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Experimental investigation of the efficiency of solar panel over which water film flows

Üzerinden su filminin aktığı güneş panelinin verimliliğinin deneysel olarak incelenmesi

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Experimental Investigation of the Efficiency of Solar Panel Over Which Water Film Flows

Highlights

- *Experimental studies in the literature showed that the effect of temperature on PV panels is very influenced by current, voltage, power output, and electrical efficiency.*
- *Increasing power output using a cooling system was examined.*
- *Power output with a cooling system is greater than without cooling.*
- *Wastewater can be used for plant irrigation because its limited temperature is suitable for plants and domestic usage.*

Graphical Abstract

In this study, the effect of temperature on electrical efficiency of PV solar panels has been investigated experimentally. For this purpose, an experimental setup, containing two PV solar panels with and without cooling, was installed. In this experimental setup, a flowing water film, which is on the panel, obtains the cooling. It was seen that power output and electrical efficiency of the cooled panel is greater than without cooling one. Temperature of the cooled panel is lower than uncooled panel.

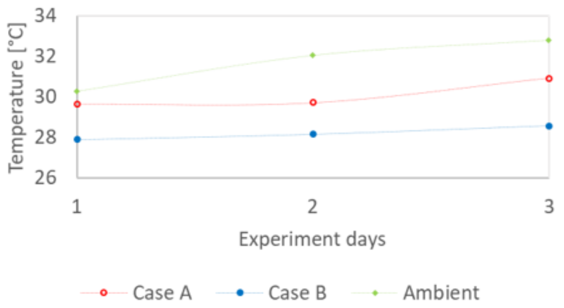

Figure 8. *Variation of average temperature of bottom surface of PV panel with the experiment days for A and B cases.*

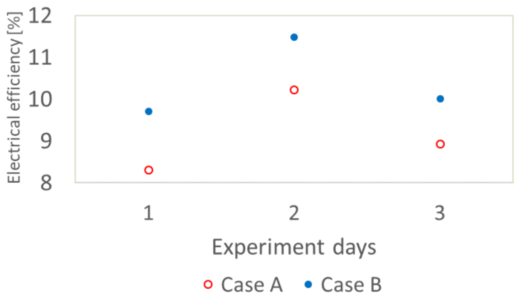

Figure 9. *Variation of electrical efficiency with the experiment days for A and B cases.*

Aim

This experimental study was designed to investigate the effect of flowing water cooling on the performance of the photovoltaic panels.

Design & Methodology

In this study, effects of the temperature on the PV panels efficiencies were investigated experimentally.

Originality

In this study, an experimental setup which is established in Ankara was examined and brought into the literature.

Findings

Power output of the PV panel with a cooling system has been found greater than without cooling system. In this context, 11.143 W electrical power was gained from the panel using the cooling system.

Conclusion

The average power increase using the cooling system is approximately 9.51%. The bottom surface temperature of the panel whose upper surface is cooled by water film is also lower than the uncooled panel. The cooled solar panel was specified to be approximately 13.69% more efficient than the uncooled panel.

Declaration of Ethical Standards

The authors of this article declares that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Experimental Investigation of the Efficiency of Solar Panel Over Which Water Film Flows

Araştırma Makalesi/ Research Article

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ABSTRACT

The most important energy source of the world is the sun. Solar energy can be converted to electricity by using photovoltaic (PV) solar panels. It is known that maximum electrical efficiency of PV solar panels is around 15%-20%. Therefore, it is clear that PV solar panels are not very efficient. This is due to some reasons. One of the most important of these reasons is the increase in the temperature of the PV solar panel. Therefore, PV solar panels should be cooled by means of any cooling methods. For this reason, in this study, the effect of temperature on electrical efficiency of PV solar panels has been investigated experimentally. For this purpose, an experimental setup, containing two PV solar panels with and without cooling, was installed. In this experimental setup, unlike the general literature a flowing water film, which is on the panel, obtains the cooling. It has been determined that power output of the cooled solar panel is greater than without cooling one. A 11.143 W electrical power has been gained from the PV panel due to cooling obtained by flowing water film. The average power increase by means of designed cooling system is about 9.51%. As a result, it was specified that the cooled solar panel was approximately 13.69% more efficient than the uncooled one. In this experimental study, uncertainty analysis was also performed. The uncertainty of the maximum power and electrical efficiency are ± 0.16130% and ± 1.28366%, respectively.

Keywords: Electrical efficiency, flowing water film, PV solar panel, solar energy, temperature effect.

