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Research Article

Thermal Analysis of Photovoltaic Panel Cooled by Electrospray Using Different Fluids

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ABSTRACT

In this study, the cooling performance of the photovoltaic (PV) panel was examined by the electrospray cooling method. The experiments were carried out under 1000 W/m² irradiation, 25 G nozzle diameter and 70 mm nozzle-to-PV panel distance and 20 kV voltage. Water, ethanol and water - ethanol (50%- 50%) mixture were atomized and sprayed on the panel surface at flow rates of 50-80-110 ml/h. The results showed that electrical power output decreased with increasing PV panel surface temperature. Ethanol and water - ethanol mixture showed a more effective cooling performance than water, especially at flow rates of 80 and 110 ml/h. At the highest flow rate, ethanol reduced the panel temperature by 59%, providing 6,8% more electrical power output than the uncooled condition. These findings show that the electrospray cooling method is effective in increasing the electrical efficiency of PV panels and that better cooling performance is achieved with ethanol, water - ethanol mixture compared to water.

Keywords: *PV panel, Electrospray cooling, Solar energy*

Farklı Akışkanlar Kullanılarak Elektrosprey ile Soğutulan Fotovoltaik Panelin Termal Analizi

ÖZ

Bu çalışmada, fotovoltaik (PV) panelin elektrosprey soğutma yöntemi ile soğutma performansı incelenmiştir. Deneyler, 1000 W/m² ışınım, 25 G nozul çapı ve 70 mm nozul-PV panel arası mesafesi ve 20 kV gerilim altında gerçekleştirilmiştir. Su, etanol ve su - etanol (%50-%50) karışımı, 50-80-110 ml/h debilerde atomize edilerek panel yüzeyine püskürtülmüştür. Sonuçlar, PV panel yüzey sıcaklığının artmasıyla elektrik güç çıkışının azaldığını göstermiştir. Etanol ve su - etanol karışımı, özellikle 80 ve 110 ml/h debilerde, suya göre daha etkili bir soğutma performansı sergilemiştir. En yüksek debide etanol, panel sıcaklığını %59 düşürerek soğutulmamış duruma göre %6,8 daha fazla elektrik güç çıkışı sağlamıştır. Bu bulgular, elektrosprey soğutma yönteminin PV panellerin elektriksel verimini artırmada etkili olduğunu ve etanol, su - etanol karışımı ile suya göre daha iyi soğutma performansı elde edildiğini göstermektedir.

Anahtar Kelimeler: *PV panel, Elektrosprey soğutma, Güneş enerjisi*

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I. INTRODUCTION

The rapid increase in energy demand and the increase in global warming and greenhouse effect caused by fossil fuel consumption have increased interest in renewable energy sources [1]. Solar energy is an important energy source for a sustainable future. In the sustainable energy production of photovoltaic panels, variable weather conditions cause uncertainties in power output. Especially the variability of weather conditions affecting PV panel power output brings some challenges. Meteorological conditions such as cloud cover, solar radiation, air temperature, humidity and dust accumulation significantly affect PV panel performance [2], [3].

The basis of solar energy systems is the generation of electricity from solar radiation through photovoltaic modules. PV panels in solar systems consist of small cells [4]. The temperature of the cells is an important factor affecting the output power of PV modules [5], [6]. An increase in solar panel temperature causes an increase in current intensity and a sudden drop in open circuit voltage [7]. As the temperature increases, the voltage drops, which leads to a decrease in the electrical efficiency of the panel [8], [9]. Therefore, cooling of PV panels is important to the operational output power closer to the rated power [10].

Many cooling methods have been used in the literature to reduce the temperature and provide thermal control of PV panels. There are two types of methods for cooling PV panels: active and passive cooling systems [11], [12]. Active cooling systems need external fans and pumps to allow heat to move away from the PV cells, while passive cooling systems rely on natural convection and do not require additional power [13].

