tests lasted about four hours each whersas the final tests lasted about two hours each. The starting time of the initial tests was from around 10:00 a.m. and the final tests started at around 11:00 a.m. The following data were recorded in each stage of the experiments at the maximum intensity of solar radiation.

PV Potential (V)

PV current (mA)

Temperature (℃)

Radiation intensity on the horizontal surface (W/m^2)

To investigate the effects of glass cover, air gap and thickness of liquid layer on the performance of the panel, a set of experiments were conducted. The environment temeperature was about 13 ℃**.** The panels were placed horizontally in a container on the ground. The test data for six different conditions of the panels, at the time of the highest solar radiation intensity of 791.3 W/m^2 are reported in Table 3.

Table 3: Comparison of the measured parameters for panels at six different conditions at the maximum intensity of solar radiation

panels	Panel 1 (reference)	Panel 2	Panel 3	Panel 4	Panel 5	Panel 6
Cooling method	-	The horizontal panelcovered by a 4 mm thick glass	The horizontal panel covered by a 4 mm thick glass with an air gap of 1.7 mm between them	The horizontal panelcovered by a 4 mm thick glass with an air gap of 3.4 mm between them	The horizontal panel covered by a 4 mm thick glass with a gap of 1.7 mm between them filled by methanol	The horizontal panel was covered by a 1 mm methanol layer
Potential (V)	13.73	13.72	13.72	13.72	14.21	14.26
current (mA)	70	61.1	61.3	61.9	63.1	72.2
Radiation (W/m^2)	791.3	791.3	791.3	791.3	791.3	791.3
PV panel efficiency %	6.94	6.05	6.07	6.13	6.47	7.43

The reported radiations in Table 3 are on the horizontal surface while the sun's altitude angle was about 39°. When the results of the first two panels are compared, the effect of the covering galss becomes evident. By covering the panel by a glass, the panel temperature increses due to the added resistance in the heat dissipation from the panel. Hence, decreased current and efficiency of the panel. Dobbling the air gap thickness (panels 3 and 4) does not have a pronounced effect on the panel's performance. When the gap between the glass and the panel is filled by methanol (panel 5), the current and efficiency of the panel increses, as compared with the panel 2. This can be attributed to the cooling effect of the liquid layer. In panel 6, the glass cover has been removed, the panel is covered by 1 mm of coolant. This case leads to increase in the cooling effect of the liquid layer due to its enhanced evaporation at its surface, hence, lower temperature, and increased current and efficiency of the panel is resulted. In this case, the open circuit voltage of the panels are not affected very much.

Figures 1-3 show the effect of solar radiation intensity on the panel's current output, potential, and efficiency, respectively. These parameter are affected by solar radiation intensity and its direction. Also the panel's temperature affects inversely on its performance and efficiency.

