

Effect of Air Gap on the Performance of Building-Integrated Photovoltaics

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ABSTRACT: The efficiency of photovoltaic (PV) devices is approximately inversely proportional to the cell temperature and air flow around PV modules installed over or beside a building envelope can facilitate ventilation cooling and so reduce the problem of module overheating. The effect of the size of air gap between PV modules and the building envelope on the PV performance in terms of cell temperature has been investigated numerically for a range of roof pitches and panel lengths under two different settings of solar radiation,. It has been found that the mean and maximum PV temperatures decrease with the increase in pitch angle and air gap. The mean PV temperature also decreases with increasing panel length for air gaps greater than or equal to 0.1 m whereas the maximum PV temperature generally increases with panel length but decreases when the panel length increases from two modules to three modules and the air gap is between 0.1 m and 0.125 m. Without adequate air circulation, overheating of PV modules would occur and hot spots could form near the top of modules with potential cell temperatures over 80°C above air temperature. To reduce possible overheating requires a minimum air gap of between 0.11 m and 0.15 m for multiple module installation and 0.16 m for single module installation.

Keywords: photovoltaics, air gap, natural convection, solar radiation, overheating

1. INTRODUCTION

The performance of crystalline photovoltaic (PV) devices depends on the cell temperature in addition to other factors such as insolation and shading. High cell temperatures resulting from overheating could occur for PVs integrated into building envelopes. For most domestic applications, PV modules are installed on the pitched roof for easier installation and higher performance than on a vertical façade. It is important then to provide an adequate gap behind the modules to allow air free circulation for ventilation cooling.

Recommended minimum gaps between PV modules and the roof to allow airflow range from several centimeters [1] to a minimum of 15 cm [2] but there is no clear consensus of optimum gap size for good PV performance. McCabe, et al. [3] demonstrated the importance of using a correct installed normal operating cell temperature which depended on the air gap as well as other factors for predicting the performance of building-integrated PV systems. Guivarch and Peuportier [4] used a dynamic simulation tool to evaluate the influence on the efficiency of the type of integration of PV collector into buildings. It was shown that an air gap of 0.1 m

improved the efficiency of PV compared with the integration without a gap. Brinkworth, et al. [5] developed an analytical model to predict air cooling of PV cladding under the assumption that equations for forced convection heat transfer would be applicable for natural ventilation. The model was able to predict mean performance parameters such as PV temperature for smooth channel surfaces. However, most commercial PV modules have protruding frames for ease of installation. The frames would interfere with air flow between the modules and roof and could trap heat behind, adversely affecting the PV performance. Such analytical models would then not be able to predict the flow behaviour and PV temperature accurately. This investigation aims to quantify the effect of air gap on the PV performance in terms of cell temperature for different roof pitches and PV sizes.

2. METHOD

Computational fluid dynamics software FLUENT [6] was used for modelling of fluid flow and heat transfer around PV modules mounted on pitched roofs and in front of a vertical facade. Modelling was carried out for one or more PV modules installed on a building envelope consecutively (defined here as panel) as shown in Fig. 1. Simulation was performed for circumstances when overheating would be most likely to occur, i.e., under bright sunshine and no wind. Consequently, PV modules absorb incident solar radiation and transfer the absorbed heat to the surroundings by natural convection and radiation. The natural convection results from buoyancy-induced air flow around the modules. The RNG k- ϵ model [7] was used for turbulent air flow and heat transfer. A discrete transfer radiation model [8] was used for modelling the radiative heat transfer from the modules to surroundings. Modelling was performed for realistic PV