Apart from forced and natural air cooling, evaporative cooling offers an effective solution for cooling PV panels by using the latent heat of the evaporation process of water [14]. Many studies have been carried out in the literature on cooling PV panels with water spray, which is one of the active cooling methods. Bevilacqua et al. [15] proposed a new thermal model by spray cooling the PV panel from its back surface. As a result, they found that the electrical power increased by 7.8% and the average cell temperature decreased by 28.2% during peak irradiation hours. Shalaby et al. [16] experimentally investigated the effect of cooling the back surface of the PV panel on electrical power generation and efficiency. As a result, the power generation of the PV panel increased by about 14.1% when the cooling system they proposed was applied. Nižetić et al. [17] obtained 16.3% increase in electrical power output and 14.1% increase in PV panel efficiency with spray cooling in their experimental study. By cooling the PV panel from both the front and the back, they reduced the temperature from 54 °C to 24 °C. With this study, the researchers emphasized that spray cooling is an effective method for PV panel cooling. Agyekum et al. [18] showed that cooling PV panels and lowering the temperature by 23 °C increased the output power by 30%. While the average efficiency was 12.83% without cooling, this rate was realized as 14.36% when the temperature was lowered. Abdolzadeh and Ameri [19] conducted an experimental study to improve the performance of photovoltaic water pumping system with water spray. As a result, they increased PV cell efficiency by 3.26%, subsystem efficiency by 1.4% and total efficiency by 1.35%. Raju et al. [20] developed a 3D CFD model to determine the optimum amount of water for a water spray cooled PV panel. As a result, they determined the optimum flow rate as 170 l/s. At this flow rate, they obtained PV panel power output as 40.25 W and panel electrical efficiency as 15.73%.

Ethanol is a promising type of additive due to its potential to improve atomization performance with low surface tension and contact angle compared to water [21], [22]. Yin et al. [23] experimentally tested the effect of spray cooling on heat transfer using both water and a 4% ethanol-water mixture as the working fluid. They showed that for a fixed nozzle, the particle mean diameter was smaller for the 4% ethanol-water mixture. As a result, they showed that the heat transfer efficiency of 4% ethanol-water mixture is superior to water. Liu et al. [24] carried out an experimental study to determine the effect of mixing different alcohols with water at different ratios on heat transfer. The results showed that adding a small amount of alcohol to water can significantly reduce the surface tension and contact angle.

As an emerging alternative cooling technology, electrospray cooling has superior advantages such as stable droplet diameter, flexible installation and low power requirements [25]. The most important advantage of this method is that the spray particles produced by electrospray are smaller than droplets produced by mechanical atomizers. In addition, homogeneous droplet production, directivity of electrically charged droplets, and easy application are among the other advantages of electrospray cooling [26]–[28].

In electrospray cooling, an electric voltage is generated between a high-temperature metal or metal-coated surface and a stainless steel nozzle. At the exit of the nozzle, the liquid with low surface tension and high dielectric constant succumbs to the electric voltage and atomization takes place [29]. In this way, the liquid particles hitting the hot surface realize high heat transfer on the surface and cause cooling by removing heat [30]. The electrospray cooling mechanism is given in **Figure 1**.

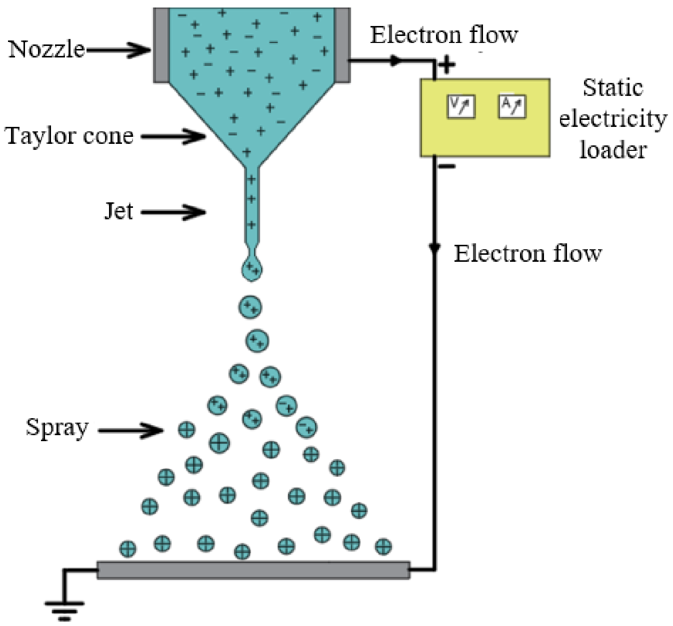

Figure 1. *Schematic view of electrospray cooling [31]*

The literature review shows that there are different parameters affecting the performance of PV panels. Among these parameters, it is stated that temperature is one of the important parameters affecting PV panel efficiency. It is stated that different cooling methods are used to minimize the effect of temperature in PV panels and to provide thermal control, and cooling with water spray is a very effective method.

