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Exploring the Impact of Diverse Cooling Duct Configurations on Photovoltaic Panel Performance

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ABSTRACT

Photovoltaic (PV) panels are an emerging technology that captures solar energy and produces electricity. One key concern with PV panels is the detrimental effect of high temperatures on their performance and efficiency, which is leading to a shorter service life. Cooling the panels can help to maintain appropriate working temperatures, reduce the adverse effects of heat, and increase overall energy production. This research aims to investigate experimentally and numerically the effectiveness of a cooling channel with different configurations in lowering PV panels' temperature. The findings of the experiments show that cooling methods improved panel efficiency by 0.35% and reduced the intake temperature by 7%. In numerical analysis, different 3D cooling channel geometries were investigated, and the tapered duct was found to be the best in reducing Tav at 1.73%.

1. Introduction

In the wake of burgeoning global energy demand and increasing environmental concerns, the imperative for sustainable and renewable energy sources has assumed unprecedented significance [1-3]. Renewable energy, characterized by its ability to harness natural resources that are constantly replenished, stands as a pivotal solution to mitigate the adverse effects of traditional fossil fuel-based energy systems [4]. Among the diverse array of renewable options, solar energy emerges as a frontrunner, captivating attention for its abundant and inexhaustible nature. Solar energy can be used thermally through solar collectors and electrically through solar photovoltaics (PV) [5].

Solar power captures the energy emitted by the sun and converts it into electricity using technologies, with photovoltaics (PV) leading the way. Photovoltaic panels are devices used for the efficient and long-term conversion of plentiful and converting solar radiation into electrical energy [6]. Over the years solar cell systems that convert sunlight into direct current electricity have made impressive progress. By incorporating PV technology, we are not embracing a transition towards cleaner energy but also addressing the urgent need to decrease carbon emissions and reduce our reliance on limited resources.

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The importance of the PV conversion process depends on the temperature of a solar PV module. Examining the thermal facets of a solar module provides a clear understanding of a power generation PV system, as the crucial specifications of a photovoltaic module rely on the surrounding circumstances of the installation area [7]. A PV cooling system is a device or technique that lowers the running temperature of photovoltaic (PV) cells. PV cooling systems can improve the efficiency and performance of PV modules, as well as extend their lifespan.

Different kinds of PV cooling systems exist, including Active cooling systems (ACS) that use an external energy source to circulate water or air over the photovoltaic system, passive cooling systems (PCS) to remove heat from PV modules by natural convection or radiation, and phase change material (PCM) cooling systems with a substance can change its physical state to absorb heat. Cooling systems play a vital role in the overall performance and reliability of PV panels [8]. Water cooling is a highly effective method for cooling PV panels compared to air cooling. Water cooling involves the use of liquid, typically water, as a heat transfer medium to dissipate excess heat generated by the photovoltaic modules [9]. Overheating can reduce the power output and degrade the lifespan of PV panels.

Siecker [10] reviewed various cooling methods that have been developed to address the issue of elevated temperatures in PV systems. They categorize and analyse these methods based on their focus, contributions, and cooling technology. The goal was to provide engineers with a comprehensive understanding of the available cooling options and guide them in selecting the most suitable method for their specific application.

Wan Ariff [11] presented a thermal control scheme for photovoltaic (PV) panels that incorporates a water-cooling system using copper piping. The purpose is to increase PV module efficiency by lowering panel temperature. The study examines the impacts of PV cells with and without a water-cooling system, demonstrating that utilizing a water-cooling system reduces panel temperature by 16 °C. For 300 lh flow rates, the panel's efficiency increases by 3%.

Murtadha studied [12] The impact of cooling solar panels and the potential for storing the heat extracted by the PV cooling system in paraffin wax phase change material. The useful energy output of the uncooled PV panel exhibited a significant increase, rising from 39.2 W to 71.7 W in the new system, surpassing the output of the cooled panel. The cooling process resulted in an increase in efficiency from 14.2% to 14.7%. Implementing a water-cooled system resulted in a notable 14.5% decrease in the operating temperatures of the PV panel in comparison to the panel without cooling.

Ali investigated [13] the effectiveness of solar panels through the implementation of micro-channel cooling. Experiments combined with computational simulations resulted in a 3D model being constructed to analyse the behaviour of a mono-crystalline solar cell when exposed to various levels of light and water flow. Subsequently, a real-world experiment was conducted using two 35W panels. One panel followed conventional manufacturing processes, while the other incorporated a 4mm aluminium sheet with micro-channels. The results were a 15 °C drop in solar panels' surface temperature and a 14% improvement in power output.

Sheikholeslami *et al.,* [14] improved the overall efficiency of photovoltaic systems by designing a PVT unit and investigating innovative methods to enhance its performance. Two techniques were utilized to improve the cooling of the PV component: introducing a novel turbulator design and incorporating confined jets. The testing fluid, water, was enriched with nanoparticles. The Finite Volume Method was selected to simulate the current 3D model, specifically for laminar flow. The photovoltaic temperature decreased between 5.69% to 6.68%.

Within the scope of this study, numerical and experimental methodology was utilized to gather additional information concerning the impact of lowering the temperature of photovoltaic panels through water cooling. Various geometries for cooling channel configurations were explored numerically. The module was instrumented with thermocouples, flow meters, and a solar heat flux sensor for experimental thermal analysis. Also, it was numerically studied with COMSOL software to obtain temperature patterns. This study introduces an innovative approach for improving solar photovoltaic panel performance and determining the best cooling shape for lowering PV temperature. The research promotes renewable energy technology and offers practical advice for improving PV system performance and lifespan in high-temperature conditions.

