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PERFORMANCE PREDICTION OF ROOF-INTEGRATED PHOTOVOLTAICS

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SYNOPSIS

Building-integrated photovoltaic (PV) systems are increasingly common in developed countries and have the potential to contribute significantly to electricity generation as a benign alternative to fossil fuel generation. The University of Nottingham has recently completed a new campus, The Jubilee Campus. PVs are integrated into the roofs of four atria for the teaching buildings in the new campus.

This paper presents the performance of roof-integrated PVs using CFD (computational fluid dynamics). A commercial CFD package was used to predict the air flow and thermal environment in the atria with radiative and convective heat transfer. The effect of ventilation strategies on the performance of PV arrays and the indoor climate was investigated. Key parameters investigated include the size and location of air inlet, ventilation rate, roof heat flux and air flow rate through a channel under the roof. For effective cooling of roof PV arrays, cool outdoor air should be introduced through an opening positioned close to the roof or an air channel underneath the roof.

1. INTRODUCTION

The University of Nottingham has recently completed a new campus, The Jubilee Campus, on a former industrial site within a mile of the existing University Park campus. The new campus is environment-friendly with extensive use of sustainable materials in the construction of buildings. The buildings are super insulated with air-tight building envelopes and make use of renewable energy by means of PVs, light pipes and wind-catching cowls. A novel super-efficient ventilation system is designed for the main teaching buildings. It makes use of the circulation spaces, corridors and stair wells as ventilation ducts to provide fresh air and remove stale air so as to minimise the pressure losses through the ventilation system. This and together with tracking wind cowls on the system exhaust would reduce the fan power requirement to less than 1 Watt per litre per second of air flow. PVs are integrated into the roofs of four atria for the teaching buildings to meet the annual energy consumption of the ventilation fans. Integrating the modules into the sloping atrium roofs has helped to offset part of the cost of the system and use has also been made of the cells to provide summer shading to reduce solar gains in the spaces below.

Fig. 1 shows the schematic diagram for one of the atria. The atrium space is 10.5m wide, 19.5m deep at floor level (30m roof) and 14.6m high at the north end. It has a long sloping roof running from north to south. The PV arrays form part of the sloping roof. There are two openable glass screens in the south and north walls, functioning as air vents. The front screen forms the south façade for the first floor and the rear screen, together with the stair well, forms the north façade for the plant room.

The atrium building was fully instrumented for monitoring its performance [1]. A weather station was installed to record the external air temperature, humidity, wind velocity and solar radiation. The temperature and power output of the PV modules were monitored. The air temperature in the atrium space was also measured. A tracer-gas decay method was used to determine the ventilation rate of the atrium. The measured ventilation rate for the atrium with screens completely shut was three air changes per hour, i.e. 3 ach.

The efficiency of crystalline silicon PV cells decreases with increasing temperature. To decrease the temperature and so to increase the efficiency, an air channel is often provided behind PV modules for ventilation cooling. However, the roof-integrated PV modules in the present investigation do not have the provision of such an air channel behind the modules to allow direct cooling by external air. This paper presents the performance of roof-integrated PVs and air flow in the atrium space. CFD is used to predict the air flow and thermal environment in the atrium for different ventilation strategies.