Although electrospray cooling is an effective method that has been used/researched in the literature in recent years, especially for cooling heat sinks, it has not been used for cooling PV panels. In this study, the change in power output and cooling time of the PV panel by electrospray cooling using different fluids (water, ethanol and water - ethanol) and fluid flow rates (50-80-110 ml/h) were investigated.

II. MATERIALS and METHODS

In this study, an experimental setup using an electrospray cooling system was established to reduce the operating temperature of the PV panel and increase its efficiency and electrical power output. A schematic view of the experimental setup is given in **Figure 2**. The cell type of the PV panel is polycrystalline and its properties under standard test conditions (T=25 °C and R=1000 W/m^2) are presented in **Table 1**. As shown in **Figure 3**, the PV panel with dimensions of 125×135×2 mm is cooled by electrospray. The PV panel is placed at an angle of 90° to the horizontal to avoid liquid accumulation on the cooling surface and to ensure that the rays from the light source are vertical to the surface. The electrospray cooling nozzle is aligned with the geometric center of the PV panel. The distance between the nozzle and the PV panel is 70 mm. The nozzle is made of stainless steel and has a diameter of 25 G (d_i=0.25 mm).

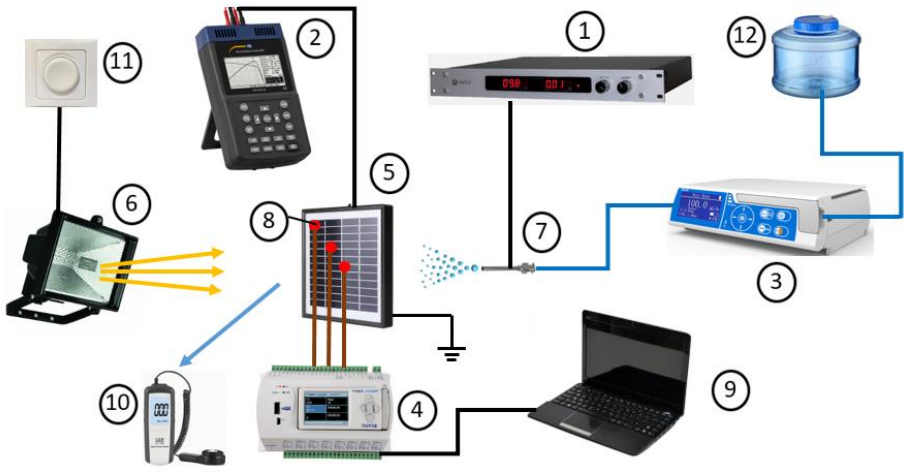

Figure 2. *Schematic diagram of the experimental setup (1- High Voltage Power Supply, 2- Solar Module Analyzer, 3- Infusion Pump, 4- Datalogger, 5- PV Panel, 6- Halogen Projector, 7- Nozzle, 8- Thermocouple, 9- Computer, 10- Solar Power Meter, 11- Dimmer, 12- Reservoir)*

Table 1. *Characteristics of the PV panel*

Electrical Characteristics	
Maximum Power Rating (P_{max})	530.8 mW
Open Circuit Voltage (V_{oc})	14.54 V
Short Circuit Current (I_{sc})	51 mA
Voltage at Maximum Power (V_{mp})	13.27 V
Current at Maximum Power (I_{mp})	40 mA
Nominal Operating Cell Temperature	25 °C
Physical Characteristics	
Cell Type	Polycrystalline
Cell Size	25×8.5 mm
Cell Number	48
Module Dimension (L×W×T)	135×125×2 mm

