Chapter

Influence of Wind Incidence Angle on the Cooling of Rooftop-mounted Solar Panels

Hadi Ahmadi Moghaddam, Matthew Phillips, Svetlana Tkachenko and Victoria Timchenko

Abstract

The cooling of PV panels is crucial because their electrical output and lifespan are adversely affected as their operating temperature rises. Considering wind current cooling impacts on the rooftop-mounted solar panels, adopting the local climate conditions such as dominant wind patterns is recommended to the building sector so that new buildings are placed considering the local wind directions. A 3D CFD model employing the URANS approach is developed to show the impacts of wind direction on the cooling rate of a PV panel installed on the surface of a slanted roof. The radiation effect is considered using the surface-to-surface radiation model. Two free stream velocities of 2 and 5 m/s and seven wind angles between 0 and 180 degrees are modelled. The results showed an optimum incidence angle at which the panel experiences lower temperatures. At wind angles below 90 degrees where there is direct contact between the wind flow and PV surfaces, the convective cooling rate is higher which in turn decreases the PV temperature. However, at higher angles, due to the presence of walls and edges of the structure, the wind flow is redirected resulting in the formation of wind flow separation. Therefore, convective cooling degrades, and PV experiences higher temperatures.

Keywords: solar panel, wind, convective cooling, CFD

1. Introduction

Due to the higher clean energy demands, many buildings nowadays are equipped with photovoltaic (PV) panels to convert solar radiation into electricity. While solar panels are generally adapted to the structure of a building in the form of façade-mounted and rooftop-mounted designs, the latter design is widespread. In the case of inclined roofs, the PV panels are installed at a distance on the surface of the roof. The gap between the panels and inclined roof surface is crucial to allow airflow to pass from the gap and cool down the PV from the backside, whether by passive cooling due to the formation of buoyant forces in the gap or forced convective cooling due to wind effects. Cooling of PV panels is crucial as their electrical efficiency and lifetime are adversely affected as they experience higher temperatures [1]. Research conducted by

Ritzen et al. [2] on the performance of rooftop-mounted PV modules showed that the efficiency of non-ventilated modules degraded by 86% after 3 years.

Several studies have been conducted to appraise the performance of PV modules under wind or passive cooling effects. Chowdhury et al. [3] performed wind tunnel experiments and CFD simulations under different wind velocities and air gaps. Experiments by Mirzaei et al. [4] showed that higher wind velocities result in higher heat exchanges between the PV panel and airflow and consequently lower PV temperatures. They also suggested installing PV modules in a stepped open arrangement instead of a flat arrangement for better cooling. Lai and Hokoi [5] performed experimental and numerical studies on double-skin façade PVs and reported that the electrical efficiency of ventilated modules was higher by about 16–44% than the non-ventilated ones. Within another numerical research, Gan [6] concluded that adequate spacing or gap between the modules and the surface of the wall is required to allow the air to pass and cool down the PVs and avoid the formation of hot spots in panels.

The current numerical study investigates the impacts of wind direction on the cooling rate of a PV panel installed on the surface of a slanted roof. The slanted structure has been studied in this research as it is a common configuration used in Australia. In the following section, the studied case and the numerical procedure have been explained. Then, the results have been presented and discussed.

2. Case study

As shown in **Figure 1**, a 2.4 m height structure with a PV panel installed on its slanted roof has been studied numerically in this research. To evaluate the effects of wind direction, seven angles between the wind direction and the structure (0, 30, 60, 90, 120, 150, and 180 degrees) and two free stream velocities of 2 and 5 m/s have been considered, the main directions are shown in **Figure 1**. The distance between the panel and the roof surface is 0.1 m. The inclination angle of the roof or module is 30 degrees. The dimensions of the module were 1 m by 1.3 m, oriented such that 10 cm of the