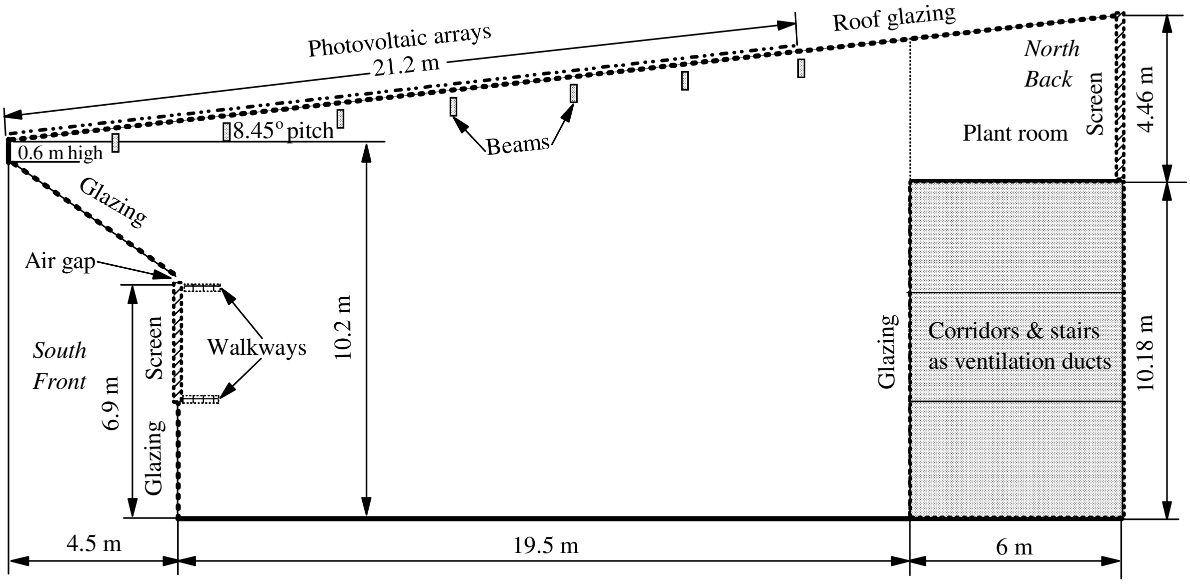

Fig. 1 Schematic diagram of the atrium cross-section

2. CFD MODELLING

A general-purpose CFD package [2] was employed for the prediction of air flow and thermal performance of the atrium.

Air flow in the atrium would be turbulent. Therefore, the standard k-ε turbulence model [3] was used to simulate the effect of turbulence of air flow. For steady-state incompressible flow, the air flow model can be represented by the following general equation:

$$\nabla \bullet (\rho V\phi - \Gamma_\phi \nabla \phi) = S_\phi \tag{1}$$

where ϕ is the flow variable such as the mean air velocity, mean enthalpy, turbulent kinetic energy and its dissipation, V is the mean air velocity (m/s), ρ is the air density (kg/m^3), Γ_ϕ is the diffusion coefficient (Ns/m^2) and S_ϕ is the source.

Because a significant proportion of heat transfer in the atrium would be by radiation, the discrete transfer radiation model [4] was used to calculate the radiative heat transfer between atrium interior surfaces. It was assumed that the interior surfaces were grey and all had an emmisivity of 0.9 for radiation heat transfer.

Modelling was performed for a two-dimensional domain due to the large space involved. A nonuniform computational grid of 152 x 106 (for the depth and height of the space, respectively) was used for the prediction of two-dimensional flow in the atrium, with dense grid cells distributed near the boundaries and openings.

The following assumptions were used as base conditions for simulation:

Fresh air flowed into the space from an inlet opening in the south façade and out of the space via an outlet opening in the north façade. The inlet opening of 0.056 m high was located beside the second floor walkway in the south façade and an extract opening of 0.22 m high was located near the top of the north façade. The inlet air velocity was calculated from the measured ventilation rate of 3 ach. The external air temperature was assumed to be 20^{o}C. A heat flux of 200 W/m^2 was imposed on the atrium roof.

3. RESULTS AND DISCUSSION

The predicted thermal performance of the atrium was characterised by the air flow patterns and temperature distribution. The effect on the PV performance was assessed by the surface temperature.

Fig. 2 shows the predicted air flow pattern in the atrium. The incoming air flowed into the space horizontally and the cool air jet soon dropped towards the floor due to a negative buoyancy effect. As a result, the air near the roof and PV arrays could not be cooled effectively. Fig. 3 shows the predicted air temperature distribution. The air temperature in the areas up to the height of the inlet opening was almost uniform at 24^{o}C. The air temperature above this level increased with height. The predicted mean temperature of the PV arrays was 55.6^{o}C.

