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THE INFLUENCE OF PHOTOVOLTAICS ON ROOF THERMAL PERFORMANCE – AN ANALYSIS OF CONVECTIVE HEAT TRANSFER COEFFICIENTS

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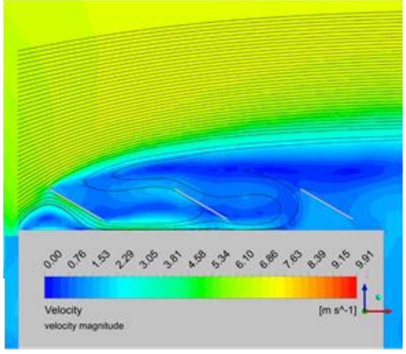


Fig 1: Flow streamlines and velocity magnitude contours over a flat roof having three rows of photovoltaic panels. Wind speed at inlet and at the building height is 6m/s.

Research summary

In a Mediterranean climate, given the absence of snow, flat roofs are typical of both vernacular and modern architecture. Thermal mass, cross ventilation and night time cooling are standard passive design aids that inhibit indoor temperature build-up on hot summer days. Such flat roofs provide a golden opportunity for free-orientation of PV (photovoltaic) panels, unlike pitched roofs.

There is established scientific evidence that their presence on flat roofs also helps curtail surface temperatures of the heavy mass structure, by means of (i) solar shading and (ii) convective cooling at given angles. Both factors in turn lower the convective heat transfer coefficient (CHTC) of the roof structure, thus inhibiting early seasonal temperature build-up. This contributes to lower cooling loads, thus reducing both the carbon footprint of the building as well as lowering energy costs for the owners. Such a holistic contribution is deemed to uphold the social, environmental and economic challenges of today. This study purports to do just that.

Through CFD (computational fluid dynamics) this study investigates the effect of flow fields over a typical flat roof building mass in a free field for a range of wind velocities. Results indicate that for a higher wind speed, the convective cooling is more significant than at lower wind speeds. This will in turn influence the elemental U-value of the roof structure, thus reducing cooling loads indoors.

Keywords: passive solar design; convective heat loss; CFD (computational fluid dynamics); CHTC (Convective Heat Transfer Coefficient)

1. Introduction

1.1 Background

The convective heat transfer coefficient (CHTC) is an important parameter in determining building thermal performance. (Sharples & Charlesworth, 1998) and (Hagishima & Tanimoto, 2003) have performed such studies.
The analysis of roof surface CHTCs are less common and is hampered by a region of recirculation and reattachment. These flow phenomena are strongly dependent on parameters such as the atmospheric wind speed profile, wind turbulence, roof roughness, roof geometry and roof temperature among others.
Researchers such as (Defraeye, Blocken, & Carmeliet, 2011) have performed a wind tunnel and a numerical study using Computational Fluid Dynamics (CFD) on the CHTCs of building surfaces. The authors focused on the windward and leeward facades of the building since, the numerical predictions of the local CHTCs were not found to correlate too well for the roof and side facades. The turbulence modelling approaches adopted by the authors include the Standard k-epsilon and Realizable k-epsilon using both wall functions as well as Low Reynolds Number Modelling (LRNM). The SST k-omega model is also used. In all cases, no good correlations on the roof surface were found. The authors propose either Unsteady Reynolds Averaged Navier Stokes (URANS) or Large Eddy Simulation (LES) closure approaches. Another solution would be to make use of non-linear two-equation models. In contrast, (Seeta Ratnam & Vengadesan, 2008) do make use of URANS using unmodified two-equation models but with no particular improvements compared to steady RANS. While the effects of vortex shedding might be important, it is not yet clear how. Interestingly, (Wright & Easom, 2003) and (Yu, Barron, & Balachandar, n.d.) both report positive comparisons of the roof flow obtained by using the Re-Normalisation Group (RNG) k-epsilon model of (Yakhot, Orszag, Thangam, Gatski, & Speziale, 1992). With the PV panels included (which can essentially be considered as inclined flat plates) an increase in recirculation behind the PV panels is expected. Close to the roof surface, the separated flow from the panels will interact with the separated flow from the roof edge. (Meroney & Neff, 2010) compare wind tunnel and CFD results of wind loads acting on solar panels on a roof. Again, the RNG k-epsilon model was found to perform very well. The limitation of this work was that the flow separation on the roof is not modelled. (Lam & Wei, 2010) provide a numerical analysis of vortex shedding from an inclined flat plate at various angles of attack. Again, they make use of the RNG k-epsilon turbulence modelling approach in view of its good performance in highly recirculating flows such as reported in (Ferreira, Sousa, & Viegas, 2002).
Photovoltaics located on building roofs will create an influence on the thermal characteristics of such roofs. The panels will provide shading against solar irradiation which contributes to a lower roof temperature, effective for hot summer days. This effect has been studied by various authors including (Dominguez, Kleissl, & Luvall, 2011) and Tian et al. (Tian et al., 2007). Another influence of PVs on roofs is their effect on the flow field over the roof. The altered flow field will influence the thermal boundary layer and hence the local CHTC. This has found little place in literature. There has also been a numerical study by (Karava, Jubayer, & Savory, 2011) and (Karava et al., 2011) which however focuses on building integrated photovoltaics. Lately, (Micallef, Buhagiar, & Borg, 2015) compiled some preliminary numerical results to understand whether the effect is worth investigating further. Although limited to one wind speed and