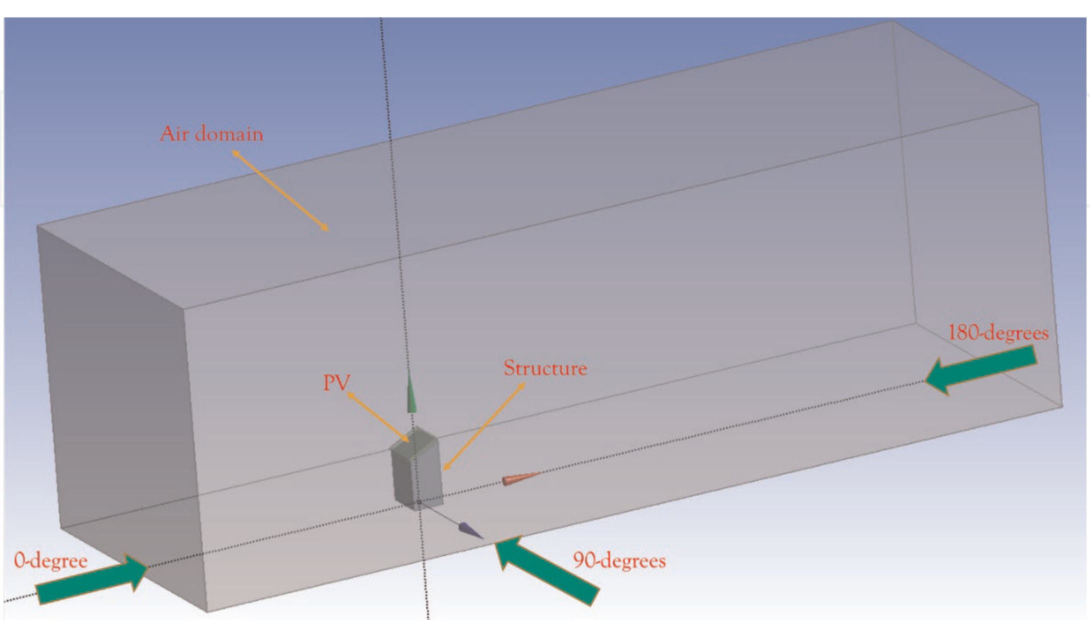

Figure 1.
Schematic view of the rooftop-mounted PV and air domain with wind directions.

Material	Thickness (m)	Thermal conductivity (W/m.K)	Heat capacity (J/kg.K)	Density (kg/m^3)
Glass	3000×10^{-6}	1.8	500	3000
EVA	500×10^{-6}	0.35	2090	960
Silicon	175×10^{-6}	130	700	2329
Tedlar	100×10^{-6}	0.2	1250	1200

Table 1.
Characteristics of the PV panel.

roof-top on all sides remained unobscured by the module when viewed from above. Adequate distance between the structure and the domain boundaries has been considered to correctly model the wind effects.

The following equation has been used for the wind velocity profile [7]:

$$U(h) = \left(\frac{h}{h_o}\right)^{\beta} U_{ref} \tag{1}$$

where β is a constant equal to 0.17, h_o is the total inlet height of 10 m, and U_{ref} is the average freestream velocity (2 or 5 m/s).

Further, the applied solar heat flux on the PV cells is 600 W/m^2. It is worth mentioning that of the total solar radiation incident upon a PV panel, a portion is reflected or converted into electricity (about 20%). The rest is converted into heat which in turn increases the PV temperature. Here, the applied heat flux of 600 W/m^2 is the amount of radiation that is converted into heat and modelled as heat generation in the simulation. The PV panel consists of five layers including glass, EVA, PV cells, EVA, and Tedlar, respectively, glass being the layer adjacent to the external domain and Tedlar adjacent to the air gap between the panel and roof. The characteristics of the PV panel are shown in **Table 1** [8].

