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ScienceDirect

Energy Procedia 78 (2015) 1865 – 1870

Energy Procedia

6th International Building Physics Conference, IBPC 2015

Validation of a Climatic CFD Model to Predict the Surface Temperature of Building Integrated Photovoltaics

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Abstract

The current market of the photovoltaic (PV) industry is dominated by silicon-based modules, which are malfunctioned and degraded in higher temperatures mainly above 25°C. Consequently, one of the challenges for such modules is finding a more efficient way in their integration into the buildings in order to reduce the mentioned temperature. The present work is a part of a comprehensive framework toward the investigation of the lifetime durability of the BIPV modules. Therefore, this paper explain the development and validation of a computational fluid dynamics (CFD) model to be later utilized to evaluate the temperature distribution of BIPV's surfaces under different arrangements and climate loadings. For this purpose, a high resolution 3D CFD model is firstly developed by generation of about 3 million cells. Then, the model is validated with a velocimetry experimental dataset from the same model tested in a wind tunnel experiment by [6]. Furthermore, the solar radiation is added into simulation to model the non-isothermal condition of the BIPV module. The non-isothermal case is further validated with a thermography observation conducted by [5] where a solar simulator is installed inside the tunnel. The simulation results show that the developed model can accurately simulate the impact of 3D flow over/underneath the PV modules.

Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL

Keywords: Building; Photovoltaics; CFD; Durability

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1. Introduction

Despite the current low share of the renewable energies, comprising about 14% of the total supplied energy, their future growth is projected to reach by 30-80% in 2100 [1]. Among all available options, solar energy has unique

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Peer-review under responsibility of the CENTRO CONGRESSI INTERNAZIONALE SRL
doi:10.1016/j.egypro.2015.11.348

advantages such as availability, inexhaustibility and cleanness, turning it to a viable solution of the future energy crisis.

Photovoltaic (PV) technology is one of the most promising types of harvesting technologies, being developed to collect the solar energy. A 30-40% per annum increase rate in the PV market is reported by [2] where more than 40% of them are grid-connected residential systems, mainly silicon based PV installed on the buildings' surfaces. The main drawback of these building integrated photovoltaics (BIPV), however, is their considerable efficiency drop due to the elevated surface temperature. In addition, the high surface temperature degrades the photovoltaic's materials, resulting in lower life-time durability than expected 30-35 years of their operation [3].

As one of countermeasures, mechanical or wind-driven cooling is proposed to be adapted into installed silicon-based BIPVs. In mechanically ventilated systems, known as a photovoltaic thermal systems (PV/T), part of heat that cannot be converted into electricity is removed from the PV surface and reused for heating purposes. The overall thermal and electrical efficiency of a PV/T system can thus reach as high as about 70% [4]. On the other hand, wind-driven or natural cooling techniques such as back ventilation of PVs are considered as practical solution for externally installed BIPVs.

To design and implement a suitable back ventilation system, it is necessary to develop tools capable of prediction of their impact on life-time durability of BIPVs. Therefore, various experimental and numerical studies have been designed and developed to evaluate the performance of such systems. For example, [5,6] conducted particle image velocimetry (PIV) and infrared thermography (IF) to investigate detail of both velocity and temperature fields around a PV module installed inside an atmospheric wind tunnel. Moreover, computational fluid dynamics (CFD) is widely utilized to study the heat removal from BIPV through back ventilation in the recent years. Various correlations thus are obtained to represent the heat transfer from the BIPVs' surface, and also many recommendations are provided for achieving optimum cooling of the BIPVs [7,8,9].