Üzerinden Su Filminin Aktığı Güneş Panelinin Verimliliğinin Deneysel Olarak İncelenmesi

ÖZ

Dünyanın en önemli enerji kaynağı güneştir. Güneş enerjisi, fotovoltaik (PV) güneş panelleri kullanılarak elektriğe dönüştürülebilir. PV güneş panellerinin maksimum elektriksel veriminin %15-%20 civarında olduğu bilinmektedir. Bu nedenle, PV güneş panellerinin çok verimli olmadıkları açıktır. Bu bazı nedenlerden kaynaklanmaktadır. Bu sebeplerin en önemlilerinden biri PV güneş panelinin sıcaklığındaki artıştır. Bu yüzden PV güneş panelleri, herhangi bir soğutma yöntemi ile soğutulmalıdır. Bu nedenle, bu çalışmada; panel sıcaklığının PV güneş panellerinin elektriksel verimliliğine etkisi deneysel olarak araştırılmıştır. Bu amaçla soğutmalı ve soğutmasız iki adet PV güneş paneli içeren bir deney düzeneği kurulmuştur. Bu deney düzeneğinde, genel literatürden farklı olarak panel üzerinden akan bir su filmi soğutmayı sağlamaktadır. Soğutulan solar panelin güç çıkışının, soğutmasız panele göre daha fazla olduğu belirlenmiştir. Akan su filmi ile yapılan soğutma sayesinde PV panelden 11.143 W elektrik gücü elde edilmiştir. Tasarlanan soğutma sistemi sayesinde ortalama güç artışı yaklaşık %9.51'dir. Sonuç olarak, soğutulan güneş panelinin soğutmasız olana göre %13.69 daha verimli olduğu hesaplanmıştır. Bu deneysel çalışmada ayrıca, belirsizlik analizi yapılmıştır. Maksimum gücün ve elektriksel verimin belirsizliği sırasıyla ± %0.16130 ve ± %1.28366'dır.

Anahtar Kelimeler: Elektriksel verim, akan su filmi, PV güneş paneli, güneş enerjisi, sıcaklık etkisi.

1. INTRODUCTION

The most fundamental since the existence of humans one of their needs was energy. Energy is necessary for humans and the universe [1]. This energy need is increasing day by day in parallel with the increase in the human population and the development of technology. The sources of energy can be divided into two fossil energy sources and renewable energy sources [2]. Energy conversion systems using fossil energy sources are very common today and are used in almost every field. The capacity for electricity generation vary with types of the usage energy. However, according to research, fossil resources in the world are being depleted rapidly. There are many types of renewable energy sources. One of the most important this type of energy is undoubtedly solar energy. Solar energy with photovoltaic (PV) electricity generation capacity approximately 0.03% in 2019 [2]. Solar energy is used in different areas of daily life. The production of electrical energy in the houses and the production of hot water and lighting can be given as a few basic examples of the use of solar energy [3]. Today,

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many systems convert solar energy into electrical energy, which is the most used form of energy [4]. Many different areas and concepts were related solar energies and its applications. In this context, one of the most important systems benefiting from solar energy is PV solar panels. Solar panels have an important place in converting the energy taken from the sun into electrical energy. The increasing interest in the use of PV panels has brought many studies on solar panels. These studies aim to get the maximum benefit from solar energy and to use this energy effectively. PV panels have the advantage to provide energy from the sun. They work in a noiseless environment; do not produce any unwanted waste.

PV panels produce power output when subjected to sun illumination. PV panels convert to incoming sunlight as 10-20% [5]. Extra illumination causes an increase in the PV panel's temperature. This issue reduces the panel's power output and electrical efficiency. The electrical efficiency of PV panels depends on many factors such as the type and size of the PV module, dust, geographical position, season of the year, and cooling technique. Coşgun and Demir [6] examined effects of dust on electrical efficiency of PV panels. They reached that dust particle size has effects on output voltage. Abdeen et al. [7] made a study about geographical position effects on PV solar systems. Among these factors, cooling techniques are vital in the efficiency of PV module electrical efficiency. Bayrak et al. [8], Zapalowicz and Zenczak [9] made a study about cooling techniques of PV panels. Many cooling methods have been developed and tested for PV panels. PV panel cooling is vital methods to enhancement the panel power and efficiency many researchers are working on this topic in recent years. Cooling of PV solar cells is an important point to increase electrical power and electrical efficiency. Many researchers made a study about cooling techniques of PV panels and efficiency effects cases. There are two types of cooling techniques in the literature. These are passive and active cooling. Sharaf et al. [10] presented review study about PV systems cooling methods and efficiency cases. Shah et al. [11] offered cooling techniques of PV panels as passive and active cooling. They examined and presented all case of cooling of PV panels. Grubišić-Čabo et al. [12] reviewed cooling techniques. They compared different cooling techniques, active cooling techniques more efficient than passive cooling.

In passive cooling techniques, no energy is corroded for PV panels. Cooling happens intrinsically. Many techniques cool the solar panels. Passive cooling techniques are divided into three main bases that cool the PV panels [13, 14]. These are:

- Gas (air) based techniques,
- Liquid-based techniques,
- Phase change materials-based techniques.

In active cooling techniques, energy is used up for cooling PV panels [15, 16]. Thus, the cooling happens unnaturally. There are many techniques used to cool the PV panels. Active cooling techniques are divided into two main bases, which are:

- Gas (air) based techniques,
- Liquid-based techniques.

Harahap and Suherman [17] present comparison of active and passive cooling techniques in their study.

Water cooling and air cooling are the basic methods in cooling of PV panels. Some research presented studies about air cooling case of PV panels. Bilen et al. [18] investigated theoretical study about effects of fin type on cooling of PV panels and electrical efficiencies. Popovici et al. [19] Arifin et al. [20] examined effects of air cooled heat sink on efficiency enhancement. Amelia et al. [21] investigated cooling of PV panels using DC fan in forced air methodology. Wu et al. [22] present thermoelectric performance of air cooled PV panels in their study.