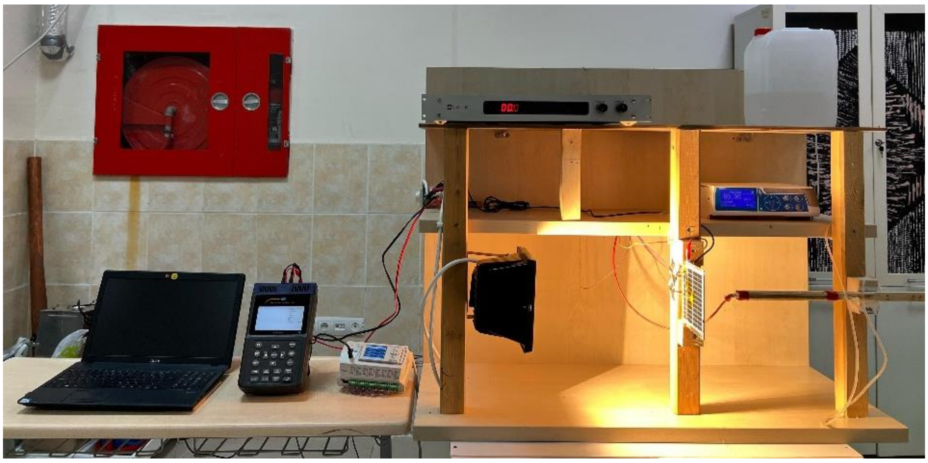

Figure 3. *View of the experimental setup*

In the experiments carried out under laboratory conditions, a 500 W halogen lamp projector was used to create artificial sunlight. The distance between the projector and the PV panel is 350 mm. The irradiance was adjusted with a dimmer and measured with Cem DT-1307 solar power meter. Water, ethanol and a mixture of water - ethanol (50%-50%) were used as coolant fluid. In the experiments, an infusion pump (Hedy 15) was used to deliver coolant fluid at a constant flow rate to the stainless steel nozzle. The coolant fluid was atomized by a high voltage power supply (Nanoliz NL-K25). The experiments were carried out under a constant voltage of 20 kV. In the experiments, multijet electrospray mode was observed at all flow rates. The electrospray view is given in **Figure 4**.

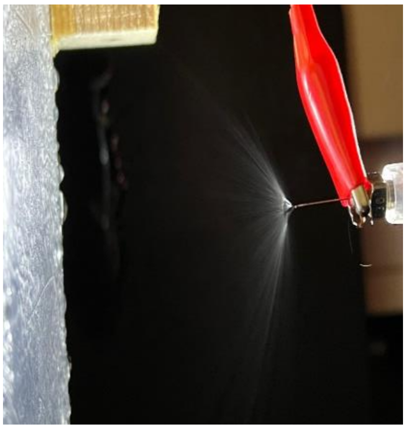

Figure 4. *Electrospray generation*

In order for the electrically charged coolant fluid particles to discharge their charges and electrospray formation to occur, the back surface of the PV panel was covered with aluminum foil and grounding connection was made. Heat conduction paste was applied between the back surface of the PV panel and the aluminum foil to prevent contact resistance. Since the thickness of the aluminum foil is too low (0.016 mm), the thermal resistance caused by the aluminum foil is neglected. A solar module analyzer (PCE-PVA 100) was used to record the voltage, current and power generated by the PV panel over time.

In the experiments, the average temperature values on the PV panel and the ambient temperature were measured with T-type thermocouples. Three thermocouples (T1, T2 and T3) were placed on the PV panel at equal intervals starting from the center to the corner point of the panel (**Figure 5**). The thermocouples were fixed to the front surface of the panel with thermal tapes in order not to be affected by the electrospray and the temperature values were read. The temperature data were transferred to the computer using a data logger (Novus-Fieldlogger). PV panel temperature values were determined by averaging the transferred temperature values.

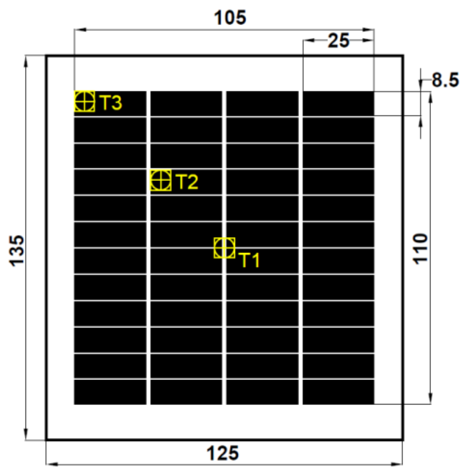

Figure 5. *PV panel dimensions and placement of thermocouples*

The experiments were carried out at 1000 W/m^2 irradiance and coolant fluid flow rates of 50-80-110 ml/h. Then, the voltage-current values were determined and the power-temperature graph was obtained. The total input power to the PV panel was calculated as follows (**Equation 1**).

$$P_g = R.A \tag{1}$$

Where P_g (W) is the amount of radiation acting on the panel, R (W/m^2) is the solar radiation measured at the PV surface and A (m^2) is the PV panel surface area. The maximum output electrical power is calculated as follows (**Equation 2**):

$$P_{maks} = I_{opt}.V_{opt} \tag{2}$$

Where P_{maks} is the maximum power, I_{opt} (A) is the current at the maximum power point and V_{opt} (V) is the optimum voltage value.