3. Numerical setup

Unsteady Reynolds-Averaged Navier–Stokes (URANS) approach has been used to model both free and forced convective flows around the structure. For this purpose, Ansys Fluent 2021 code has been used. The working fluid (air) is considered to follow the ideal gas behaviour. The governing equations of the current problem, i.e., conservation of mass, momentum, and energy are:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u_j)}{\partial x_j} = 0 \tag{2}$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \sigma_{ij}}{\partial x_j} + \left(\rho - \rho_{ref}\right) g_i \tag{3}$$

$$\frac{C_p \partial (\rho T)}{\partial t} + \frac{C_p \partial (\rho u_i T)}{\partial x_j} = k \frac{\partial}{\partial x_j}\left(\frac{\partial T}{\partial x_j}\right) + \frac{\partial q_j}{\partial x_j} \tag{4}$$

In Eqs. (2)–(4), g, ρ_{ref}, u, T, P, C_p, σ_{ij}, k, and q_j show the gravity vector, reference density, velocity vector, temperature, dynamic pressure, the specific heat capacity of constant pressure, stress tensor, thermal conductivity, and turbulent thermal flux vector, respectively.

To model the turbulent flow, the $k-\omega SST$ model has been used. SST is a hybrid model that utilises $k-\omega$ formulation within the boundary layer where viscous forces are dominant and then switches to $k-\varepsilon$ formulation outside the boundary layer making it suitable for a wide range of engineering applications [9]. A pressure-based solver along with a second-order discretization scheme has been used to solve the flow variables, and the coupled algorithm has been used for velocity–pressure coupling. The solution residual target is set to 10^{-5}.

An unstructured mesh with 2.06 million cells has been used to model the flow. It was found that a further increase in the number of cells did not affect the results. To correctly capture the flow behaviour within the boundary layer, inflation has been used on the solid boundaries. Generally, the mesh has been refined around the structure, within the gap between the panel and roof, and close to walls where a sharp gradient of flow variables such as velocity or temperature is expected.

The surface-to-surface radiation model has been used to simulate the radiation effects. This model uses the following formulation to compute the radiative energy transfer from surfaces:

$$q_{out,m} = \epsilon_m \alpha T^4 + \Omega_m \cdot \sum_{j=1}^{N} F_{jm} q_{out,j} \quad (5)$$

where $q_{out,m}$ is the energy flux leaving the surface m, α is the Stefan–Boltzmann constant, $\Omega_m = 1 - \epsilon_m$ is the reflectivity of surface m, ϵ_m is the emissivity of the surface m, and F_{jm} is the view factor between surface m and surface j.

4. Results and discussion

Prior to presenting the results, it should be noted that all presented results are averaged over time. The change of the mean temperature of PV with wind direction is shown in **Figure 2**. It is seen that for both wind velocities of 2 and 5 m/s, the mean temperature of the PV is lower at angles below 90 degrees which is associated with higher surface heat transfer coefficients, as shown in **Figure 3**. Under these conditions, there is direct contact between the wind and module surfaces which contributes to forced convective cooling of the PV, thereby increasing the surface heat transfer coefficient, and decreasing the temperature of PV. At lower angles, the wind penetrates the gap between the PV and roof surface resulting in an increased heat transfer. In other words, the forced convective cooling effects on both sides (front and back) of the module are prominent at angles below 90 degrees. It is noticeable that by increasing the angle from 0 to 60 degrees, there is a slight decrease in the mean temperature of PV. This is mainly because, at angles higher than 0 degrees (and below 90 degrees), more airflow penetrates the gap between the PV and roof which in turn intensifies the convective cooling effects from the backside of the PV. **Figure 4** shows the schematic view of the airflow penetrating the gap between the PV module and roof for the wind angles of 0 and 60 degrees. As seen, when the wind angle is 0 degrees, the airflow mainly enters the gap from the bottom side. However, for the 60 degrees case, the