The water cooling method is more efficient than the other methods. Water cooling of PV panels can be applied in different ways. There are lots of studies that were done by researchers about the cooling of PV solar cells using water cooling methods in experimental studies. Salih et al. [23] made an experimental investigation to show the effects of water cooling on PV panels. Cooling was done by a thin continuous film of water flowing and water spraying on the front of the panels. They present in their study; electrical efficiency was increased by using desired cooling system up to 0.6%.

Hachicha et al. [24] made an experimental investigation to show the effects of water cooling on PV panels. In this study, different scenarios were tested such as front, back, and double cooling. As a result, temperature of module was shortened by 11% using fore cooling. PV cell temperature was decreased 18% and electrical efficiency was improved 4%.

Milind et al. [25] made an experimental study to show the effects of water-cooling on PV panels. Experimental setup with a cooling system that is free flow over the PV panel. Nižetić et al. [26] were demonstrated the effects of water cooling on PV solar panels. In this experimental study using a monocrystalline solar panel, water was sprayed on the back surface of the panel with a specially designed cooling system, and various results were achieved by using this cooling system. In this study, a 16.3% increase in power output and a 5.9% increase in electrical efficiency were achieved. Yıldırım et al. [27] examined and presented study about water base cooling of PV panels. They reached that efficiency increase is more than normal one PV panels in their studies. Agyekum et al. [28] made an experimental study about effects of two side cooling (panel back side and front side) on electrical efficiency of PV panels. Result of this study, electrical efficiency increased up to 11.9% by using desired cooling systems.

Shalaby et al. [29] made an experimental study about effects of water cooling of PV panels. Electrical efficiency of the desired cooling system is greater than un cooled panel. Electrical efficiency presented up to

19.8% in cooled panel. Zubeer and Ali [30] presented experimental and numerical study about effects of water cooling of PV panels. Their cooling systems increased electrical efficiency up to 17%.

Salman et al. [31] examined water flow effects on PV panel electrical efficiency in porous media. This study showed that, average temperature of the module decreased 9-14 °C.

Swese and Hançerlioğulları [32] experimentally investigated the effects of magnetic nanofluids on PV/T performance. They found that the $NiFe_2O_4$ added nanofluid enhanced the efficiency of the PV panel.

As can be understood from the literature research, it is known that PV panels are cooled in order to increase their electrical efficiency. However, this cooling is usually done from the bottom surface and using air of the PV panels. In this experimental study, unlike the general literature, cooling is done from the upper surface of the PV panel using a flowing water film. Thus, dusting of the surface of the PV panels will be prevented.

2. MATERIAL and METHOD

The experimental setup was designed to scrutinize the outcome of water cooling on the presentation of the PV panel. The first PV panel with water flow over the upper surface, while the second PV panel is a reference panel without water flow over the upper surface. Two panels were used to show the effects of temperature on PV panels. During the experiment day voltage, current, and cell temperature were taken from the panel. Decreasing panel temperature provides more power than uncooled solar panels. The location of the experiment setup was located at Ankara Yıldırım Beyazıt University, Faculty of Engineering and Natural Sciences in Ankara, Turkey. The location of the experimental setup was shown in Figure 1.

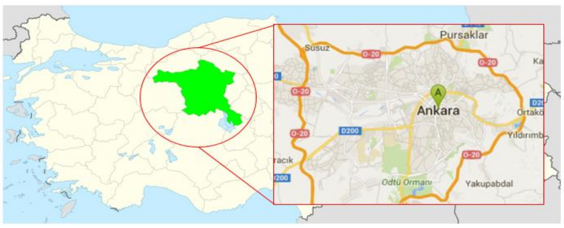

Figure 1. Location of the experimental setup.

Koçer et al. [33] also made a study. That study, based on the Ankara Center and districts, is about determining the optimum slope angle to maximize solar collector and solar panel performance. The optimum angle of inclination is 34° for the annual optimum angle. The panel angle shown in Figure 2 is selected optimum annual angle as 34° for Ankara. Two polycrystalline PV panels (poly-Si) were used for an experimental study that is a first-generation solar panel in a market known as traditional types of solar panel. Their efficiency values reach up to 15%.

Figure 2. PV panels placed with an optimum annual angle of 34°.

General technical characteristics of examined PV panels were displayed in Table 1.

Table 1. General characteristics of examined PV panels.

Parameter	Value
Model	SLN0160P270
Dimensions	1.6 m · 0.9 m · 0.03 m
Maximum power (P_m)	270 W
Maximum power voltage (V_{pm})	31.59 V
Maximum power current (I_{pm})	8.55 A
Open circuit voltage (V_{oc})	39.15 V
Short circuit current (I_{sc})	8.97 A
Module efficiency at STC*	16.60%
Module operating temperature (T_m)	− 45 °C ~ + 85 °C
Temperature coefficient of P_m	− 0.43%/°C

*Standard test conditions: 1000 W/m^2, 25 °C, 1.5 a.m.