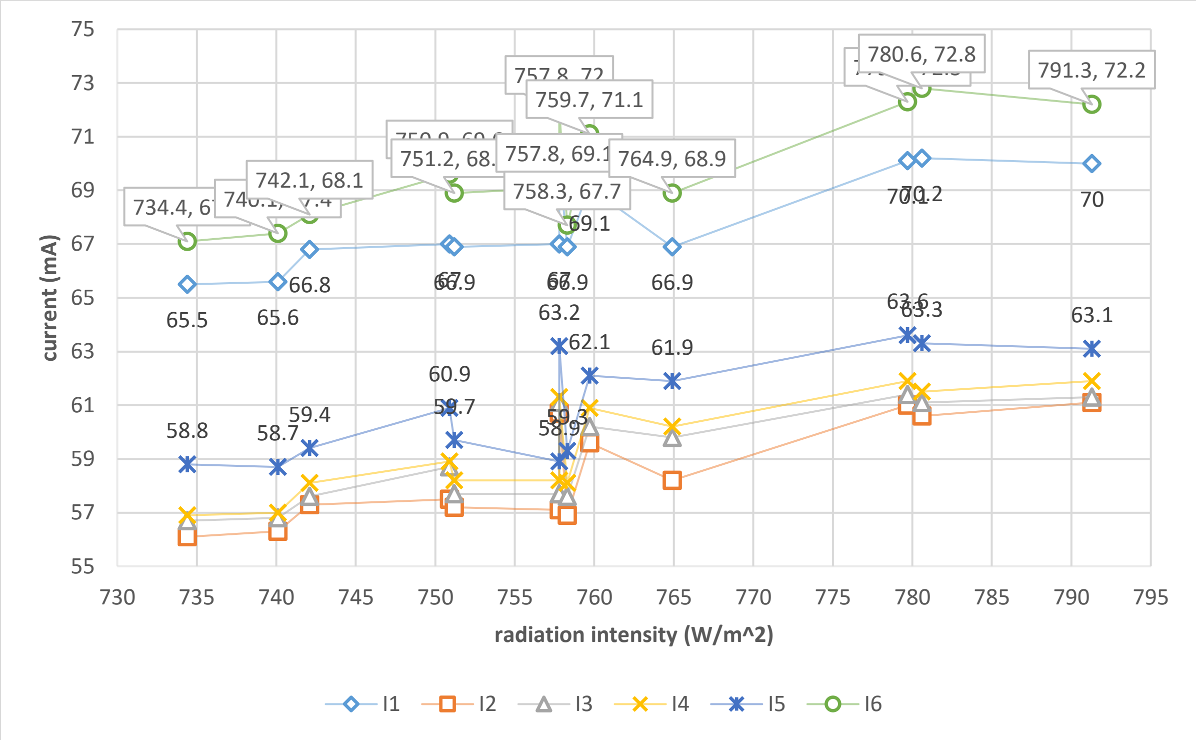

Figure 1: Current (mA) vs radiation intensity (W/m^2)

In this diagram, it can be observed that, in general, the current intensity has decreased over the entire course of the testing process due to the reduction in radiation intensity, except in the case of cooling without a reduction in radiation intensity, where the current intensity has increased due to the effect of cooling on current intensity. Overall, it is evident that an increase in radiation intensity leads to an increase in the current intensity generated by the panels, indicating a direct relationship between radiation intensity and the current intensity produced by the panels.

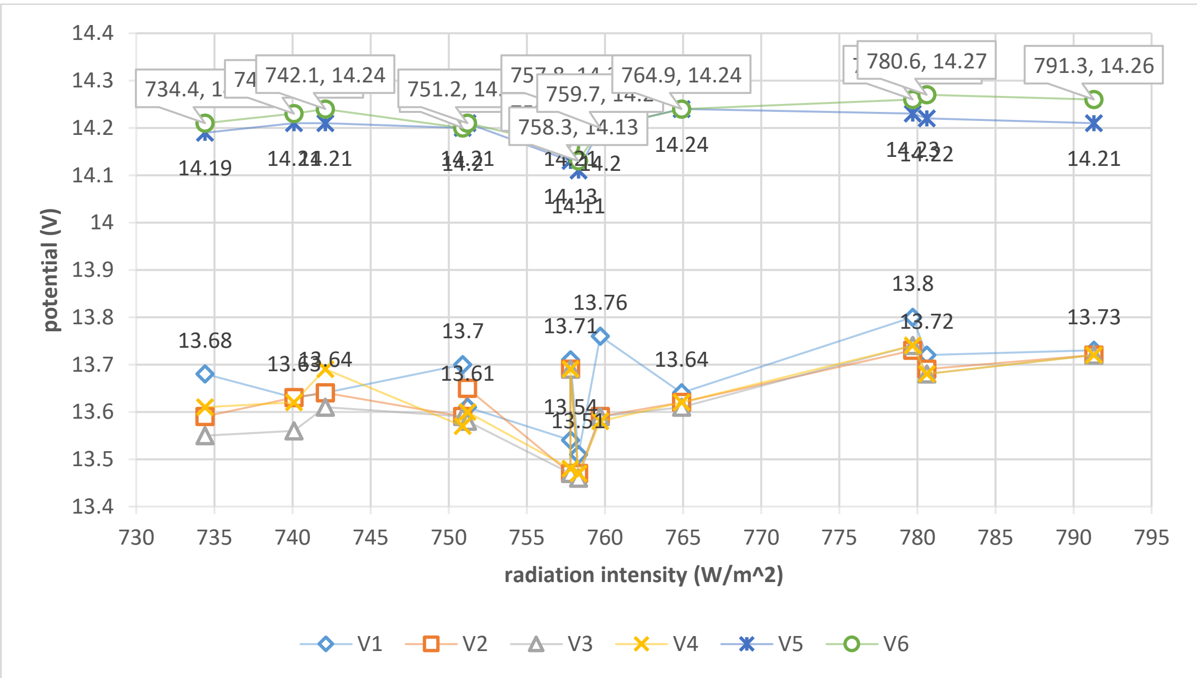

Figure 2: Potential (V) vs radiation intensity (W/m^2)

In this diagram, it can be observed that, overall, during the entire testing process, the potential difference in the panels subjected to cooling has increased. In general, the heating of panels results in a decrease in the generated potential difference of the panels. However, in panels that have been cooled, this potential difference reduction is less significant. These findings highlight the influence of temperature on the potential difference generated by the panels and underscore the significant effect of panel cooling on this potential difference.