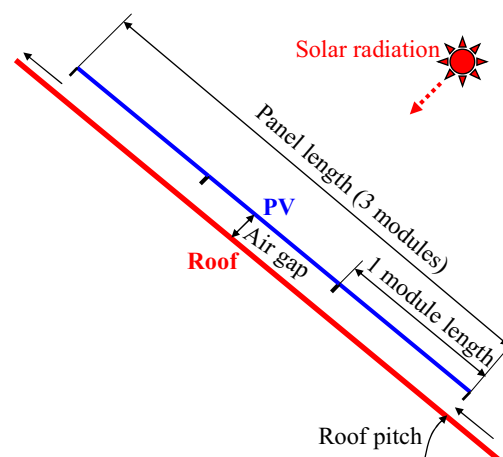


Figure 1 PV modules mounted on a pitched roof

modules [9] with dimensions shown in Fig. 2 for a range of roof pitches and gap sizes. The ambient air temperature was fixed at 20°C. The incoming solar radiation was first fixed at 1000 W/m² and then varied with inclination of roof-mounted PV modules for an example location. The building envelope would normally gain heat from the radiation. Part of the heat gain could transfer to the building interior, the amount of which depends on the construction of the envelope. For simplicity, the heat transfer from the envelope to the interior was neglected.

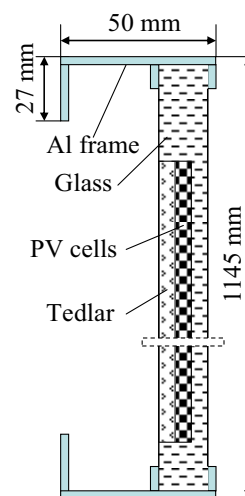


Figure 2 Module structure

3. RESULTS AND DISCUSSION

Results are discussed first for all roof pitch angles and air gaps at a fixed solar insolation of 1000 W/m² and the effect of variation in insolation is then presented at the end of the section.

Figures 3 and 4 show air flow patterns and temperature distribution, respectively, around a single module installed 0.2 m above a roof with a pitch of 45 degrees. It is seen that air was induced through the air gap due to the buoyancy effect. The mean velocity through the 0.2 m gap was 0.26 m/s. At the two ends of the module frame, the velocity was higher (0.33 m/s) due to the reduced flow area (0.16 m gap). The configuration of the frame largely prevented air circulation near the two ends of the module. Consequently, heat from the module accumulated near the top end. The predicted average PV temperature was 67°C but the temperature of the PV cells near the top reached as high as 76°C.

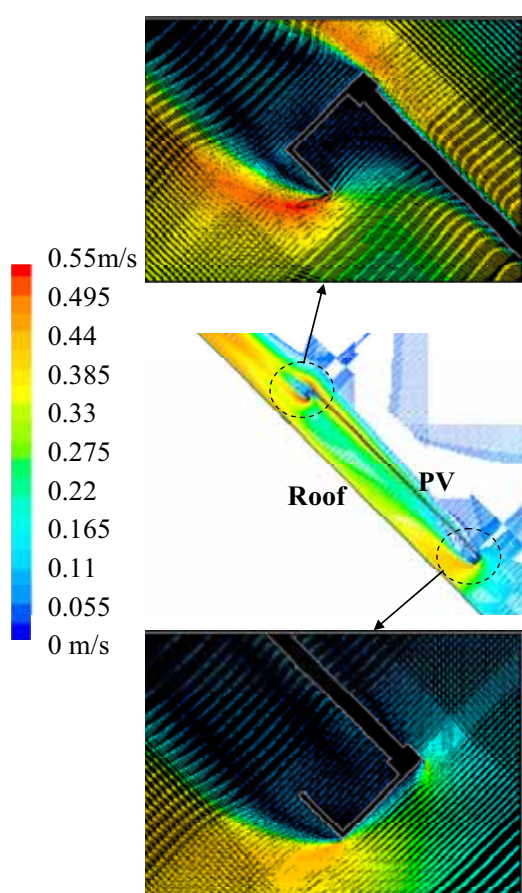


Figure 3 Air flow patterns around one module installed 0.2 m above a roof at 45 degree pitch angle

3.1 Effect of Pitch Angle

Fig. 5 shows variations with roof pitch angle (inclination) of mean velocity (V_{mean}) in the 0.2 m gap, mean and maximum PV temperatures (T_{mean} and T_{max} respectively) for two panels – one for a single module and the other for a 3-module panel, i.e., a panel consisting of three modules of the same size mounted consecutively. Because of the interdependence between velocity and temperature in buoyancy, the velocity in the air gap does not change monotonously with pitch angle. For a panel of one module long, the mean velocity increased with the pitch angle up to an angle of about 60 degrees due to increased vertical height and hence thermal buoyancy. The mean velocity then decreased with further increase in the pitch. For longer panels, the peak velocity would occur at larger pitch angles. The mean and