Despite the above mentioned studies, climatic models that can simulate realistic airflow around and underneath BIPVs are barely developed. Moreover, the previous studies mainly focused on the efficiency of cavity cooling and scarcely investigated their long-term, 30-35 years, durability enhancement. Therefore, this study aims to investigate the cooling effect of the simultaneous airflow above and underneath the PV modules by developing a dynamic climatic CFD model. Hence, the developed model is firstly validated with a series of isothermal measurement data by [6]. The simulation will be performed under similar condition as the experiment where upstream velocity is altered between 0.5m/s and 2m/s and solar intensity is adjusted between 50W/m^2 and 200W/m^2. Once the model is developed and validated, it can be later adapted for assessing PV life-time durability with actual climatic conditions.

2. Methodology

2.1. 3D model and CFD setup

Computational fluid dynamics (CFD) is utilized in this study to develop a comprehensive model for long-term investigation of the durability of the BIPV modules. First, a 3D mesh is generated according to a wind tunnel experiment by [5,6]. In latter experiment, a scaled BIPV system is mounted on the windward roof of a 1:20 building (Fig. 1). The cavity between the roof and BIPV has a 30mm width. The building height and roof inclination are respectively designed to be 45° and 582.8mm. Furthermore, a solar simulator system with six infrared lamps of 250W is installed inside the wind tunnel to provide various radiation intensities on the BIPV's surface.

As depicted in Fig. 2, a hybrid mesh is allocated to different part of the geometry. Building area has a dense and structured cells to resolve boundary layer above all the walls (Fig. 2a), whilst very fine cells are utilized within the cavity. Similarly, the vicinity of the solar simulator is covered with structured/unstructured and small cells (Fig. 2b). Eventually, structured and coarse cells are generated to cover these latter regions in addition to the wind tunnel. The number of cells for entire domain and around the building prototype are respectively 3.07M and 1.97M. Moreover, the boundary layer cells are carefully generated to ensure a small Y^+ in order to include the wall impact in the calculations [10,11]. The assigned boundary conditions and initial setups are also provided in Table 1.

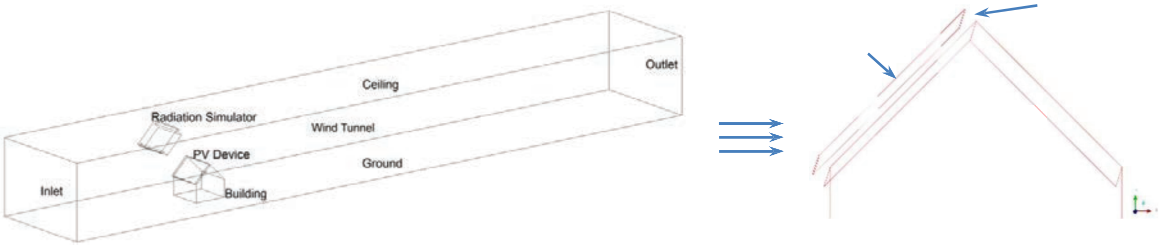

Fig.1. 3D sketches of the BIPV in the atmospheric wind tunnel

Table 1. Boundary condition and CFD setup [12]

Inflow	Normal velocity vector to the boundary with magnitudes of 0.5m/s, 1m/s, and 2m/s
Outflow	Pressure outlet
Wall/ceiling/ground/BIPV	No-slip wall
Turbulence model	RNG k — s model with Length scale of 0.5828m and turbulent intensity of 5%
Discretization scheme	Momentum: second order upwind - TKE and dissipation rate: first order upwind
Pressure-velocity coupling method	Simple scheme
Irradiation intensities	Uniform 50W/m^2, 100W/m^2 and 200 W/m^2