roof temperature, the result concluded that the difference in the average CHTC could be of more than 10%. This is considered to be an important deviation which requires further attention.

1.2 Research Objectives

It is hypothesized that photovoltaics will have a substantial influence on the roof CHTC. The research questions addressed in this work can be compiled as follows: What is the difference between the CHTC prediction of a bare flat roof and a flat roof having photovoltaic (PV) panels? To address this research questions the following two objectives set the scene for this paper:

1. To investigate the variation of the roof CHTC with wind speed with and without the presence of photovoltaics
2. To analyze the influence of the roof temperature on the resulting predictions

2. Method

2.1 Numerical model

A CFD approach is used to investigate the research question in this work. A 10m x 10m x 10m cubic building is modelled in an empty domain of dimensions 17H x 11H x 6H where H is the building height. Two model versions are used; one with a bare roof and one with three rows of photovoltaics extending along the entire building width. Details of the dimensions of the PV panels as well as their placement on the roof is shown in Fig 2. There is an overwhelming number of variables which can be altered to give different results. These include for instance, the PV row to row spacing, PV panel dimensions, PV panel elevation from the roof surface, PV orientation etc. To maintain focus, all of these geometric variables are maintained fixed and are also shown in Fig 2.

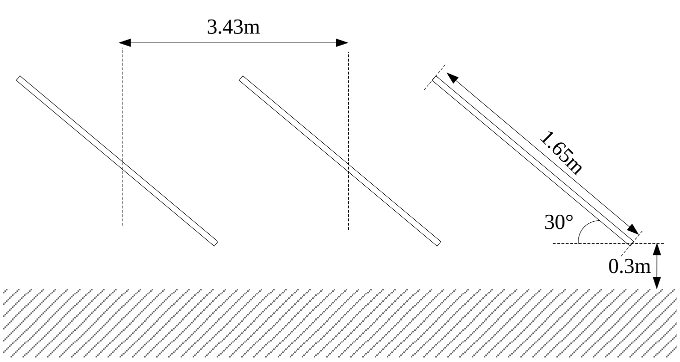


Fig 2: PV panel sideview and relevant dimensions.

The geometric models are meshed using a mapped mesh for the domain away from the building. Close to the building, a tetrahedral mesh is used with an inflation layer on the building surface as well as on the PV panels. The meshed model is shown in Fig 3.