2.1 Experimental Setup and Cooling System

In this experimental study, consists of many devices and parts to show the effect of the temperature on the PV panel's power output and electrical efficiency. These are circulation pump, filter, water pipes, and water tank. A circulation pump was wielded to spread the water upper of the panel. The circulation pump was selected according to the demanding power to circulate the water over the solar panels. GM motor branded circulation pump works with AC electricity. The general properties of the circulation pump are scroll pump, 2 m discharge head and 75% efficiency. Carbon and dust filters were used to catch any dust, unwilling moving parts. To collect the recirculation water, the water tank selected desired volume and dimensions. Other important materials to transport the water from the water tank to again water tank were pipe and connections. Pipe and their connections were selected at a low price and more feasibility. A water collection tank made of plastic selected desired volume and dimensions. Water pipes were selected as a garden hose (irrigation hose) its relevant parts were used to connect desired devices and parts to the hose. All material was selected to provide the correct result in this experimental study. A spreader was used to swell the circulated water on a PV solar panel. Collector was used to collect downside water on a PV solar panel. The spreader was made using metal pipe and the collector was made using plastic pipe. A cooling system was created before to install on the PV panels. Circulation pump takes place to mount with cooling pipe system. The water tank and filter were taken and put in the system. All parts of the cooling system were connected. The cooling system was built as previously thought. Experimental setup and the cooling system are shown in Figure 3.

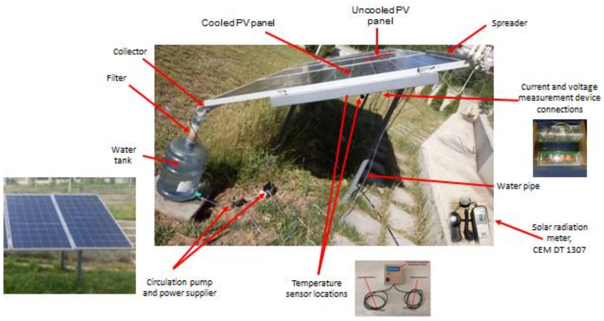

Figure 3. Experimental setup and designed cooling system.

2.2 Measurements

Measurements were taken using devices that were made to measure desired values such as current, voltage, related temperatures, and solar radiation. The system consists of two solar PV panels. A microcontroller that manages the control circuit controls these PV solar panels. Voltage and current as a result of power output from the panel were measured by the designed special electrical device. This electrical measurement device is shown in Figure 4.

Figure 4. Photo of the electrical measurement device.

Solar panel (cell, module) bottom surface temperatures were measured using temperature sensors. CEM DT 1307 is a device that measures solar radiation. Both measurement systems were shown in Figure 5.

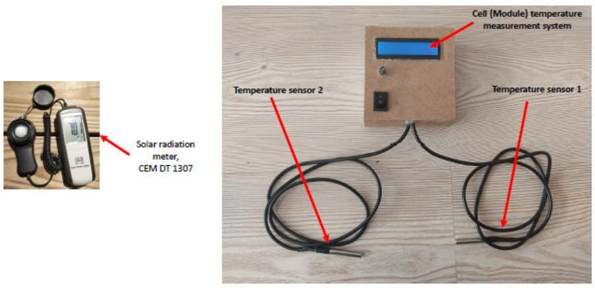

Figure 5. Solar radiation measurement and temperature measurement devices.

Experiments performed within three days in June 2019 the cooling was done during the part of the day. The experimental study was done constant flow rate with cooling and without cooling.

2.3 Theoretical Analysis

Desired parameters were calculated using some formulations [34]. Power output is calculated using taken voltage and current values from the electrical measurement system. Power output at maximum is calculated by Eq. 2. V_{mp} voltage at maximum power, I_{mp} current at maximum power. Voltage and current values measured by using electrical device, power output is calculated.

$$P_m = V_{mp} I_{mp} \tag{1}$$

Electrical efficiency is calculated by Eq. 2. G is the solar radiation flux which measured by using CEM DT 1307 solar radiation fluxmeter. A_p is the area of the panel which calculated with dimensions of panel.

$$\eta_e = \frac{P_m}{G A_p} \tag{2}$$

Thermal energy extracted by cooling water over the panel is calculated by Eq. 3.

$$\dot{Q}_w = \dot{m}_w c_{p,w} (T_{w,o} - T_{w,i}) \tag{3}$$

Where,

$$\dot{m}_w = \rho_w \dot{V}_w \tag{3a}$$

$\dot{m}_w$ is mass flow rate of water, $c_{p,w}$ is specific heat capacity of water at average of temperature inlet and outlet, $T_{w,o}$ is outlet temperature of water which is measured, $T_{w,i}$ is inlet temperature of water which is measured, ρ_w is density of water at average of temperature inlet and outlet, and $\dot{V}_w$ is volume flow rate measured by using flowmeter.