Further predictions were performed to investigate the effect of different ventilation strategies on the indoor environment and cooling of roof PV arrays. Table 1 presents the predicted PV performance.

3.1 Effect of ventilation openings

When the inlet opening was moved closer to the roof of the south façade from its original second floor level, most of the inlet air flowed along the underside of the PV arrays. Part of the incoming air was, however, deflected downwards by the beam near the opening. The rate of heat exchange between the roof and air was increased, thus increasing the effectiveness of cooling of the PV arrays. The predicted mean PV temperature was reduced substantially to 50.6^{o}C. The air temperature near the roof decreased, although in areas between the first and second floor levels it increased. The air temperature in the lower part of the atrium remained at 24^{o}C. Therefore, moving the air inlet closer to the roof could increase the effectiveness of ventilation cooling of PV arrays while not compromising thermal comfort in the occupied zone (< 2 m high) of the atrium space.

When air was assumed to supply uniformly from the entire floor at the same ventilation rate of 3 ach, the mean PV temperature was 51.6^{o}C. This was lower than the PV temperature for the original inlet position but higher than that for the inlet near the roof. The air temperature in the occupied zone (below 2 m height) was reduced considerably to 22^{o}C. All these changes resulted from the reduced floor temperature (= inlet air temperature of 20^{o}C). In this case, the floor behaved like a large radiative cooling panel which would absorb heat from air by convection as well as from the roof by radiation. In comparison, when the air at the same ventilation rate was supplied from three slot openings on the floor with a total slot width of 1.245 m, the air temperature in the occupied zone and the PV temperature were similar to corresponding values for the original inlet position.