Uncertainty analysis

In the experimental system, parameter values for voltage-current, radiation and temperature were measured. Uncertainty analysis was performed for the results obtained from the measurements of these parameters. Uncertainty analysis provides information about the reliability of the experimental system and reveals the parameter that causes the highest deviation [32]. The sensitivity and uncertainties of the equipment in the experimental system are given in **Table 2**.

Table 2. *Accuracy and uncertainty of measurement equipment*

Equipment	Accuracy (%)	Uncertainty
High Voltage Power Supply	±0.01	±5 mV
	±0.2	±2 mA
Solar Module Analyzer	±1	±0.1 V
	±1	±9 mA
Infusion Pump	±2	±0.2 ml
Datalogger	±0.2	±1 °C
Solar Power Meter	±5	±10 W/m^2

At the result of the experimental study, the uncertainty analysis was performed with **Equation 3**.

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \ldots\ldots\ldots\ldots + \left(\frac{\partial R}{\partial x_n} w_n\right)^2\right]^{0,5} \tag{3}$$

Where w_R is the system uncertainty, $(x_1, x_2, \ldots\ldots, x_n)$ are the independent variables, R is the function of independent variables, $(w_1, w_2, \ldots\ldots, w_n)$ is the uncertainty of independent variables [33]. Using the above mentioned equation, the experimental uncertainty is calculated as P_{maks} 0.25% for the panel power output.

III. RESULTS and DISCUSSION

In this study, the cooling performance of a photovoltaic panel by electrospray is experimentally investigated. The experiments were conducted at 1000 W/m^2 irradiance, 25 G (d_i=0.25 mm) nozzle diameter, 70 mm nozzle-to-PV panel distance and 20 kV nozzle-to-PV panel voltage. These parameters were chosen for the condition where the highest contact area of the spray particles occurs on the PV panel surface. Water, ethanol and a mixture of water - ethanol (50%-50%) were used as coolant fluid.

The coolant fluids were atomized at flow rates of 50-80-110 ml/h and sprayed on the panel surface. The experiments were carried out in the laboratory environment where the coolant fluid temperature and ambient temperature were stable and the same.

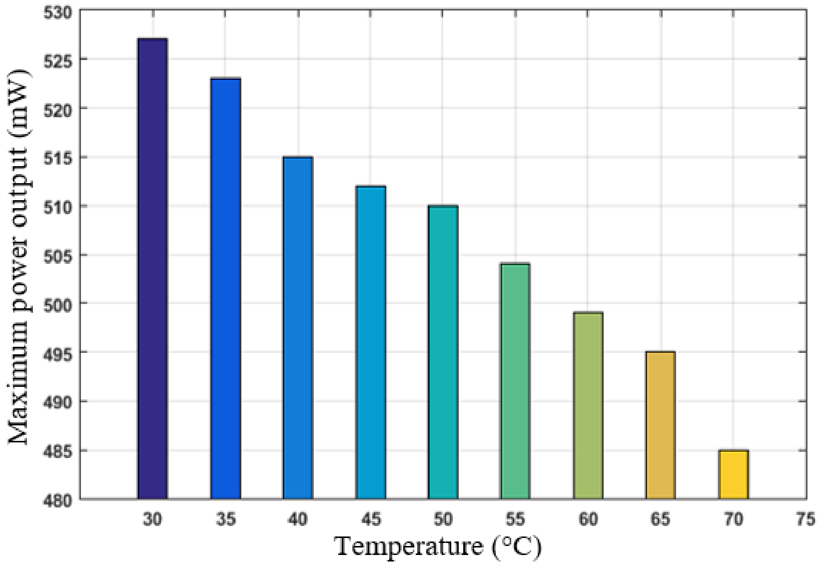

Figure 6. *Variation of PV panel power output with temperature at 1000 W/m^2 irradiance*