The thermal efficiency of the system is calculated by Eq.4.

$$\eta_{th} = \frac{\dot{Q}_w}{G A_p} \tag{4}$$

Required time for the cooling is calculated by Eq. 5 [35].

$$Q_{removed\ by\ cooling\ water} = Q_{dissipated\ from\ PV\ panel} \tag{5}$$

$$\dot{m}_w c_{p,w} (T_{w,o} - T_{w,i}) \Delta t = m_p c_{p,p} (T_{p,final} - T_{p,initial}) \tag{5a}$$

$$T_{p,final} - T_{p,initial} = \Delta T_p = \frac{\dot{m}_w c_{p,w} \Delta T_w \Delta t}{m_p c_{p,p}} = \frac{\dot{Q}_w \Delta t}{m_p c_{p,p}} = \frac{Q_w}{m_p c_{p,p}} \tag{5b}$$

$$m_p = \rho_p V_p = \rho_p A_p h_p \tag{5c}$$

Here, Δt is required cooling time, m_p is mass of panel taken from datasheet of solar panel, $c_{p,p}$ is specific heat capacity of panel at average of initial and final temperatures of the panel. $T_{p,final}$ is temperature of the cooled panel, $T_{p,initial}$ is uncooled panel temperature. ρ_p is density of panel at average of initial and final temperatures of the panel, h_p is the thickness of panel taken from solar panel datasheet [35]. Power of the pump and energy consumption of the pump are calculated by using Eq. 6 and Eq. 7, respectively.

$$P_{pump} = \frac{\dot{m}_w g H}{\eta_{pump}} \quad (6)$$

$$E_{pump} = P_{pump} \Delta t \quad (7)$$

Here, g is gravity acceleration, H is height at which the pump raises the water which pump reach water that location which measured, η_{pump} is efficiency of pump taken from datasheet.

3. RESULTS AND DISCUSSION

In this section results of measurements have been presented and analyzed. In this experimental study, uncertainty analysis was performed. In the case of using uncertainty analysis, the amount of error made was found as a percentage. The uncertainty of the maximum power ($\pm w_{P_m}$%) was calculated as is ± 0.16130%. The uncertainty of the electrical efficiency (w_{η_e}%) was calculated as ± 1.28366%. Experiments were done on the 14th, 18th, and 19th of June between 11:30 – 14:30 hours 2019. It can be seen from Figure 6 that incoming the solar radiation on the panels in three experiment days.

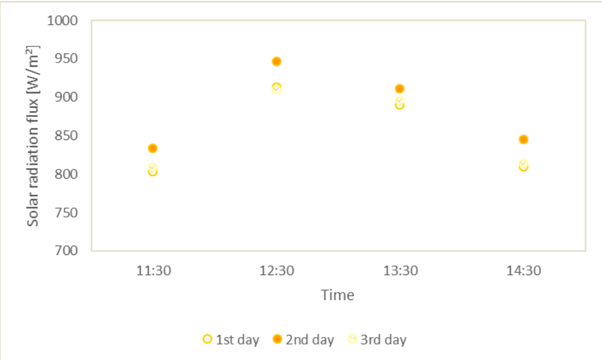

Figure 6. Variation of incoming solar radiation flux on panels with time in the experiment days.

In this section, the data obtained during the experiment days and their interpretation are made. Since the power, current, and voltage values taken from the cooled and uncooled panels will be shown in a graph, the uncooled panel data will be shown with the letter A, the cooled panel data will be shown with the letter B.

3.1 The First Experiment Day (June 14, 2019)

The experiment is started by operating the cooling system. All necessary information; voltage, current, and temperature values were recorded. Figure 7a shows voltage and time relations for the first experiment day. When the panel was cooled using an active cooling system, the voltage increased. This rise causes increasing efficiency of the panel. Figure 7b presents the current and time for the first experiment day. Current for cooled and uncooled are close to each other. When the panel cooled, current decreased slightly. Figure 7c presents experiment results in power output and time relations for the first experiment day. The power output is calculated by using Eq. 1. Figure 7c shows the power output of panels with and without cooling. Power output with cooling is greater than power output without cooling. Maximum power was obtained at approximately 162.8 W. Average power output during the cooling is about 118.33 W and without cooling is 108.79 W. Average of about 9.54 W power output was gained doing this designed cooling system. Consequently, power output is increased by 8.76% using a cooling system. This increase is found using Eq. 8.

$$(\text{Increasing of power output})\% = \frac{|P_m - P_{m,cooled}|}{P_m} \cdot 100 \quad (8)$$

3.2 The Second Experiment Day (June 18, 2019)

The experiment is started by operating the cooling system. All necessary information; voltage, current, and temperature values were recorded. Figure 7a shows voltage and time relations for the second experiment day. When the panel was cooled using an active cooling system, the voltage increased. This rise causes increasing efficiency of the panel. Figure 7b presents the current and time for the second experiment day. Current for cooled and uncooled are close to each other. When the panel cooled, current decreased slightly. Figure 7c presents experiment results in power output and time relations for the second experiment day. The power output is calculated using Eq. 1. Figure 7c shows the power output of panels with and without cooling. Power output with cooling is greater than power output without cooling. Maximum power was obtained at approximately 192.72 W. Average power output during the cooling is about 142.94 W and without cooling is 132.06 W. Average of about 10.88 W power output was gained doing this designed cooling system. Consequently, power output is increased by 8.23% using a cooling system according to Eq. 8.