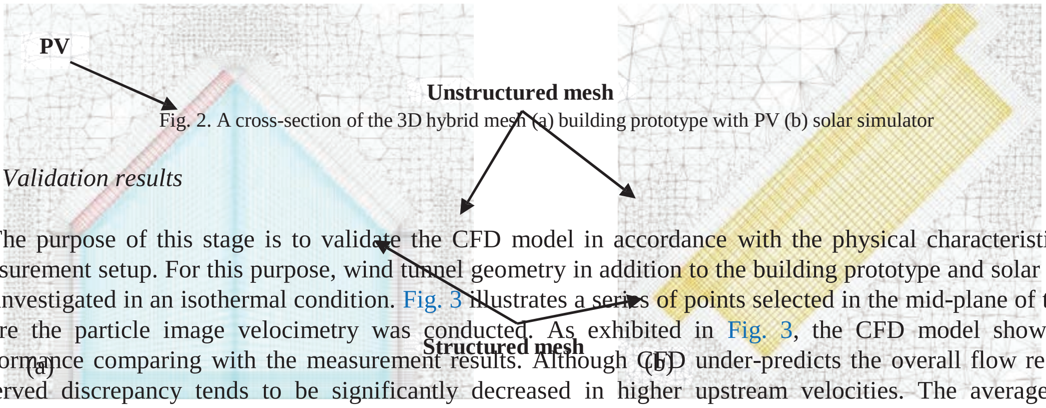

Fig. 2. A cross-section of the 3D hybrid mesh (a) building prototype with PV (b) solar simulator

2.2. Validation results

The purpose of this stage is to validate the CFD model in accordance with the physical characteristics of the measurement setup. For this purpose, wind tunnel geometry in addition to the building prototype and solar simulator are investigated in an isothermal condition. Fig. 3 illustrates a series of points selected in the mid-plane of the BIPV where the particle image velocimetry was conducted. As exhibited in Fig. 3, the CFD model shows a good performance comparing with the measurement results. Although CFD under-predicts the overall flow regime, the observed discrepancy tends to be significantly decreased in higher upstream velocities. The average error is respectively recorded 19.3%, 8.7%, and 6.0% for upstream velocities of 0.5m/s, 1m/s and 2m/s. The maximum errors (about 24.1% in 0.5m/s, 12.8% in 1m/s and 9.3% in 0.5m/s) are associated to the points 12 to 17 where the flow start to reaccelerate after being decelerated at the windward edge of the BIPV (Fig. 4a).

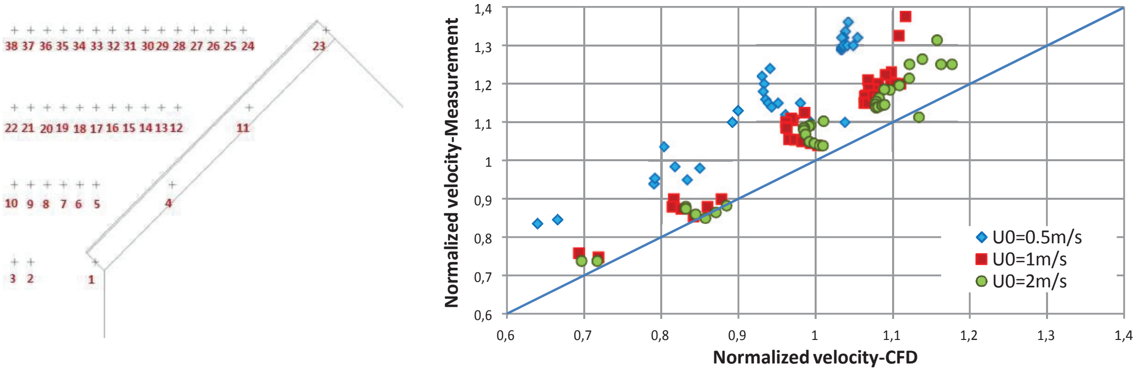

Fig. 3. Comparison between CFD and wind tunnel measurement for upstream velocities of 0.5m/s, 1m/s, and 2m/s

3. Results

3.1. Velocity field

The velocity field of the CFD model is compared with the measurement results of [6] in Fig. 4. Evidently, the CFD model is capable of resolving all three important regions of the study, including cavity, main stream and leeward back-circulation.

