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A new approach to cooling photovoltaic panels: Electrospray cooling

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A R T I C L E I N F O

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A B S T R A C T

In recent years, rise in carbon emissions has increased the focus on renewable energy. Solar energy systems are widely used for energy production due to their easy applicability and being an unlimited resource. There are factors affecting the efficiency of these systems. One of the most prominent of these is temperature. Enabling thermal control of the solar panels not only increases their electrical efficiency but also extends their economic life. In this study, electrospray cooling, which is not found to be used in the literature for cooling PV panels, was analyzed. Electrospray cooling performance in PV panels was examined for different flow rates and irradiance values using water as the coolant fluid. As a result, it was determined that the optimum flow rate was 80 ml/h water flow rate, and the panel temperature at this flow rate was reduced from approximately 77 °C–32.2 °C at 1200 W/m^2 radiation. The output power obtained increased by 56.6 % at optimum flow rate and radiation. Compared to the studies in which PV panels were cooled by spray, it was found that electrospray requires approximately 1.5–137 times less water.

1. Introduction

The technological development and the increase in human population have led to a high demand for energy. In today's world, fossil fuels are potently used to meet the requirement for energy. However, because of the high CO_2 emissions of fossil fuels, they cause irreversible damage to nature [1,2]. Thus, renewable energy sources, which contribute to reducing carbon footprint and are eco-friendly, have attracted more attention in recent years. Renewable energy sources are divided into categories such as solar, wind, geothermal, hydropower, and biomass [3].

Among renewable energy sources, solar energy stands out due to its being cheap, eco-friendly, easily applicable and unlimited energy source [4,5]. PV panels have a huge capacity to meet requirement in energy of a growing population [4,6]. Despite all these advantages, there are some factors that affect the performance of PV panels. The factors mentioned are provided in Table 1.

Temperature is one of the main factors affecting the efficiency of the PV panel [13]. When the solar rays reach the PV panel surface, the thermal energy is converted into electrical energy. While some of these rays are used as useful energy, some are converted into waste energy. This waste energy causes the temperature of the PV panel cells to increase, so, it reduces the efficiency of the PV panel [14].

The following **Eq. (1)** is used to analyze the effect of temperature changes on PV panel performance [15].

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$$I = I_L - I_S\left[e\left[\frac{q(V+IR_S)}{AkT}\right]-1\right]-\frac{V+IR_S}{R_{Sh}} \tag{1}$$

In this equation, I_L is the photo-generated current, I_S is the reverse saturation current, R_S is the series resistance, R_{Sh} is the shunt resistance, and the other parameters have their standard meanings. When the equation is analyzed, it is seen that the reverse saturation current is exponentially affected by the increase in temperature.

Although the performance of PV panels is optimized at 25 °C, it can be said that the temperature of the PV panel cells in open air shows ideal performance at about 45 °C. At this temperature, even though the photo-generated current produced thermally increases slightly with the decrease in the bandwidth of the cell material, the PV panel efficiency goes down with the decrease in voltage (Fig. 1) [15]. With each 1 °C increase in temperature of PV panel cells, there occurs approximately 0.4 % of the decrease in panel efficiency [16].

On the other hand, overheat on the PV panel causes thermal stress. Thus, the lifetime of the panel is reduced [18]. There have been used many cooling methods in the literature to reduce the temperature of PV panels and to provide thermal control. In this way, the PV panel is kept at the ideal operating temperature. Also, the maximum efficiency of the PV panel is obtained, and its lifetime is increased.

1.1. Cooling of PV panels

By cooling photovoltaic panels, there is obtained stable/high power output from the panel. In addition, some studies have indicated that the lifetime of panel cells can be increased by up to fifty years by cooling the PV panels [18,19]. In the literature, there are many methods used for cooling photovoltaic panels. These methods can be divided into three categories: passive methods [20–26], active methods [27–32] and combined methods [33–35]. The PV cooling methods are given in Fig. 2 [36].

Reducing the amount of water used for cooling PV panels is of great importance because of the increasing need for clean water in the world out of environmental concerns and water scarcity reaching critical levels [37]. For the solution of this problem, it is important to use of hygroscopic materials, reverse osmosis, flash distillation as well as the water-saving methods [38,39]. In this study, it is aimed to increase electrical efficiency by cooling PV panels and saving water by using less water flow rate.

