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Efficiency improvement of air-cooled photovoltaic modules utilizing copper heat dissipators

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ABSTRACT

During the photovoltaic conversion of solar panels, heat is generated, increasing the temperature of the photovoltaic cell, and reducing its efficiency. This phenomenon results when a percentage of the solar radiation is not absorbed by the cells, causing the cells to heat up. The current study included a numerical analysis of employing an air-cooled heat dissipator to enhance the cooling of photovoltaic (PV) panels. The proposed heat dissipator was constructed as a copper plate with cylindrical ribs which were placed behind the PV panel. Numerical simulations were achieved in ANSYS-Fluent software, for 3D model, in forced convection and turbulent flow. The simulations were carried out at three different mass flow rates (0.03, 0.045, and 0.061 kg/s) and a temperature of 35°C under 500 W/m^2 solar radiation. The results indicated that increasing flow velocity enhanced heat transfer by convection, resulting in a reduction in temperature and an improvement in the panel's electrical efficiency.

Keywords: Photovoltaic panel; Solar energy; Heat transfer; Numerical model; Heat sink

1. Introduction

Solar energy is one of the most reliable renewable energy sources on the earth, due to its widespread availability, particularly in warmer regions (e.g., Southern Algeria). Generally, solar energy is used and transferred by systems such as solar panels. Currently, this energy is exploited in two different ways: photo-thermal and photovoltaic (PV), Photo-thermal systems use solar radiation heat for various applications, including solar ovens, harvest drying, and solar water heaters [1]. In photovoltaic (PV) systems, solar cell technology transforms photons from the sun rays directly into electric energy [2].

A photovoltaic panel consists of a PV module, this basic element converts solar energy into electrical energy. The efficiency of photovoltaic panels determines how much solar radiation (W/m^2) is converted into electric energy in specific conditions. Currently, the type of monocrystalline solar cells is the most efficient solar cell with power conversion efficiency ranging between 17% and 22% [3]. While the other 80% of solar radiation is almost entirely converted to heat. Scientific studies Jafari Fesharaki et al. [4], and data from manufacturers [5,6], have all shown that when the temperature of PV cells rise, the electrical efficiency drops. It has been discovered that even raising the temperature of PV modules by 1°C decreases their electrical