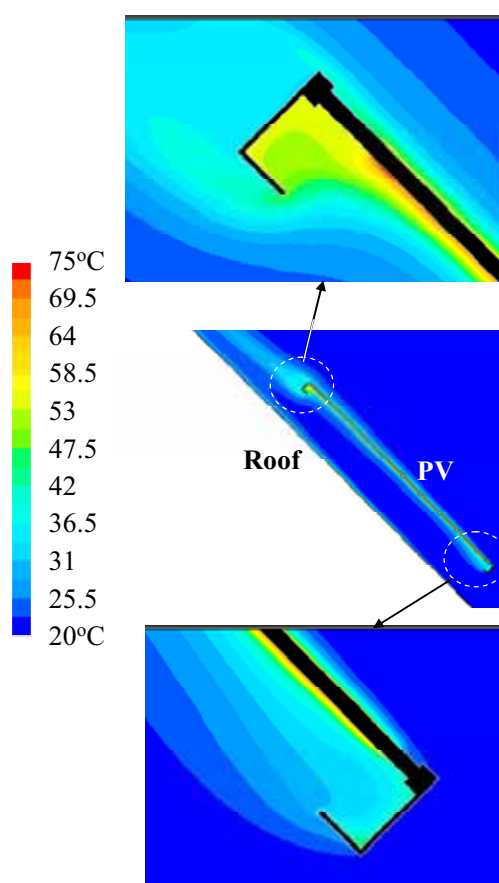


Figure 4 Temperature distribution around the module

maximum PV temperatures decreased with increase in the pitch angle. The mean temperature for a single module decreased from 72°C at 15-degree pitch to 67°C at 45 degrees and further to 65°C for vertical or nearly vertical installation (i.e., pitch angles between 75 and 90 degrees). The maximum temperature reached 85°C at 15-degree pitch but decreased to 76°C at 45 degrees and to 72°C for vertical installation. The variation in the temperatures was however negligible for pitch angles between 75 and 90 degrees. Similar temperature variations were observed for other air gap sizes and panel lengths. The mean velocity and maximum temperature were higher but the mean temperature was lower for a 3-module panel than those for a single module with a 0.2 m air gap for all the pitch angles.

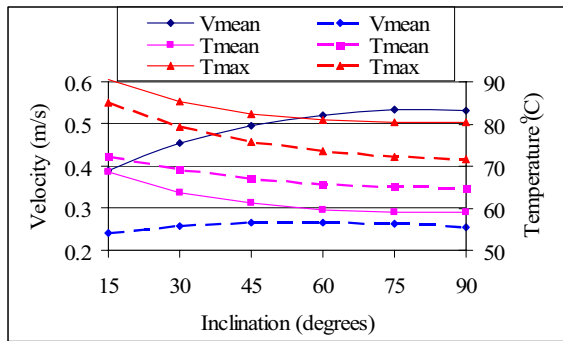


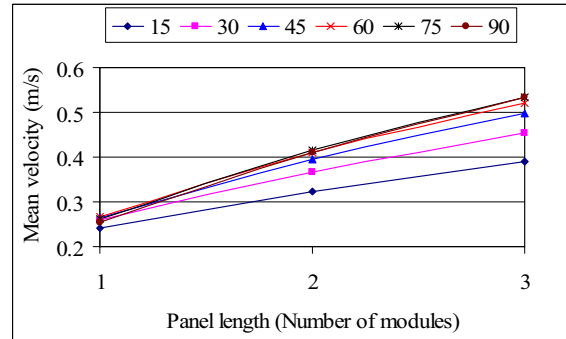
Figure 5 Variations of air velocity and cell temperatures with inclination for two PV panels with a 0.2 m air gap from building envelope (solid lines for a panel of 3 modules and dashed lines for a panel of a single module)

3.2 Effect of Panel Length

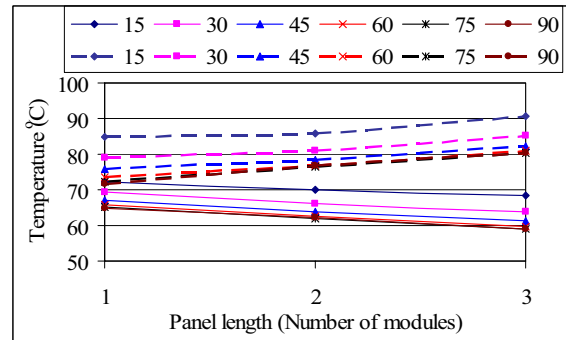
The thermal buoyancy is influenced by the height of panel and so the mean velocity increases with panel length.