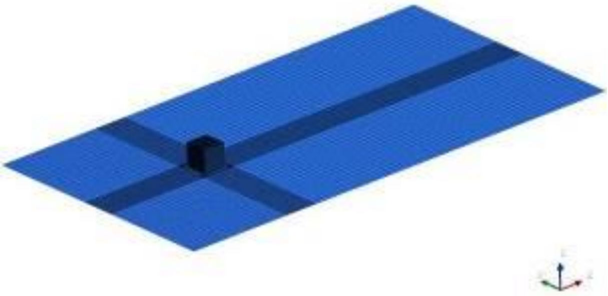


Fig 3: Diagram showing the surfaces of the meshed model.

The importance of accurately modelling the near wall region using Low Reynolds Number Modeling (LRNM) was emphasized in (Defraeye, Blocken, & Carmeliet, 2010). This approach is hence preferred for the present research. The reader is referred to (Defraeye et al., 2010) for a mroe detailed description of the method.

The boundary conditions used for the model are shown in Fig 4. The inlet boundary is specified as a velocity inlet with a logarithmic velocity profile defined by the equations specified in (Defraeye et al., 2010).

The ambient temperature is set for a hot summer day at 30°C. The choice of summer conditions is rather arbitrary in order to maintain focus on one ambient temperature test condition which is more synonymous to warm countries where PV panels are relevant as a renewable energy technology. Under these conditions, the PV panel temperatures are chosen to be 70°C as indicated in (Mavromatakis, Kavoussanaki, Vignola, & Franghiadakis, 2014). Two building surface temperatures are tested which are 40°C and 50°C. The ground is taken as a non-slip adiabatic surface. The outlet of the domain is specified as a pressure outlet while the sides and top surface of the domain are set as slip wall boundaries with zero normal gradients.

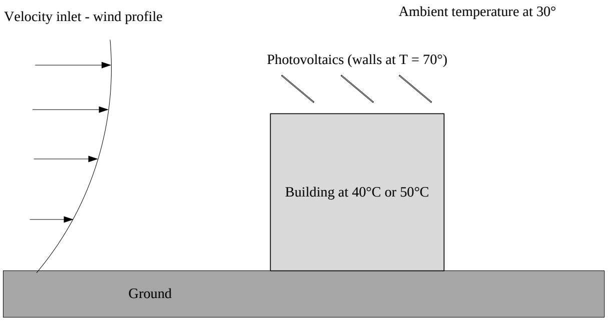


Fig 4: Main boundary conditions used in the model.

To address the research question, two variables are changed (i) the reference mean wind speed at building height U_{10} (from 1m/s to 6m/s – typical wind speeds in the built environment) and (ii) the building surface temperature. All other boundary conditions are maintained fixed.

The turbulence model used in this work is the RNG k-epsilon model in steady state. This option is used on the basis of the positive experiences mentioned earlier from (Wright & Easom, 2003) and (Yu et al., n.d.) in their prediction of the roof flow. For a more in-depth discussion of the CFD approach the reader is referred to textbooks such as (Versteeg & Malalasekera, 2007), (Tu, Yeoh, & Liu, 2007) and (Wendt, Anderson, & for Fluid Dynamics, 2008). For the RNG k-epsilon turbulence model used the reader is referred to (Yakhot et al., 1992).

3. Results

3.1 Flow characterization

The streamline patterns for 6m/s wind speed or the case with no PVs and that with PVs is shown in Fig 5. The figure shows a side view plane cutting through the building centerline. The wind direction is from left to right (PVs are facing south). The flow separates at the windward corner of the building. For the case of no PVs, a region of slow moving air can be observed. The flow reattaches at around the mid-building length (circa 5m). This is important to note since many turbulence models such as the standard k-epsilon model do not manage to predict flow re-attachment at all.

On the other hand, the PV panels alter the flow field dramatically. Towards the leading wind-ward corner of the building, a flow separation zone develops but reattaches itself completely after a few meters due to the presence of the first row of PV panels. The flow accelerates under this PV panel and energizes the slow moving air behind the PV panel. This can again be observed to occur under the second row of PV panels. Fig 6 gives a closer inspection of the flow streamlines for the case with PV panels. Streamlines can be observed below the first and second row but not for the third row. This will have a substantial influence on the local heat transfer characteristics of the roof.