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efficiency around 0.45%. Moreover, the generated heat has the potential to change the inner structure of the photovoltaic cell, leading to thermal degradation [7]. Furthermore, to improve electrical efficiency and to protect the life span of photovoltaic cells, cooling must be carried out. Scientists have developed new cooling techniques and designs. These include active cooling, which uses a coolant like water and air with forced flow circulation that typically requires fan or pump power, and passive cooling, which uses air and water as a coolant without any mechanical technique or with additional components like heat pipes, heat sinks, cooling by PV floating, hybrid integrated PV/thermal systems and cooling by utilization nano fluids or phase change materials [8,9]. Hudişteanu et al. [10] presented a numerical study. In order to increase the efficiency of PV panels by using active water cooling in comparison to conventional PV panels, behind the PV panel they attached a water film heat exchanger consisting of two metal plates on the backside of the PV panels, they evaluated the impact of the temperature, velocity and width of the water film on the operating temperature of PV panel and its efficiency. Their result indicated that the impact of the cooling system on operating temperature and electrical efficiency of PV panels is directly related to cooling water inlet velocity with an optimal value of 0.01 m/s and inversely related to its inlet temperature and to the thickness of water film with optimal values as 20°C and 3 mm respectively. Under these conditions, they achieved the highest electrical efficiency of 30.6%, which is greater than in the conventional PV panels. Additionally, splashing cold water on the front surface of PV modules can be used as an efficient method to reduce the temperature of the module. Krauter [11] has presented an experimental study that shows how water flow over the top face of a PV panel can increase the electrical efficiency of photovoltaic cells. They used twelve nozzles to spray the water over the top of the PV module and preserved the water layer thickness at about 1 mm. according to the results from his experiments, the functional PV cells' temperature was decreased to 22°C, which was lower than in the typical reference PV panel, and conversion efficiency was enhanced, the water evaporation was further cause the additional cooling. The increase of electrical power over the whole day was 10.3%. Huang et al. [12] employed another technique to enhance cooling PV modules that involved the use of phase change materials, they studied experimentally the influence of convection and crystalline segregation in a PCM as a function of thermal efficiency within a finned PV/PCM system, the experimental results proved that the presence of the fins lead effectively to reduce the temperature of the top face of the PV/PCM system. In another study presented by Hasan et al. [13] that looked at experimentally and numerically developed PV/PCM systems under different climate conditions to cool the PV cells temperature, they used two types of phase change materials; including a salt hydrate, $CaCl_2·6H_2O$, and a eutectic mixture of fatty acids, capric acid-palmitic acid. Their results indicated that regardless of the type of the PCM, using PCMs helped to reduce the PV cells temperature and prevented the PV power loss and increased PV conversion efficiencies. Other method to reduce PV cells temperature have been presented by Alkhalidi et al. [14] they used a heat dissipating fins compiled with repurposed materials such as high-density polyethylene and plastic bags placed under the PV panels, their results showed that the utilization of heat dissipating fins with repurposed materials helped to decries the temperature of the PV panel and increased its efficiency. Photovoltaic panels cooling for instance can be enhanced by mounting metallic materials with fins on the back of the panels to provide good air circulation [15–17]. Reports described the electrical behavior of PV panels and the effect of increasing the temperature of the solar cell on the efficiency of PV panels [18,19], improving the electrical efficiency of PV panels has been presented experimentally by Mazón-Hernández et al. [20], they employed two photovoltaic panels with different designs, the first panel was in normal conditions to be used as a reference and the second-one was modified which has been placed above a steel plate, with an air circulation channel underneath. Their experimental results showed that there is a negative relationship between temperature and the electrical efficiency of the panels, they discovered that decreasing the average temperature of the photovoltaic panel significantly improved the efficiency of solar cells production of electrical energy. Using a variety of heat sinks and wick structures made of different metal materials, such as copper and aluminum fins, to lower PV cells' temperature and increase their electrical efficiency was experimentally tested by Parkunam et al. [21]. They discovered that the presence of fins aided in heat removal from the PV module's back surface, which lead to reduce the PV cell's temperature and increase their electrical efficiency for both types of fins, However, copper fins had a greater impact on the electrical efficiency of the PV module than did aluminum fins, due to copper metal has a higher thermal conductivity. Firoozzadeh et al. [22] have conducted another experimental investigation to lower the temperature of PV panels. They used rectangular aluminum fins with a 4 cm width that were placed at the back surface of the PV panels as a coolant, and the tests were carried out under conditions that included the maximum operating temperature for PV panels, which is known as 85°C, and two different solar irradiation values (630,420 W/m^2). The experimental results showed that the use of aluminum fins caused the temperature of the PV panels to decrease by 7.4°C, and this reduction gave rise to a 2.72% in the electrical efficiency.

In order to increase the efficiency of solar panels, decrease the operating temperature of the solar cells, and extend the life span of the cells, many numerical simulations have been conducted using the software ANSYS Fluent. In the case of using an aluminum heat sink with ribs, Hudişteanu et al. [23] have conducted a numerical simulation to optimize cooling PV panels, used varied heights of ribs. In other paper, Popovici et al. [24] utilized different angles of the ribs. The results of an CFD models analysis indicated a significant drop in the working temperature of the solar cells and an improvement in PV panel efficiency at high-velocity values for longest rib h = 5 cm, and rib angle ≤90°. In another work, Egab et al. [25] has presented a numerical analysis that uses an air heat sink with various fin configurations to improve the cooling of a PV panel. The heat sink was constructed of rectangular, copper-based fins with and without perforations that were made of a high thermal conductivity material such as copper. For different ambient temperatures (25°C and 35°C), different heat flux values (800, 1,000 and 1,250 W/m^2), and various configurations of the heat sink, which are obtained by changing the fin numbers and hole distances are chosen as variable parameters to examine their effects on the PV panel temperature. The numerical results showed that augmentation of the number of fins and holes helped to reduce the temperature of the PV panel by around 50% compared to PV panels without fins.