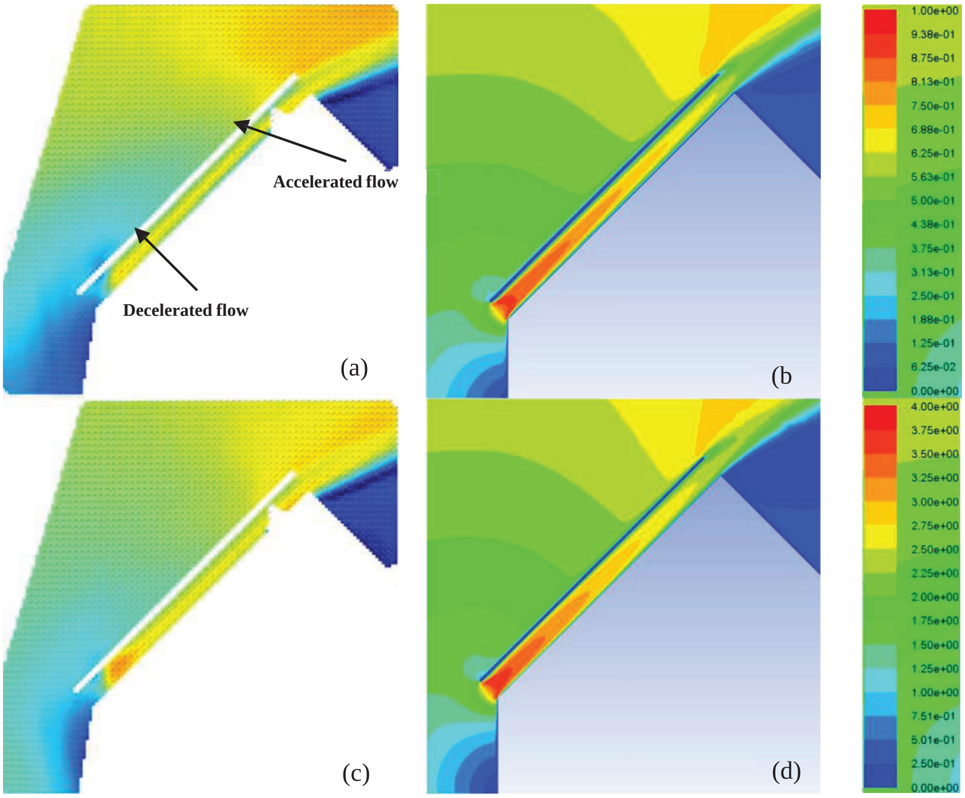

Fig. 4. Comparison of the velocity field between PIV [6] (left) and CFD (right) at upstream velocities of 0.5m/s (a-b) and 2m/s (c-d)

The cavity region is important due to its significant role in the cooling of the BIPV module. Due to 3D effect within the cavity, the airflow velocity decreases slightly when it reaches toward the upper edge of the cavity. Moreover, the main stream has almost a similar pattern in the CFD model in comparison with the PIV results. The flow slightly separates from the entrance of the cavity and then slowly decelerates toward the middle of the BIPV where it again accelerates until reaching the upper edge. At this point, both flow under and above the cavity join together. Furthermore, a weak back circulation is formed at the leeward of the building prototype, which is again fairly simulated in the CFD model.

As it is shown in Fig. 4, the CFD model precisely simulates the separated airflow at the leading and trailing edges of the panel, which creates weak eddies at points of separation. The momentum of the air passing through the upper surface of panel is slightly dropped against theses eddies, implying a reduced flow velocity near the PV surface after first separation for almost one quarter of the panel surface (Fig. 4a). The airflow regains its momentum and reaches its maximum velocity before the second separation at the trailing edge of the PV module. On the other hand, the airflow faces lower resistance in the cavity, leading to the higher velocities, which significantly benefit the dissipation of heat from the PV. Similar to the cavity flow, the non-slip effect results in lower velocities attached to walls while the higher velocities appear along the centreline of the cavity parallel to the windward roof. As it is shown in Fig. 4, CFD slightly over-predict the maximum velocity at the center of the cavity.

