Hindawi
International Journal of Energy Research
Volume 2024, Article ID 5180627, 9 pages
https://doi.org/10.1155/2024/5180627

Research Article

Enhancing Heat Transfer of Photovoltaic Panels with Fins

Fang Wang, Zhenfei Li, Dongqing Pang, Zhiqiang Li, Xinke Zhao, Xiaoqian Cheng, Mengwei Liu, Yichi Zhang, and Wenliang Guo

School of Energy and Environment, Zhongyuan University of Technology, Zhengzhou 450007, China

Correspondence should be addressed to Fang Wang; fwang@zut.edu.cn

Received 8 August 2023; Revised 6 December 2023; Accepted 28 January 2024; Published 11 March 2024

Academic Editor: Mumtaz Ahmad Qaisrani

Photovoltaic power generation can directly convert solar energy into electricity, but most of the solar energy absorbed by the photovoltaic panel is converted into heat, which significantly increases the operating temperature leading to a reduction in the power generation efficiency of the panels. To reduce the working temperature of photovoltaic panels and improve the photoelectric conversion efficiency, this paper installs aluminum fins and air channels at the traditional photovoltaic cell back sheets and cools them with forced-circulation cooling through fans. The relationships between fin spacing, fin height, air channel inlet wind speed and panel temperature, power generation, and electrical efficiency were investigated. The results show that the temperature of the photovoltaic panel decreases and then increases with the decrease of the fin spacing during natural convection and gradually decreases with the increase of the fin height. The use of forced-circulation cooling technology can effectively reduce the PV panel temperature and increase the net power generation. When the solar radiation intensity is 1000 W/m^2, the ambient temperature is 35°C, the fin spacing is 6 mm, the height is 80 mm, the inlet wind speed is 1 m/s, the net generating power reaches the maximum value, and the net generating power and the electrical efficiency are increased by 14.6% and 2.25%, respectively.

1. Introduction

Renewable energy sources are becoming increasingly important as overexploitation of traditional energy sources leads to increasing energy consumption and climate degradation. Solar energy, as a renewable energy source with abundant reserves, wide distribution range, nonpolluting, and simple technology, has been widely used for photovoltaic (PV) power generation in recent years [1]. Solar cell technology can directly convert photons radiated by the sun into electrical energy [2], and the most popular application in the market is crystalline silicon PV panels, which already have a market share of more than 95% by 2020 [3]. Although crystalline silicon PV panels can absorb 80%-90% of the light energy from solar radiation, they can only convert about 8%-20% of the solar energy into electricity [4], and more solar energy is converted into heat energy. This significantly raises the temperature of the PV panels, reducing their photoelectric conversion efficiency and shortening their service life [5]. In general, the photoelectric conversion efficiency of a crystalline silicon PV panel decreases by 0.4% to 0.5% for every 1°C increase in temperature [6, 7].

Although the use of photovoltaic power generation technology is an important way to cope with the global energy crisis and improve the environment, the photoelectric conversion efficiency of PV panels is greatly affected by the temperature, so the search for an effective way to dissipate heat is the future of the technology that can be widely used in the top priority [8]. Specific cooling technologies can effectively reduce the PV panel's own heat, thus lowering the PV panel temperature and improving power generation efficiency [9, 10]. Cooling technologies are categorized as active or passive depending on whether they require additional energy consumption. Active cooling is typically through equipment such as fans or pumps and requires an external power input [11]. Passive cooling does not require additional power, but it does require the addition of

Table 1: Physical parameters of PV panel layers.

Layer	Thickness (mm)	Density (kg/m^3)	Thermal conductivity (W/m K)	Specific heat capacity (J/kg K)
GLASS	3.2	2450	0.7	790
EVA	0.5	960	0.311	2090
PV cell	0.21	2330	130	677
EVA	0.5	960	0.311	2090
PVF	0.3	1200	0.15	1250

fins with better thermal conductivity to absorb the heat and quickly exchange it with the surroundings, which in turn lowers the temperature of the panels [12]. Installing fins on a PV cell back plate significantly increases heat dissipation and improves efficiency under intense irradiation [13]. The heat dissipation of photovoltaic panels is achieved by increasing the number and height of fins to dissipate heat through heat conduction. On the other hand, it enhances heat transfer by increasing the heat exchange area between the heat sink and the surrounding environment and dissipates heat through convection and radiation between the heat sink and the surrounding environment. Under forced convection conditions, radiant heat transfer is negligible due to the high convective heat transfer coefficient [14]. Rectangular fins show better cooling than triangular and parabolic fins, and aluminum fins cool more significantly than brass and nickel fins [15]. Air channels can also be added to the fins, and the air speed at the channel inlet can be controlled through a fan [16], which effectively reduces the PV panel temperature [17]. Under different wind speeds, the power generation and electrical efficiency of finned PV panels have been increased by 11.8% and 1.8% [18, 19].

Many researchers use passive cooling technology to add fins to the PV cell back plate to reduce panel temperature to achieve higher photoelectric efficiency [20–23]. Fin material is one of the most important factors affecting the heat transfer of PV panels, and it was found that compared to copper and iron, aluminum fins are undoubtedly the most suitable choice due to their cheapness and lightweight, although their heat dissipation effect is not as good as that of copper fins [24, 25]. However, the fins are not effective in dissipating heat from the PV panels under natural convection conditions. If the PV panels are actively cooled, the additional energy consumption may reduce the net output power [26–28]. To achieve the best PV panel efficiency, this paper studies the influence of fins during natural convection, and the influence of fin spacing and fin height on the cooling effect of PV panels. Active cooling technology is simulated and optimized on this basis. The simulation results are used to determine the optimal fin spacing, fin height, and channel inlet wind speed, taking the net power generation and electrical efficiency as the optimization criteria.