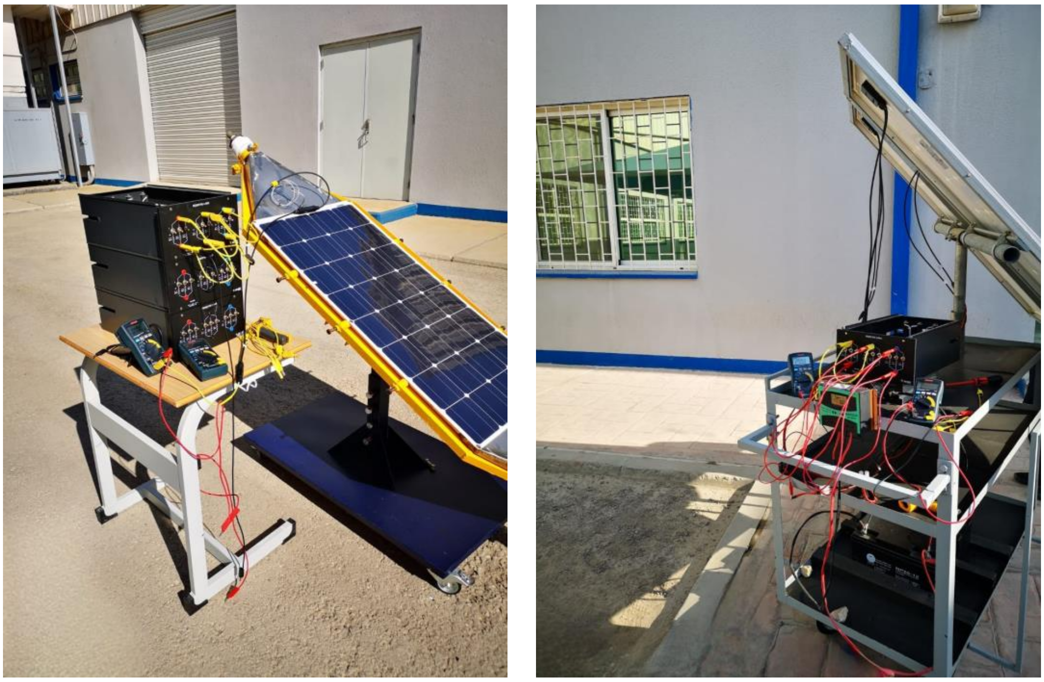
The weather conditions, such as the speed of wind, clouds, humidity, and sun radiation, contrast throughout the day according to the zone area [15]. The authentic design was examined in physical tests at Jubail Technical Institute, located in Jubail, Saudi Arabia, in November, where the average ambient temperature is 26 ℃.

2. Materials and Method

A cooling duct was fabricated to investigate the effect of a thin film of water on cooling the PV solar panel. In addition, a three-dimensional model of cooling ducts was numerically investigated using COMSOL Multiphysics® to determine which duct was most capable of minimizing the solar panel temperature.

2.1 Experimental Approach

An experimental approach is employed to study the effect of cooling the panel with water. In this experimental study, an innovative design of a solar panel cooling duct is suggested to improve its mechanical and thermal behaviour under operational conditions. Inlet and outlet temperatures were measured by two thermocouples. Data logger HUATO's S220-T8 with an eight-channel was used with Accuracy ±1℃. T-type thermocouples of stainless steel were used; the outer surface temperature of the electrical heater was measured by an infrared thermometer. The experimental setup details are illustrated in Figure 1.



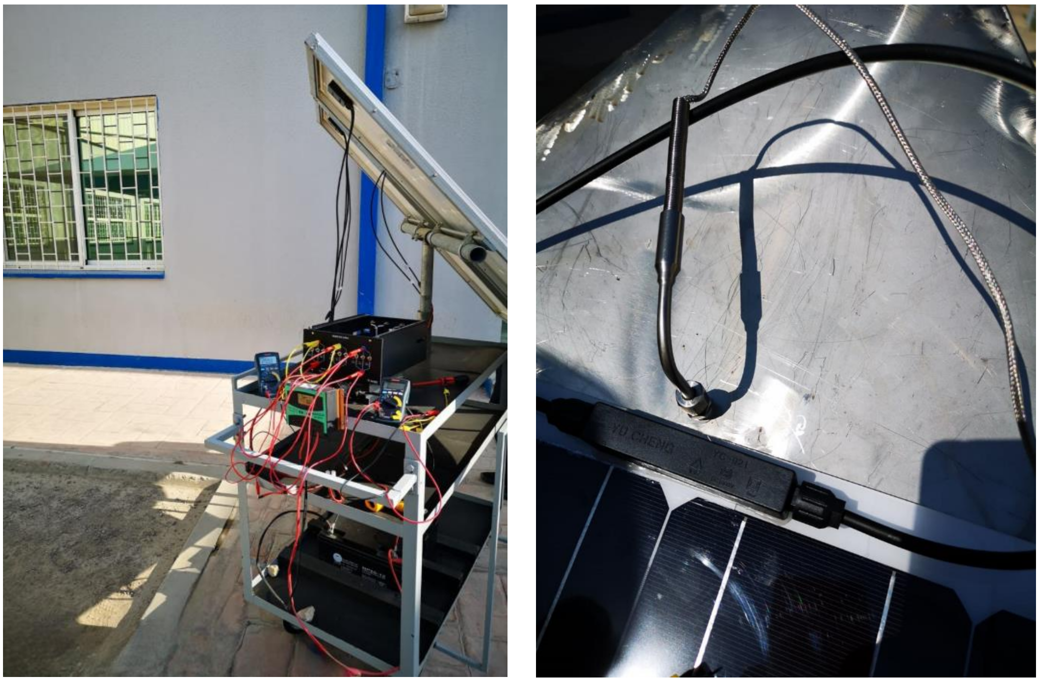


Fig. 1. PV system experimental with connections and thermocouple's locations

The accuracy of the experimental results was confirmed through uncertainty analysis. A standard error analysis was performed to determine the uncertainties related to the obtained results. Table 1 provides the precise values of uncertainty.