Hadipour et al. stated that air and water are utilized as coolant fluids in most of the methods used for cooling PV panels. They stated that air cooling is less costly than water cooling, but the cooling capacity of water is higher than the cooling capacity of air [40]. PV cooling with water spray is one of the active cooling methods that has been studied in the literature. Bevilacqua et al. suggested a new thermal model in which the PV panel is cooled down by spraying from its back surface. As a result, they determined that during the hours when the radiation was most intense, the electrical power increased by 7.8 %, and the average cell temperature decreased by 28.2 % [41]. In their experimental study, Nižetić et al. achieved a 16.3 % of increase in electrical power output and a 14.1 % increase in PV panel efficiency through the spray cooling. They reduced the temperature from 54 °C to 24 °C by cooling the PV panel from both the front and the back. In this study, the researchers emphasized that spray cooling is an effective method for PV panel cooling [42]. Abdolzadeh and Ameri conducted an experimental study to improve the performance of a photovoltaic water pumping system through the water spray. As a result, they increased PV cell efficiency by 3.26 %, subsystem efficiency by 1.4 %, and total efficiency by 1.35 % [43]. Raju et al. developed a 3D CFD model to determine the optimum amount of water for a spray-cooled PV panel. As a result, they determined 170 l/s of the optimum flow rate. At this flow rate, they obtained 40.25 W of PV panel power output and 15.73 % of panel electrical efficiency [44]. Yang et al. designed a spray cooling system integrated into the geothermal energy heat exchanger to reduce the decrease in efficiency of the PV panel. As a result, they stated that a 14.3 % increase in efficiency could be achieved with this system, and material depreciation could occur in 8.7 years [45]. In their experimental study, Nateqi et al. examined the parameters affecting the PV panel performance in spray cooling. They found that the PV panel efficiency increased to 19.78 % at a spray angle of 15° and the PV panel temperature decreased from 64 °C to 24 °C. They also obtained 25.86 % of electrical power output at the lowest nozzle-panel distance (10 cm). At a frequency of 0.2 Hz, they reduced water consumption by half [46].

Table 1
The factors affecting the performance of PV panels.

Factors	Explanation
Material of PV Panels [7]	The properties of the silicon material used for the production of PV panels directly affect electric power generation. With the development of crystalline silicon technology, the goal of mono-crystalline PV panel efficiency has been set at 25 % by 2030.
Solar Radiation [8]	In the PV panel, solar radiation is directed perpendicular to the panel surface. For this reason, the PV panel angle and the geography where the PV panel is installed are vital for the panel efficiency.
Dust Accumulation [9]	Dust accumulated on the PV panel reduces the solar radiation transmittance of the panel surface, and thus, reduces the panel efficiency.
Shading [10]	Since PV panel cells are connected in series, in the case of shading, the entire panel is negatively affected by electricity production. If there occurs 25 % shading formation in a monocrystalline PV panel, it causes an approximately 40 % decrease in the power output of the panel.
Humidity [11]	High relative humidity causes the formation of a vapor layer on the PV panel. Due to this layer, some of the rays coming from the sun are absorbed by this layer and some of them are reflected. For this reason, there is observed a 15 %–30 % decrease in the efficiency of the PV panel.
Temperature [12]	Because of their physical properties, the efficiency of semiconductors decreases with increasing temperature. The reason is that the open circuit voltage decreases linearly with increasing temperature.

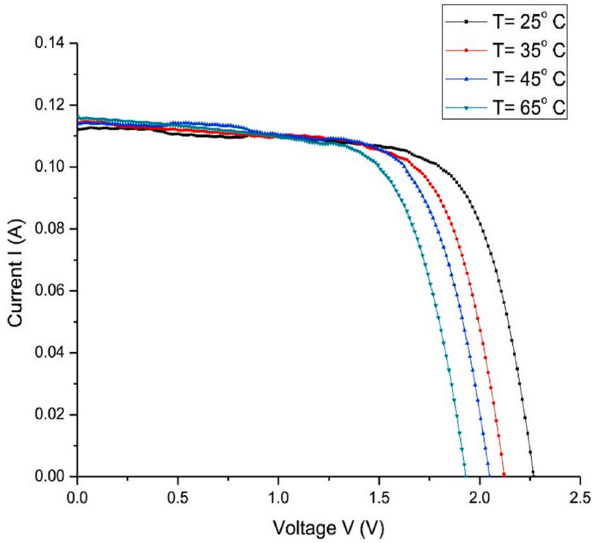

Fig. 1. Variation of PV panel V–I values with increasing temperature [17].

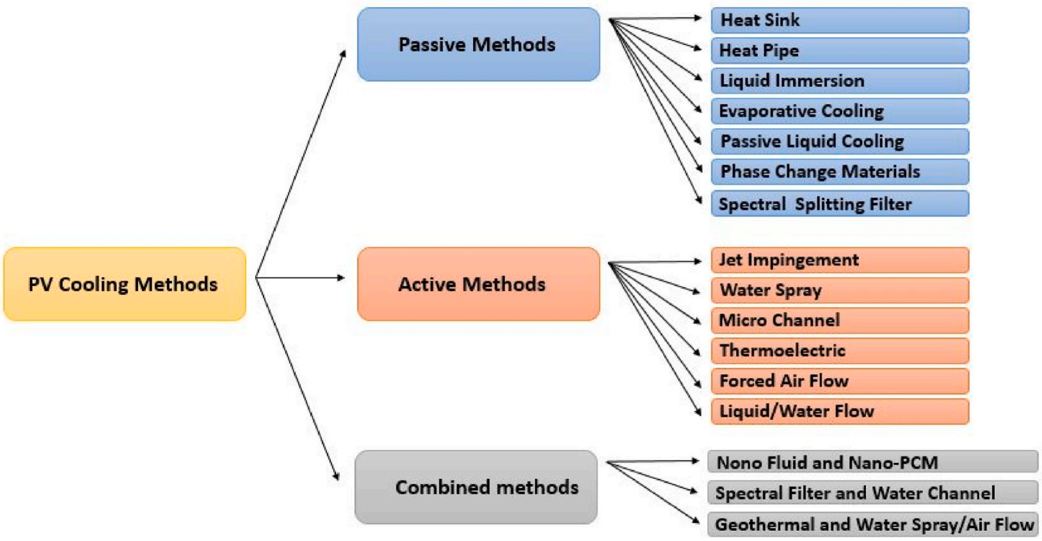

Fig. 2. The PV cooling methods.