Fig. 6 shows variations of mean velocity in the 0.2 m gap, mean and maximum PV temperatures with the length of panels consisting of 1 module, 2 and 3 modules for different roof pitch angles. The mean velocity increased with panel length at any inclination angle. For panels of 2 and 3 modules long, the mean velocity peaked at about 75 and 90 degrees respectively

compared with 60 degrees for a single module as mentioned before.



(a) Mean velocity behind modules



(b) Mean (solid line) and maximum (dashed line) PV temperatures

Figure 6 Variations of air velocity and PV temperatures with panel length for a 0.2 m gap

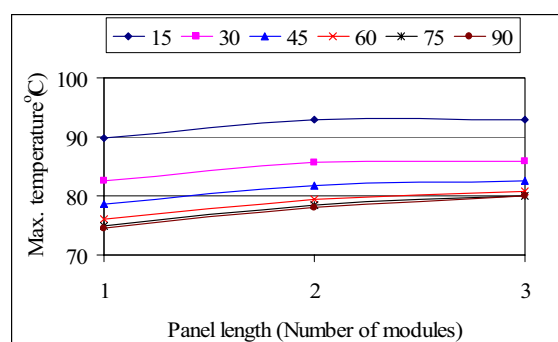
The mean temperature decreased linearly with the increase in the length of panels for an air gap of 0.2 m behind. The mean temperature for a 3-module panel was 2 to 4°C lower than that for a 2-module panel which was 3°C lower than that for a single module. The lower mean temperature for a longer panel resulted from the higher mean velocity of cooler ambient air flowing behind the panel.

In contrast with the decrease in mean temperature, the maximum PV temperature increased with increasing panel length for a 0.2 m air gap. The maximum temperature for a 3-module panel was 4°C higher than that for a 2-module panel. The difference in the maximum temperature between a 2-module panel and a single module depended highly on the pitch angle – increasing from

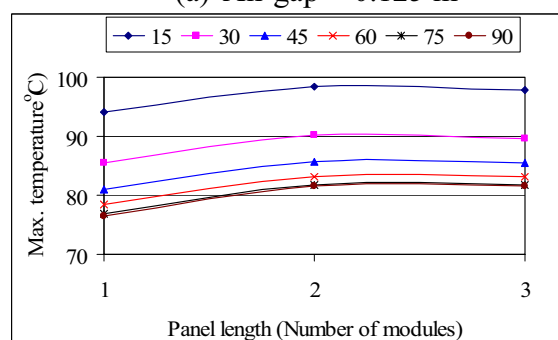
1°C to 5°C when the pitch angle increased from 15 to 90 degrees. However, the effect of panel length on the maximum PV temperature was found to depend on the air gap. Fig. 7a shows that with an air gap of 0.125 m, there was hardly any variation in the maximum temperature with panel numbers from 2 to 3 for pitch angles between 15 and 45 degrees. When the air gap was reduced to between 0.1 and 0.11 m, the maximum temperature decreased slightly when the panel length increased from 2 to 3 modules long (Fig. 7b). This resulted from the higher ventilation cooling effect with the longer panel which more than compensated for larger heat accumulation near the top of higher modules. It suggests that long panels would be beneficial in reducing not only the maximum temperature but also the mean temperature of the PV cells with air gaps between 0.1 and 0.11 m. This is because although heat accumulated at the top of the 2-module panel would be less than that near the top of the 3-module panel at the same velocity, the top of the 2-module panel with a lower mean velocity behind would accumulate as much heat as that of the 3-module panel. However, when the air gap was reduced to 0.09 m, the maximum temperature increased again with panel length, though slightly, as shown in Fig. 7c. When the air gap was reduced further to 0.075 m, while the increase in the maximum temperature with panel length was appreciable, the decrease in mean temperature with increasing panel length became negligible as shown in Fig. 8. This is because with such a small air gap, flow resistance in the gap particularly at the two ends of modules became excessive, thus preventing ambient air flowing freely behind the panel, as is discussed below.