Table 1
Uncertainty analysis

Item	Uncertainty
Water flow rate	±2.0%
Outlet temperature	0.3% + 1 °C
Infrared Thermometer	±3.0%
Data logger temperature	±1℃
DC voltage accuracy	0.08% + 5

A comparison was made between experimental data and numerical results to validate the experimental and numerical model, which agreed with the results obtained by [14,16]. The electrical and physical characteristics of the PV modules are shown in Table 2.

Table 2
PV characteristics

Item	Value
Maximum Power (Pmax)	100 W
Maximum Power Current (Imp)	6.25 A
Maximum Power Voltage (Vmp)	16 V
Short Circuit Current (Isc)	6.68 A
Open Circuit Voltage (Voc)	19.2 V

2.2 Numerical Approach

In my numerical investigation, COMSOL [17]. The results indicated a significant decrease in temperature, which is reflected in enhancing panel efficiency and improvement of power output.

This study highlights the potential of water cooling as a possible solution for maximizing the performance of solar energy systems.

Grid dependence studies were conducted to assess the number of elements that affect the rise of the outlet temperature of the heat transfer fluid. The studies focused on a laminar flow regime and covered an inlet Reynolds number range of 700 to 800. The grid was carefully refined to ensure no significant impact on the numerical results. To determine the minimum number of elements needed in a model to ensure that changes in the mesh size do not affect the results of an analysis. COMSOL provides various options for generating the mesh of the domain to ensure that the current numerical simulation is independent of the grid cells. These options include selecting predefined physics-controlled meshes with different levels of coarseness, ranging from extremely-coarse to extremely-fine. Mesch selected was finer with 120,000 elements with relative error 3.0E-04

3. Results and Discussion

The change in temperature will influence the cells' power production. The voltage depends heavily on temperature, and a reduction in temperature will raise the voltage. The PV panel surfaces are divided into six areas: Upper left (Point 1), Upper right (Point 2), middle left (Point 3), middle right (Point 4), Lower left (Point 5), Lower right (Point 6). The temperature was measured before and after cooling with a flow rate of 1.30 litre/min. Figure 2 illustrates the temperature measured by an infrared thermometer at six different points on the PV solar panel surfaces. Undoubtedly, the temperature of panel surfaces decreases by an average of about 15 °C. The difference in temperature fails to reach a considerable difference towards the top of the panel; however, it increases as the thin film of water moves toward the bottom of the panel.

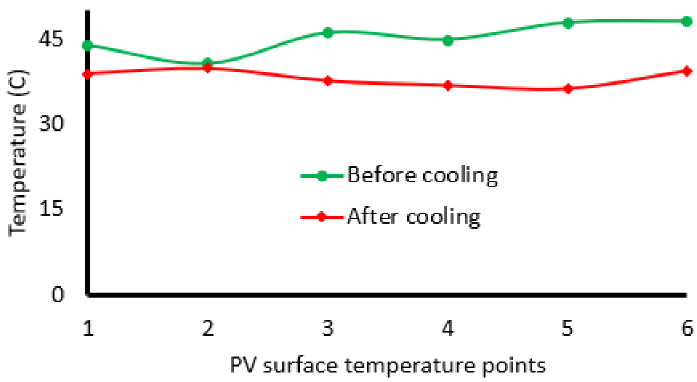


Fig. 2. PV surface point temperatures

The efficiency of the photovoltaic panel is calculated using the formula in Eq. (1) and Eq. (2) [18].

$$\%\ Efficiency = \left[\frac{Power\ output\ of\ PV\ cell}{Power\ input\ from\ the\ sun}\right]\times 100 \tag{1}$$

$$\%Efficiency = \left[\frac{Voc \times Isc\times\ fill\ factor}{Cell\ area\ \times 1000}\right]\times 100 \tag{2}$$

where, Voc is the voltage at open circuit [Volts], and Isc is the open circuit current [Amps].

The cooling of the PV solar panel increases the efficiency by 0.35%; likewise, the inlet and outlet temperatures were measured with T-type thermocouples. There was an observed decline in the inlet temperature by 7% in the panel outlet. The Isc was found to be 6 Amp, and Voc was 18.23 Volt before cooling and 18.6 Volt after cooling. The results are considered acceptable if compared with similar studies, such as the findings in [14], as the difference in results between the two studies does not exceed 5%. The approach employed may vary slightly between the two studies; however, this is the anticipated quantity of temperature reduction when cooling PV panels.

Different geometry has been investigated numerically using COMSOL for laminar flow with Reynolds number (Re) equal to 780. In order to validate the numerical module, a comparison was conducted with [19]. The calculation of the Nusselt number (Nu) was performed using various ratios of the length of the rectangular cross-section, precisely the height (b) and the base length (a), as shown in Figure 3.