Moreover, a downstream jet at the outlet of the cavity is fairly simulated in the CFD model. This jet is gradually mixed at a short distance after the outlet. It should be noted that a part of the mismatch between CFD and experiment shown in the deceleration region (see Fig. 4) can be explained by the perspective effect. The measurement plane is set to be the mid plane of the domain where it is partially masked with front edge of the BIPV (see [6] for further information).

3.2. Temperature field

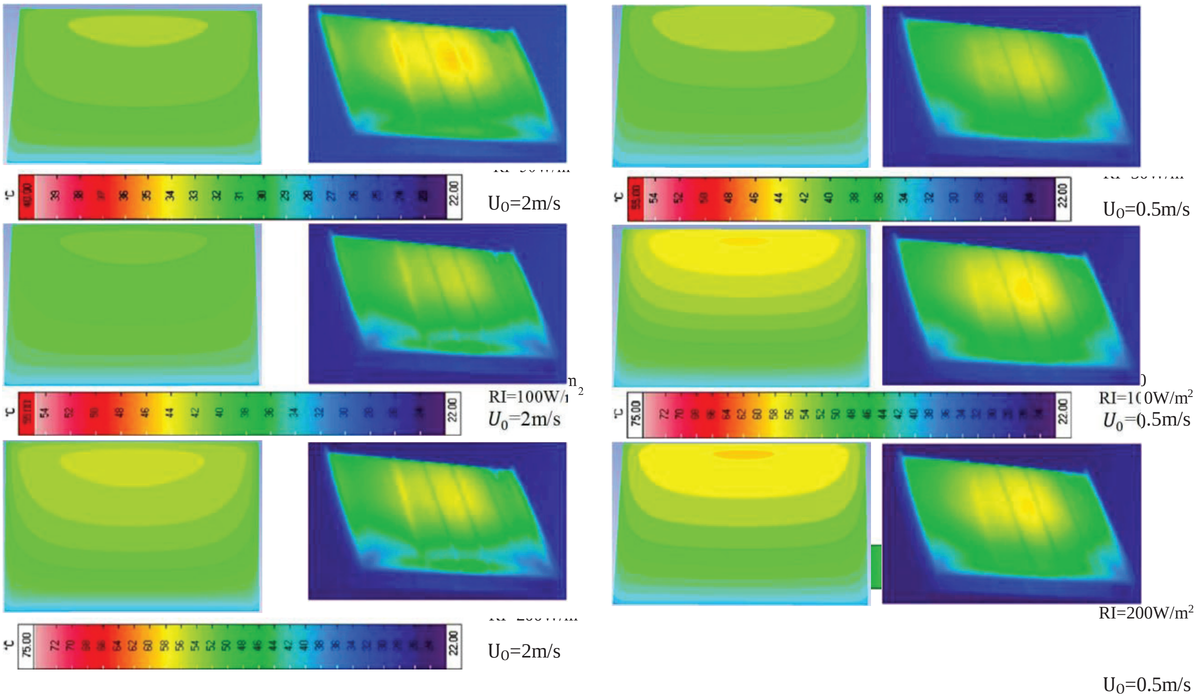

Fig. 5. BIPV's surface temperature – comparison between infrared thermography [5] and the developed CFD model

Solar radiation is further simulated in the CFD model with a solar ray tracing model, in which both direct and diffuse radiations are combined together to represent exactly the same radiation intensity (RI) as emitted in the measurement by [5]. The simulated RIs are similar to the experimental study, including 50 W/m^2, 100 W/m^2 and 200 W/m^2. The irradiance is assumed to be uniform in the CFD model, deviating slightly from the measurement study where it fluctuates about 15% (see [5] for further details). As illustrated in Fig. 5, the simulated surface temperatures of the BIPV show a similar pattern to the experiment.