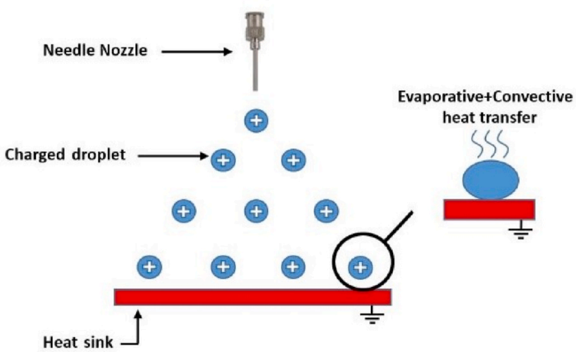

Fig. 3. Schematic diagram of electrospray cooling [49].

1.2. Electrospray cooling

In recent years, electrospray cooling has started to find its place in studies because it has some advantages over spray cooling. The most important advantage of this method is that the spray particles formed by electrospray are smaller than mechanical atomizers. And other advantages of electrospray cooling are homogeneous droplet production, directivity of electrically charged droplets, easy application and lower energy consumption compared to spray cooling [47–49]. Therefore, electrospray is an effective method that achieves high heat transfer with a low coolant flow rate.

In electrospray cooling, there is generated an electric voltage 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 submits to the electrical voltage, and atomization takes place [50]. In this way, the liquid particles hitting the hot surface cause cooling by removing heat through the high heat transfer on the surface [51]. Electrospray cooling mechanism is given in Fig. 3.

1.3. Originality and contribution to the literature of the article

It has been seen after reviewing the literature that there are different parameters affecting the performance of PV panels. Among these parameters, it is stated that the temperature is one of the most important parameters affecting the PV panel efficiency. It is, thus, indicated that different cooling methods are used to minimize the effect of the temperature on the PV panels, and to provide thermal control; for this, it is stated that cooling with water spray is a very effective method.

In this study, the cooling performance of electrospray, which has never been used before in the cooling of photovoltaic panels, was analyzed. 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 through the electrospray cooling were analyzed. Because, in addition to the thermal control of the PV panels, the amount of water required for cooling is also very important, the optimum amount of water consumed was determined. Finally, the amount of water required for electrospray cooling of the PV panel was compared to the studies in the literature, in which the spray cooling method was used for cooling the PV panels.

2. Materials and methods

In this study, there was established an experimental setup using an electrospray cooling system to reduce the operating temperature of the PV panel and to increase its efficiency and electrical power output. A schematic diagram of the experimental setup is provided in Fig. 4. The cell type of the PV panel is polycrystalline and its properties under STC ($T = 25$ °C, $R = 1000$ W/m^2 and $AM = 1.5$) are presented in Table 2. As shown in Fig. 5, the cooling of the 125 × 135 × 2 mm PV panel is provided through the electrospray. The PV panel is placed at an angle of 90° to the horizontal so that no liquid accumulates on the cooling surface and the rays from the light source are perpendicular to the surface. The nozzle in the electrospray cooling is placed in alignment with the geometric center of the PV panel. The distance between the nozzle and the PV panel is 60 mm. The nozzle is made of stainless steel and has a diameter of 30 G ($d_i = 0.15$ mm).

During the experiments carried out in a laboratory environment, a 500 W halogen lamp projector was used to generate artificial sunlight. The distance between the projector and the PV panel was 350 mm. The radiation intensity was adjusted with a dimmer and measured by a Cem DT-1307 solar power meter. In the study, water was utilized as the coolant fluid. In this experiment, an infusion pump (Hedy 15) was used to deliver refrigerant to the stainless steel nozzle at a constant flow rate. The water was atomized into

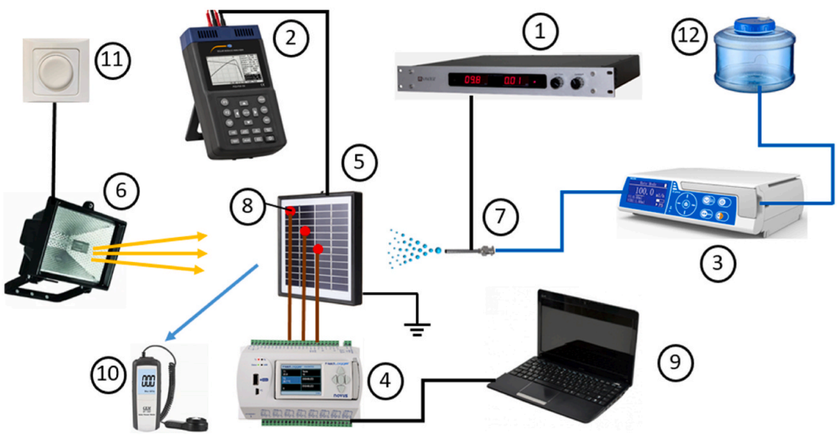

Fig. 4. Schematic diagram of the experimental setup.
(**1**-High Voltage Power Supply, **2**-Solar Module Analyzer, **3**-Infusion Pump, **4**-Datalogger, **5**-PV Panel, **6**-Halogen Projector, **7**-Nozzle,**8**-Thermocouple, **9**-Computer, **10**-Solar Power Meter, **11**-Dimmer,**12**-Reservoir).