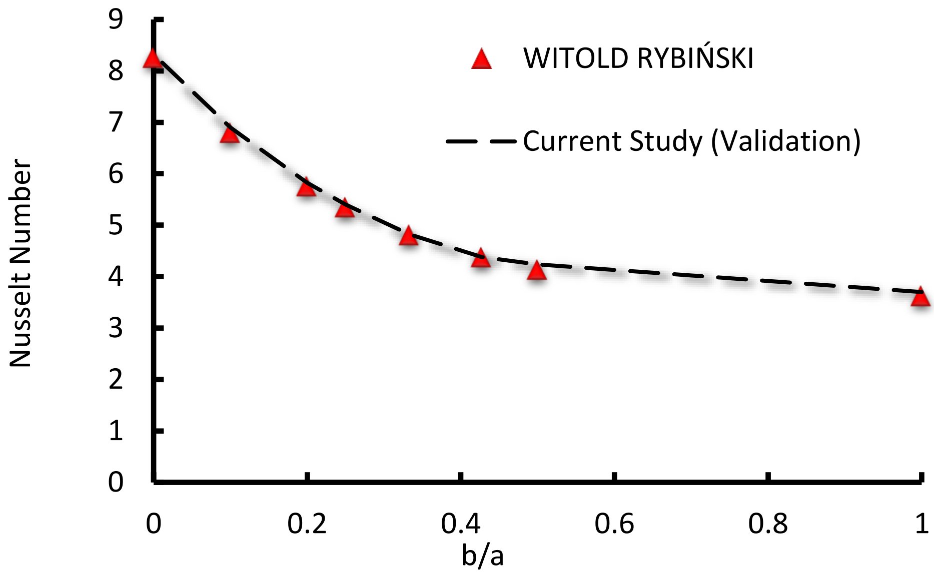


Fig. 3. Validation of COMSOL module compared with [19]

Case 1: Normal rectangular duct with a thickness of 2mm, inlet dimensions 175X5 mm, and the length of solar cell is 330 mm, as shown in Figure 4.

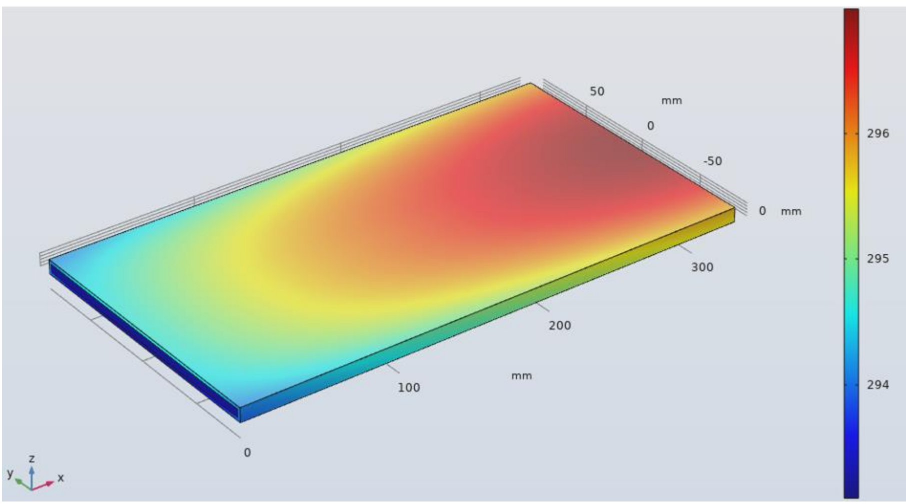


Fig. 4. Normal rectangular duct with thickness inlet dimensions 175X5 mm

Reynolds number can be defined as in Eq. (3)

$$Re = \frac{\rho u_{in} D_h}{\mu} \tag{3}$$

ρ: density [Kg/m^3], μ: dynamic viscosity [kg/ms], u_{in}: velocity[m/sec], D_h : the hydraulic diameter and can be defined in Eq. (4)

$$D_h = 4.A/P \tag{4}$$

A is the inlet area [m^2], and P is the inlet parameter [m].

The cooling fluid enters the duct at inlet temperature (Tin) and leaves the duct at outlet temperature (Tout). The upper surface of the duct is affected by the constant temperature of the solar panel. The average upper surface temperature of the duct (Tave) was reduced by 1.4% after cooling. Figure 5 represents the temperature contour for the same case.

The range of colour contour plots in this figure depicts the various temperature values [20]. The bright red represents the hottest areas in the geometry model with the highest temperature. In contrast, dark blue is the coldest area of the geometry model and the lowest temperature generated by the PV panel.

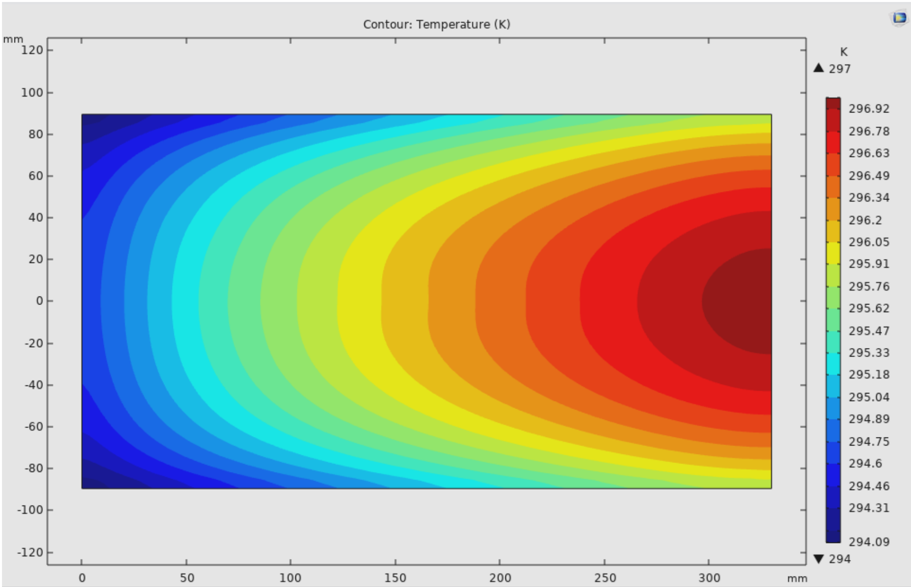


Fig. 5. Normal rectangular duct with thickness inlet dimensions 175X5 mm

Case 2: The panel cooling system. is used to dissipate heat from solar panels and conserve their optimal operating temperature. The duct undergoes a process of expansion, followed by a section where it maintains a straight structure and subsequently transitions into a contraction phase. The duct has a thickness of 2 mm, inlet dimensions of 145X5 mm, and the length of the solar cell is 330 mm as shown in Figure 6. The average upper surface temperature of the duct (T_{ave}) was reduced by 1.36% after cooling.