As it can be seen in Fig 5, the CFD model slightly under-predict the maximum temperature of the BIPV surface. The centroids of the hot regions ellipse are also simulated toward the upper edge of the BIPV. The reason can be partially due to the ununiformed irradiance impacted the BIPV surface in the measurement campaign. These ellipses are further expanded with increasing of the surface temperatures when the heat removal rate is dramatically reduced as the airflow gains heat at the lower regions of the BIPV.

As expected, the highest surface temperature occurs at the lowest upstream velocity (0.5m/s) and tends to decrease in higher upstream velocities (2m/s) where the wind-driven convection simultaneously increases in the cavity and the BIPV surface. In general, it can be concluded that the mean and maximum surface temperatures are relatively close to experimental result in majority of cases, suggesting the capability of the developed model to mock the actual temperature distribution of the BIPV.

Conclusion

A CFD model based on a comprehensive wind tunnel measurement by [5,6] is validated in this study. The model presents the airflow regime underneath and above surfaces of a roof integrated PV module. The model is also capable of representing all heat mechanisms contributing in surface temperature of a BIPV. The potential of heat removal from cavity cooling is briefly investigated in this paper.

As a future work, the validated model will be employed to investigate the impact of the installation configuration of the BIPV modules on their surface temperatures. Furthermore, this model will be integrated into a microclimate model to investigate the lifetime durability of the BIPV modules.

Acknowledgment

The authors would like to express their gratitude to the Faculty of Engineering of the University of Nottingham for their financial support.

References

[1] Panwar N.L., Kaushik, S.C., Kothari, S. Role of renewable energy sources in environmental protection a review. Renewable and Sustainable Energy Reviews 2011 15 p. 1513–24.

[2] Razykov, T.M., Ferekides, C.S., Morel, D., Stefanakos, E., Ullal. H.S., Upadhyaya, H.M. Solar photovoltaic electricity: current status and future prospects. Solar Energy 2011 85 p. 1580–1608.

[3] Bahaj, A.S. Photovoltaic roofing: issues of design and integration into buildings. Renewable Energy 2003 28 p. 2195–2204.

[4] Kumar, R., Rosen, M.A., A critical review of photovoltaic–thermal solar collectors for air heating. Applied Energy 2011 88 p. 3603–3614.

[5] Mirzaei PA, Carmeliet J. Influence of the underneath cavity on buoyant-forced cooling of the integrated photovoltaic panels in building roof: A thermography study. Progress in Photovoltaics: Research and Applications 2013 DOI: 10.1002/pip.2390

[6] Mirzaei PA, Paterna E, Carmeliet J. Investigation of the role of cavity airflow on the performance of building-integrated photovoltaic panels Solar Energy 2014 107 p. 510-522.

[7] Brinkworth, B. J., Sandberg, M. Design procedure for cooling ducts to minimise efficiency loss due to temperature rise in PV arrays. Solar Energy 2006 80(1) p. 89-103.

[8] Wilson, M. J., Paul, M. C. Effect of mounting geometry on convection occurring under a photovoltaic panel and the corresponding efficiency using CFD. Solar Energy 2011 85(10) p. 2540-2550.

[9] Corbin, C. D., Zhai, Z. J. Experimental and numerical investigation on thermal and electrical performance of a building integrated photovoltaic–thermal collector system. Energy and Buildings 2010 42(1) p. 76-82.

[10] Mirzaei P.A., Rad M., (2013) “Toward design and fabrication of wind-driven vehicles: procedure to optimize the threshold of driving forces”, Applied Mathematical Modeling, 37: 50–61.

[11] Mirzaei, PA, Haghighat, F. Pollution removal effectiveness of the pedestrian ventilation system. Journal of Wind Engineering & Industrial Aerodynamics, Journal of Wind Engineering and Industrial Aerodynamics 2011 99 p. 46–58.

[12] Mirzaei, PA, Carmeliet, J, (2013) Dynamical Computational Fluid Dynamics Modeling of the Stochastic Wind for Application of Urban Studies. Building and Environment, 70 p. 161-170.