Table 2
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

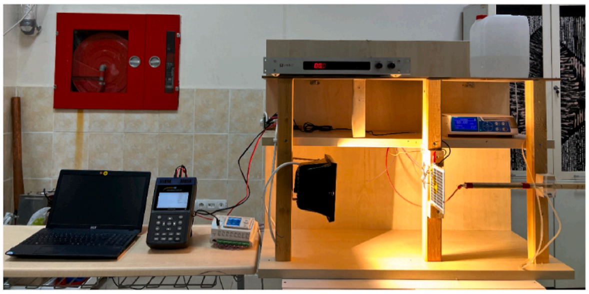

Fig. 5. Design of the experimental setup.

particles by a high voltage power supply (Nanoliz NL-K25). The picture of the electrospray created is given in Fig. 6.

In order for the electrically charged water particles to discharge and for the formation of electrospray, the back surface of the PV panel was covered with aluminum foil, and its 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. Because the aluminum foil has a very low thickness (0.016 mm), the thermal resistance caused by the aluminum foil is negligible. A solar module analyzer (PCE-PVA 100) was used to record the voltage, current, and power values generated by the PV panel over time.

In the experiments, the average temperature values on the PV panel and the ambient temperature were measured by T-type thermocouples. Three thermocouples (T1, T2, and T3) were used on the PV panel, starting from the center and equally spaced from the corner point of the panel (Fig. 7). 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 observed. Temperature data were transferred to the computer using a data logger (Novus-Fieldlogger). Temperature values of the PV panel were determined by averaging the transferred temperature

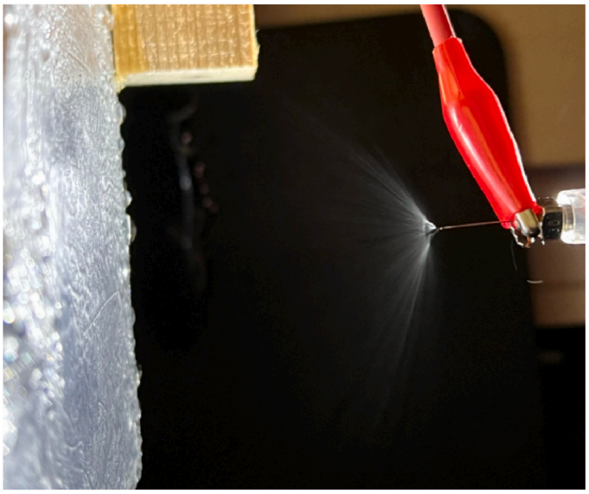

Fig. 6. Electrospray formation.

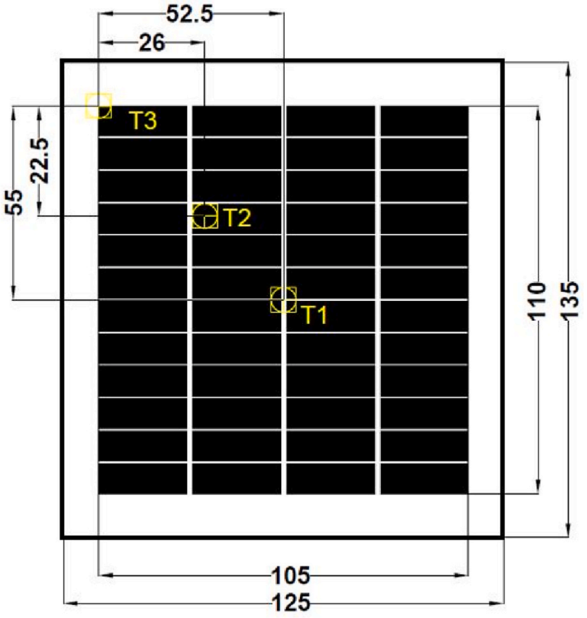

Fig. 7. PV panel dimensions and thermocouple placement.

values.

The experiments were carried out for 800, 1000, and 1200 W/m^2 radiation intensity, 20 kV electrical voltage, and 40-60-80-100-120 ml/h coolant fluid flow rates. After that, the power-temperature graph was obtained by determining the voltage-current values.