2. Theoretical Analyses

2.1. Modeling. The object of study in this paper is based on a PV panel with dimensions of 796 × 660 mm, with a maximum power generation capacity of 60 W and a maximum power generation efficiency of 14% under standard operating conditions [29]. The PV module is mainly divided into 5 layers, and the physical parameters of the materials of each layer are shown in Table 1.

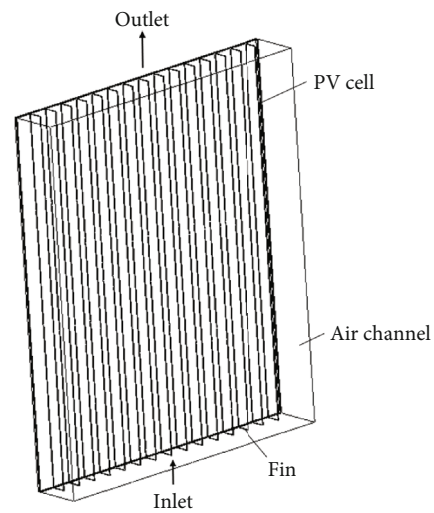

Figure 1: Optimized PV panel structure.

Figure 1 shows a diagram of the optimized structure. The air channel width is 100 mm, the fan is connected to the air channel inlet, and the outlet is directly connected to the external environment. The raw material for the fins is selected from higher thermal conductivity and cheaper, low-density aluminum fins with a thickness of 2 mm. Under natural convection conditions, the surface of such PV panels can only convert a small portion of the incoming solar energy into electricity, and more solar energy is converted into heat resulting in a gradual increase in panel temperature. And in the case of forced-circulation ventilation cooling, turn on the fan when the panel temperature is too high, and air with a certain flow rate is forcibly confectioned with the battery back plate and fin wall in the air channel to discharge the heat to the surrounding environment, thereby reducing the temperature of the PV panel.

Gomaa et al. [30] passively cooled the PV panels by mounting the fins on the backside of the panels using a similar structural design and found that the fin-cooled modules resulted in a 7% increase in daily harvested energy compared to noncooled modules. By randomly installing aluminum fins with epoxy conductive adhesive on the back surface of the PV panels, Filip et al. [10] found that the modified structured panels showed better performance response throughout the insolation spectrum, averaging about 2% in

efficiency improvement relative to the total power output for the specific obtained measurement period. The structure of the PV panel is simple, is easy to install the use of inexpensive aluminum fins, is low cost, does not require additional maintenance costs, and can be widely used in a variety of environments of the photovoltaic power generation system.

2.2. Photoelectric Conversion Performance. The relationship between the photovoltaic conversion efficiency of crystalline silicon PV panels and temperature is

$$W_T = W_{T_0}\left[1 - 0.4\%\left(T_p - T_0\right)\right], \tag{1}$$

where T is the working temperature of the PV panel, T_0 is the working temperature in the standard state (25°C), and W_T is the output power of the PV panel under temperature T (W).

The electrical efficiency of a PV panel is

$$\eta_T = \eta_{T_0}\left[1 - 0.45\%\left(T_p - T_0\right)\right], \tag{2}$$

where η_T is the power generation efficiency of the PV panel under temperature T, and η_{T_0} is the electrical efficiency under temperature T_0.

The use of forced-circulation cooling requires additional electricity consumption. This technology is not useful if the increased power generation of a PV panel under active cooling is not enough to provide the energy consumed by the fan, so the fan power needs to be considered:

$$W_{\text{fan}} = Q \times \frac{\Delta P}{\eta_1 \times \eta_2}, \tag{3}$$

where W_{fan} is the fan power (W), Q is the air supply volume (m^3/s), ΔP is the difference between air passage inlet and outlet pressures (Pa), η_1 is the electrical efficiency of the wind turbine (0.8), and η_2 is the mechanical transmission efficiency of the fan (0.95).

The net output power of the PV panel under forced convection is

$$W_n = W_T - W_{\text{fan}}, \tag{4}$$

where W_n is the net power generation (W).

2.3. Boundary Conditions and Governing Equations. The different boundary conditions are as follows.

(a) At the inlet: Air enters with a constant ambient temperature of 35°C. Velocity is considered uniform

(b) At the outlet: Static pressure is fixed at the ambient pressure

(c) At the top plate, which is the transparent glass cover. The heat transfer between the glass cover plate and the surrounding environment is mainly convective and radiative. In the simulation process, the transmittance of the glass cover plate is set to $\tau = 0.9$, and the relationship between the convective heat transfer coefficient of the transparent glass cover plate and the surrounding environment can be expressed as

$$h_t = 5.7 + 3.8v, \tag{5}$$

where h_t is the convective heat transfer coefficient (W/(m^2·K)). v is ambient wind speed (m/s).

At the bottom and lateral plates that are opaque aluminum panels, the heat transfer with the surrounding environment is mainly convective heat transfer, and the relationship between its convective heat transfer coefficient and the surrounding environment wind speed can be expressed as

$$h_b = 2.8 + 3.0v, \tag{6}$$

where h_b is the convective heat transfer coefficient (W/(m^2·K)).

Considering changes in the air velocity at the inlet air passage, the gas turbulence intensity changes according to

$$\begin{aligned} I &= 0.16\ \mathrm{Re}^{-(1/8)}, \\ \mathrm{Re} &= \frac{\rho V D}{\mu}, \end{aligned} \tag{7}$$

where I is the turbulence intensity, Re is the Reynolds number, ρ is the fluid density (kg/m^3), μ is the fluid viscosity (Pa s), D is the hydraulic diameter (m) set to 0.174 m for the model, and V is the fluid flow rate (m/s).