If the roof has more than three rows of PV panels, the wake breakdown would be expected to progress in a similar manner beyond the third row of PVs.

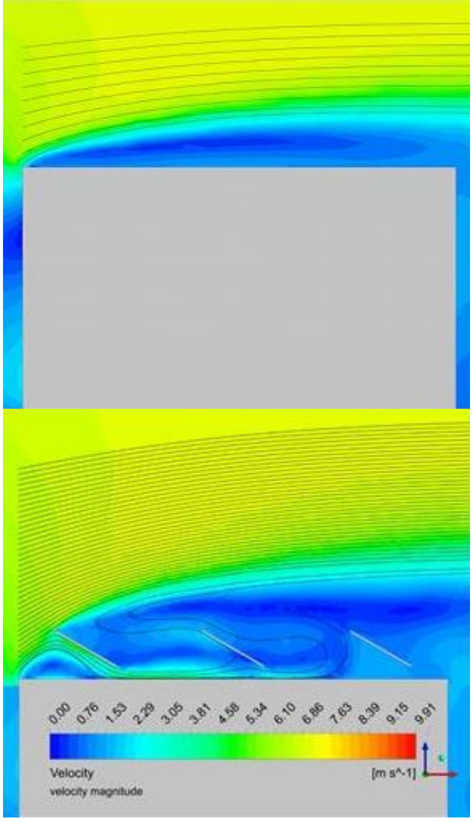
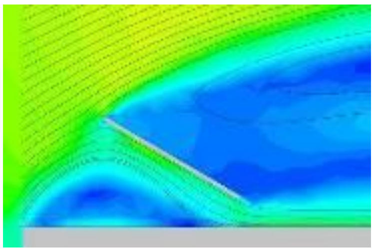
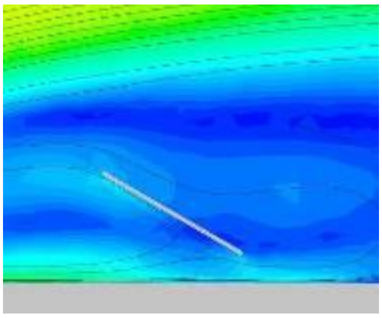


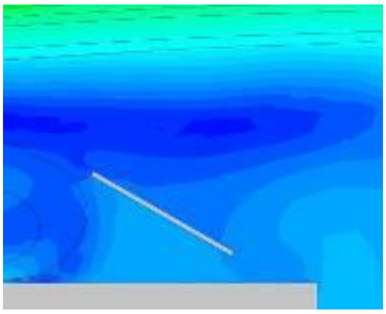
Fig 5: Side view of velocity contours and streamlines for (a) a roof with no PV panels and (b) a roof with PV panels. The inlet windspeed is at 6m/s at the building height.



(a) Upstream row



(b) Middle row



(c) Downstream row

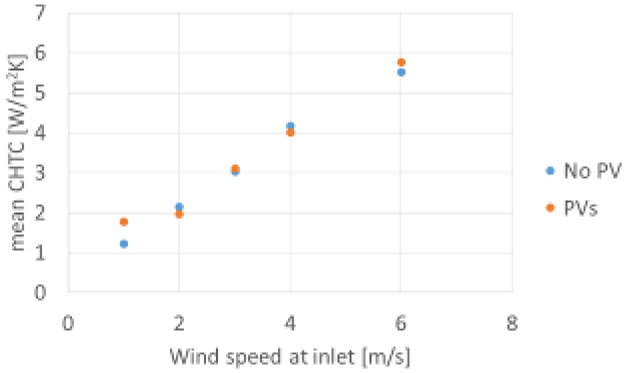
Fig 6: Detailed flow streamlines at each panel row location. The inlet windspeed is at 6m/s at the building height.