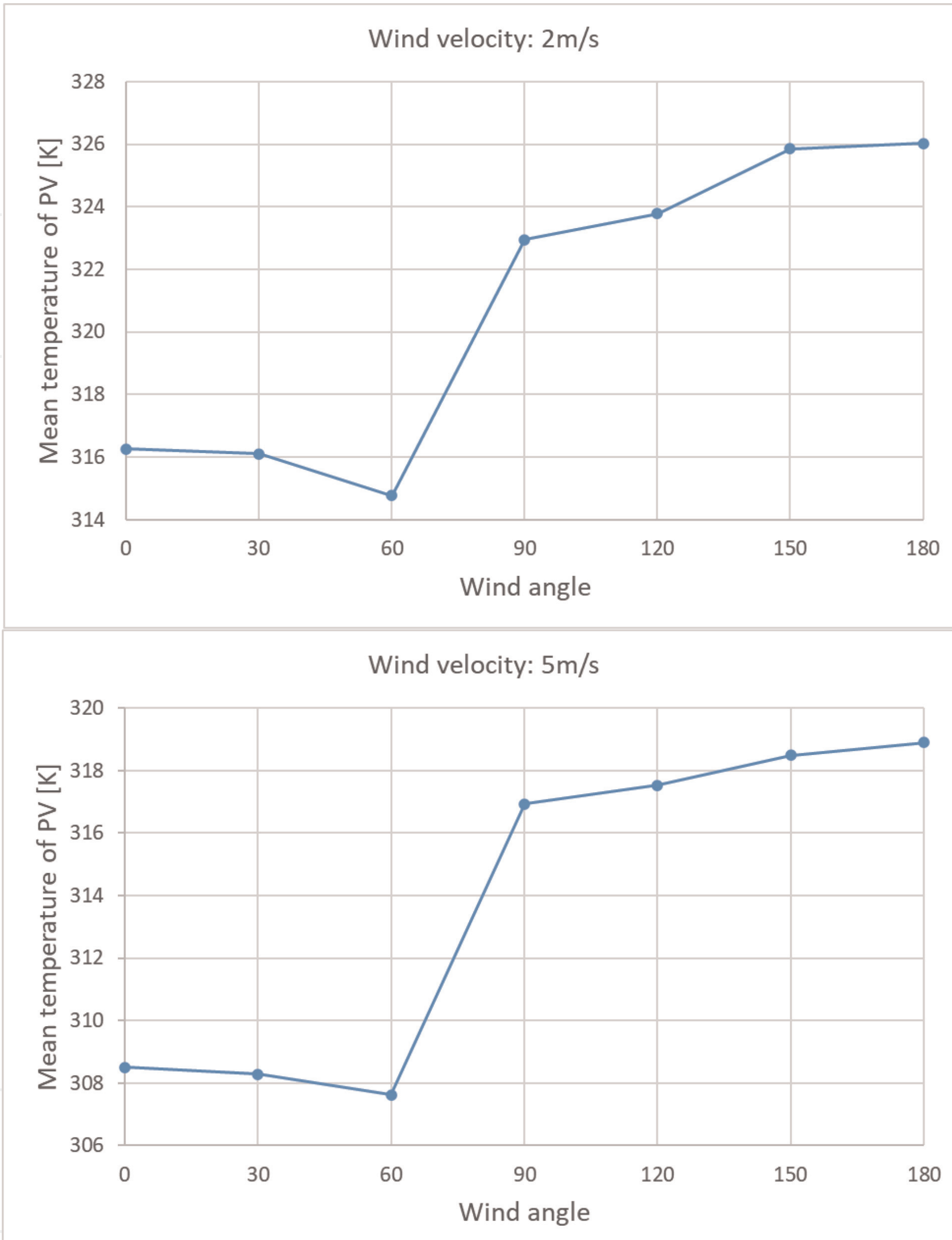

Figure 2.
Effects of wind angle on the mean temperature of PV.

airflow enters the gaps mainly from both bottom and left side of the gap, thereby intensifying convective cooling effects.