3.3 Critical Air Gap

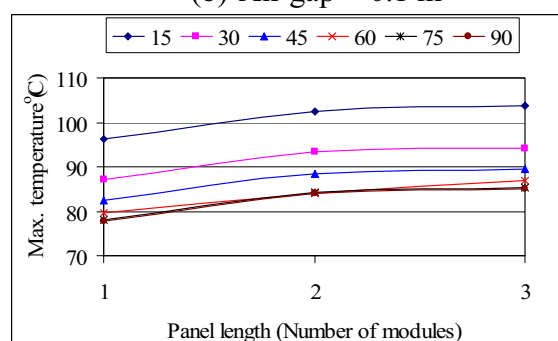
Fig. 9 shows variations of mean velocity, mean and maximum PV temperatures with air gap behind a 3-module panel for different pitch angles. The mean velocity



(a) Air gap = 0.125 m



(b) Air gap = 0.1 m



(c) Air gap = 0.09 m

Figure 7 Effect of air gap on the variation of maximum PV temperature with panel length

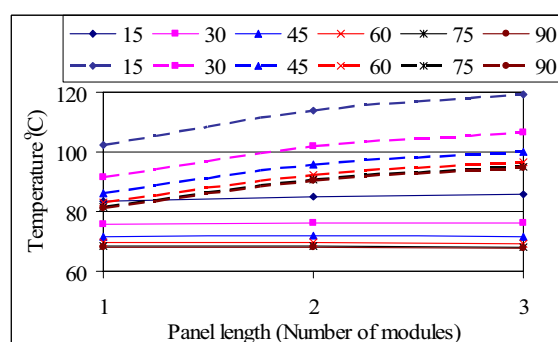


Figure 8 Variation of mean (solid line) and maximum (dashed line) temperatures with panel length for a 0.075 m gap

behind the module was lower for smaller air gaps. This was mainly due to the relatively larger flow resistance of smaller air gap resulting from the configuration of the module frame which formed the air inlet and outlet 0.04 m smaller than the air gap behind PV. For example, the inlet and outlet openings were reduced by 167% from 0.16 m to 0.06 m when the gap size was reduced by only 100% from 0.2 m to 0.1 m. The flow rate, product of opening size and air velocity, would be much lower for the smaller gap at lower mean velocity. As a result, the mean and particularly maximum PV temperatures increased with decreasing air gap. For example, for a single module at 15-degree pitch angle (Fig. 10), the mean temperature increased by about 3°C from 74°C with a 0.2 m gap to 77°C with a 0.1 m gap whereas the corresponding maximum temperature increased by 9°C from 85°C to 94°C. The maximum temperature for a panel

of 3 modules at 15-degree pitch reached 98°C for a 0.1 m gap and over 100°C for air gaps less than 0.095 m. The variation was most significant when the air gap was less than 0.11 m.

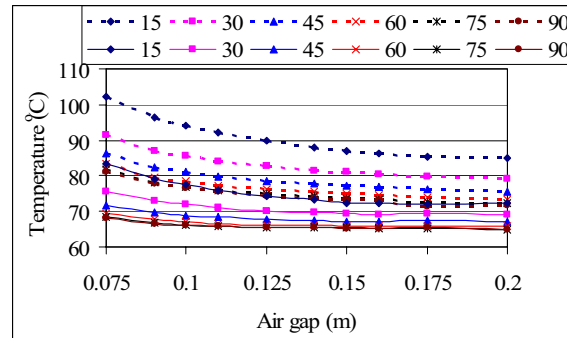
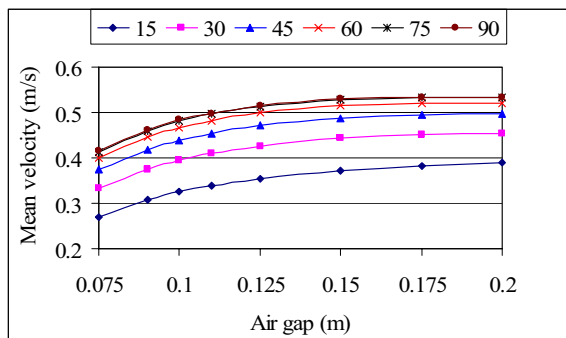
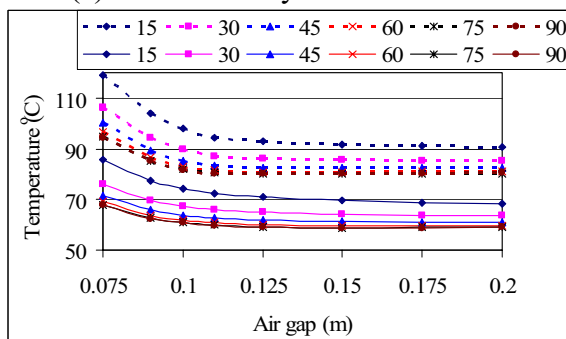