The variation of the electrical power output of the PV panel with temperature at 1000 W/m^2 irradiance is given in **Figure 6**. The experiments were started at the temperature value where the panel and ambient temperature were the same and completed at the maximum temperature value that can be reached with the irradiation applied to the PV panel. **Figure 6** shows that the PV panel power output decreases with increasing temperature. There is approximately 7.4% difference between the power output obtained from the panel with a surface temperature of 30 °C and the panel with a surface temperature of 70 °C. In order to increase the power output by decreasing the surface temperature of the PV panel used in the experiments, a mixture of water, ethanol and water - ethanol was atomized by electrospray and sprayed on the PV panel surface. The time dependent variation of PV panel temperature at different flow rates is presented in **Figures 7-8-9**.

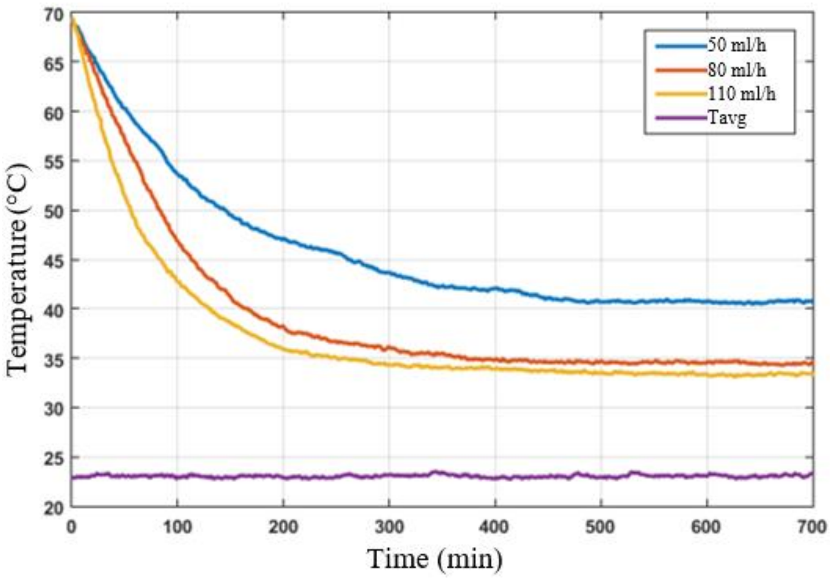

Figure 7. *Time dependent variation of the temperature of the PV panel cooled with water at different flow rates*

The temperature change-time graph obtained by cooling the PV panel with water spray at a flow rate of 50-80-110 ml/h is given in **Figure 7**. At 1000 W/m^2 irradiation, the PV panel temperature reached a maximum of 70 °C. This temperature was reduced to approximately 40.4 °C at 50 ml/h flow rate, 34.3 °C at 80 ml/h flow rate and 33.1 °C at 110 ml/h flow rate. The temperatures stabilized in about 500 seconds at 50 ml/h flow rate and in about 400 seconds at 80 and 110 ml/h flow rates. In the experiments, the ambient temperature was measured as approximately 23 °C. In the experiments with water, it was observed that the PV panel surface temperature stabilized earlier with increasing flow rate and similar surface temperatures were obtained at 80-110 ml/h flow rates.

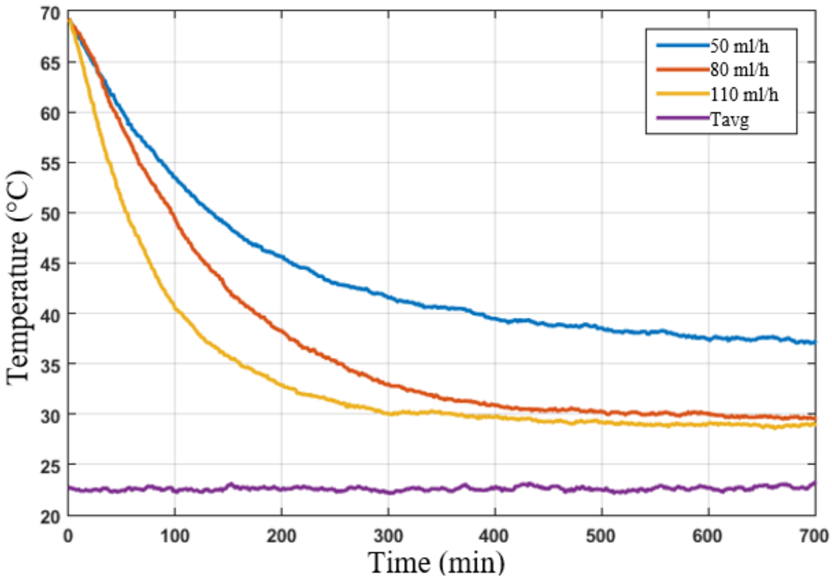

Figure 8. *Time dependent variation of the temperature of the PV panel cooled with ethanol at different flow rates*