It is worth noting that similar observations were reported by the experiments of Wen [10] who studied the cooling effects of wind direction on a PV panel whose surface was parallel to the wind and observed that the convective heat transfer coefficient reached a maximum value for the angles in the range of 60–120 degrees depending on the wind velocity. However, as will be discussed in the following, the HTC drops drastically in the current research for angles beyond 60 degrees due to the edges of the structure that act as a barrier.

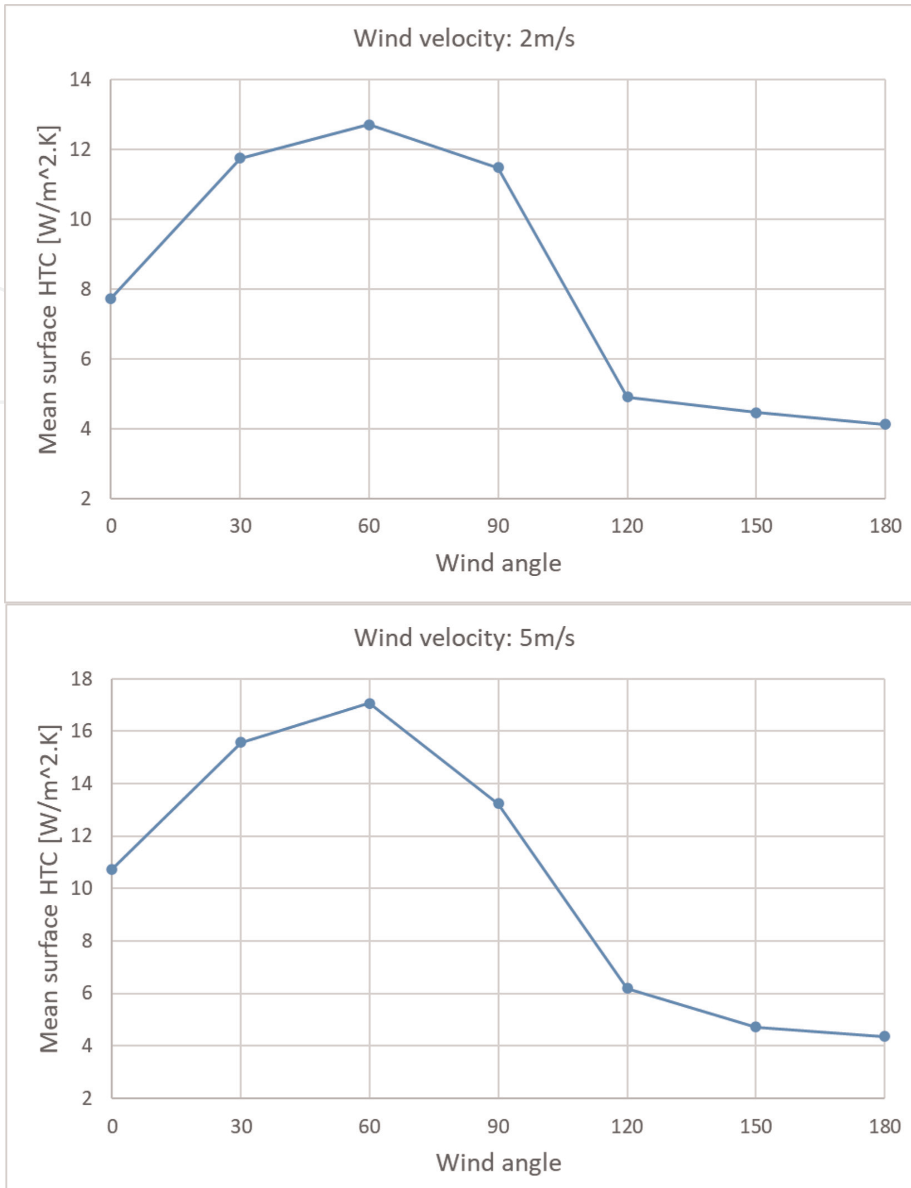

Figure 3.
Effects of wind angle on the mean surface heat transfer coefficient (HTC) of PV.