Air is set as an incompressible ideal gas model during Fluent simulations, which indicates that air density does not change with pressure, only with temperature. Heat transfer methods include heat conduction and convection heat transfer in fluid and solid regions. Based on the above analysis, the physical model is governed by the continuity, momentum, and energy equations as follows.

The continuity equation for steady-state flow in the fluid channel is

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \vec{\mathrm{v}}\right) = 0. \tag{8}$$

The momentum conservation equations for an incompressible fluid are

$$\begin{aligned} \frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u u)}{\partial x} + \frac{\partial(\rho u v)}{\partial y} + \frac{\partial(\rho u \omega)}{\partial z} &= \frac{\partial}{\partial x}\left(\mu \frac{\partial u}{\partial x}\right) \\ &+ \frac{\partial}{\partial y}\left(\mu \frac{\partial u}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial u}{\partial z}\right) - \frac{\partial p}{\partial x} + F_x, \\ \frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho v u)}{\partial x} + \frac{\partial(\rho v v)}{\partial y} + \frac{\partial(\rho v \omega)}{\partial z} &= \frac{\partial}{\partial x}\left(\mu \frac{\partial v}{\partial x}\right) \\ &+ \frac{\partial}{\partial y}\left(\mu \frac{\partial v}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial v}{\partial z}\right) - \frac{\partial p}{\partial y} + F_y, \\ \frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho \omega u)}{\partial x} + \frac{\partial(\rho \omega v)}{\partial y} + \frac{\partial(\rho \omega \omega)}{\partial z} &= \frac{\partial}{\partial x}\left(\mu \frac{\partial \omega}{\partial x}\right) \\ &+ \frac{\partial}{\partial y}\left(\mu \frac{\partial \omega}{\partial y}\right) + \frac{\partial}{\partial z}\left(\mu \frac{\partial \omega}{\partial z}\right) - \frac{\partial p}{\partial z} + F_z, \end{aligned} \tag{9}$$

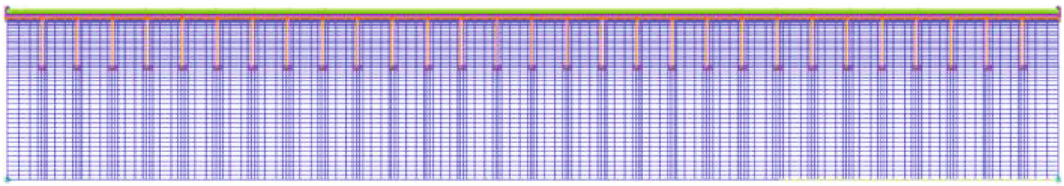

Figure 2: Cross-sectional view of finned PV panel griding.

where p is the pressure on the fluid microbody (Pa) and F_x, F_y, and F_z are the volumetric forces of the microbody in the x, y, and z directions, respectively. If the volumetric force is only gravity and the axis is vertically upward, then F_x, F_y, and F_z are equal to 0.

The energy conservation equation is

$$\frac{\partial(\rho T)}{\partial t} + \frac{\partial(\rho u T)}{\partial x} + \frac{\partial(\rho v T)}{\partial y} + \frac{\partial(\rho \omega T)}{\partial z} = \frac{\partial}{\partial x}\left(\frac{k}{C_p}\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\frac{k}{C_p}\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\frac{k}{C_p}\frac{\partial T}{\partial z}\right) + S_T, \tag{10}$$

where C_p is the specific heat capacity of the fluid (J/(kg•K)), T is the fluid temperature (K), k is the heat transfer coefficient of the fluid, and S_T is the heat source in the fluid.

2.4. Simulation Procedures. In this study, the finite volume method was used in the simulation software Fluent to solve the control equations for continuity, momentum, and energy in a steady state, and the energy equations remained available as heat transfer models. The turbulence model was a realizable $k-\varepsilon$ model that is closer to real-world conditions and is more accurate, and it is a semiempirical model using the Boussinesq concept that links Reynolds' constraints to the average rate of deformation. The fluid was air, and the density changed with temperature, so gravity needed to be considered in the calculation, and the Boussinesq hypothesis was used to improve computational speed and stability.

There are five radiation models available in the Fluent solver for the simulation of heat transfer processes between media, only two of which are suitable for the simulation of radiation in confined cavities: The S2S (surface to surface) model and the DO (discrete ordinates). Due to the presence of obstacles in the model volume of this study and the need for a very high RAM capacity during the computation process, a DO model with higher accuracy and shorter computation time was selected.

The first-order upwind scheme was chosen for energy and momentum equations. Air in the flow process density change is not very large and can be approximated as an incompressible fluid, Fluent software in the low-speed incompressible flow heat transfer problem solving, and the default is to pressure correction SIMPLE algorithm. This method uses a relationship between velocity and pressure corrections to enforce mass conservation and to obtain the pressure field. The SIMPLE algorithm was chosen as the coupling scheme for pressure and velocity; it is more economical, more stable, and has more accurate results than other algorithms. The gradient space discretization is performed using least square-based cells, second-order upwind equations are used for pressure, momentum, and energy, and first-order upwind equations are used for both turbulent kinetic energy and turbulent dissipation rate. The sub relaxation factors are set as follows: pressure is 0.3; density, volumetric force, energy, and discrete coordinates are all 1; and momentum is 0.7. The residuals for the different directional velocities, k and ε, are set to 0.001, and for the energy equations, 10-6 is used to achieve convergence.

2.5. Grid-Dependence Analysis and Model Validation. ICEM CFD (computation fluid dynamics) is a pre- and postprocessing software for geometry creation, griding, preprocessing condition setting, postprocessing, and other functions. Its advantages are even more prominent in CFD grid generation. The number of grids is a major factor in the accuracy of the results during the calculation process. A smaller number of grids will lead to inaccurate results, and a larger number will take more computation time, so the right number of grids is extremely important for the results. In this study, ICEM CFD was used to grid the model, and the temperature change of the PV panel under different grid numbers was analyzed by changing the global size and local area encryption. The model griding is shown in Figure 2.