According to literature review, numerous research advances have been focused on improving or finding new techniques and designs to cool PV panels and increase their efficiency. The aim of the current simulations was to evaluate the impact of using a new copper heat dissipator design on the efficiency of a photovoltaic panel utilizing a simplified combination of computational fluid dynamics techniques, the proposed heat dissipator contains a novel shape of the ribs, which are cylindrical ribs with two different configurations (with and without perforations). The proposed method presents qualitative and quantitative advantages over the ones analyzed in literature: the uniformity of the heat flow extracted and the reduction of the air flow requirement for cooling, due to the low speeds. The numerical simulation was performed with the ANSYS Fluent program, and 3D modelling was accomplished to determine the optimal operating temperature of the photovoltaic module.

2. Materials and methods

2.1. Numerical approach

Fig. 1 shows the layout and structure of a photovoltaic panel with a copper heat dissipator, which was realized using ANSYS – Design Modeler. The copper heat dissipator was attached to a perpendicular photovoltaic panel at the back, and the ribs of the heat dissipator have circular holes with diameters (D) of 0.006 m, placed at 0.03 m from one to another. These holes were designed to improve air circulation around the ribs and enabling the capture of greater quantities of waste energy from the photovoltaic module. The base and ribs of the heat dissipator were both 2 mm thick. The fluid domain for air had a width (w) of 0.1 m, with the resulting hydraulic diameter (D_h) of 0.166 m. The mass flow rates ($\dot{m}$) at the inlet were 0.03, 0.045, and 0.061 kg/s, with a temperature of 35°C. Different cases studied were realized by changing the ribs model. The ribs in the first case were not perforated, whereas the ribs in the second-case were perforated. The construction of PV panel which used in this study was presented by Armstrong and Hurley [26] that included external glass, ARC (anti-reflective coating), PV cells, EVA (ethylene-vinyl acetate), metal rear contact, and Tedlar (realized from PVF). Table 1 shows the thermo-physical characteristics of these various layers.

The mesh (Fig. 2) was accomplished with different refinements for the heat dissipator and air channel. Hence, the minimum cell size in the interest domain for the heat dissipator and ribs was 2 mm, and the air channel was 8 mm. This was necessary to obtain precise and accurate results. The mesh was generated using ANSYS-Meshing, that resulted in a total of 1, 314, 416 nodes and 6, 955, 239 elements.

The numerical simulation was carried out with the use of the ANSYS-Fluent software. To estimate the velocity distribution and temperature of the airflow in the field as well as the temperature of PV cells, the equations of continuity, momentum, and energy were solved for the conservation of the volume control. The average temperatures of photovoltaic cells were determined under a steady-state regime for the two configurations of the heat dissipator and for inlet mass flow rates of 0.03, 0.045, and 0.061 kg/s. According to the meteorological conditions

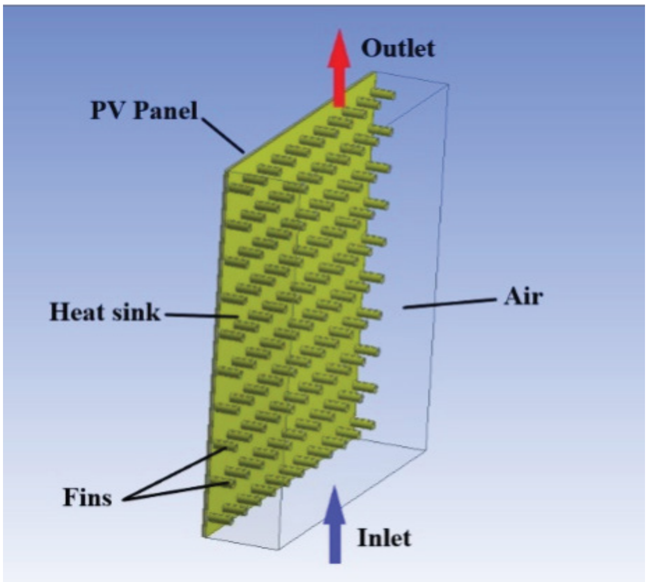

Fig. 1. Geometry of the proposed model.