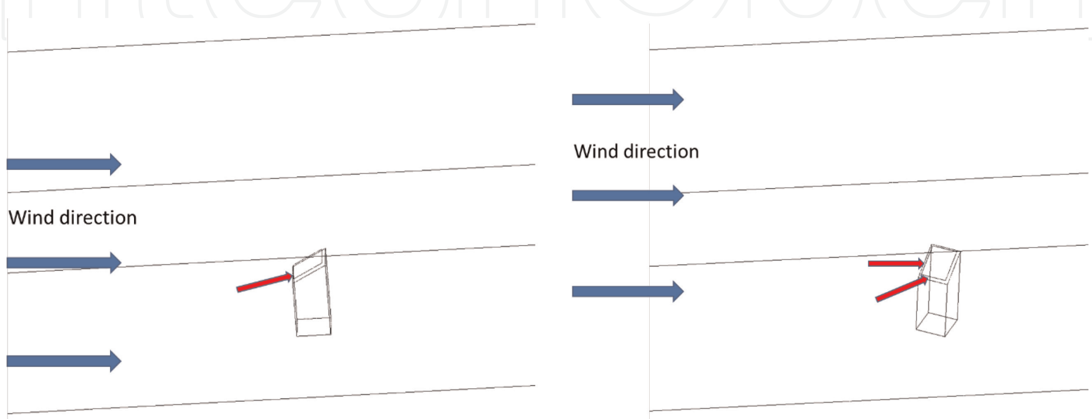

Figure 4.
Schematic view of the airflow penetrating the gap between the PV and roof, left) 0 degrees and right) 60 degrees wind angle.