Due to the regular shape of the physical model established in this study, the structured grid delineated by ICEM CFD is characterized by fast grid generation and high quality of the generated grid, which also leads to higher accuracy of the calculation results. In this study, the ratio of the largest Jacobi matrix determinant to the smallest Jacobi matrix determinant is used as an evaluation criterion for the quality of the model grid. Normal grids take values between 0 and 1. A value of 1 indicates a perfect grid, and a smaller ratio indicates a poorer quality grid. Negative values indicate the presence of a negative volume grid, which will report an error when solving. The grid quality of the model is shown in Figure 3, which shows that the grid quality is high and meets the computational accuracy requirements.

For more accurate calculation of the numerical model, the independence of the number of grids was first checked. Figure 4 shows that the temperature change of the PV panel gradually tends to stabilize as the number of grids increases. After considering the accuracy of the calculation results and the complexity of the calculation, 1.3 million was finally selected as the number of grids for subsequent calculation.

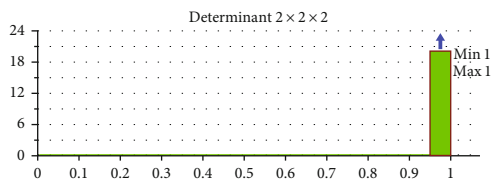

Figure 3: Finned PV panel grid quality.

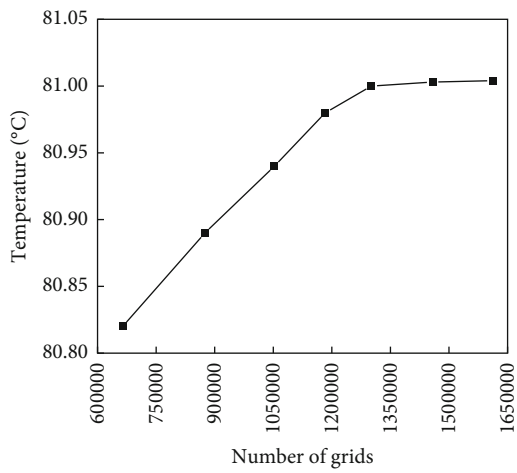

Figure 4: Panel temperature varies with number of grids.

Arifin et al. [1] studied the temperature variation of a 50 w PV panel with dimensions 655 × 670 × 25 mm under different solar radiation intensities. Incident solar irradiance was measured using a LI-COR LI-250A pyranometer, and the temperature of the PV panels was measured using the K-type thermocouple, which was placed at the top of the PV panels to measure the average temperature. An anemometer was used to measure the wind speed at the bottom surface of the PV panels, and a uniform wind speed of about 1.5 m/s was obtained by adjusting the position and distance between the 35 w fan and the PV panels.

To validate the PV panel model, the air channel inlet wind speed was set to 1.5 m/s, the relationship between the PV panel temperature and the solar radiation intensity was investigated by varying the light intensity on the panel surface, and the simulated values were compared with the experimental values given by Arifin et al. The comparison results are shown in Figure 5, and the maximum difference between the numerical and experimental results is within 5%. We can so confirm that our numerical model is designed correctly.

3. Results and Discussion

3.1. Effect of Fin Spacing on Cooling Performance of PV Panels. The traditional PV cell was simulated under an ambient temperature of 35°C, light intensity of 1000 W/m^2, natural convection, and a PV panel temperature of 81°C. The power generation of a PV panel is 46.56 (W). The electrical efficiency of a PV panel is 10.47%.

For a fin installation height of 30 mm, the fin spacing was changed to simulate the PV panel under natural convection conditions. The corresponding change in panel temperature is shown in Figure 6. The size of the fin spacing affects the finning coefficient, and when the fin spacing is reduced for better cooling of the PV panels, the finning coefficient becomes larger, and when the fin spacing is too small resulting in the overlap of the heat transfer boundary layer and a reduction in heat dissipation from the PV panels, the finning coefficient decreases. The PV panel temperature gradually decreases as the fin spacing decreases, which is explained as follows. The number of fins increases with decreasing fin spacing, which increases the contact area between the fin and the air. This results in an increase in convection heat transfer between the fin and the air, so the temperature of the PV panel gradually decreases. When the fin spacing is less than 6 mm, the panel temperature gradually increases. This is because, although the convective heat exchange area with the air increases when the fin spacing is very small, the surface thermal resistance of the PV panel and the fluid flow resistance during natural convection also increase, and the heat transfer boundary layers of adjacent fins coincide. This results in a low finning coefficient of the fin, which affects the fin heat dissipation, so the temperature of the PV panel does not fall but rises. As can be seen from the temperature

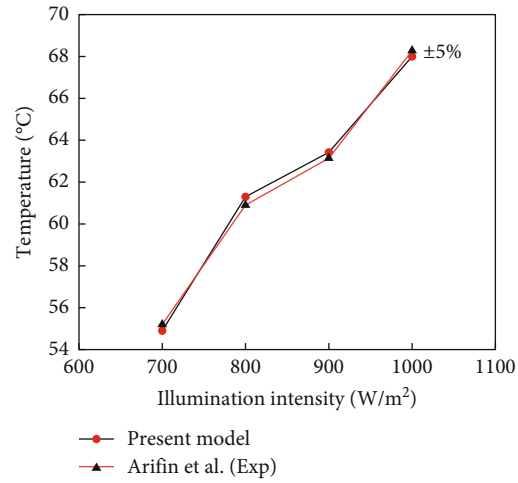

Figure 5: Model temperature verification at different irradiation intensities.