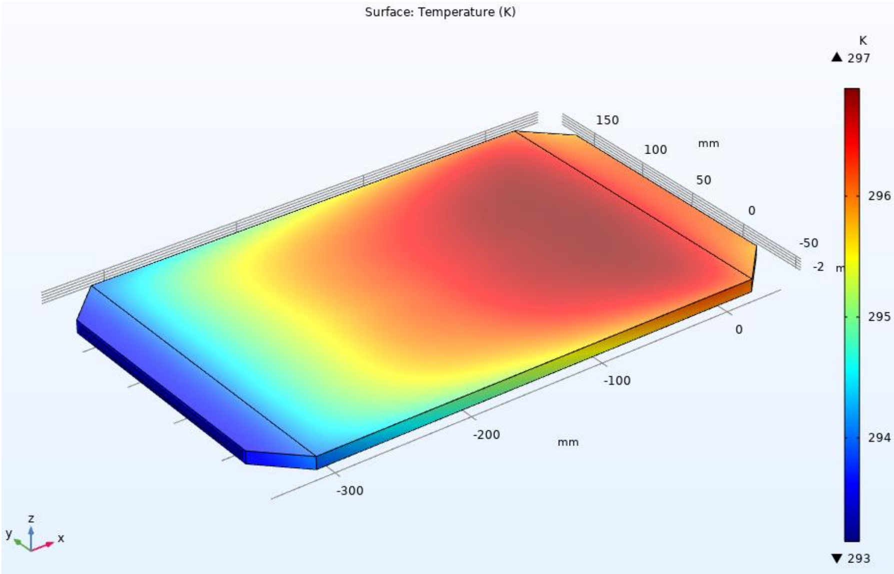


Fig. 6. Normal rectangular duct with thickness inlet dimensions 175X5 mm

Figure 7 represents the temperature contour for the same case. The reduction in temperature observed in the average temperature is less significant compared to the normal one, mainly because of the uncovered area of the solar panel with the cooling duct.

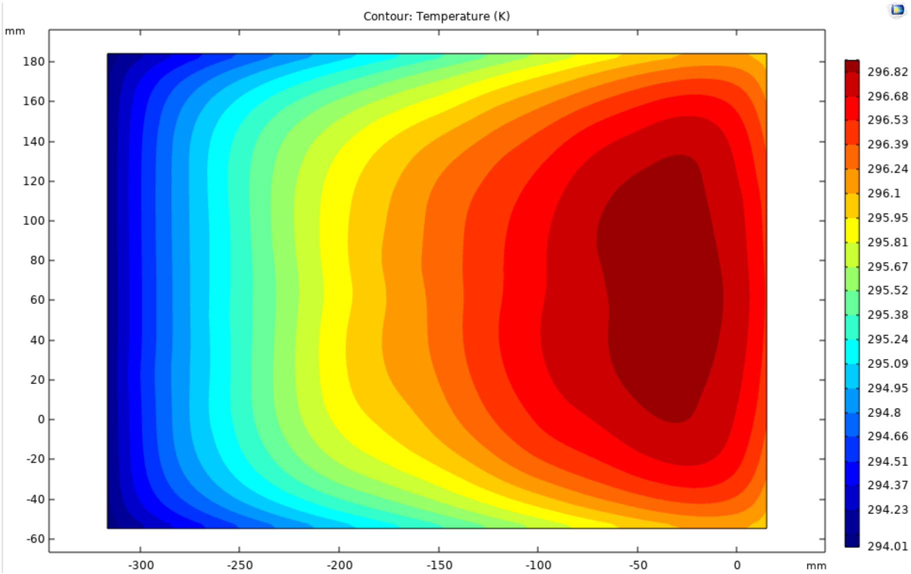


Fig. 7. Temperature contour for Expansion-Contraction duct, inlet 145X5 mm

Case 3: To avoid the uncovered area of the solar panel, the expansion and contraction formed outside the area of the panel as in Case 3, where the inlet dimensions are 175x5 mm, as represented in Figure 8.

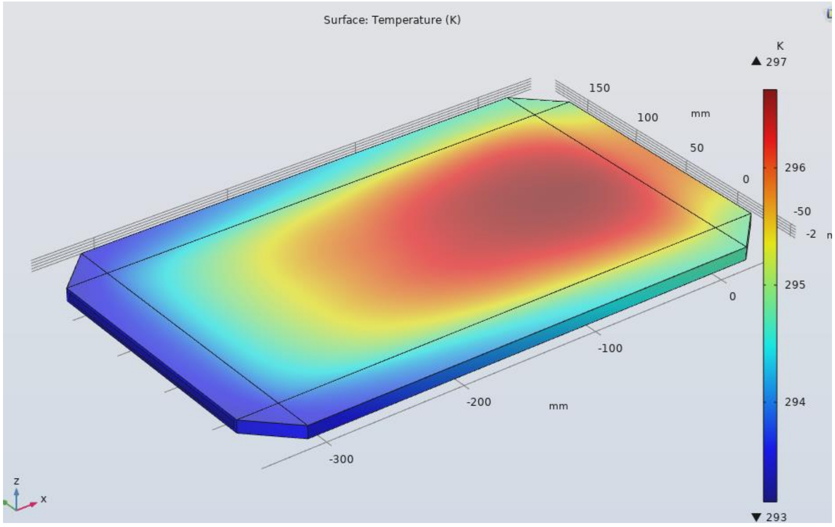


Fig. 8. Expansion-Contraction duct with inlet dimensions 175X5 mm

After implementing the cooling system, the average surface temperature (T_{ave}) experienced a reduction of 1.54%. Figure 9 depicts the temperature distribution for the same scenario.