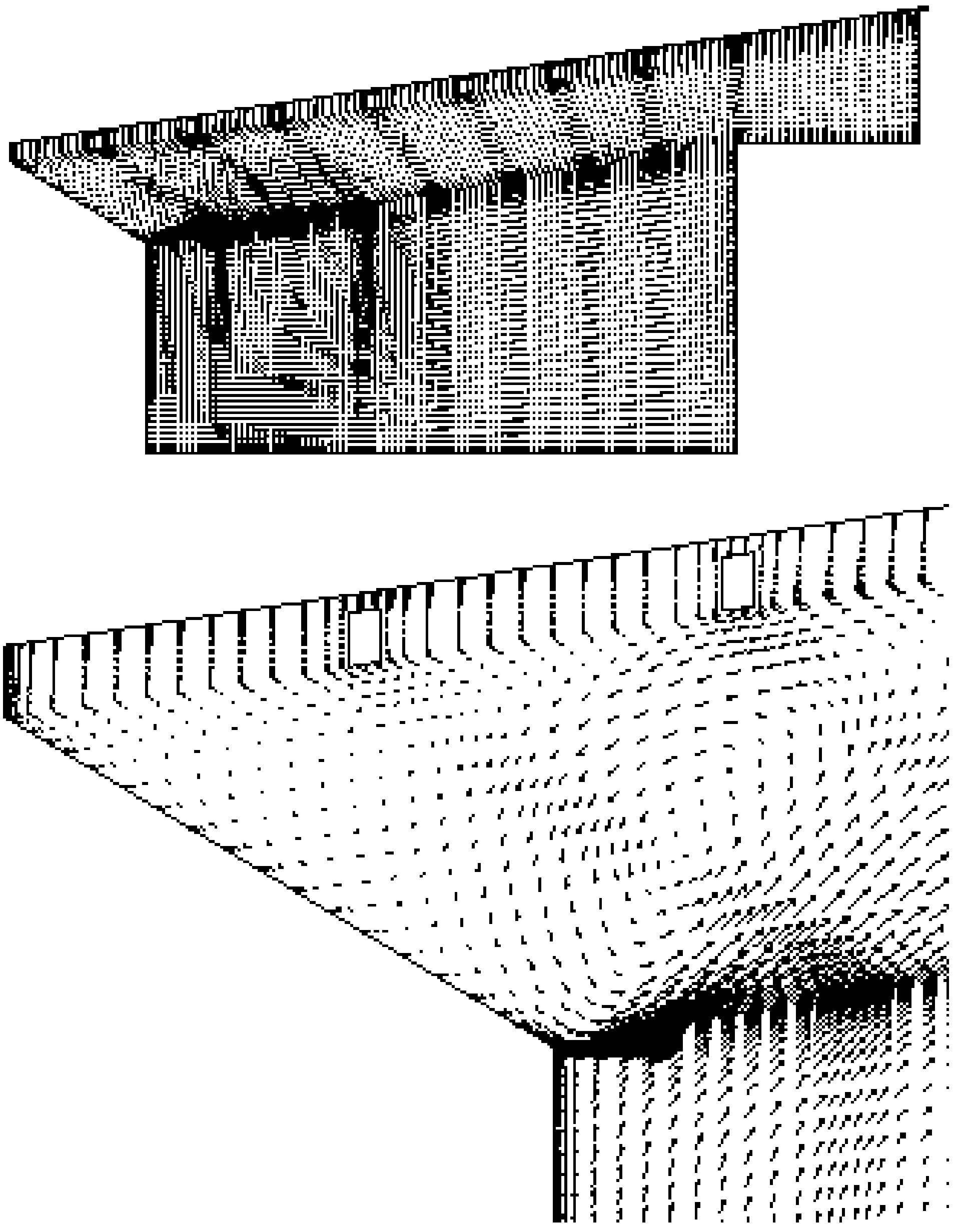

Fig. 2 Air flow pattern in the atrium

When the height of the inlet opening at the original position (second floor level) was doubled but with the same ventilation rate, i.e., the mean inlet air velocity was halved, the predicted temperature of PV arrays hardly changed (=55.9^{o}C). However, when the size of the inlet close to the roof was doubled, the mean PV temperature rose from 50.6^{o}C to 52.4^{o}C. This comparatively large increase in the PV temperature was due to the increased proportion of downward deflection of the cool air jet by the beam near the opening. As a result, less incoming air was utilised to cool the PV arrays.