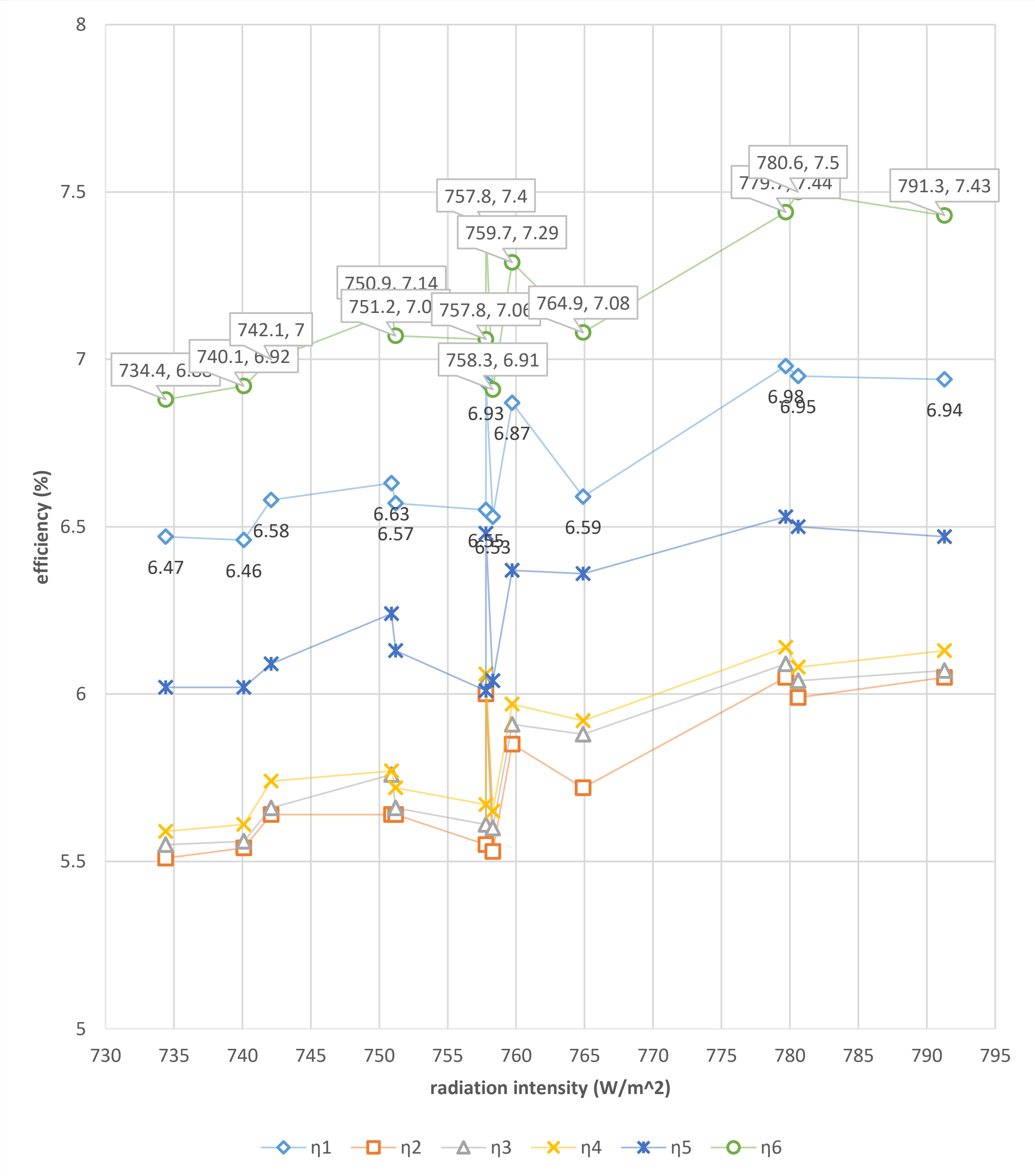

Figure 3: Changes in efficiency (%) vs radiation intensity (W/m^2)

In this diagram, overall, the efficiency has decreased throughout the entire testing process, primarily due to the reduced cooling effect at lower temperatures and the reduction in current intensity due to a decrease in radiation intensity. However, an exception to this trend is observed when cooling is applied, and there is no reduction in radiation intensity. In this specific scenario, the efficiency has noticeably increased. This increase is attributed to a simultaneous increase in potential difference and current intensity, which are two parameters that have a synergistic effect on efficiency due to panel cooling without a reduction in radiation intensity. Consequently, efficiency has significantly improved in this case.