Table 1
Thermo-physical properties of the PV panel layer [26]

Layer	Thickness (m)	ρ (kg/m^3)	C_p (J/kg·K)	λ (W/m·K)
Glass	0.003	3,000	500	1.8
ARC	100×10^{-9}	2,400	691	32
PV cells	225×10^{-6}	2,330	677	148
EVA	500×10^{-6}	960	2,090	0.35
Rear contact	10×10^{-6}	2,700	900	237
PVF	0.0001	1,200	1,250	0.2

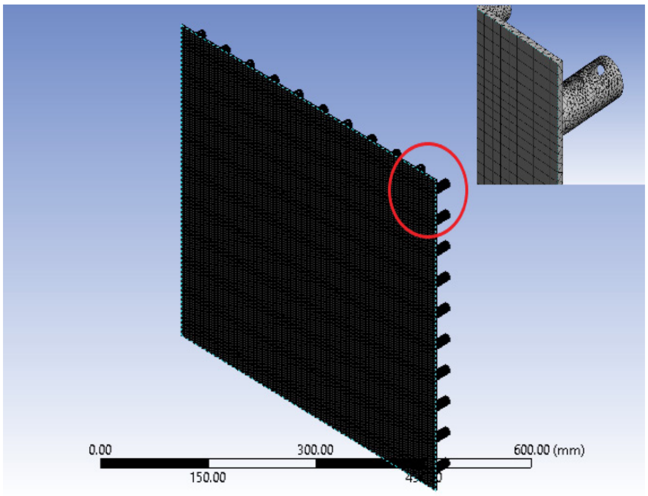

Fig. 2. Mesh of the proposed model.

which reported by Popovici et al. [24]. The sunlight conditions and the ambient temperature were taken into consideration for a summer day without clouds and for a vertical location of a photovoltaic panel. The maximum solar radiation and the ambient temperature for these conditions were around 500 W/m², and 35°C respectively.

The Reynolds (Re) number and turbulence intensity (I) were calculated using Eqs. (1) and (2):

$$\mathrm{Re} = \frac{\rho V D}{\mu} \tag{1}$$

$$I = 0.16\,\mathrm{Re}^{-1/8} \tag{2}$$

where ρ and μ are density (kg/m³) and viscosity (kg/m s) of fluid, respectively [24].

The Reynolds number for the imposed mass flow rates was between 4,310 and 13,100. Therefore, the flow regime considered was turbulent, and the predicted intensity of the turbulence was 5.4%, 5.16% and 5%, respectively for inlet mass flow rates of 0.03, 0.045, and 0.061 kg/s. The simulations were conducted using constant conditions with the k–ε (RNG) turbulence model, which is the most realistic for airflow inside channels [27]. The equations were solved using the semi-implicit method for pressure-linked equation (SIMPLE) pressure velocity coupling and the second-order upwind scheme, with convergence criteria of 10^{-6} for energy and 10^{-3} for pressure, velocity, and continuity equations.

3. Results and discussion

The simulation results revealed that the temperature of the photovoltaic panel varied depending on the inlet mass flow rates. The temperature distributions and velocity spectra for various types of cylindrical ribs are illustrated in Figs. 3–8 to provide a better understanding of the events happening inside the channel and adjacent to the ribs of the heat dissipator.

3.1. Temperature distribution

During the simulation process, temperature had a very important influence. Figs. 3–5 demonstrate the evolution of the total temperature distribution on the surface of the photovoltaic modules with and without copper heat dissipators with a solar radiation of 500 W/m², as well as in the sections of the cooling ducts.

According to Fig. 3, it can be observed that the surface temperature of a non-cooled photovoltaic panel (without a heat dissipators) increased to about 115°C at low mass flow rates values because the PV cells transform only tiny percentage of the solar radiation incident into electrical energy and the remaining accumulates as heat losses in the unit except when it was recovered and used by another thermal system.