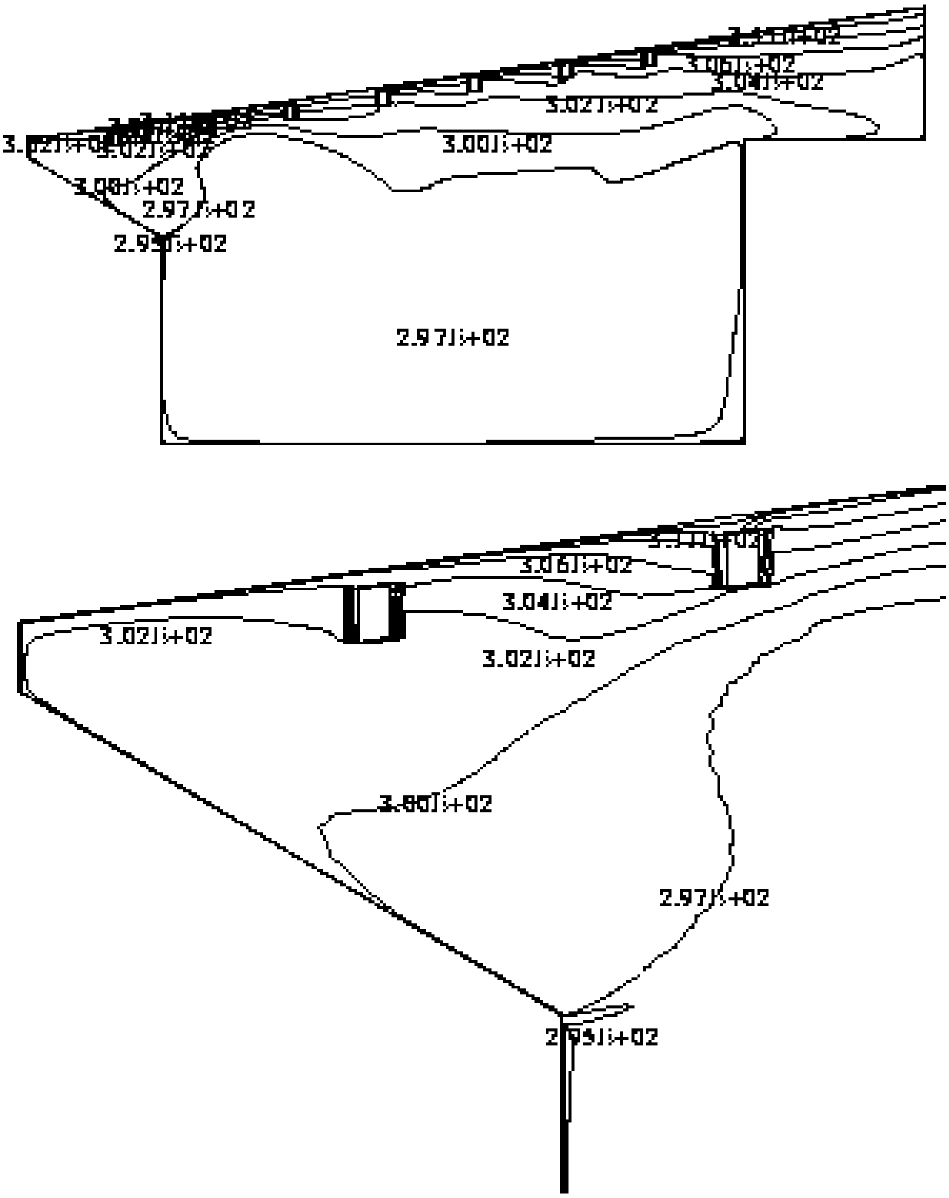

Fig. 3 Air temperature in the atrium

When the outdoor air entered the space from the entire south façade screen and left the space from the north screen at a fixed ventilation rate of 3 ach, the cool incoming air dropped immediately towards the floor. The air temperature in the atrium was quite uniform and the mean PV temperature was reduced slightly to 54.1°C.

3.2 Effect of ventilation rate

When the ventilation rate through the original inlet opening was increased from 3 to 6 ach, the PV temperature decreased from 55.6 to 51.3°C. For the same increase in the ventilation rate through the inlet closer to the roof, the PV temperature was reduced from 50.6 to 45.1°C. The PV temperature decreased further to 48.4°C and 42°C for the original inlet opening and for the opening closer to the roof, respectively, when the ventilation rate was increased to 9 ach. Therefore, the temperature of PV arrays could be reduced by increasing the ventilation rate. The reduction would again be more pronounced for cool outdoor air supplied via an opening closer to the PV arrays. The effect of the ventilation rate on the PV temperature was small when the outdoor air entered the space from the entire south façade screen and left the space from the north screen or when the air was supplied from three slot openings on the floor with a total slot width of 1.245 m. For example, the mean PV temperature decreased from 54.1°C to 53.3°C and 52.1°C when the ventilation rate of air entering the space from the entire south façade screen was increased from 3 to 6 and 9 ach respectively.