Uncertainty of the results

All in all, efforts have been made to reduce errors by conducting experiments four times, precise equipment calibration, and conducting experiments under consistent environmental conditions. This approach aimed to minimize the effects of sources of uncertainty, such as repeatability, measurement equipment, equipment calibration, and environmental factors. Nevertheless, the overall average error over the entire duration of the experiments, for all four repetitions and the total duration of the experiments, was approximately 0.012. Error percentages in the entire test period are reported in Figure 4. In the best-case scenario, the photovoltaic panel performance increased by an average of approximately 6.1% compared to the reference state. Overall, with a confidence level of 98.8%, the photovoltaic panel performance, in the best-case scenario, increased by 6.1% ± 2.2% over the entire duration of the experiments.

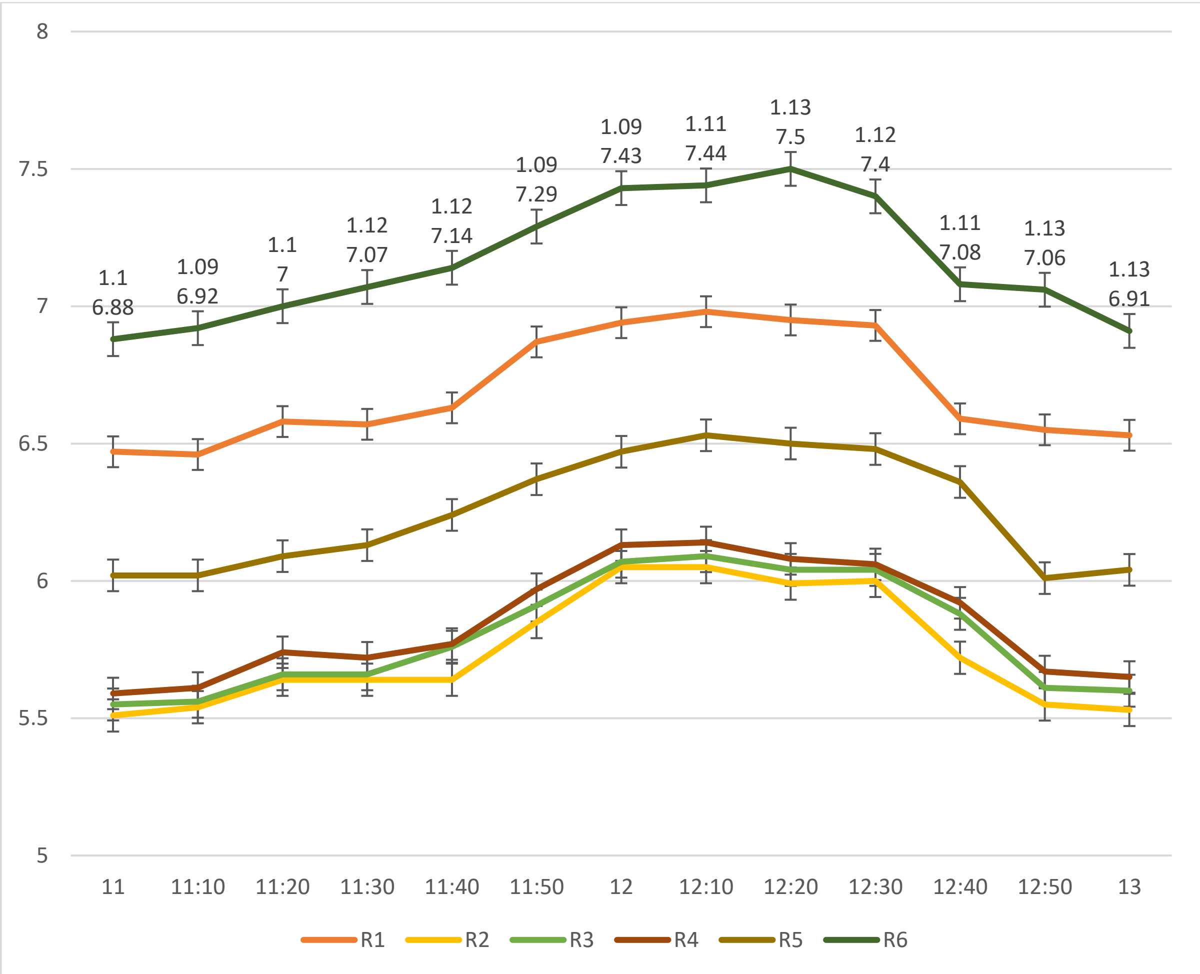

Figure 4: Error percentage in the entire test period (%)