The presence of a heat dissipator with ribs affects heat transfer and airflow from the PV module to the ventilated channel. To ensure that the required cooling was achieved at the cell temperature, heat transfer surface area was increased by utilizing ribs. Convection heat transfer was doubled using forced circulation, and various rib types (perforated and non-perforated ribs) were employed with the aim of slowing the airflow in order to have time to carry heat.

According to Figs. 4 and 5, it was observed that the lowest temperature of the PV cells was achieved at a high mass flow rate value of 0.061 kg/s. A more intense heat transfer of the solar cell was recorded when perforated fins were utilized with a value of 59.2°C, compared to when non-perforated fins were utilized with a value of 62.5°C.

3.2. Velocity iso-contours

Figs. 6–8 show the velocity contours of circulated cooling air flowing through the ventilation channel. It can be clearly observed from these contours that, the presence of ribs in the heat dissipator created turbulence in the airflow, which increased the heat transfer from the photovoltaic module into the cooling air, High mass flow rates cause a high level of turbulence, which can reduce the thickness of the thermal boundary layer and affect the high-temperature gradient at the bottom of the PV panel.

As seen in Figs. 6–8, the air flow and temperature distributions throughout channel ventilation in the case using perforated fins were more intense and homogeneous than when using non-perforated ribs. Furthermore, it can be deduced that the air circulation in the case of the use of perforated fins was more efficient because it helped to increase the heat transfer by convection.

4. Conclusions

The installation of thermal devices and photovoltaic solar systems is rapidly increasing due to the sheer growing demand for electricity and heat. The photovoltaic modules electrical performance rapidly drops as the surface temperatures increase. PV module face cooling is an effective method to overcome this drop in efficiency. To improve the performance of PV panels, a CFD simulation was performed for cooling photovoltaic modules using a new design of an economical and easy-to-manufacture copper

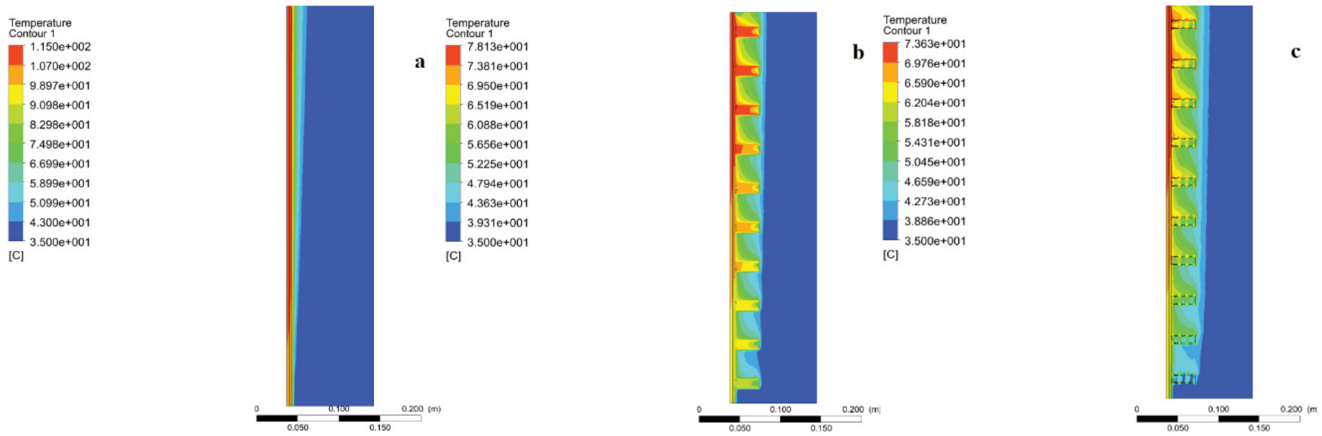

Fig. 3. Temperature distributions at $\dot{m}$= 0.03 kg/s for cases: (a) without ribs, (b) with non-perforated ribs, and (c) with perforated ribs.