3.3 The Third Experiment Day (June 19, 2019)

The experiment is started by operating the cooling system. All necessary information; voltage, current, and temperature values were recorded Figure 7a shows voltage and time relations for the third experiment day. When the panel was cooled using an active cooling system, the voltage increased. This rise causes increasing efficiency of the panel. Figure 7b presents the current and time for the third experiment day. Current for cooled and uncooled are close to each other. When the panel cooled current decreased slightly. Figure 7c presents experiment results in power output and time for the third experiment day. The power output is calculated using Eq. 1. Figure 7c shows the power output of panels with and without cooling. Power output with cooling is greater than power output without cooling. Maximum power was obtained as approximately 175.30 W. The average power output during the cooling is about 122.60 W and without cooling is 110.59 W. Average of about 12.20 W power output was gained doing this designed cooling system. As a consequence, power output is increased by 10.85% using a cooling system according to Eq. 8.

Some electrical measurement device errors were detected doing the experimental study. There are some fluctuations in measured values on figures. Simultaneous fluctuations can be neglected in results. During these three experiment days' circulation pump power (2.1 W)

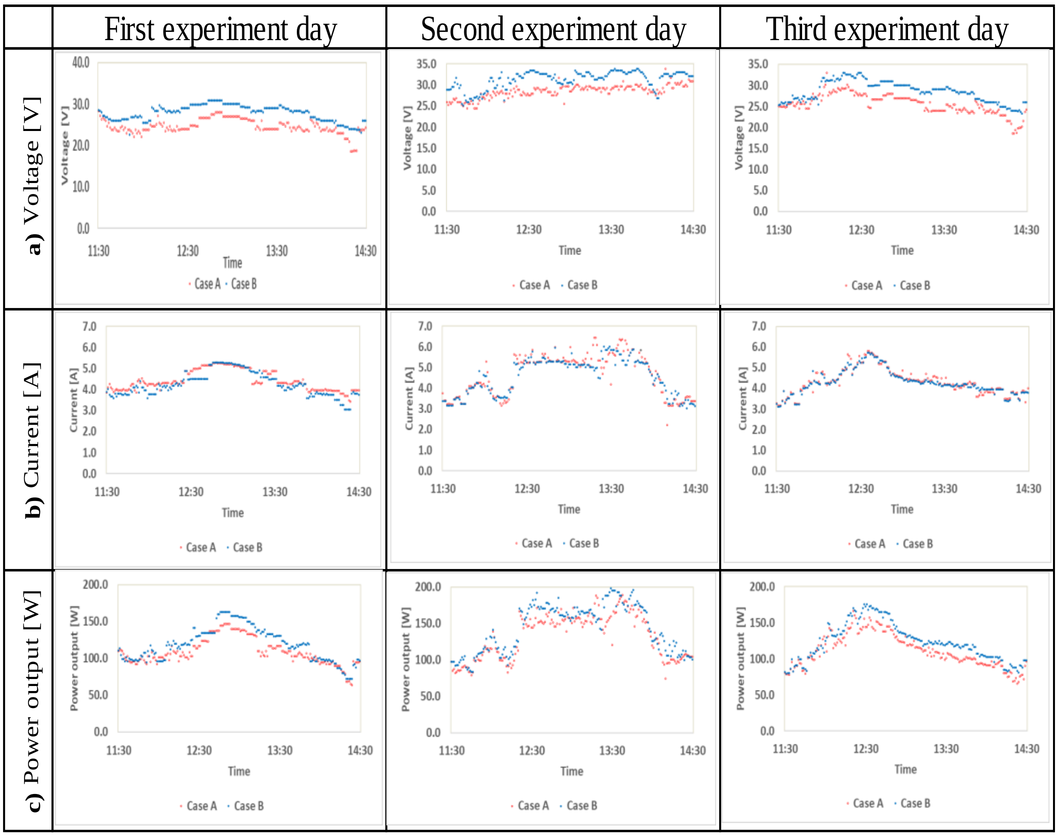

Figure 7. Variation of voltage, current, and power output with time, respectively.

was used in a total of 6.3 W of electrical power was used to circulate the water.

On average, about 11.143 W of electrical power was gained from the panel using a designed cooling system. The average power increase using the designed cooling system is 9.51%.

The temperature of the bottom surface of the panel is another factor that affects the efficiency. In Figure 8, the temperature variation of the bottom surface of the panel and the ambient temperature values according to the test days are given. When Figure 8 is examined, the bottom surface temperature of the panel whose upper surface is cooled by water film is also lower than the uncooled panel. This also increases the efficiency of the cooled panel.

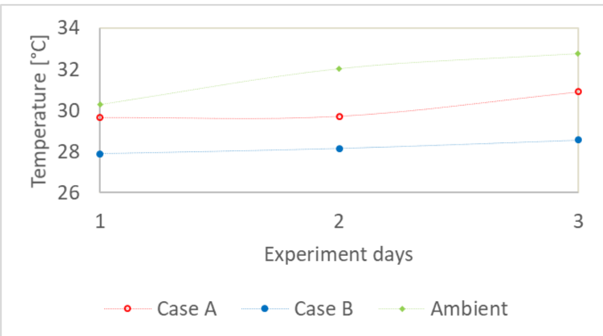

Figure 8. Variation of average temperature of bottom surface of PV panel with the experiment days for A and B cases.