Table 1 Predicted performance of the PV arrays

Inlet			PV arrays	
Location*	Height (m)	Ventilation rate (ach)	Temperature (°C)	ΔT_{pv} (K)
1	**0.057**	**3**	**55.6**	**0.0**
2	0.055	3	50.6	5.0
3	19.50	3	51.6	4.0
3	1.245	3	55.7	-0.1
3	1.245	6	55.0	0.6
3	1.245	9	53.0	2.6
1	0.114	3	55.9	-0.3
2	0.110	3	52.4	3.2
1	3.3**	3	54.1	1.5
1	3.3**	6	53.3	2.3
1	3.3**	9	52.1	3.5
1	0.057	6	51.3	4.3
2	0.055	6	45.1	10.5
1	0.057	9	48.4	7.2
2	0.055	9	42.0	13.6

* Inlet location:
1 - south façade at the second floor level
2 - south façade near the roof
3 - ground floor (inlet dimension: width instead of height)
** Both south (inlet) and north (outlet) façade screens fully open
ΔT_{pv} = PV temperature reduction from the base conditions

3.3 Effect of heat flux

The effect of the heat flux on the indoor environment and PV performance was investigated by varying the heat flux from 25 to 400 W/m^2 but with the same values for other base simulation conditions. If one-third of solar radiation was converted into heat by PV cells, this range of heat flux would represent the in-plane irradiance between 75 and 1200 W/m^2. Fig. 4 shows the variation of the predicted mean PV temperature with heat flux. The vertical coordinate, i.e., PV temperature above ambient, is the temperature difference between the PV arrays and external air. The predicted mean PV temperature increased linearly with heat flux in the range from 25 to 400 W/m^2 according to the following correlation:

$$T_{pv} - T_o = 0.1475\, q + 5.783 \qquad (r = 0.999) \qquad \textbf{(2)}$$

where T_{pv} is the mean temperature of the PV arrays (^oC), T_o is the external air temperature (^oC) and q is the roof heat flux (W/m^2).

The mean PV temperature would increase from 35.6 K at a heat flux of 200 W/m^2 to 63.7 K at a heat flux of 400 W/m^2 above the external air temperature. Therefore, the PV arrays would substantially be overheated at very high insolation levels. The air temperature in the atrium would also increase with the heat flux. For example, the predicted internal air temperature was 24°C at a heat flux of 200 W/m^2. When the heat flux was increased to 400 W/m^2, the internal air temperature rose to 30.8°C, which would be too high for thermal comfort.

Hence, in summer when solar radiation is very high, both the PV arrays and atrium space would be overheated if cooling by additional ventilation or other means is not provided, leading to low operating efficiency for the roof PV arrays and thermal discomfort in the space below.