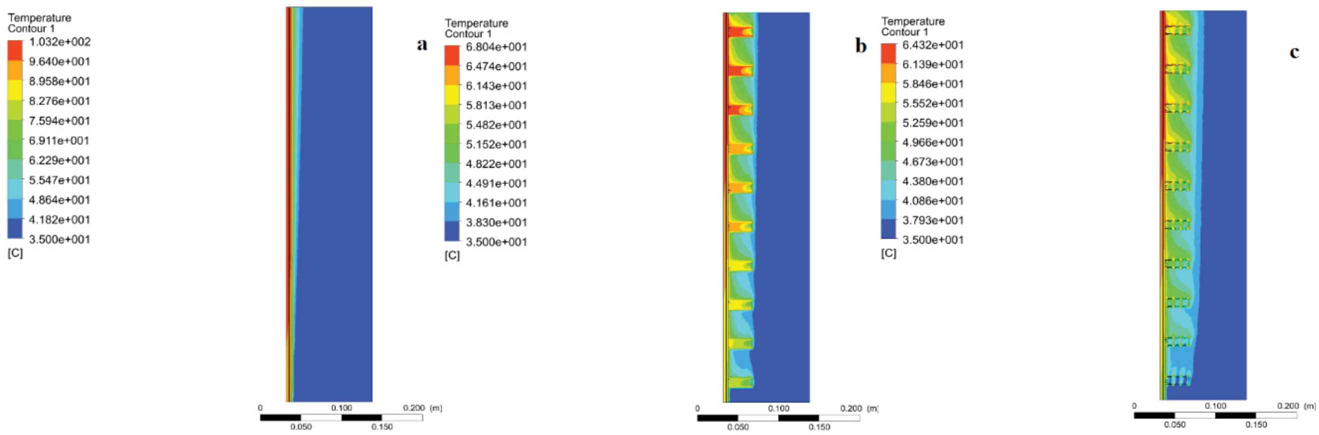

Fig. 4. Temperature distributions at $\dot{m}$= 0.045 kg/s for cases: (a) without ribs, (b) with non-perforated ribs, and (c) with perforated ribs.

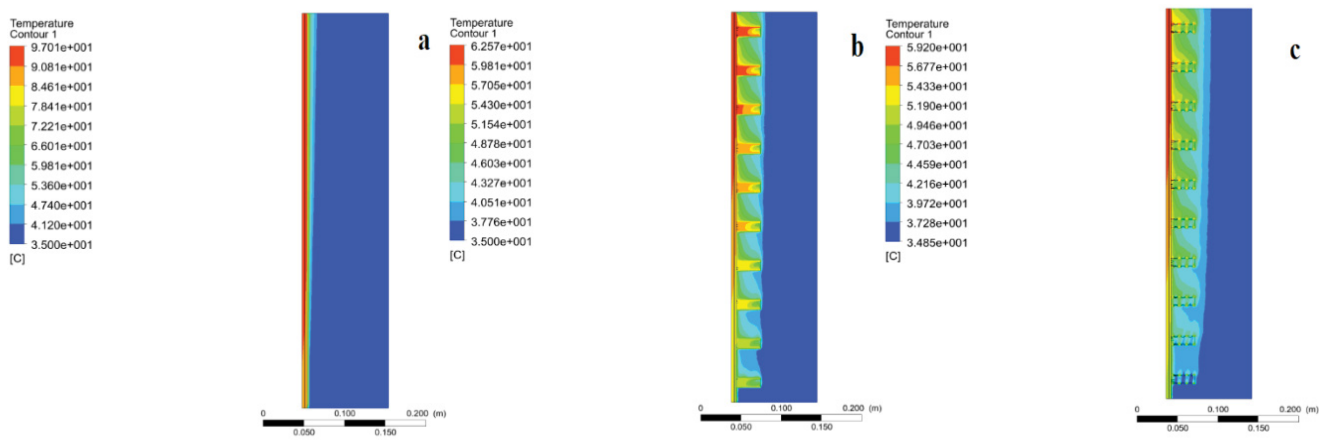

Fig. 5. Temperature distributions at $\dot{m}$= 0.061 kg/s for cases: (a) without ribs, (b) with non-perforated ribs, and (c) with perforated ribs.