Figure 10 Effect of air gap on the mean (solid line) and maximum (dashed line) PV temperatures for a single module



(a) Mean velocity behind modules



(b) Mean (solid line) and maximum (dashed line) PV temperatures

Figure 9 Effect of air gap on the mean velocity and PV temperatures for 3-module panel

A critical air gap or minimum air gap required in order to minimise overheating can be defined as the air gap at which the mean or maximum PV temperature increases markedly with decreasing gap size. Fig. 11 shows the predicted critical air gaps for different pitch angles and panel lengths. The critical air gap varied with panel length and roof pitch, increasing with decreasing length/pitch. It also depended on which temperature was used as a criterion, being generally larger according to the maximum PV temperature than that based on the mean PV temperature. The critical air gap was 0.11 m for the 3-module panel. For a 2-module panel, the critical air gap increased to 0.125 m at 30-degree roof pitch and to 0.2 m at 15-degree roof pitch based on the mean PV temperature. Based on the maximum PV temperature, it increased to 0.15 m for roof pitches larger than 30 degrees, and 0.175 m to 0.2 m for roof pitches from 30 to 15 degrees. For a single module, the air gap based on the mean PV temperature was about 0.125 m for all but 15-degree roof pitch where it was 0.15 m, and the value based on the maximum temperature was 0.16 m for all pitch angles.

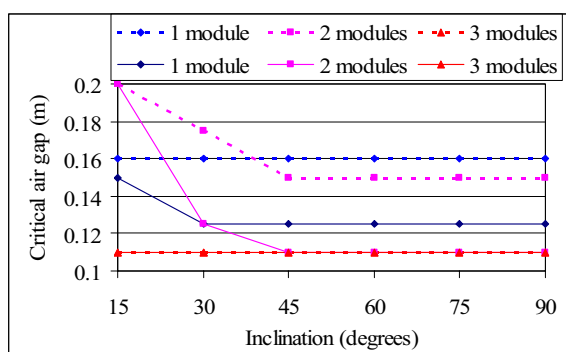
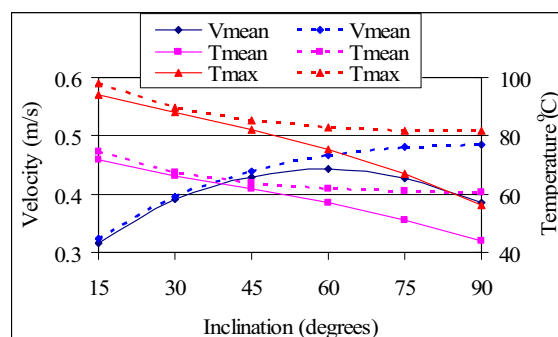


Figure 11 Critical air gaps based on the mean (solid line) and maximum (dashed line) PV temperatures

