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CFD analysis of convective heat transfer from ground mounted solar panels

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Abstract

The present study deals with the wind induced convective heat transfer from a ground mounted stand-alone solar panel using Reynolds-Averaged Navier–Stokes (RANS) simulation with Shear Stress Transport (SST) k–ω turbulence model. An unsteady solver with a steady inlet condition is employed. The numerical modeling approach is validated for wind flow field around the solar panel with a Particle Image Velocimetry (PIV) experiment performed in the boundary layer wind tunnel. The solar panel is subjected to two different wind directions (0° and 180°), and for each wind direction, three different incoming flows (wind speeds of 1, 5 and 10 m/s at 10 m height) are considered. The Convective Heat Transfer Coefficient (CHTC) distributions on the surfaces of the solar panel are analyzed with respect to the flow field around the solar panel. Similar CHTC distribution is observed on both windward and leeward surfaces of the solar panel where natural convection is dominant over forced convection. In contrast, where forced convection is dominant, higher CHTC values (up-to 128%) are found on the windward surfaces compared to the leeward surfaces of the panel. Relation between the dimensionless CHTC parameter Nusselt number (*Nu*) and the Reynolds number (*Re*) are presented and the results are compared with previous existing correlations. The lowest *Re* case (1.0×10^5), which produces the maximum panel surface temperature and thus will result in minimum electrical efficiency of the panel, is identified to be the most critical case in this study.

Keywords: Solar PV panels; Ground mounted; Convective heat transfer coefficient; Computational Fluid Dynamics (CFD)

1. Introduction

Electrical efficiency of photovoltaic (PV) solar panels is greatly dependent on the PV cell temperature. According to Evans (1981), the electrical efficiency of silicone cell PV module reduces by 0.45% per degree temperature rise. Skoplaki and Palyvos (2009) analyzed the existing correlations between the operating temperature and the electrical efficiency of commercial grade silicone cell PV modules and observed that the electrical efficiency of the solar module reduces linearly with the rise of the module operating temperature. An accurate prediction of solar panel temperature is therefore necessary for the estimation of the potential electrical output of the PV panel.

To measure or estimate the PV panel temperature, thermal energy balance of the entire solar panel system is required. Major parameters related to the thermal energy balance of a ground mounted PV system are shown in Fig. 1. The incoming energy flux in the given system is the solar irradiance. A portion of this energy is reflected from the panel upper surface. The fraction of energy absorbed by the panel is converted into electricity and rest is converted into heat. This heat exits from upper and lower surfaces of the panel as convective and radiative heat losses. Convective heat loss is the dominant mode and is a strong function of the wind behavior that flows over

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Nomenclature

B	breadth of the panel (m)
b	distance from the leading edge of the panel on the panel surface along the breadth of the panel (m)
c_p	specific heat (J/kg-K)
Cr	Courant number (–)
C_μ	turbulent model constant ($= \beta^*$ for SST k–ω)
G	incoming solar flux (W/m^2)
Gr	Grashof number (–)
e	emissivity (–)
H	height of the panel (m)
h_C	convective heat transfer coefficient (W/m^2-K)
k	turbulent kinetic energy per unit mass (m^2/s^2)
k_p	turbulent kinetic energy per unit mass at the first cell center from the wall (m^2/s^2)
k_m	thermal conductivity (W/m-K)
Pr	Prandtl number (–)
Q_C	convective heat loss (W/m^2)
Nu	Nusselt number (–)
Re	Reynolds number (–)
Re_{EH}	Reynolds number at the eaves height of a building (–)
Ri	Richardson number (–)
T	temperature in a cell (K)
T_0	reference temperature for Boussinesq approximation (K)
T_{amb}	ambient temperature (K)
T_p	temperature of the panel (K)
t	flow time (s)
t^*	dimensionless flow time ($= t\overline{U}_H/B$)
U	mean wind speed at height Y from the ground (m/s)
$\overline{U}_H$	mean wind speed at height H (m/s)
U_{1mT}	mean wind speed at 1 m above the top edge of the panel (m/s)
U_{10m}	mean wind speed at 10 m height from the ground (m/s)
u^*	friction velocity (m/s)
v	local mean velocity in a cell (m/s)
W	width of the panel (m)
y_0	aerodynamics roughness length (m)
y_p	first cell center distance from the bottom surface of the domain (m)
y^*	dimensionless wall distance ($= C_\mu^{1/4}k_p^{1/2}y_p/v$) (–)
y^+	dimensionless wall distance ($= u^*y_p/v$) (–)

Greek symbols

α_S	solar absorption coefficient (–)
β	thermal expansion coefficient (1/K)
Δt	time step (s)
Δl	grid cell size (m)
ε	dissipation rate of turbulent kinetic energy per unit mass (m^2/s^3)
σ	Stefan–Boltzmann constant ($= 5.67 \times 10^{-8}$ W/m^2-K^4)
ρ_k	effective kinematic density (–)
ρ_0	effective kinematic density at T_0 (–)
θ	panel inclination angle (°)
μ	dynamic viscosity (Pa·s)
v	kinematic viscosity (m^2/s)
ω	specific dissipation rate of turbulent kinetic energy per unit mass (s^{-1})

Abbreviations

ABL	Atmospheric Boundary Layer
BLWT	Boundary Layer Wind Tunnel
CFD	Computational Fluid Dynamics
CHTC	Convective Heat Transfer Coefficient
ESDU	Engineering Sciences Data Unit
PIV	Particle Image Velocimetry
PISO	Pressure Implicit with Splitting of Operators
PV	photovoltaic
RANS	Reynolds-Averaged Navier–Stokes
SST	Shear Stress Transport
TI	Turbulence Intensity

the panel (Karava et al., 2011). Convective heat loss (Q_C) per unit area is defined as, $Q_C = h_C(T_p - T_{amb})$, where h_C in the convective heat transfer coefficient (W/m^2-K), T_p is the panel temperature (K) and T_{amb} is the ambient temperature (K). PV panels are usually installed on roof tops or on the ground as stand-alone units. Extensive studies have been performed to determine wind induced convective heat transfer from PV panels flush mounted on inclined roofs of low-rise buildings (e.g., Karava et al., 2012; Karava et al., 2011; Kind et al., 1983; Mittelman et al., 2009; Shakerin, 1987; Sharples and Charlesworth, 1998). However, due to significant difference in the wind flow behavior between the roof-mounted and ground-mounted solar panels, the heat transfer characteristics obtained for the roof-mounted panels cannot be applied to that on the ground-mounted stand-alone panels.

There is a scarcity of studies investigating the convective heat transfer due to wind flowing over the ground-mounted stand-alone PV systems. The closest to such configuration is the inclined flat plate and several studies, two to three decades ago, have investigated the heat transfer from inclined plates as a classical heat transfer problem. Sparrow and Tien (1977) performed a wind tunnel experiment to determine the forced convective heat transfer from