Figure 9 shows electrical efficiencies with and without a cooling system concerning experiment days. Electrical efficiencies were calculated using Eq. 2. The electrical efficiency of the cooled panel is greater than the uncooled solar panel. As a result, the cooled panel was calculated to be 13.69% more efficient than the uncooled solar panel in average. This increase is found using Eq. 9.

$$(\text{Increasing of electrical efficiency})\% = \frac{|\eta_e-\eta_{e,cooled}|}{\eta_e} \cdot 100 \qquad (9)$$

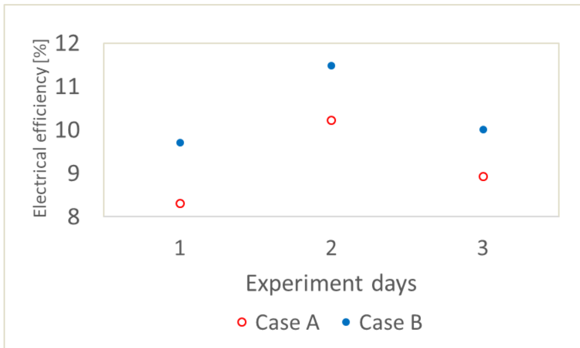

Figure 9. Variation of electrical efficiency with the experiment days for A and B cases.

Enhancement of the electrical efficiency in this experimental study was compared to the electrical efficiency enhancements of the previous studies in Figure 10. In other words, the differences between percentage efficiencies of cooled and uncooled panels for the previous studies and this study are shown in Figure 10. It can be seen from Figure 10 that the difference between percentage efficiencies of cooled and uncooled panels is approximately 1.25 for this study.

Since the studies of Nižetić et al. [15], Salih et al. [23], and Schiro et al. [35] have similar characteristics to this study, the electrical efficiencies are close to each other. In the studies carried out by Hachicha et al. [24] and Nižetić et al. [26], it was observed that the efficiency increase was higher than others since both the upper surface and the lower surface of the panel were cooled in these studies.

Figure 10. Comparison of enhancement of electrical efficiency of this study and previous studies.

3.4 Experimental Errors and Uncertainty Analysis

The accuracy of the measured values during the experimental study is important. Many factors affect the accuracy of the measured data. The most important of these factors is the errors that may occur during the experiment. These errors are the structure of the experimental setup, the structure and use of measurement tools, and unpredictable errors and errors caused by the experimenter. It is easier to detect the errors caused by the person than the errors caused by the measuring instrument and the experimental setup. It is difficult to detect the errors caused by the experimental setup and measurement tools and is not always possible. Uncertainty analysis provides convergence in the precision of the results for detecting errors occurring in the experiment. The uncertainties occurring in the measuring devices used in the experiments are shown in Table 2.

Table 2. Uncertainties detected in measurement devices.

Measurement devices	Uncertainty values
Temperature measurement device	± 0.03 ºC (0 ~ 60 ºC)
Solar radiation fluxmeter	± 10 W/m^2 (0 ~ 1999 W/m^2)

In the uncertainty analysis, the total error calculation of the errors that may occur while measuring a value can be done with Eq. 10 [36].

$$w_R = \pm\left[\left(\frac{\partial R}{\partial x_1} w_{x_1}\right)^2 + \left(\frac{\partial R}{\partial x_2} w_{x2}\right)^2 + .. + \left(\frac{\partial R}{\partial x_n} w_{xn}\right)^2\right]^{1/2} \quad (10)$$

Here, R is the size to be calculated, n independent variables affecting this size x_1, x_2, x_3,…., x_n, constant error amount of the independent variable $\pm w_{x_1}$, $\pm w_{x_2}$, $\pm w_{x_3}$,…., $\pm w_{x_n}$, the uncertainty of the magnitude R is expressed by $\pm w_R$. With this uncertainty analysis, the independent variable causing the biggest error is determined.

3.5 Experimental Errors and Uncertainty Analysis

The independent variables causing error in the experiments voltage value at maximum power were determined as V_{mp}, the current value at maximum power I_{mp}, incoming solar radiation flux, G. In the light of the information given above, the maximum power P_m, and the electrical efficiency η_e are calculated using Eq. 11a, 11b and 12a, 12b respectively.

$$w_{P_m} = \pm\left[\left(\frac{\partial P_m}{\partial V_{mp}} w_{V_{mp}}\right)^2 + \left(\frac{\partial P_m}{\partial I_{mp}} w_{I_{mp}}\right)^2\right]^{1/2} \quad (11a)$$

$$w_{P_m} = \pm\left[\left(I_{mp} w_{V_{mp}}\right)^2 + \left(V_{mp} w_{I_{mp}}\right)^2\right]^{1/2} \quad (11b)$$

$$w_{\eta_e} = \pm\left[\left(\frac{\partial \eta_e}{\partial V_{mp}} w_{V_{mp}}\right)^2 + \left(\frac{\partial \eta_e}{\partial I_{mp}} w_{I_{mp}}\right)^2 + \left(\frac{\partial \eta_e}{\partial G} w_G\right)^2 + \left(\frac{\partial \eta_e}{\partial A_p} w_{A_p}\right)^2\right]^{1/2} \quad (12a)$$

$$w_{\eta_e} = \pm\left[\left(\frac{I_{mp}}{GA_p} w_{V_{mp}}\right)^2 + \left(\frac{V_{mp}}{GA_p} w_{I_{mp}}\right)^2 + \left(-\frac{V_{mp}I_{mp}}{G^2A_p} w_G\right)^2 + \left(-\frac{V_{mp}I_{mp}}{GA_p^2} w_{A_p}\right)^2\right]^{1/2} \quad (12b)$$