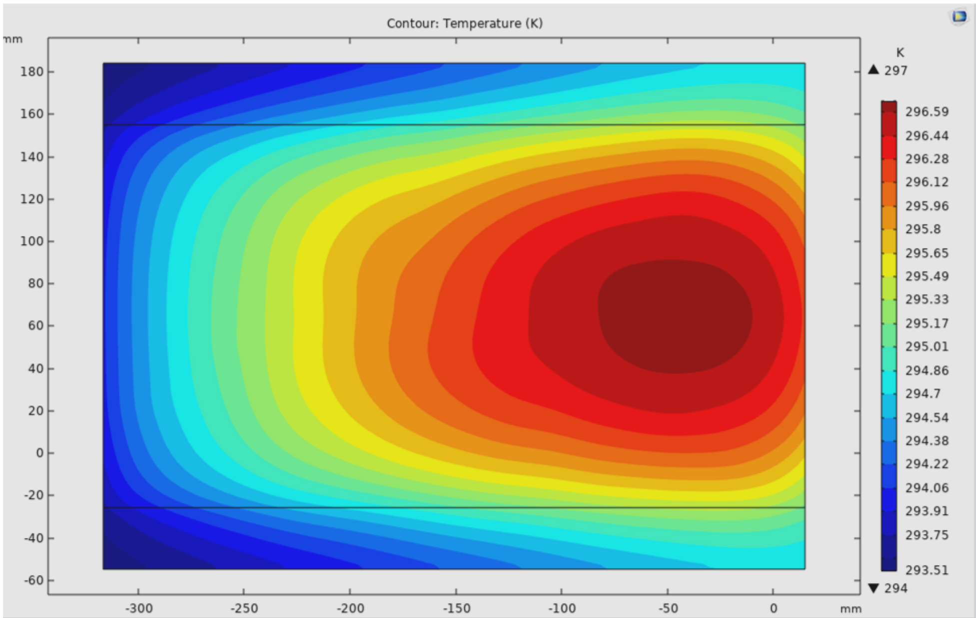


Fig. 9. Temperature contour for Expansion-Contraction duct with inlet 145X5 mm

Case 4: A sudden-expansion duct with inlet dimensions 175X5 mm was used, as indicated in Figure 10. The sudden expansion along the solar panel plays a significant role in enhancing the heat transfer, with a decrease in Tav of 1.67%. This prevents the panel from overheating, which can reduce its performance and lifespan.

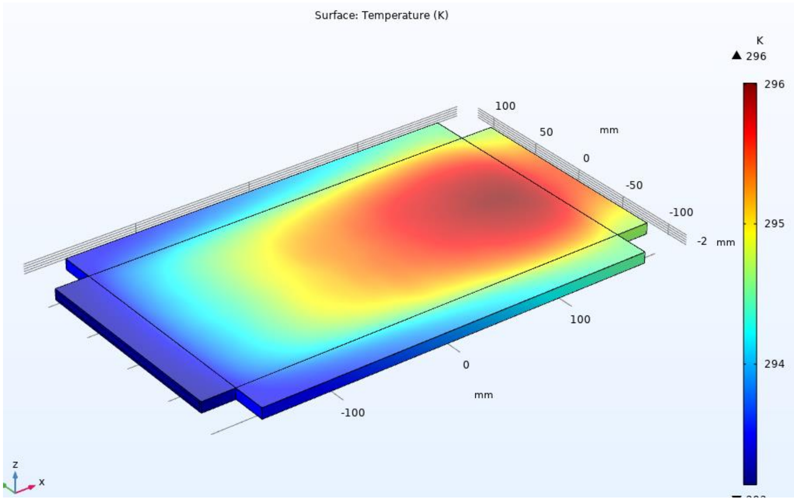


Fig. 10. Sudden-expansion duct with inlet dimensions 175X5 mm

The enhancement in temperature reduction is attributed to the vortices generated in the flow due to the sudden expansion. Figure 11 represents the temperature contour for sudden expansion.