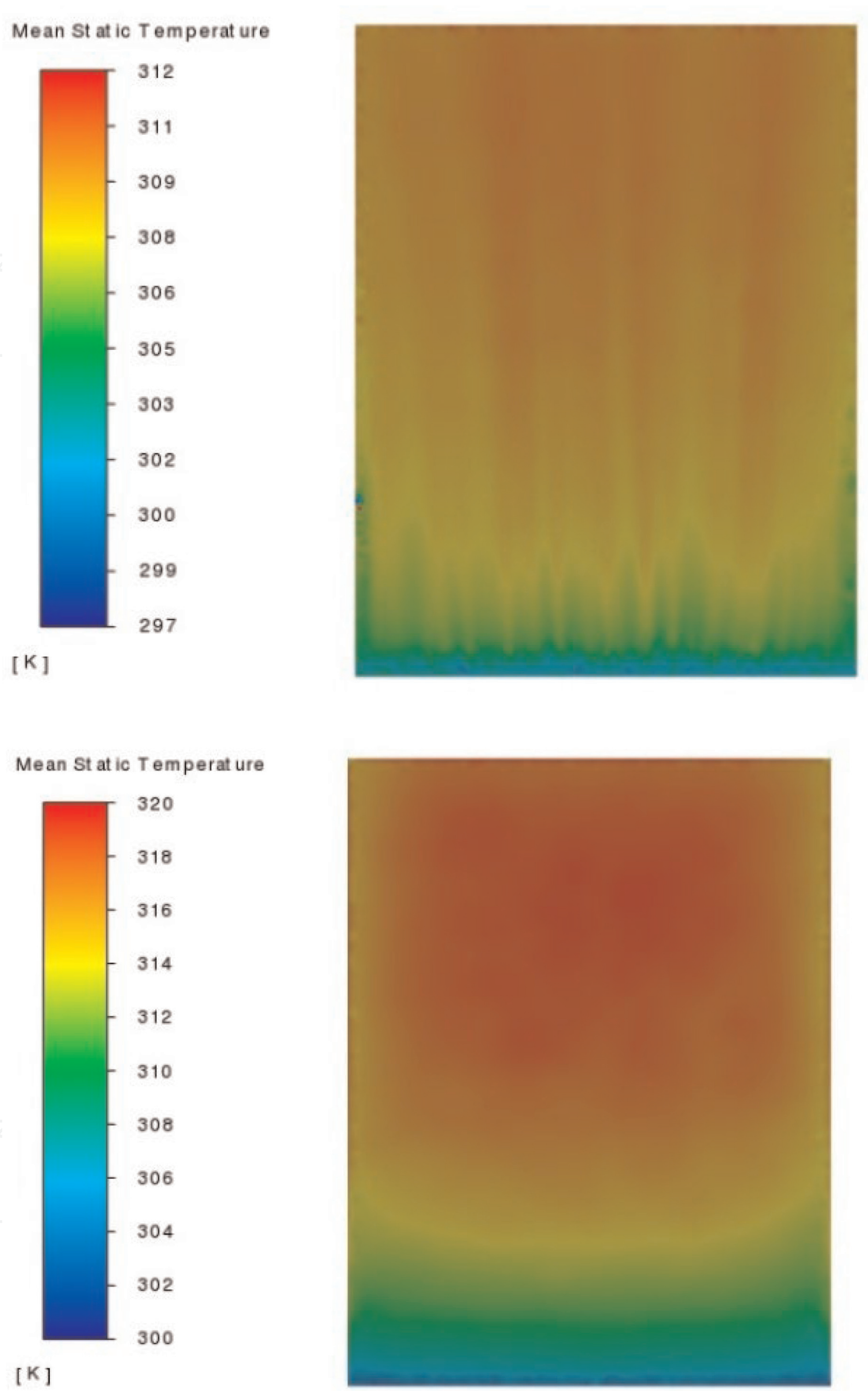

Figure 5.
Contours of mean static temperature of PV panel for free stream velocity of 5 m/s, top) 0 degrees, bottom) 180 degrees.

By increasing the wind angle beyond 60 degrees, there is a sharp increase in the mean temperature and a decrease in the mean surface HTC of the PV, as shown in **Figures 2** and **3**, respectively. The reason behind this is that at higher angles, the