The total input power to the PV panel is calculated as follows (**Eq. (2)**).

$$P_{in} = R.A \tag{2}$$

Here, P_{in} (W) is the amount of radiation affecting the panel, R (W/m^2) is the solar radiation measured on the PV surface, and A (m^2) is the PV panel surface area. The maximum output electrical power was calculated as follows (**Eq. (3)**).

$$P_{max} = I_{opt}.V_{opt} \tag{3}$$

Herein, P_{max} is the maximum power, I_{opt} (A) is the current at the maximum power point, and V_{opt} (V) is the optimum voltage value. The PV panel electrical efficiency (η_{elec}) was estimated as follows **(Eq. (4))**.

$$\eta_{elec} = \frac{P_{max}}{P_{in}} \tag{4}$$

2.1. Uncertainty analysis

The parameters measured in the experimental system are voltage-current, radiation, and temperature values. Uncertainty analysis was also 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 [52]. The sensitivities and uncertainties of the equipment in the experimental system are given in Table 3.

As a result of the experimental study, uncertainty analysis was performed with **Eq. (5)**.

Table 3
Accuracy and uncertainty of the measuring 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

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

In the equation, w_R is the system uncertainty, $(x_1, x_2, \dots, x_n)$ is the independent variables, R is the function of the independent variables, $(w_1, w_2, \dots, w_n)$ is the uncertainty of the independent variables [53]. Using the equation mentioned above, the experimental uncertainty is calculated as P_{max} 0.25 % and η_{elec} 2.3 % for the panel power output.

3. Results and discussions

In the experimental study, the performance of the PV panel with electrospray cooling was analyzed. The experiments were carried out at 800-1000-1200 W/m^2 radiation, 40-60-80-100-120 ml/h flow rate, 30 G (d_i = 0.15 mm) nozzle diameter, 20 kV voltage, and 60 mm nozzle-PV panel distance. Water was used as the coolant fluid. The parameters determined to form the electrospray were such that the PV panel surface used in the experiments could be completely sprayed. The experiments were carried out in a laboratory environment, where the cooling water temperature is approximately constant and steady-state with the ambient temperature. Cooling water temperature and ambient temperature were measured and recorded with thermocouples.

As seen in Fig. 8, the experiments were started at the same temperature of the panel and the ambient temperature, and completed at the maximum temperature value that can be reached as a result of the applied radiation. In this way, the effect of temperature on the performance of the PV panel was examined. When the maximum power output-temperature graphs obtained for different radiations were analyzed, it was detected that the power output decreased as the temperature increased for all radiation values. The power output variation between the lowest and the highest temperature occurred at 1200 W/m^2 irradiance. The maximum power output variation by the increase in the panel temperature was about 6 %, 9 %, and 11 % for 800-1000-1200 W/m^2 irradiances, respectively.

The graphs in Fig. 9 were obtained by electrospray cooling after the PV panel reached the highest temperature value at 800-1000-1200 W/m^2 irradiations, using flow rates of 40-60-80-100-120 ml/h. The experiments were carried out at approximately 21 °C of an ambient temperature. At 800 W/m^2 irradiance, the PV panel temperature reached to 65 °C at maximum. This temperature was reduced to 29.3 °C at a 40 ml/h flow rate, 28.5 °C at a 60 ml/h flow rate, and approximately 26.5 °C at 80-100-120 ml/h flow rates. At all flow rates, the temperature stabilized in about 300 s (Fig. 9a and d). At 1000 W/m^2 irradiation, the PV panel temperature reached to 70 °C at maximum. This temperature was reduced to 34.6 °C at a 40 ml/h flow rate, 30.2 °C at a 60 ml/h flow rate, and approximately 27.6 °C at 80-100-120 ml/h flow rates. The temperatures stabilized in 540 s at a 40 ml/h flow rate, 420 s at a 60 ml/h flow rate, and approximately 300 s at 80-100-120 ml/h flow rates (Fig. 9b and d). At 1200 W/m^2 irradiation, the PV panel temperature reached 77 °C at maximum. This temperature was reduced to about 36.1 °C at a 40 ml/h flow rate, about 34.8 °C at a 60 ml/h flow rate, and about 32.2 °C at 80-100-120 ml/h flow rate. The temperatures stabilized in 540 s at a 40 ml/h flow rate, 480 s at a 60 ml/h flow rate, and approximately 300 s at 80-100-120 ml/h flow rates (Fig. 9c and d). When Fig. 9 is analyzed, it is detected that the flow rate increase after 80 ml/h flow rate for all irradiation values did not cause a visible change in temperature alteration and 80 ml/h of flow rate was the optimum cooling flow rate. At 80 ml/h of flow rate, the decrease in the temperature rate was determined as 0.13, 0.14, and 0.15 °C/s for 800-1000-1200 W/m^2 irradiances, respectively.

Fig. 10 shows the power output values for the lowest temperatures obtained after cooling the PV panel. It is seen that the highest power output values are obtained at 80-100-120 ml/h of flow rates. When the power outputs obtained for 80-100-120 ml/h of flow rates at all irradiances are analyzed, it is seen that they were very close to each other. Approximately 426, 529, and 667 mW of power output was obtained at 800-1000-1200 W/m^2 of irradiances for 80-100-120 ml/h of flow rates, respectively. It is also seen in Fig. 10 that the flow rates above 80 ml/h did not cause a significant power increase. The output power obtained increased by 56.6 % at 1200 W/m^2 and 24.2 % at 1000 W/m^2 compared to 800 W/m^2 radiation at optimum flow rate.