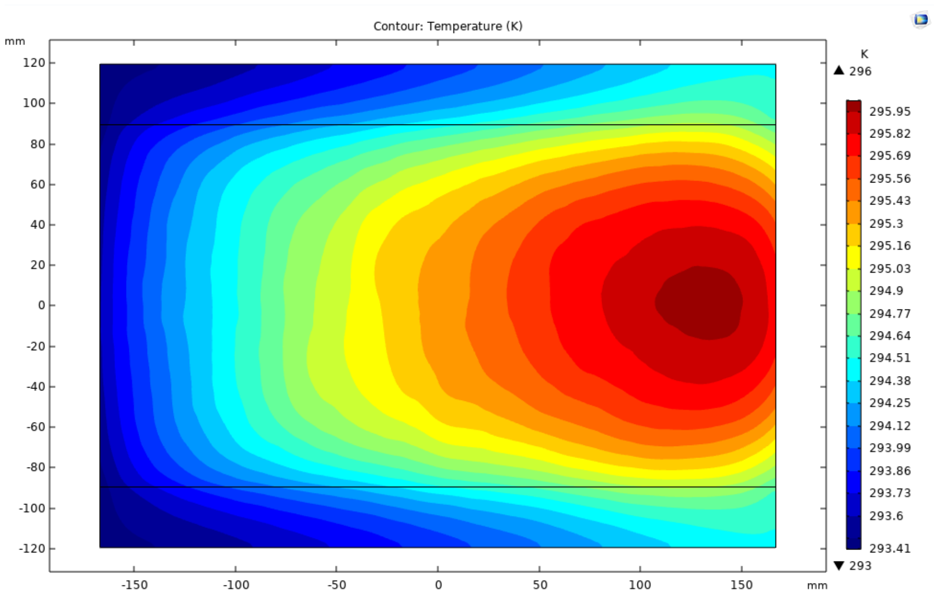


Fig. 11. Temperature contour for sudden expansion duct with inlet 175X5 mm

Case 5: The duct expands gradually in a tapered duct as illustrated in Figure 12, and the fluid velocity tends to increase. This higher velocity promotes better mixing of the fluid, which, in turn, enhances heat transfer. The reduction in Tav was found at 1.73%, which is considered the best reduction in Tav; meanwhile, the flow is laminar, and the tapered duct reduced flow separation, where the flow separation can lead to losses and turbulence, thus restricting the heat transfer.

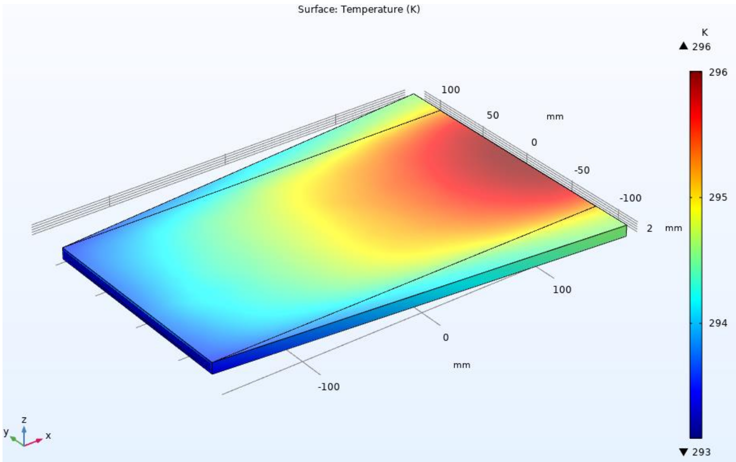


Fig. 12. Tapered duct with inlet dimensions 175X5 mm

Figure 13 represents the temperature contour for the tapered duct.

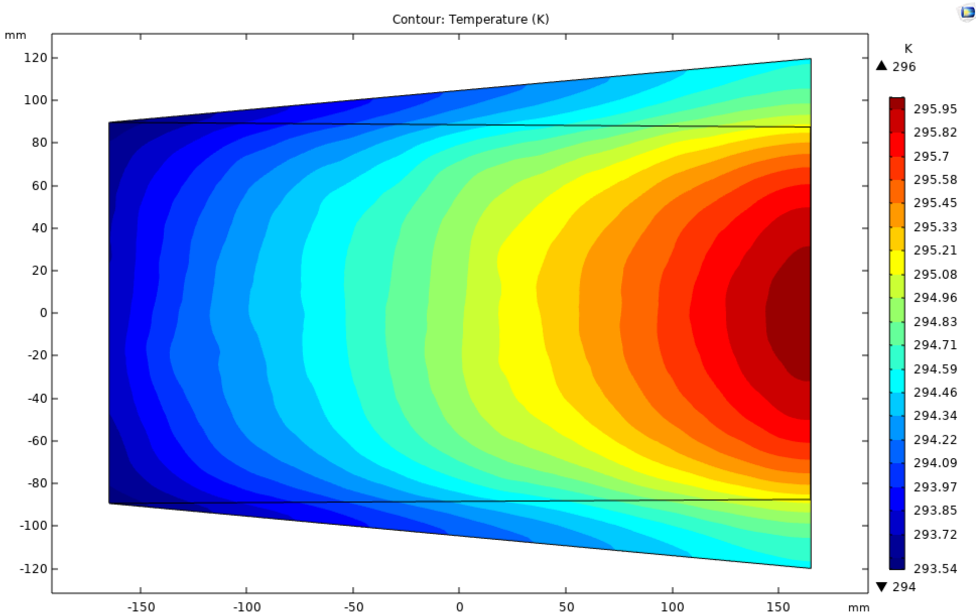


Fig. 13. Temperature contour for a tapered duct with inlet dimensions 175X5 mm

Case 6: The duct is corrugated in a vertical direction as illustrated in Figure 14. The reduction in Tav was found to be about 1.26 %, which is considered the worst case where the streamlines move in the opposite direction of the solar panel without cooling effectively.

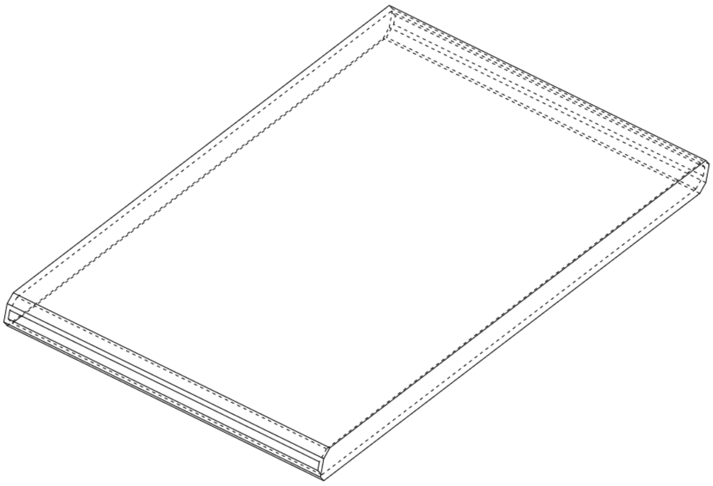


Fig. 14. A 3-D model design for a corrugated duct

Figure 15 and 16 represent the design of the 3D model of the corrugated duct, temperature distributions, and temperature contours.