Figure 8 shows the temperature change-time graph obtained by cooling the PV panel with ethanol. When the graph is examined, the PV panel temperature, which reached a maximum of 70 °C, was reduced to 37 °C at 50 ml/h flow rate, 29.5 °C at 80 ml/h flow rate and approximately 28.6 °C at 110 ml/h flow rate. The temperatures stabilized in about 600 seconds at 50 ml/h flow rate and in about 400 seconds at 80 and 110 ml/h flow rates. The ambient temperature in the experiments was measured as approximately 23 °C. In the experiments with ethanol, it was observed that the PV panel surface temperature stabilized earlier with increasing flow rate and similar surface temperatures were obtained at 80-110 ml/h flow rates.

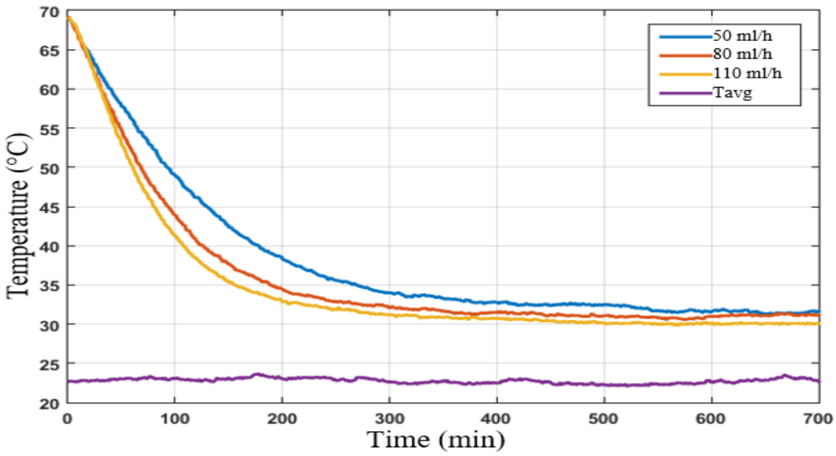

Figure 9. *Time dependent variation of the temperature of the PV panel cooled with water - ethanol mixture at different flow rates*

Figure 9 shows the temperature-time variation of the panel cooled with water - ethanol mixture. With the water - ethanol mixture, the panel temperature of 70 °C was reduced to 31.1 °C at 50 ml/h flow rate, 30.5 °C at 80 ml/h flow rate and approximately 29.8 °C at 110 ml/h flow rate. The temperatures stabilized in about 600 seconds at 50 ml/h flow rate and in about 500 seconds at 80 and 110 ml/h flow rates. The ambient temperature was measured as approximately 23 °C in the experiments. When the temperature-time curves were analyzed, it was observed that the temperature decreased more rapidly at higher flow rates, but after the panel temperature stabilized, approximately the same temperature value was obtained at all three flow rates.

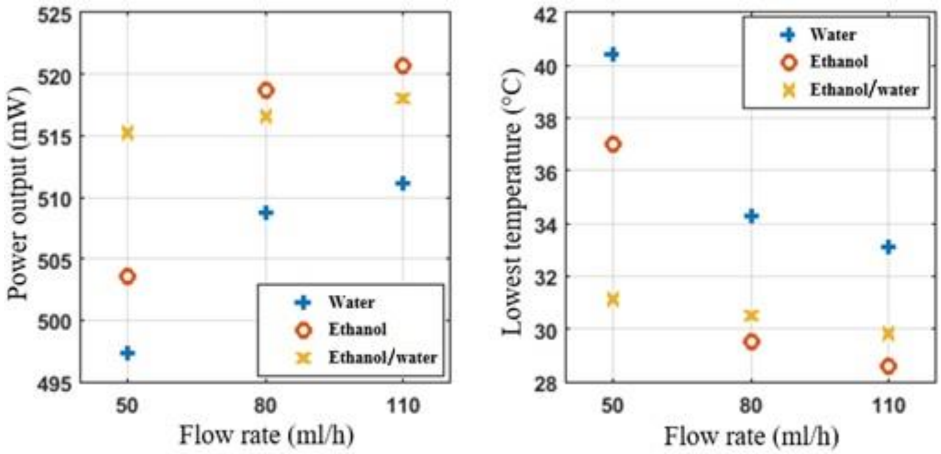

Figure 10. *Variation of power output and lowest temperatures obtained for different coolant fluids according to flow rate*