The variation of the lowest temperatures with the electrical efficiency increase rate obtained for 800-1000-1200 W/m^2 of irradiation values at 80 ml/h flow rate is given in Fig. 11. When the graph is analyzed, the increase in the efficiency value obtained at 1200

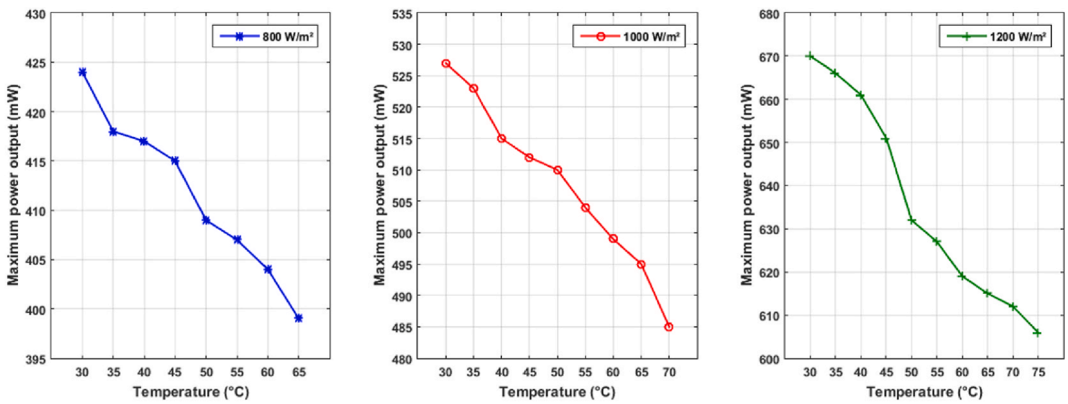

Fig. 8. Maximum power output-temperature variation at different radiation.

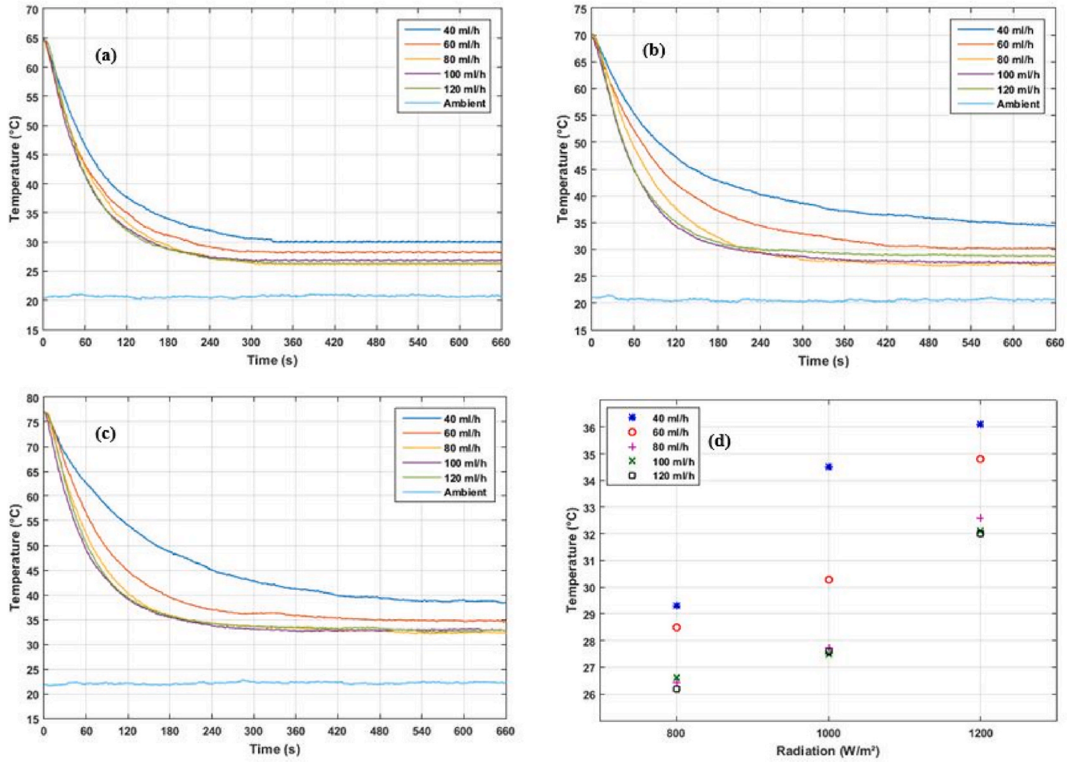

Fig. 9. Variation of power output at different flow rates at irradiances of **(a)** 800 W/m^2, **(b)** 1000 W/m^2, **(c)** 1200 W/m^2 for the lowest temperatures obtained after cooling the PV panel **(d)** Variation of lowest PV panel temperatures by radiation for different flow rates.