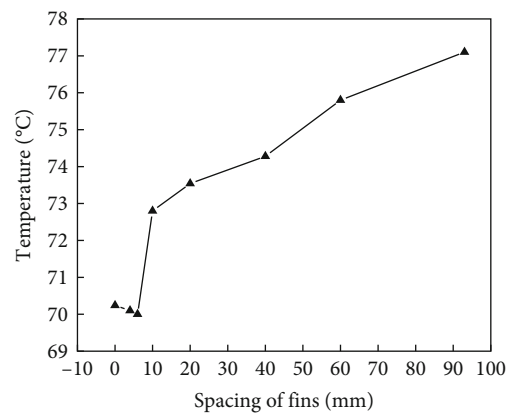

Figure 6: PV panel temperature varies with fin spacing.

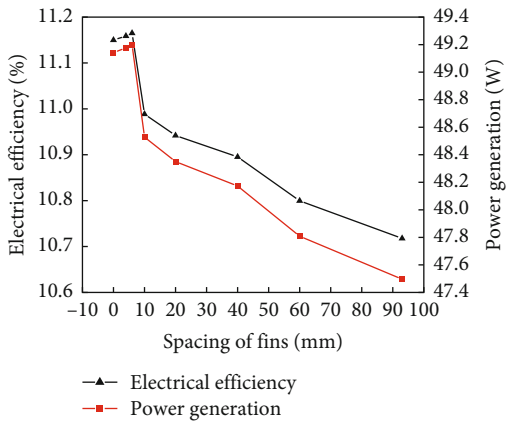

Figure 7: The power generation and electrical efficiency of PV panels change with fin spacing.

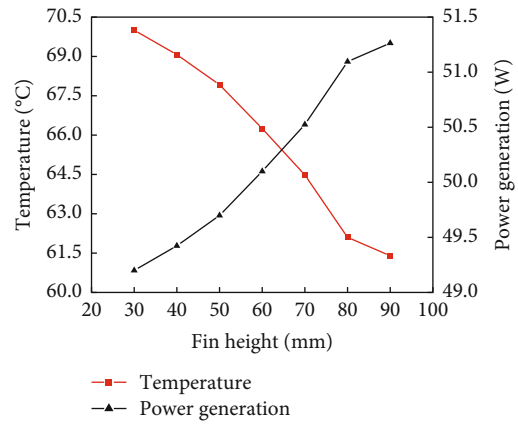

Figure 8: The temperature and power generation of the PV panel change with fin height when the fin spacing is 6 mm.

variation curve of the PV panel in Figure 6. The cooling effect on the PV panel is best when the fin spacing is 6 mm, when the panel temperature is 70°C, which is 11°C lower than the temperature without fins.

Figure 7 shows the power generation and electrical efficiency of the PV panel for varying fin spacing. When the fin spacing is 6 mm, the power generation and electrical efficiency of the panel reach their maxima of 49.2 W and 11.17%, respectively, which are 5.67% and 0.7% higher than those of finless PV panels.

3.2. Effect of Fin Height on PV Panel Cooling. Figure 8 shows the simulated temperature and power generation as functions of fin height for a PV panel with a fin spacing of 6 mm under natural convection.

As the fin height increases, the PV panel temperature decreases rapidly and then slowly, when the fin height is between 50 mm and 80 mm, and the temperature change is no longer obvious when the fin height is greater than 80 mm, while the power generation shows a mirror trend of increasing quickly and then slowly. This is because, within a certain range, the fin height increases, the heat dissipation area with the air increases, and the heat transfer is more obvious. Although the heat transfer area increases, the thermal resistance between the fin and the battery plate gradually increases if the fin is too high, and the influence on the heat dissipation gradually becomes less obvious. When the height of the fin is 90 mm, the temperature of the panel is 61.4°C. The temperature is reduced by 19.6°C compared with that without fins, and the power generation and electrical efficiency are increased by 10.09% and 1.24%.

3.3. Influence of Channel Inlet Wind Speed on PV Panel Performance. The fin height of the PV panel was simulated at different inlet wind speeds using forced-circulation cooling with the air channel inlet connected with the fan. The change in panel temperature is shown in Figure 9.

As the inlet speed of the air channel gradually increases, the PV panel temperature gradually decreases for different fin heights. The reduction trend gradually flattens, and the temperature of the nonfinned panel is significantly higher than that of PV panels with fins. This is because, when the air inlet wind speed increases, the internal fluid turbulence of the air channel becomes more intense, and the convective heat transfer between the fluid and both the PC cell back plate and fin gradually increases. The increase in fin height increases the convective heat transfer area between the fin and the air, so the PV panel temperature decreases as the fin height increases. However, when the inlet wind speed of the air channel is greater than 2 m/s, the heat exchange of PV panels with different fin heights is no longer obvious, and the decrease in panel temperature gradually becomes slower. This is due to the fact that when the wind speed is high, the intensity of turbulence in the air channel is high, and when the heat absorbed on the surface of the PV panels is transferred to the fins through heat transfer, the heat on the fins is taken away by strong convective heat transfer with the surrounding fast-flowing air, and therefore, the temperature of the PV panels decreases in a flat trend.

When the inlet wind speed of the air passage is constant, the flow state of air in the channel is affected by fin height. This leads to a change in pressure difference between the inlet and outlet of the channel, as shown in Figure 10.

As the fin height and inlet wind speed increase, the pressure difference between the inlet and outlet of the air passage gradually increases. The increased amplitude also gradually increases, which means that the growth rate of the fan power is slow and then fast. PV panel temperature can be effectively reduced, and photoelectric conversion efficiency improved using active cooling and changing the fin height. Considering that the fan needs to consume additional electric energy, the net power generation of the PV panel can be effectively increased only when the increase in PV power generation is greater than the additional energy consumed by the fan. Therefore, improving the net power generation of PV panels requires selecting the appropriate inlet wind speed for different fin heights to ensure that the additional energy consumed by the fan is within a reasonable range.