heat dissipator that contains a novel shape of the ribs, which are cylindrical ribs with two different configurations (with and without perforations). Theoretical and numerical research was provided for the case models in this study, including the maximum solar radiation value of 500 W/m^2 as a constant and a photovoltaic panel with a small size of 0.5 m × 0.5 m. The results showed that high mass flow rate inlets could reduce the average temperature of photovoltaic modules with a heat dissipator by up to 38°C, which was better than the results achieved by Popovici et al. [24] and

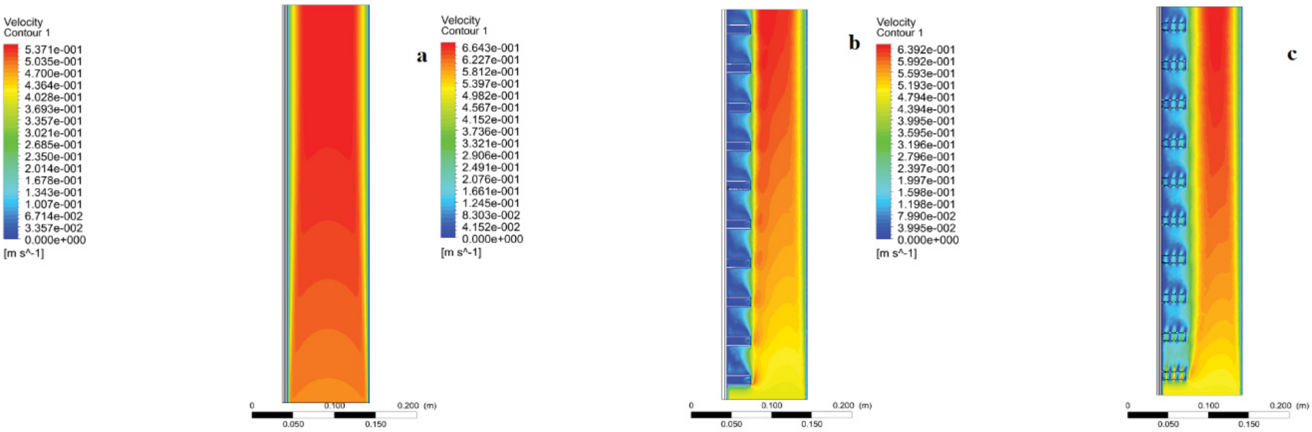

Fig. 6. Velocity spectra at $\dot{m}$ = 0.03 kg/s for cases: (a) without ribs, (b) with non-perforated ribs, and (c) with perforated ribs.