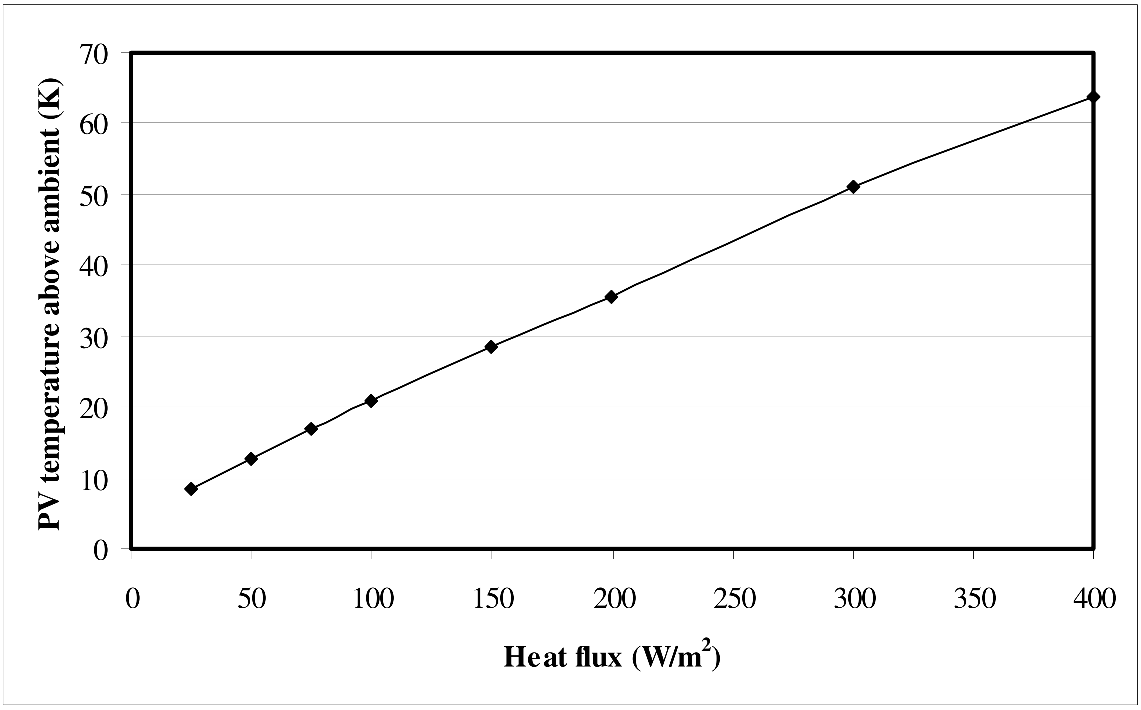

Fig. 4 Effect of roof heat flux on the predicted mean PV temperature

3.4 Effect of air channel under PV arrays

When a large glass panel was assumed to be installed under the PV arrays to form an air channel of 0.1 m gap and additional outdoor air was forced through the channel for cooling, the predicted mean PV temperature would depend on the air flow rate through the channel and the ventilation rate for the space, as shown in Table 2.

For a ventilation rate of 3 ach for the atrium space, when the air flow rate through the channel was 1 ach, the predicted mean PV temperature was much higher than that without the air channel because the heat gain due to radiation was larger than the heat removal by convection. The effect of the radiation heat gain could be offset by the convection cooling at an air flow rate through the channel of approximately 1.6 ach in terms of the mean PV temperature. When the air flow rate was increased to 2 ach, the heat removed by ventilation cooling outstripped the radiation heat gain. As a result, the PV temperature was reduced by 3.8 K from the original conditions without the air channel. The temperature reduction increased further to 9.8 K when the air flow rate through the channel was increased to 3 ach.

Table 2 Effect of an under-roof air channel on the predicted PV performance

Ventilation rate (ach)		PV arrays	
Space	Channel	Temperature (^oC)	ΔT_{pv} (K)
3	1	63.1	-7.5
3	1.5	56.6	-1.0
3	1.6	55.6	0.0
3	2	51.8	3.8
3	3	45.8	9.8
6	1	62.1	-6.5
6	1.5	55.9	-0.3
6	2	51.3	4.3
6	3	45.5	10.1

For the same air flow rate through the channel, the effect of the ventilation rate for the atrium space on the PV temperature was negligible. For example, at an air flow rate through the channel of 3 ach, when the ventilation rate was increased from 3 to 6 ach, the predicted reduction in the PV temperature increased very little, from 9.8 K to 10.1 K.

The predicted mean PV temperature can be correlated with the air flow rate through the channel in the range between 1 and 3 ach as follows:

at a ventilation rate of 3 ach,

$$T_{pv} - T_o = 43 - 15.86 \ln(N) \qquad (r = 0.999) \qquad \textbf{(3)}$$

at a ventilation rate of 6 ach,

$$T_{pv} - T_o = 42 - 15.12 \ln(N) \qquad (r = 0.999) \qquad \textbf{(4)}$$

where N is the air flow rate through the air channel (ach).

4. CONCLUSIONS

The thermal performance of a roof-integrated PV system has been evaluated using CFD modelling. The work demonstrates that CFD can be used for optimising building ventilation systems to provide a comfortable indoor environment and effective cooling of building-integrated PVs. For effective cooling of roof PV arrays, cool outdoor air should be supplied through an opening close to the roof or an air channel under the PV arrays. Increasing the ventilation rate can also reduce the temperature and so improve the performance of PV arrays, in particular if cool outdoor air is supplied via an opening close to the PV arrays.

ACKNOWLEDGEMENTS

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