Figure 11 shows the change in net power generation of PV panels with fin height under forced-circulation cooling. The net power generation of PV panels increases slowly and, after peaking, decreases rapidly with increasing inlet

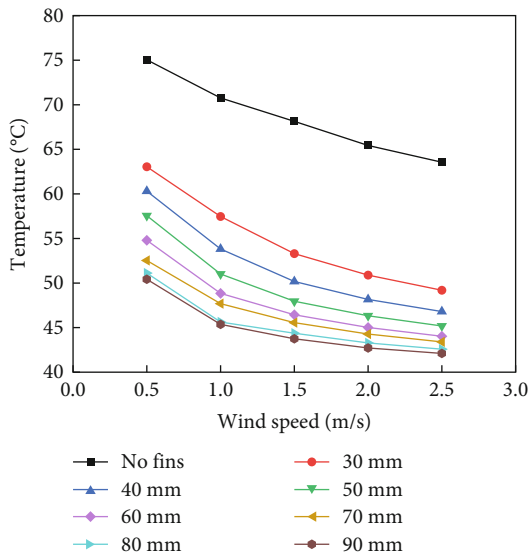

Figure 9: PV panel temperature varies with inlet wind speed for different fin heights.

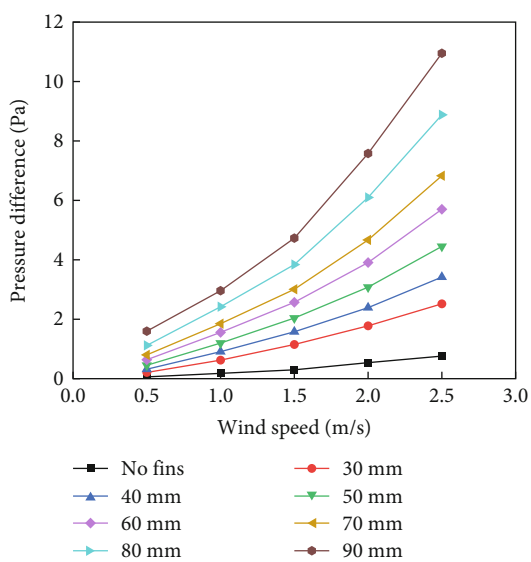

Figure 10: The inlet and outlet pressure difference of the air passage varies with the inlet wind speed at different fin heights.

wind speed. This is because the additional electric energy consumed by the fan has a linear relationship with the inlet and outlet pressure difference of the channel, and the pressure difference between the inlet and outlet of the channel increases exponentially with the inlet speed while the PV power generation changes slowly with the inlet wind speed. When the wind speed is low, the pressure difference between the inlet and outlet of the air channel is very low, and the additional energy consumed by the fan is very low. At this time, the increase in power generation of the PV panel is greater than the additional power consumed by the fan, so the net power generation of the panel improves. When the wind speed increases, the additional power consumed by the fan increases rapidly, which makes the power generation increment of the PV panel equal to or even less than the

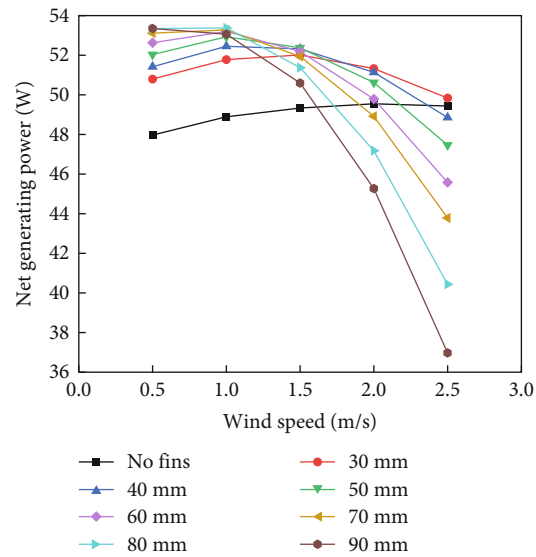

Figure 11: The net power generation of PV panels varies with the inlet wind speed for different fin heights.

additional power consumed by the fan. This results in the net power generation of the PV panel being lower than under natural convection, making the active cooling technology meaningless. At the same inlet wind speed, the pressure difference between the inlet and outlet increases with increasing fin height. When the fins are higher, the fan consumes more electrical energy. The net PV power generation can only be increased if the PV power increment due to increasing fin height is greater than the electrical energy consumed by the fan.

Different fin heights correspond to different effective wind speeds, when the wind speed is 0-1.5 m/s, the net power generation of PV panels with different fin heights is greater than that without fins. When the wind speed is greater than 1.5 m/s, increasing the wind speed will reduce the net power generation of the PV panels. Choosing the right fin height and inlet wind speed can maximize the net electrical efficiency of PV panels. Figure 11 also shows that when the fin spacing is 6 mm, the fin height is 80 mm, and the inlet wind speed is 1 m/s, the net power generation of the PV panel reaches the maximum. The power generation and electrical efficiency are increased by 14.6% and 2.25% compared with natural convection without fins.

To the PV panel plus aluminum fins and air channels, although it will increase the PV system investment in the early stage, but because the aluminum material is cheap, fin processing is simple, is easy to install, has no additional maintenance costs, and has a better cooling effect, it not only can effectively improve the photoelectric conversion efficiency but also be able to slow down the service life of the PV module. The increase in the number and height of fins is beneficial for the heat dissipation of PV panels, but it also increases the weight of fins, which affects the stability of the structure and the convenience of installation. The specific impact of factors such as initial capital investment and power consumption of fans on the energy output of PV modules is complex and difficult to evaluate theoretically.