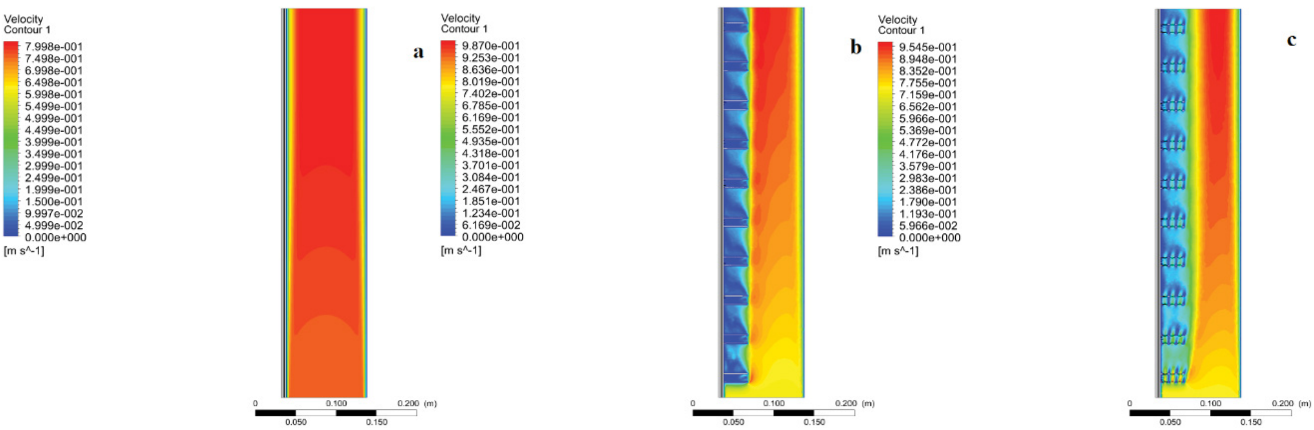

Fig. 7. Velocity spectra at $\dot{m}$ = 0.045 kg/s for cases: (a) without ribs, (b) with non-perforated ribs, and (c) with perforated ribs.

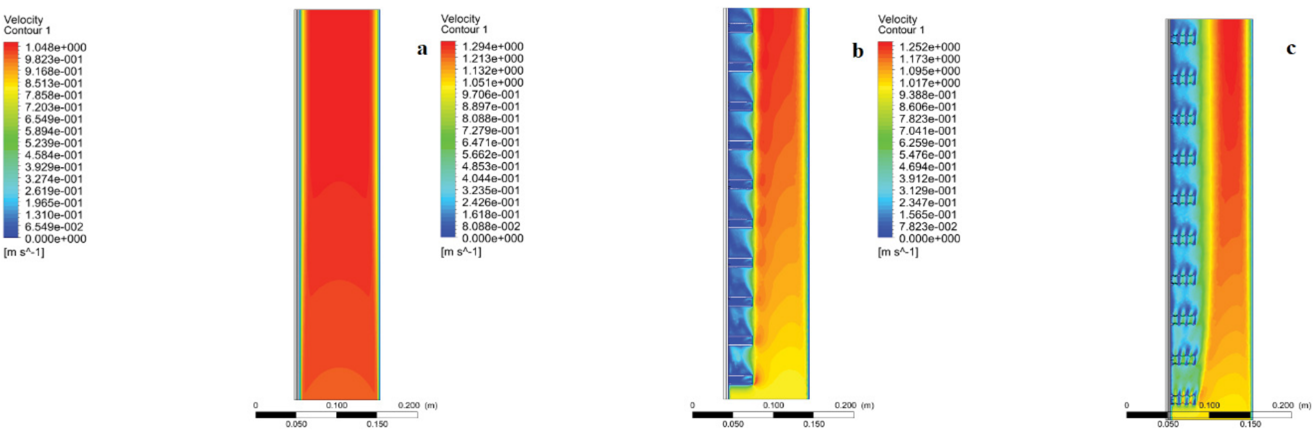

Fig. 8. Velocity spectra at $\dot{m}$ = 0.061 kg/s for cases: (a) without ribs, (b) with non-perforated ribs, and (c) with perforated ribs.

Arifin et al. [28] in the case of using an aluminum heat dissipator with rectangular ribs, where they were able to reduce the temperature by up to 10°C lower than the value obtained in the basic case. The presence of ribs enhanced the heat transfer area and heat transfer performance. Comparing the two types of ribs, perforated ribs were the best option for cooling PV panels because they could improve the uniformity of the airflow distribution inside the ventilation channel, reduce stagnant zones, contribute to thermal homogeneity, and improve temperature and cooling distribution, especially in the vicinity of the fins.

It can be concluded that the PV panels operating temperature has a significant effect on its conversion efficiency. The design of the heat dissipator model outlined in this study could represent a cost-effective and energy-efficient option for cooling photovoltaic panels and may lead indirectly to a lowering of CO_2 emissions due to higher electricity generation efficiency.

Symbols

C_p	—	Specific heat of air, J/kg·K
D	—	Circular tube diameter, m
D_h	—	Hydraulic diameter, m
I	—	Turbulence intensity, %
$\dot{m}$	—	Mass flow rate, kg/s
w	—	Width of air duct, m
Re	—	Reynolds number
V	—	Velocity, m/s

Greek

λ	—	Thermal conductivity, W/m²·K
ϱ	—	Density, kg/m³
μ	—	Dynamic viscosity, Ns/m²

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