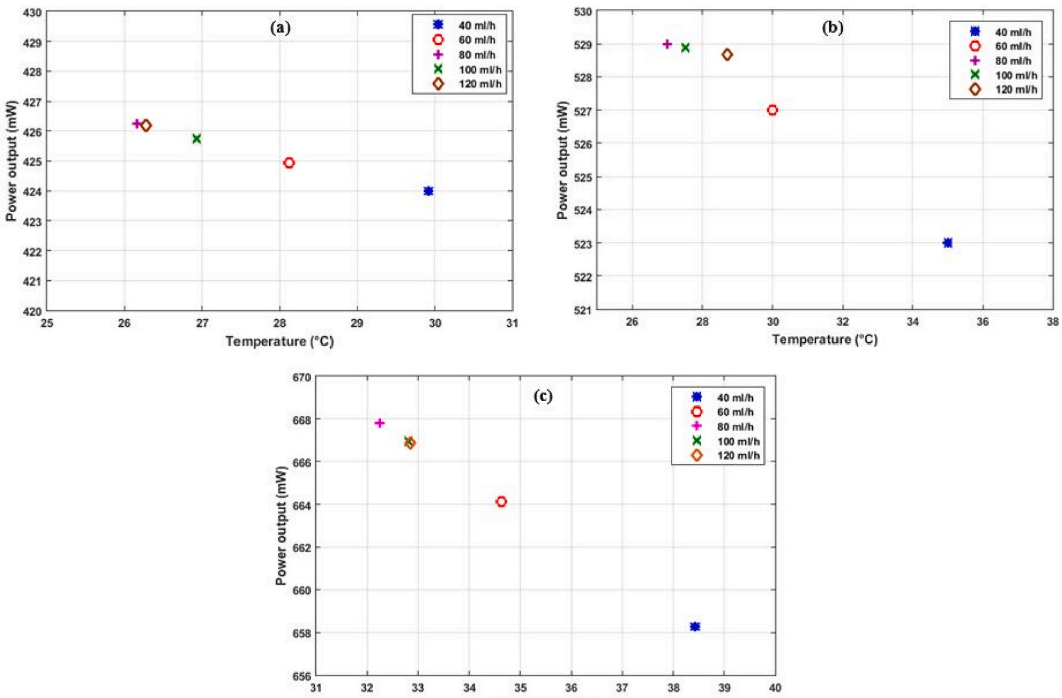

Fig. 10. Variation of power output at different flow rates at irradiances of (a) 800 W/m^2, (b) 1000 W/m^2, and (c) 1200 W/m^2 for the lowest temperatures obtained after cooling the PV panel.

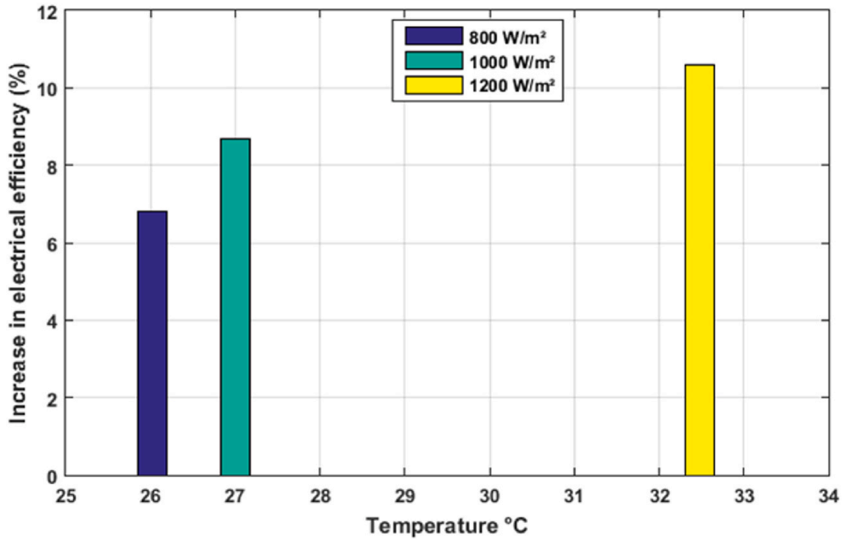

Fig. 11. Electrical efficiency increase rate for the lowest panel temperatures obtained at different irradiances.

W/m^2 of radiation value in the uncooled state (75 °C) is approximately 11 % compared to the electrical efficiency obtained in the cooled state (32.5 °C). At 1000 W/m^2 of radiation value, the increase in the efficiency value obtained in the uncooled state (70 °C) is approximately 8.5 % compared to the electrical efficiency obtained in the cooled state (27 °C). At 800 W/m^2 of irradiance value, the increase of the efficiency value obtained in the uncooled state (65 °C) is approximately 6.5 % compared to the electrical efficiency obtained in the cooled state (26 °C). As the irradiation intensity increased, the electrical efficiency rate increased, too. At 1000 W/m^2 of irradiation, a 29.9 % of the increase was observed compared to 800 W/m^2 of irradiation, and at 1200 W/m^2 of irradiation, a 55.9 % of the increase was observed compared to 800 W/m^2 of irradiation.

