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Numerical study on convection heat transfer from inclined PV panel under windy environment

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ABSTRACT

Due to the negative correlation between PV cell temperature and its efficiency, study on convection heat transfer from PV panel under real windy condition seems essential. Then a 3D numerical model has been established to investigate the impact of PV tilt angle, wind condition and different heat flux boundary conditions. To reveal the influence of photoelectric conversion characteristic on convection heat transfer, two boundary conditions, i.e., constant heat flux and heat flux varying with temperature are adopted and compared. Velocity vector field, temperature and velocity contours are also provided for detailed analysis. Within the studied range of tilt angle α, it is interesting to find there exists a minimum Nu_c, and the corresponding α shifts to a larger value with increasing wind velocity. As wind direction varies, a decrease in Nu_c is discovered at first, and then a rising tendency is followed. In addition, as wind velocity is relatively lower, higher heat flux enhances Nu_c at random α, especially for the case of $\alpha \geq 45°$. Finally, a novel empirical correlation about convection Nusselt number incorporating the factors of tilt angle, wind direction and wind velocity is put forward.

1. Introduction

The efficiency of photovoltaic (PV) solar cell gains the primary concern during the realization of photoelectric conversion process. The striking effect that the operating temperature of PV cell has on its efficiency was well documented by Skoplaki and Palyvos (2009). However, the temperature distribution is closely related with the combined convection and radiation heat losses to the environment. In other words, windy condition, incorporating wind velocity and wind direction in reality, plays a significant role on convection heat transfer from PV panel.

In Palyvos' (2008) review, a critical discussion and a suitable tabulation for the external convection coefficients were presented. It is on the basis of algebraic form of the coefficients and their dependence upon characteristic length, wind direction and wind speed. Generally, two types of correlations are widely used. One is in the linear form, written as $h_w = a + bV$ (Furushima et al., 2006; Ito et al., 1972; Jayamaha et al., 1996; Kumar et al., 1997; Sharples and Charlesworth, 1998), and the other power law form is $h_w = a + bV^n$ (Loveday and Taki, 1996; Sogin, 1964; Taki and Loveday, 1996; Yazdanian and Klems, 1994). For a square plate situated at various orientations to the flow direction, wind tunnel experiments have been performed by Sparrow and Tien (1977) and Tien and Sparrow (1979). As the plate is inclined, one interesting finding is that the stagnation region migrates from a central position at normal incidence to a more forward position. Later, by testing a 1:32 scale model in highly turbulent non-uniform flows, convective heat transfer coefficients (CHTC) on the surface of flat-plate solar collectors were measured by Kind et al. (1983). Results indicated that, coefficients show some sensitivity to wind direction but are insensitive to the characteristics of the wind. Towards a raised heated flat plate attached to the pitched roof, Sharples and Charlesworth (1998) made a series of full-scale measurements in the real environment. For a range of wind directions, both power and linear relationships between h_w and V were found adequate to represent the experimental results. Onur (1993) pointed out that, the obtained experimental results are approximately 10% less than those predicted by Sparrow and Tien (1977). Turgut and Onur (2009, 2010) evaluated the average heat transfer coefficients from the surface of a rectangular flat plate, both experimentally and numerically. Mass transfer rather than heat transfer has been used in experimental study, which was achieved using the naphthalene sublimation technique. Results conveyed that as the angle of attack decreases, the heat transfer rate increases. To evaluate the wind-induced CHTC from the

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Nomenclature

a	absorption coefficient, m^{-1}
h	convection heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
I	radiation intensity, $W\,m^{-2}$
L	PV panel length, m
N	refractive index
Nu_c	convection Nusselt number
Q	total incident irradiation, $W\,m^{-2}$
q	heat flux, $W\,m^{-2}$
q_t	total released heat flux, $W\,m^{-2}$
q_r	released radiation heat flux, $W\,m^{-2}$
$\vec{r}$	position vector
s	source term due to radiation, $W\,m^{-3}$
$\vec{s}$	direction vector
$\vec{s}'$	scattering direction vector
Δt	temperature difference between panel and ambient air, K
T	temperature, K
t_m	average temperature of the top panel, K
t_{bm}	average temperature on the bottom of the panel, K
v	wind velocity, $m\,s^{-1}$