4. CONCLUSION AND RECOMMENDATIONS

Energy can be examined mainly in two parts; renewable and non-renewable. These two energy types also have subtitles within themselves. There are many ways to utilize these types of energy. In this study, PV solar panels which generate electricity by utilizing solar energy, have been examined. Efficiency and some factors that affect the efficiency are summarized. The main subject of this study is decreasing of the average temperature of the PV panel. In this study, this subject was experimentally examined in detail.

In this context, in this experimental study, upper surface of the PV panel cooled with a flowing water film. That is an active cooling method, the water-cooled technique was used. In the study, two poly-crystalline solar panels were used to show the effects of the cooling on PV solar panels. One PV panel was used with the water cooling system while another solar panel was not used water cooling system. Cooling of the upper surface of the PV panel and cleaning dust from the panel surface directly affected the panel's efficiency. In other words, as the temperature difference between the top surface and the bottom surface of the PV panel increases, the amount of electricity produced by the panel also increases. The characteristics of the two different solar PV panels which are current, voltage, output power generated by these panels, and electrical efficiency of the panels were examined. Results are:

- It can be seen from experimental studies in the literature that operation temperature affects PV panel's current, voltage, output power, and electrical efficiency.

- Output power of the PV with a cooling system is greater than without the cooling system.
- Average electrical power of the cooled and uncooled PV solar panels were measured as 127.69 W and 116.55 W, respectively, as shown in Figure 7. Hence, 11.14 W electrical power was extra gained from the cooled panel using the designed cooling system. The average output power increase with the using the cooling system is approximately 9.51%.
- The bottom surface temperature of the panel over which water film flows is also lower than the uncooled panel. Bottom surface average temperatures of the uncooled and cooled panels were measured as 30.09 °C and 28.21 °C, respectively, as shown in Figure 8.
- Average electrical efficiency of the uncooled and cooled panels were determined as 9.15% and 10.40%, respectively, as shown in Figure 9. Hence, the cooled solar panel was specified to be approximately 13.69% more efficient than the uncooled panel.

Some recommendations for the future studies:

- Wastewater originated from the cooling system can be used for plant irrigation and domestic usage because of its limited temperature.
- The spreader in this system can be made moveable to decrease effect of the spreader on shading.
- Besides the cooling, it is possible to clean PV panels using this type of cooling system in dusty regions.

NOMENCLATURE

A_p	Panel area [m^2]
$c_{p,p}$	Specific heat of panel [J/(kg·K)]
$c_{p,w}$	Specific heat of water [J/(kg·K)]
ΔT_p	Temperature difference of panel between inlet and outlet [°C]
ΔT_w	Temperature difference of water between inlet and outlet [°C]
Δt	Required cooling time [s]
E_{pump}	Energy consumption of pump [kW·h]
g	Gravity acceleration [m/s^2]
G	Incoming solar radiation flux [W/m^2]
h_p	Thickness of the panel [m]
H	Height [m]
η_e	Electrical efficiency [-]
$\eta_{e,\ cooled}$	Electrical efficiency of cooled panel [-]
η_{pump}	Pump efficiency [-]
η_{th}	Thermal efficiency [-]
I_{mp}	Maximum power current [A]
m_p	Mass of panel [kg]
$\dot{m}_w$	Mass flow rate of water [kg/s]
P_m	Maximum power [W]
$P_{m,\ cooled}$	Maximum power of cooled panel [W]
P_{pump}	Power of pump [W]
Q	Thermal energy [J]
$\dot{Q}_w$	Heat transfer to the flowing water [W]
ρ_p	Panel density [kg/m^3]
ρ_w	Water density [kg/m^3]
$T_{p,final}$	Temperature of cooled panel [°C]
$T_{p,initial}$	Temperature of uncooled panel [°C]
$T_{w,i}$	Temperature of water at inlet [°C]
$T_{w,o}$	Temperature of water at outlet [°C]
V_{mp}	Maximum power voltage [V]
$\dot{V}_w$	Volumetric flow rate of water [m^3/s]

DECLARATION OF ETHICAL STANDARDS

The authors of this article declares that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

İsmail ERDOĞAN: He has established experimental setup, performed experiments, evaluated experimental data, and written of article.

Kemal BİLEN: He has contributed establishing of experimental setup, evaluated experimental data, and written of article. Also, he has consulted the related graduated project.

Sinan KIVRAK: He has contributed establishing of experimental setup, evaluated experimental data, and written of article.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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