Therefore, experimental research on the heat dissipation and energy output performance of finned battery panels will be conducted soon. The purpose of this article is to achieve the cooling performance of fins on PV panels. Therefore, the research focus of this article is on the effects of different fin structure parameters and different wind speeds on the temperature changes of PV panels. This is conducive to evaluating the cooling performance of fins and preparing for future experimental work to obtain the economic impact of fin configuration, including material cost and feasibility, which is necessary for the popularization of PV power generation system and is very important in the future.

4. Conclusion

In this study, Fluent was used to numerically simulate finned PV panels under natural convection and forced-circulation cooling to determine the influence of fin spacing, fin height, and air channel inlet wind speed on photoelectric conversion efficiency of PV panels. The results are as follows.

(1) Fins can effectively reduce the average temperature of PV panels under natural convection and constant solar irradiation intensity and ambient temperature. When the fin spacing gradually decreases, the temperature of the battery plate first decreases and then increases. When the fin height is 30 mm and the fin spacing is 6 mm, the panel temperature is reduced to the minimum, the power generation is 5.67% higher than without a fin, and the electrical efficiency is increased by 0.7%

(2) The PV panel temperature gradually decreases with increasing fin height for a fin spacing of 6 mm under natural convection. When the fin reaches a certain height, the heat dissipation is no longer obvious

(3) Under forced-circulation cooling, the additional power consumed by the fan increases rapidly with increasing fin height and inlet wind speed, but the power generation growth rate of the PV panel is relatively flat. The net power generation of the PV panel reaches the maximum when the fin spacing is 6 mm, the fin height is 80 mm, and the inlet wind speed is 1 m/s. Compared with natural convection without a fin, the temperature is reduced by 35.38°C, and the power generation and electrical efficiency are increased by 14.6% and 2.25%, respectively

In short, PV panels can effectively reduce the working temperature and improve their photoelectric conversion efficiency by adding fins under the conditions of forced-circulation cooling technology. This is a good impetus to improve the utilization rate of solar energy and achieve the global carbon neutral goal. PV panels that commonly used cooling methods also include water cooling and PCM cooling, water cooling usually uses water pumps, and other active equipment will be water on the panel surface to form a layer of water film or directly submerged panels in the water; compared with air, the thermal conductivity of the water is greater, and this method can have a better cooling effect. PCM cooling utilizes its latent heat storage property to absorb the heat from the PV panels, thus obtaining a good cooling effect. Future research efforts could explore the use of water cooling or phase change material cooling for improved cooling efficiency.

Data Availability

No data was used for the research described in the article.

Conflicts of 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.

Authors' Contributions

Fang Wang was responsible for the conceptualization, investigation, methodology, project administration, validation, and writing the manuscript. Zhenfei Li was responsible for the CFD simulation, data processing, writing of original draft preparation, and data analysis. Dongqing Pang was responsible for the conceptualization, writing, and manuscript editing. Zhiqiang Li was responsible for the conceptualization, writing, and manuscript editing. Xinke Zhao was responsible for the conceptualization, writing, and manuscript editing. Xiaoqian Cheng was responsible for the conceptualization, writing, and manuscript editing. Mengwei Liu was responsible for the conceptualization, writing, and manuscript editing. Yichi Zhang was responsible for the conceptualization, writing, and manuscript editing. Wenliang Guo was responsible for the conceptualization, writing, and manuscript editing.

Acknowledgments

This work was supported by the Program for Innovative Research Team in Science and Technology at the University of Henan Province (24IRTSTHN019), the Postgraduate Education Reform and Quality Improvement Project of Henan Province (YJS2021JD08, YJS2023KC15), and the Young Talent Innovation Fund project of Zhongyuan University of Technology (K2022QN011).

References

[1] Z. Arifin, D. D. D. P. Tjahjana, S. Hadi, R. A. Rachmanto, G. Setyohandoko, and B. Sutanto, "Numerical and experimental investigation of air cooling for photovoltaic panels using aluminum heat sinks," *International Journal of Photoenergy*, vol. 2020, Article ID 1574274, 9 pages, 2020.

[2] B. Sutanto and Y. S. Indartono, "Computational fluid dynamic (CFD) modelling of floating photovoltaic cooling system with loop thermosiphon," in *AIP Conference Proceedings. Vol. 2062. No. 1*, AIP Publishing, 2019.

[3] J. Huang, X. Yu, D. Hu et al., "Crystal growth and resistivity modulation of n-type phosphorus-doped cast mono-like silicon," *Solar Energy*, vol. 236, pp. 294–300, 2022.

[4] S. Dubey, J. N. Sarvaiya, and B. Seshadri, "Temperature dependent photovoltaic (PV) efficiency and its effect on PV production in the world – a review," *Energy Procedia*, vol. 33, no. 33, pp. 311–321, 2013.

[5] K. Egab, A. Okab, H. S. Dywan, and S. K. Oudah, "Enhancing a solar panel cooling system using an air heat sink with different fin configurations," *IOP Conference Series Materials Science and Engineering*, vol. 671, no. 1, article 012133, 2020.

[6] C. G. Popovici, S. V. Hudis Teanu, T. D. Mateescu, and N. C. Chereches, "Efficiency improvement of photovoltaic panels by using air cooled heat sinks," *Energy Procedia*, vol. 85, pp. 425–432, 2016.

[7] R. Ahmed and K. A. I. Nabil, "Computational analysis of phase change material and fins effects on enhancing PV/T panel performance," *Journal of Mechanical ence & Technology*, vol. 31, no. 6, pp. 3083–3090, 2017.