Greek symbols

α	tilt angle, °
α_s	solar absorbance of the PV panel
α'	wind incident angle, °
β	temperature coefficient, K^{-1}
ρ_s	solar reflectance of the PV panel
γ	wind direction, °
γ'	wind yaw angle, °
σ	Stefan–Boltzmann constant
σ_s	scattering coefficient, m^{-1}
Φ	phase function
Ω'	solid angle
λ_a	thermal conductivity of air, $W\,m^{-1}\,K^{-1}$
η_0	reference efficiency of PV cell

inclined windward roof, CFD simulations have been carried out by Karava et al. (2011), where a linear relation was derived between the incident turbulence intensity and CHTC. Mahboub et al. (2011) was concerned with the effect of the positive angle of attack on CHTC over a flat plate surface. Through numerical investigation, the variation of CHTC as a function of the angle of attack was discovered not to behave in the same manner for small and large values of *Pr*. A methodology was proposed by Defraeye and Carmeliet (2010) to estimate the statistical mean convective heat transfer coefficient ($CHTC_{SM}$) for a building surface. An experimental and analytical parametric study assessing the effect of wind direction on unglazed transpired collectors (UTC) was described by Vasan and Stathopoulos (2014). When the wind incidence angle is 45°, wind direction was shown to have the greatest impact on CHTC.

Referring to the researches about wind effects on PV panels, Jubayer and Hangan (2014) simulated wind load and flow field around a ground mounted stand-alone PV system with 25° tilt angle, where 180° was found to be the critical wind direction in terms of maximum uplift. Arpino et al. (2015) have undertaken an experimental and numerical investigation of PV efficiency dependence on environmental conditions, with particular reference to the wind velocity. From the analysis, it was possible to observe that the modules temperature decreases as the tilt angle increases. From Goverde et al. (2015), it was suggested that the temperature differences may amount to 21 °C and more, depending on the wind speed and the location on the module. A theoretical and experimental analysis of PV module temperature under various environmental conditions was conducted by Kaplani and Kaplanis (2014), with the consideration of module inclination, wind velocity and direction. The experimental measurement implied heat convection from the PV module becomes weaker with increasing wind incidence angle, particularly at high wind velocities.

Although there exist abundant literatures, some defects are found in the real application of PV panel. Firstly, the bulk of the researches take the building facades or roof as objects, which are parallel or horizontal. While for PV panel, it is usually inclined at an angle to maximize the irradiation. Secondly, even though Refs. (Arpino et al., 2015; Goverde et al., 2015; Jubayer and Hangan, 2014; Kaplani and Kaplanis, 2014) have considered the wind effect, most of them paid attention to the pressure distribution, power output or temperature coefficient, few focused on convection heat transfer coefficient. Thirdly, correlations at different wind incident angles were separately proposed in Sharples and Charlesworth (1998), however, to the best knowledge of authors, a comprehensive formula merging both tilt angle and wind incident angle has not been proposed up to now. Last but not least, under the condition of higher heat flux or lower wind velocity, such as in the concentrated PV/T system, the role of natural convection may be gradually enhanced. Nevertheless, no associated results have been reported.

Concerning about the above analysis, the motivation behind the present paper is to numerically analyze the conjugated effect of tilt angle and wind condition on convection heat transfer of the PV panel. Comparison between different thermal boundary conditions also has been carried out. Finally, a novel correlation is put forward, which incorporates tilt angle, wind direction and wind velocity.

2. Physical and mathematical model

2.1. Physical model of the PV panel

The simulated three-dimensional PV panel and side view are portrayed in Fig. 1. The dimension of PV panel is 385 mm × 385 mm × 3 mm. Due to the focus of this paper is on the heat loss from the front surface, insulation material is covered on the side and bottom. Three discrete heating parts at 5 mm apart are adopted to simulate three PV cells, each having the dimension of 125 mm × 385 mm. They are denoted as the bold lines on the panel bottom displayed in Fig. 1(b). The system rotates in the *xoy* plane. The rotation angle with respect to horizontal is defined as the tilt angle, α. The tilt angle α of PV panel is varied by location so as to achieve the maximum irradiation. Hence, the tilt angle investigated in this paper is in the range of 15–75°. The wind is supposed to flow horizontally in the *xoz* plane, which is also parallel to the ground. Then the wind direction γ is defined as the angle between wind blowing direction and *x*-axis direction. Various wind velocities v from 0.5 m/s to 9 m/s and wind direction γ from 0° to 75° are in the consideration.

2.2. Combined turbulent convection and radiation model

Aiming to simulate the combined convection and radiation heat transfer above the PV panel in the environment, the Realizable κ-ε turbulence model is selected. The air flow is assumed in steady