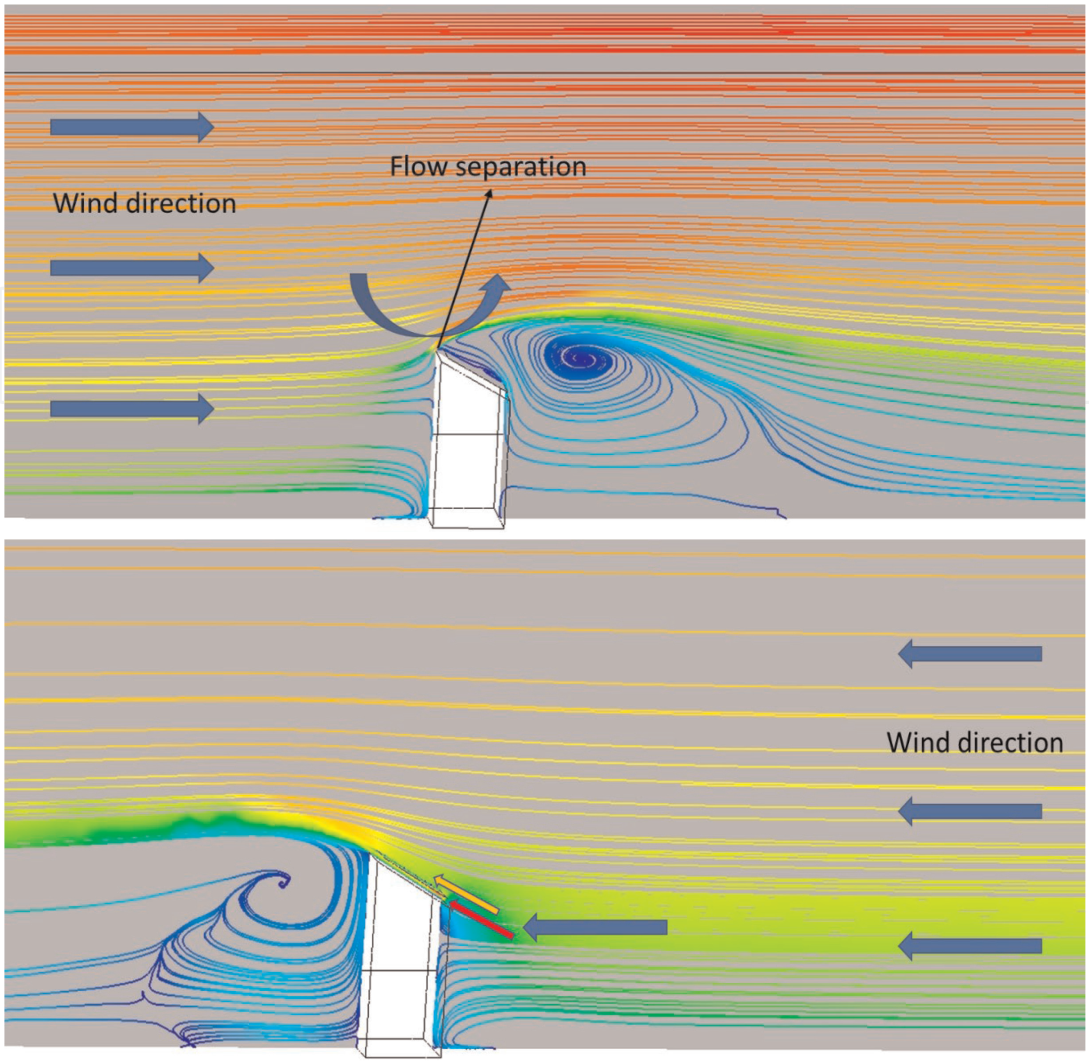

Figure 6.
Flow streamlines for wind velocity of 5 m/s, top) 180 degrees, bottom) 0 degree.

inclined roof and sidewalls of the structure act as a barrier between the module and wind, thereby decreasing the direct contact between the wind and module and consequently degrading the forced convective cooling effects.

Figure 5 illustrates the temperature contours of the PV panel for wind angles of 0 and 180 degrees. As observed, PV experiences lower temperature due to higher cooling effects at zero wind angle. It is also observed in **Figures 2** and **3** that, as expected, mean HTC augments and mean temperature of PV decreases as the wind velocity increases due to the enhanced forced convective cooling effects.

To get a better understanding of the wind and structure interactions, **Figure 6** is presented showing the streamlines for the wind velocity of 5 m/s and angles of 0 and 180 degrees. As seen, for the wind angle of zero degrees, the wind flow approaching the PV is divided into two streams, one passing beneath the PV and the second passing over the surface of the PV resulting in convective cooling effects from both sides. A large vortex is being also generated behind the structure. However, at the angle of 180 degrees, the walls and edges of the structure result in the separation of flow and formation of a large vortex in the vicinity of PV which weakens the convective cooling rates.

5. Conclusion

A 3D transient CFD model was developed to illustrate the impacts of wind direction on the cooling of a PV panel installed on the surface of a slanted roof. The simulation includes radiative effects by surface-to-surface radiation model, natural convection generated by the heated PV due to the buoyancy effects and forced convection due to the wind effects. The numerical results showed that the wind direction has a significant impact on the cooling rates of the module. At angles below 90 degrees, due to direct contact between the wind and sides of the PV panel, the cooling rate of the PV is higher resulting in lower PV temperatures. However, at higher angles, the walls and edges of the structure act as a barrier between the wind flow and PV and prevent direct contact between them. Therefore, the convective cooling rates degrade, and PV temperature rises.

It should be noted that the results may depend on other geometrical parameters such as distances from the edges of the PV module to the edges of the roof and building height, which could be investigated in future studies.

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