3.2 Variation of the CHTC with wind speed

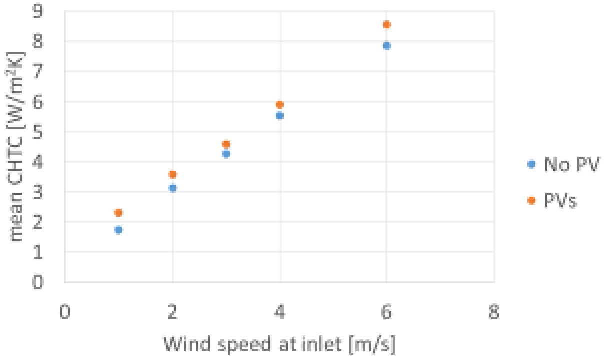
The variation of the mean CHTC with wind speed is shown in Fig 7 for a building temperature of 40°C and 50°C. The mean CHTC is defined by:

$$\bar{h} = \frac{1}{A}\int_A h(x,y)dA \qquad (1)$$

Where $h(x,y)$ is the local CHTC variation over the (x,y) coordinates of the roof. The resulting CHTCs for the 40°C temperature case is, as expected, lower than that for a building temperature of 50°C. For the former case, the differences between the CHTC for a bare roof and a roof with PVs is very small, with no clear trend of whether the PVs increase or decrease the mean CHTC.For the 50°C case, the differences are more discernible and seem to show that, especially for the higher wind speed, the PVs tend to improve the cooling performance of the roof (the mean CHTC increases). The maximum difference is around 8%. For the summer conditions investigated here, these results suggest that the PV provide a marginal improvement in the cooling effect. The reason for this slight improvement, is associated with the localized flow accelerations occurring just below the PV rows. This should therefore be analyzed further with different mounting heights and spacing.



(a) Building temperature 40°C



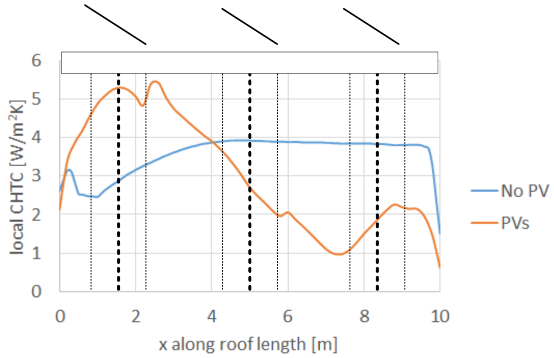
(b) Building temperature 50°C

Fig 7: Variation of the mean CHTC with wind speed with and without PV panels for a building temperature of (a) 40°C and (b) 50°C.

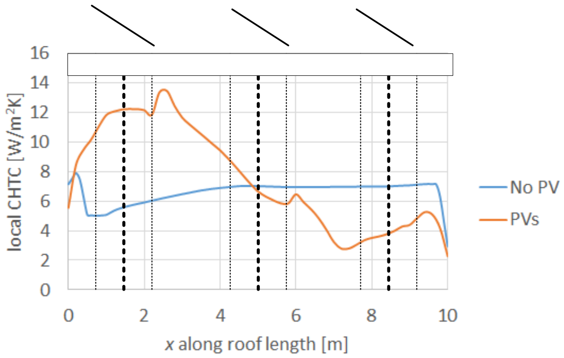
3.3 Local variations of the CHTC

The local CHTC variations are important on the effects of the heat transfer characteristics of different zones within the building. Two wind speeds are chosen to analyze the effects on the local CHTC (2m/s and 6m/s). Results are shown for a building temperature of 50°C since these showed the highest mean CHTC variations with wind speed between roofs with PVs and those without. A comparison is shown in Fig 8.