At 1000 W/m2 irradiation, the lowest panel temperatures and the panel electrical power output obtained by cooling the PV panel, which reached the maximum temperature, with different fluids and flow rates are given in **Figure 10**. When the graphs are analyzed, it is seen that approximately the same temperature values are achieved for all coolant fluids at 80 and 110 ml/h flow rates. The reason for this situation is that the heat flux produced on the surface due to the radiation affecting the PV panel surface is constant. While the heat flux removed from the surface increases up to the 80 ml/h refrigerant flow rate value, the amount of heat flux removed after the 80 ml/h flow rate is minimized. The amount of heat flux removed from the surface did not change and the PV panel temperature reached the lowest and stable value. It was determined that ethanol and water - ethanol mixture showed a more effective cooling performance than water, especially at 80 and 110 ml/h flow rates. It is seen that the water - ethanol mixture achieves a temperature of approximately 30 °C at all flow rates and provides effective cooling. Depending on the temperature variations, the highest power output from the PV panel was obtained with 100 ml/h flow rate and ethanol (~520 mW), while the lowest power output (~497 mW) was obtained with 50 ml/h flow rate and water. At the highest flow rate, ethanol reduced the panel temperature by about 59%, while water reduced it by about 52%. At the lowest flow rate, water - ethanol mixture reduced the PV panel temperature by 55%, while water reduced it by about 42%. Due to the reduction of panel temperatures, about 6.8% more electrical power output was obtained with ethanol and 5.1% more with water at the highest flow rate compared to the uncooled case. At the lowest flow rate compared to the uncooled case, about 6.2% more electrical power output was obtained with water - ethanol mixture and 2.5% more with water.

IV. CONCLUSION

In this study, the cooling performance of different flow rates and fluids on PV panels by electrospray atomization was investigated. The experiments were carried out at 1000 W/m^2 irradiance, 25 G (d_i=0.25 mm) nozzle diameter, 70 mm nozzle to PV panel distance and 20 kV nozzle to PV panel voltage. Water, ethanol and water - ethanol (50%-50%) mixtures were atomized at 50-80-110 ml/h flow rates and sprayed on the panel surface. The following results were obtained from the experimental study.

- With the increase in PV panel temperature (from 30 °C to 70 °C), the electrical power output of the PV panel decreased and a difference of approximately 7.4% was observed.
- In the experiments with water, the lowest PV panel surface temperature was obtained at a flow rate of 110 ml/h (33.1 °C) and it took about 400 seconds for the PV panel to reach a stable temperature.
- In the experiments with ethanol, the lowest PV panel surface temperature was obtained at a flow rate of 110 ml/h (28.6 °C) as in the experiments with water and it took about 400 seconds for the PV panel to reach the stable temperature.
- In the experiments with water - ethanol (50%-50%) mixture, the lowest PV panel surface temperature was 29.8 °C at a flow rate of 110 ml/h and it took about 500 seconds for the PV panel to reach the stable temperature.
- The ethanol and water - ethanol mixture had a more effective cooling performance than water at 110 ml/h flow rate. This is due to the lower evaporation temperature of ethanol particles hitting the PV panel surface. Since ethanol particles remove heat from the panel surface by evaporation as well as convection, higher heat transfer was realized from the PV panel surface. In PV panels, the panel surface temperature range caused by the effect of solar radiation is low. For this reason, ethanol, which has a lower evaporation temperature, made a positive contribution to the removal of heat from the panel. In systems operating at higher temperatures, the effect of ethanol will be quite low compared to water, which has a higher enthalpy of vaporization.
- At a flow rate of 110 ml/h, ethanol reduced the panel temperature by 59% and water by 52%. Accordingly, approximately 6.8% more electrical power output was obtained with the ethanol-cooled panel and approximately 5.1% more electrical power output was obtained with the water-cooled panel.

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