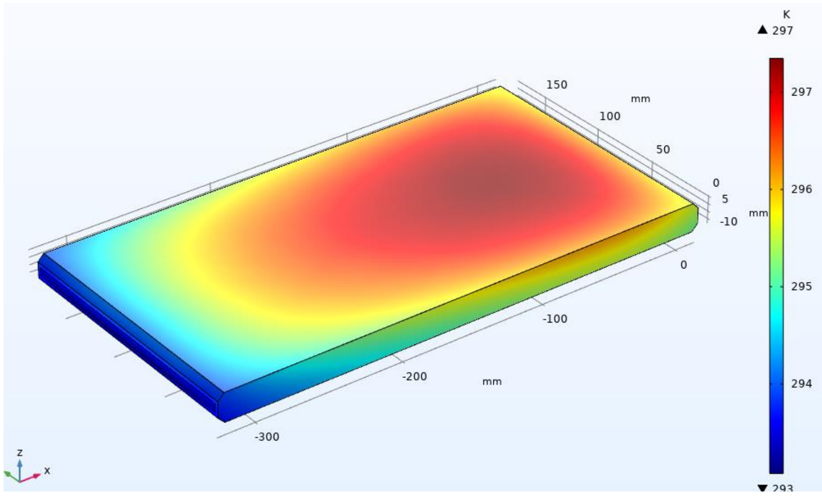


Fig. 15. Corrugated duct with inlet dimensions 175X5 mm

The simulation results revealed the uneven temperature distribution, which is anticipated to impact the PV modules' efficiency and longevity due to hot spots. It is worth observing that the surface of the PV panel lacking an effective cooling system may become coated with a vivid red hue, indicating that this PV panel is experiencing the highest temperature. The lower side of the module exhibited elevated temperatures due to the impact of the water flow. This was because the water entered the duct at its initial temperature, and after cooling the PV panels, the water temperature raised. Consequently, the cooling efficiency declined as the water transferred less heat from the PV panel. In addition, the corners exhibited a distribution of relatively low temperatures due to the active convective heat transfer and the lowest velocity.

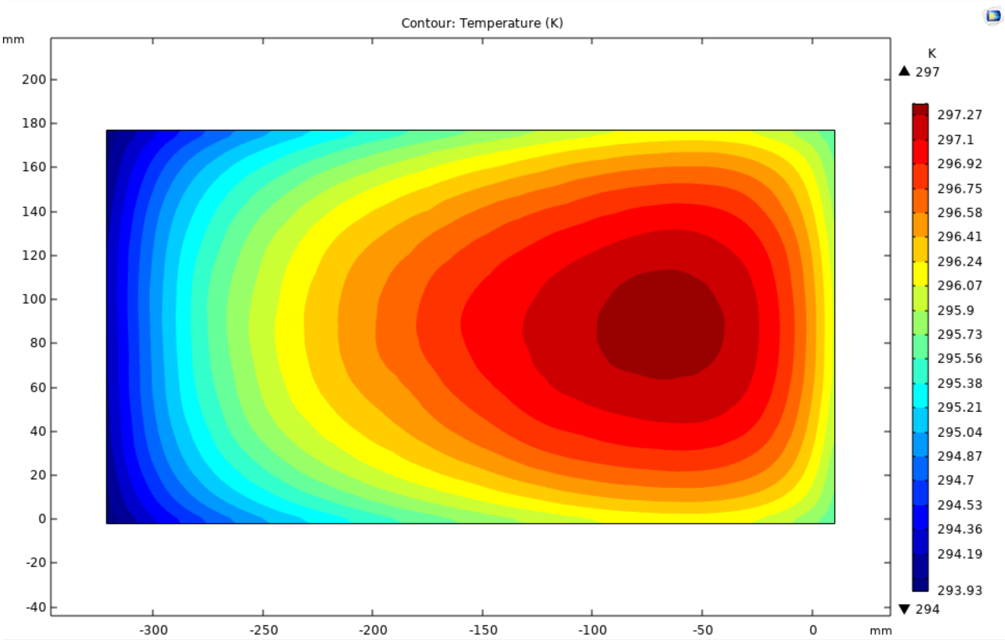


Fig. 16. Temperature contour of a corrugated duct with inlet dimensions 175X5 mm

Ultimately, the temperature drop that occurs when using water in general and the tapered duct configurations may prompt consideration of designing and producing solar panels to maximize cooling by not making the panels square or rectangular in shape but rather by gradually expanding them. Further research and investigation are needed in this area.

4. Conclusions

Photovoltaic (PV) energy stands out as an important choice for renewable energy options, producing clean and easily attainable energy. The weather and environmental conditions greatly influence the effectiveness of solar cells. These solar systems contribute to reducing humanity's reliance on non-renewable resources. An experimental analysis, as well as a computational analysis using COMSOL software, has been conducted on a three-dimensional thermal model of PV panels equipped with a water-cooling system. The primary objective of this simulation analysis is to forecast the decrease in temperature of the PV panel caused by various cooling duct geometries. The overall efficiency of the panel has risen by 0.35 %. In addition to that, the cooling system was responsible for a significant drop of 7% in the temperature of the inlet. In the numerical study, different cooling ducts were used: Normal, expansion-contraction duct, sudden expansion, vertical sudden expansion, and tapered duct. The tapered duct demonstrated the best heat transfer reduction by 1.73%. This modelling and analysis have made a substantial contribution to the cooling system of the PV panel application.

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