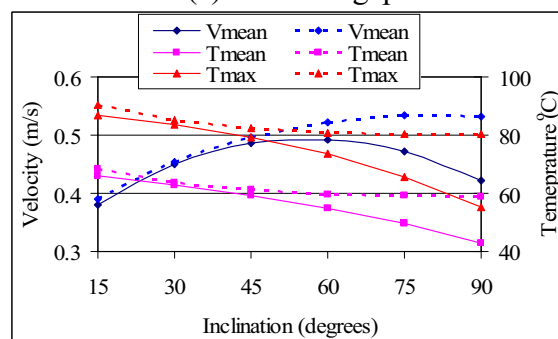
3.4 Effect of Solar Heat Gain

In practice, for a given location and time, solar heat gain by PV panels depends on the inclination. When the variation of solar radiation with inclination is taken into account, the heat gain by panels installed away from 'optimum' inclination would be less than the fixed high value. Fig. 12 shows a comparison of the velocity and temperatures for a panel of 3 modules with 0.1 m and 0.2 air gaps for two different settings of solar heat gain. The comparison is given for south facing PV modules between the values obtained with solar heat gain varied with pitch angle from the maximum of 965 W/m^2 at 30-degree inclination (London conditions in summer) and those for a fixed insolation of 1000 W/m^2 . One obvious difference in mean velocity (trend) is that the velocity peaked at a panel inclination of 60 degrees and then decreased sharply towards vertical installation due to the reduced solar heat gain when it varied with inclination whereas the velocity increased continuously though at a decreasing rate from horizontal to vertical installation when the insolation was fixed. The PV temperatures decreased at an increasing rate with inclination for varying solar heat gain but the temperatures for a fixed insolation decreased at a decreasing rate. Consequently, the mean and maximum temperatures at the optimum inclination of 30 degrees for the varying insolation were similar to those for the fixed insolation. In

comparison, the mean and maximum temperatures at the vertical installation with a 0.2 m gap dropped from 59°C and 80°C with fixed insolation to 43°C and 55°C with varying insolation, respectively. For a 0.1 m gap, the mean and maximum temperatures dropped from 61°C and 82°C with fixed insolation to 44°C and 56°C with varying insolation, respectively.



(a) 0.1 m air gap



(b) 0.2 m air gap

Figure 12 Effect of insolation on the mean velocity and PV temperatures for 3-module panels (solid lines for varying insolation, dashed lines for constant insolation)

For a given pitch angle, the variations of the velocity and temperatures with air gap or panel length for the varying insolation were similar to those for the constant insolation. It can be inferred that variations in the velocity and temperatures with pitch angle, air gap or panel length discussed in Sections 3.1 to 3.3 would also be applicable to other insolation levels ($> 490 \text{ W/m}^2$) than 1000 W/m^2 .

4. CONCLUSIONS

Computational fluid dynamics has been used to predict the effect of gap size on the PV performance in terms of cell temperature for a range of roof pitches and PV panel lengths at different solar radiation levels. It has been found that the mean velocity in the air gap behind PV modules due to natural convection increased with air gap. For constant solar radiation, the air velocity increases, in general, with the increase in pitch angle but only to a point depending on the air gap and length of PV panel composed of modules installed consecutively. The longer the PV panel or the smaller the air gap, the higher the pitch angle where the peak velocity would occur. For a given location where solar radiation varies with inclination from horizontal plane, the air velocity increases with roof pitch up to an angle of about 60 degrees and then decreases regardless of panel length and air gap.

The mean and maximum PV temperatures have been found to decrease with the increase in the air gap due to reduced flow resistance mainly from the module frame. The mean and maximum temperatures also decrease with increasing pitch angle of roofs. In addition, the mean PV temperature decreases with increasing panel length due to increasing buoyancy-induced air flow in the air gap behind modules greater than 0.08 m. By contrast, the maximum PV temperature associated with hot spots resulting from heat accumulation near the top of modules generally increases with panel length. However, the maximum temperature decreases when the panel length increases from two modules to three modules and the air gap is between 0.1 m and 0.125 m.

The computer modelling has indicated that without adequate air circulation, overheating of PV modules would occur and hot spots could form near the top of modules with cell temperatures over 80°C above air temperature under bright sunshine. To

reduce the overheating potential, a minimum air gap of 0.11 m between a very long PV panel (formed by mounting three modules continuously) and the building envelope would be required. For a PV panel of 2 modules long, this gap should be increased to 0.15 m for roof pitches ≥ 45 degrees or even larger gap for smaller roof pitches. For single module installation, the gap should be 0.16 m in order to minimise the hot spot temperature.

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