In the introduction, there was mentioned about a summary of the literature on spray cooling of the PV panels. There is no study in the literature on electrospray cooling of the PV panels. In order to examine the cooling performance of the electrospray on the PV panels, the results of the PV panel cooling with mechanical atomizers in the literature are compared in Table 4. When Table 4 is analyzed, it is seen that there was used different irradiance, panel area, and refrigerant flow rate. The researchers have carried out studies to achieve high PV panel temperatures with low flow rates. Hadipour et al. obtained $\Delta T = 33$ °C of temperature difference through spray cooling by using 0.12 l/min.m^2 of water flow rate. When analyzing the table, it is seen that the cooling performance was achieved by using a very low flow rate. Nateqi et al. used a flow rate of 2.29 l/min.m^2 to obtain $\Delta T = 40$ °C of temperature difference. Although the temperature difference was higher, they carried the cooling through a high flow rate. When other studies are examined, it is seen that the situation is similar.

In this study, in which the PV panel cooling performance with electrospray was analyzed in, it is seen that a higher temperature difference is obtained with a lower water flow rate compared to the other studies. The particle size obtained by electrospray atomization is smaller than the particle size obtained by mechanical atomization. Thus, the spray droplets falling on the PV panel surface evaporate more easily and remove the heat from the surface more effectively. Since the charged droplets produced by electrospray are directed towards the grounded panel surface, and a homogeneous spray distribution is obtained, there is no scattered spray formation. Therefore, cooling fluid wastage is prevented and more effective cooling is achieved with less fluid flow rate. When the literature table is analyzed, it is seen that the flow rates used in the studies are approximately 1.6–137 times higher than the flow rate used in our study

Table 4
Literature summary of the PV panel mechanical spray cooling and comparison of this study.

Reference	Radiation (W/m^2)	Area (m^2)	Flow rate per unit area (l/min.m^2)	PV panel uncooled temperature (°C)	PV panel cooled temperature (°C)
Bevilacqua et al. [41]	1000	1.66	5.15	40	27.6
Nižetić et al. (front) [42]	850	0.36	10.42	56	32
(front-back) [42]	850	0.36	10.42	56	24
Abdolzadeh and Ameri [43]	825	0.36	7.87	55	26
Yang et al. [45]	876	0.55	1.04	65	28
Nateqi et al. [46]	1000	0.59	2.29	64	24
Hadipour et al. [40]	985	0.65	0.12	57	24
Schiro et al. [54]	700	1.6	1.26	39.3	20.9
Moharram et al. [55]	–	7.55	3.84	45	35
This study	**1000**	**0.017**	**0.076**	**70**	**27**

conducted with the electrospray cooling. In the PV panel exposed to 1000 W/m^2 of radiation, $\Delta T = 43\ ^\circ C$ of temperature difference was obtained with 80 ml/h of water flow rate. In this case, it is seen that electrospray cooling is an effective method that can be used for cooling the PV panels.

4. Conclusion

In this study, the PV panel cooling performance through electrospray was analyzed. The experiments were carried out with 800-1000-1200 W/m^2 of irradiation, 40-60-80-100-120 ml/h of flow rate, 30 G nozzle diameter, 20 kV voltage, and 60 mm of nozzle to PV panel distance. The following results were obtained after the experiments.

- For all irradiance values, the panel temperature decreased as the flow rate increased. At flow rates above 80 ml/h, there was no significant change in temperature alternation. 80 ml/h of flow rate was determined as the optimum flow rate.
- At a flow rate of 80 ml/h, the rate of the temperature decrease was determined as 0.13, 0.14, and 0.15 °C/s for 800-1000-1200 W/m^2 of irradiances, respectively.
- The output power obtained increased by 56.6 % at 1200 W/m^2 and 24.2 % at 1000 W/m^2 compared to 800 W/m^2 of irradiation at optimum flow rate.
- In the study, $\Delta T = 43\ ^\circ C$ of temperature difference was obtained with 80 ml/h of water flow rate in the PV panel exposed to 1000 W/m^2 of radiation.
- As a result of cooling the PV panel, the panel temperature was reduced to 32 °C at 1200 W/m^2 irradiance and the panel efficiency increased by about 11 %. At 1000 W/m^2 irradiance the panel temperature decreased to 27 °C and the panel efficiency increased by about 8.5 % and at 800 W/m^2 irradiance the panel temperature decreased to 26 °C and the panel efficiency increased by about 6.5 %.
- It is seen that the flow rates used in spray cooling of the PV panel are approximately 1.6–137 times higher than the flow rate used in the study we carried out with electrospray cooling.

The experiments carried out are the first time electrospray cooling analysis has been investigated using a mini PV panel. As a result of the study in which electrospray cooling of PV panels was investigated, it was determined that higher cooling performance was achieved with electrospray cooling in PV panels with less water consumption compared to conventional spray cooling.

In future studies, electrospray cooling performance on industrial panels can be investigated. In addition, the effects of the number of nozzles, coolant fluid flow rate, power consumption, and coolant fluid type can be examined in industrial panels. The experiments were carried out in a laboratory environment. Experiments can be carried out in the outside environment to examine the electrospray cooling performance according to the irradiation at different times of the day.

CRediT authorship contribution statement

Abdüssamed Kabakuş: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization, Investigation, Supervision. **Ahmet Öztürk:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Methodology, Investigation, Conceptualization, Data curation. **Fatin Sönmez:** Writing – review & editing, Writing – original draft, Validation, Resources, Investigation, Data curation, Conceptualization, Methodology, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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