For both wind speeds, the trends are similar. For the 6m/s wind speed, the magnitude of the differences are greater. With no PVs, there is a dip in the CHTC close to the building leading edge. This is then followed by an increase in the CHTC to a maximum threshold value. This corresponds closely to what was observed by (Voutsinas, MA, & Rados, 1995). This variation was not observed by (Defraeye et al., 2011) who, as mentioned earlier, did not use non-linear two-equation turbulence models or for instance the RNG model used in this work. This qualitative agreement with the experimental measurements of (Meinders, Hanjalic, & Martinuzzi, 1999) further support the results obtained in this work – at least for the bare roofs. (Meinders et al., 1999) attribute the dip in CHTC to the localized high temperature zone associated with the separation vortex flow in the leading edge region. The gradual increase of the CHTC is attributed by the same authors to be due to the lower temperature air (and hence lower enthalpy) which cause an increase in the heat transfer rate. Following on the observations made in Fig 8, the case with PVs shows a high peak in the region of the first row of PVs. This is attributed to the flow acceleration occurring in this region which enhances the heat transfer rate. This gradually reduces due to the diffusion and slowdown of this high speed fluid stream. Under the second row of PVs, the heat transfer rate reduces due to the slower air flow. Downstream of the second row, the flow is highly diffused and slow moving and hence a low heat transfer rate occurs. This corresponds to a local minimum. An increase in CHTC can be observed towards, the leeward edge of the roof. On inspection of the flow field of Fig 6, a slight increase in speed of the air below the last row of panels can be observed which corresponds to this increase in CHTC at the third PV panel row position. For the 2m/s case, the difference between the no PV and the PV case is larger and the maxima and minima observed are less pronounced. Still, the same physics prevails for this range of wind speeds.



(a) Wind speed = 2m/s



(b) Wind speed = 6m/s

Fig 8: Variation of the local CHTC along the roof length (at the building centreline). Results are shown for wind speeds of (a) 2m/s and (b) 6m/s at the domain inlet. The building temperature is at 50°C.

4. Discussion

The practical significance of such a research is of course related to the influence of the CHTC on the overall heat transfer coefficient, that is the U-value of the building element, in this case the roof.

Considering a typical flat roof made up of a 150mm reinforced concrete slab (having a thermal conductivity (λ) of 2.5 W/mK), externally topped with a layer of 100mm backfill layer (λ - 0.8W/mK), a 75mm screed layer (λ – 1.93W/mK) and a 4mm light coloured finished membrane (λ – 0.23W/mK) and internally finished with a 4mm ceiling plastered ceiling (λ – 0.21W/mK), the total U-Value for the building element assuming the calculated convective heat transfer coefficients due to the different wind speeds, with and without PV panels is as shown in Fig 9. The indoor CHTC was assumed to be 7.2W/m^{2}K.

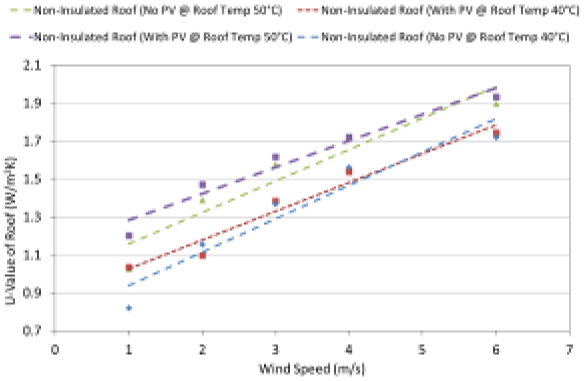


Fig 9: Variation of the roof (non-insulated) U value for different building temperatures with and without PVs.

As expected the overall heat transfer coefficient increases, with increasing wind speed. Considering the roof having a surface temperature of 40°C, trends show that the difference in the overall heat transfer coefficient between the roof with photovoltaic panels and that without is more pronounced at lower wind velocities. At higher velocities the effect of having photovoltaic panels appears to be insignificant as the two trends for the overall heat transfer coefficient converge; similarly for the roof having a surface temperature of 50°C. In the latter case however, compared to the roof having a surface temperature of 40°C, the overall heat transfer coefficient results obtained are higher by around 16%.

5. Conclusions

The following main conclusions may be drawn:

1. the mean CHTC of a flat roof with no PV and with PV panels differs more significantly at the low wind speeds. This is particularly true for a a high building temperature of 50°C.
2. When PVs are installed, the local CHTC varies substantially from a roof with no PVs. This may lead to uneven thermal performance between different rooms at the top-most floors.

Practical aspects such as surface roughness effects, parapett walls, PV panel pitch, mounting height and spacing have not been considered and could be subject of further research.

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