4. Conclusions and suggestions

This research was conducted experimentally to investigate the effects of different parameters on a PV panel efficiency. The effects of a glass cover, air gap thickness, and liquid coolant thickness when the panel was submerged were investigated. Increase in the air gap thickness does not affect the panel efficiency, but when the glass cover is removed while the panel is submerged, the efficiency of the panel increases which is attributed to the enhanced cooling effect of the liquid layer.

References

[1]Craciun B-I, Sera D, Man EA, Kerekes T, Muresan VA, Teodorescu R, editors. Improved voltage regulation strategies by PV inverters in LV rural networks. 2012 3rd IEEE International Symposium on Power Electronics for Distributed Generation Systems (PEDG); 2012: IEEE.

[2]Archer MD, Green MA. Clean electricity from photovoltaics: World Scientific; 2014.

[3]Nelson JA. The physics of solar cells: World Scientific Publishing Company; 2003.

[4]https://www.energy.gov/eere/solar/photovoltaics last visited 2/2/2023.

[5]Schumacher JO. Numerical simulation of silicon solar cells with novel cell structures 2000.

[6]https://www.iea.org/data-and-statistics last visited 2/2/2023.

[7]Fthenakis VM, Kim HC. Photovoltaics: Life-cycle analyses. Solar Energy. 2011;85(8):1609-28.

[8]Royne A, Dey CJ, Mills DR. Cooling of photovoltaic cells under concentrated illumination: a critical review. Solar energy materials and solar cells. 2005;86(4):451-83.

[9]Krauter S, Araújo RG, Schroer S, Hanitsch R, Salhi MJ, Triebel C, et al. Combined photovoltaic and solar thermal systems for facade integration and building insulation. Solar Energy. 1999;67(4-6):239-48.

[10]Berney Needleman D. Optical design guidelines for spectral splitting photovoltaic systems: A sensitivity analysis approach: Massachusetts Institute of Technology; 2014.

[11]Sato D, Yamada N. Review of photovoltaic module cooling methods and performance evaluation of the radiative cooling method. Renewable and Sustainable Energy Reviews. 2019;104:151-66.

[12]Dubey S, Solanki S, Tiwari A. Energy and exergy analysis of PV/T air collectors connected in series. Energy and buildings. 2009;41(8):863-70.

[13]Krauter S. Increased electrical yield via water flow over the front of photovoltaic panels. Solar energy materials and solar cells. 2004;82(1-2):131-7.

[14]Dorobanțu L, Popescu M, Popescu C, Crăciunescu A, editors. Experimental assessment of PV panels front water cooling strategy. International conference on renewable energies and power quality (ICREPQ'13) Bilbao (Spain), 20th to 22th March; 2013.

[15]Nižetić S, Čoko D, Yadav A, Grubišić-Čabo F. Water spray cooling technique applied on a photovoltaic panel: The performance response. Energy conversion and management. 2016;108:287-96.

[16]Irwan Y, Leow W, Irwanto M, Amelia A, Gomesh N, Safwati I. Indoor test performance of PV panel through water cooling method. Energy Procedia. 2015;79:604-11.

[17]Abdolzadeh M, Ameri M. Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells. Renewable energy. 2009;34(1):91-6.

[18]Hachem F, Abdulhay B, Ramadan M, El Hage H, El Rab MG, Khaled M. Improving the performance of photovoltaic cells using pure and combined phase change materials–Experiments and transient energy balance. Renewable Energy. 2017;107:567-75.

[19]Sornek K, Żołądek M, Papis-Frączek K, Szram M, Filipowicz M. Experimental investigations of the microscale concentrated photovoltaic/thermal system based on a solar parabolic trough concentrator. Energy Reports. 2023;9:86-97.

[20]Rosa-Clot M, Rosa-Clot P, Tina G, Scandura P. Submerged photovoltaic solar panel: SP2. Renewable Energy. 2010;35(8):1862-5.

[21]Sun Y, Wang Y, Zhu L, Yin B, Xiang H, Huang Q. Direct liquid-immersion cooling of concentrator silicon solar cells in a linear concentrating photovoltaic receiver. Energy. 2014;65:264-71.