[8] H.-l. Bai, C. Wang, J. Lu, and K. Xue, "Solar cell heat dissipation technology and development status of concentrated photovoltaic system," *Chemical Industry Progress*, vol. 191, 2022.

[9] Z. Özcan, M. Gülgün, E. Şen, N. Y. Çam, and L. Bilir, "Cooling channel effect on photovoltaic panel energy generation," *Solar Energy*, vol. 230, pp. 943–953, 2021.

[10] F. Grubišić-Čabo, S. Nižetić, D. Čoko, I. M. Kragić, and A. Papadopoulos, "Experimental investigation of the passive cooled free-standing photovoltaic panel with fixed aluminum fins on the backside surface," *Journal of Cleaner Production*, vol. 176, pp. 119–129, 2018.

[11] M. Hasanuzzaman, A. B. M. A. Malek, M. M. Islam, A. K. Pandey, and N. A. Rahim, "Global advancement of cooling technologies for PV systems: a review," *Solar Energy*, vol. 137, pp. 25–45, 2016.

[12] D. Sato and N. Yamada, "Review of photovoltaic module cooling methods and performance evaluation of the radiative cooling method," *Renewable and Sustainable Energy Reviews*, vol. 104, pp. 151–166, 2019.

[13] H. G. Teo, P. S. Lee, and M. N. A. Hawlader, "An active cooling system for photovoltaic modules," *Applied Energy*, vol. 90, no. 1, pp. 309–315, 2012.

[14] E. Ahmad, A. Fazlizan, H. Jarimi, and A. Ibrahim, "Enhanced heat dissipation of truncated multi-level fin heat sink (MLFHS) in case of natural convection for photovoltaic cooling," *Case Studies in Thermal Engineering*, vol. 28, article 101578, 2021.

[15] E. Cuce, T. Bali, and S. A. Sekucoglu, "Effects of passive cooling on performance of silicon photovoltaic cells," *International Journal of Low Carbon Technologies*, vol. 6, no. 4, pp. 299–308, 2011.

[16] A. M. Elsafi and P. Gandhidasan, "Comparative study of double-pass flat and compound parabolic concentrated photovoltaic–thermal systems with and without fins," *Energy Conversion & Management*, vol. 98, pp. 59–68, 2015.

[17] R. Kumar and M. A. Rosen, "Performance evaluation of a double pass PV/T solar air heater with and without fins," *Applied Thermal Engineering*, vol. 31, no. 8-9, pp. 1402–1410, 2011.

[18] H.-b. Chen, X.-l. Chen, Q. Wang, L. Zhang, and S. Chu, "Study on the influence of cooling ribs on the power generation performance of photovoltaic panels," *Renewable Energy Resources*, vol. 33, no. 3, pp. 346–350, 2015.

[19] H. Chen, X. Chen, S. Li, and H. Ding, "Comparative study on the performance improvement of photovoltaic panel with passive cooling under natural ventilation," *International Journal of Smart Grid and Clean Energy*, vol. 3, no. 4, pp. 374–379, 2014.

[20] M. Ammar, A. Mokni, H. Mhiri, and P. Bournot, "Numerical analysis of solar air collector provided with rows of rectangular fins," *Energy Reports*, vol. 6, pp. 3412–3424, 2020.

[21] F. Bayrak, H. F. Oztop, and F. Selimefendigil, "Effects of different fin parameters on temperature and efficiency for cooling of photovoltaic panels under natural convection," *Solar Energy*, vol. 188, pp. 484–494, 2019.

[22] J. C. Mojumder, W. T. Chong, H. C. Ong, and K. Y. Leong, "An experimental investigation on performance analysis of air type photovoltaic thermal collector system integrated with cooling fins design," *Energy & Buildings*, vol. 130, pp. 272–285, 2016.

[23] M. Chandrasekar and T. Senthilkumar, "Passive thermal regulation of flat PV modules by coupling the mechanisms of evaporative and fin cooling," *Heat & Mass Transfer*, vol. 52, no. 7, pp. 1381–1391, 2016.

[24] J. Kim, S. Bae, Y. Yu, Y. Nam, and E. Sciubba, "Experimental and numerical study on the cooling performance of fins and metal mesh attached on a photovoltaic module," *Energies*, vol. 13, no. 1, 2020.

[25] N. Sukesh, P. S. Lakshmisagar, and G. Kumar, "Heat transfer analysis of fin performance for PVT absorber," *Journal of Mechanical Engineering and Automation*, vol. 5, no. 3B, 2015.

[26] S.-Y. Wu, T. Wang, L. Xiao, and Z.-G. Shen, "Effect of cooling channel position on heat transfer characteristics and thermoelectric performance of air-cooled PV/T system," *Solar Energy*, vol. 180, pp. 489–500, 2019.

[27] J. C. Mojumder, H. C. Ong, W. T. Chong, K. Y. Leong, and N. Izadyar, "An empirical analysis on photovoltaic thermal system with fin design by forced air circulation," *Journal of Mechanical Science and Technology*, vol. 31, no. 5, pp. 2549–2557, 2017.

[28] F. Chabane, N. Moummi, and S. Benramache, "Experimental study of heat transfer and thermal performance with longitudinal fins of solar air heater," *Journal of Advanced Research*, vol. 5, no. 2, pp. 183–192, 2014.

[29] N.-w. Liang, "Research on water cooling characteristics of photovoltaic panels based on numerical simulation," *Anhui University of Technology*, vol. 291, 2021.

[30] M. R. Gomaa, W. Hammad, M. Al-Dhaifallah, and H. Rezk, "Performance enhancement of grid-tied PV system through proposed design cooling techniques: an experimental study and comparative analysis," *Solar Energy*, vol. 211, pp. 1110–1127, 2020.