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THERMAL ANALYSIS OF A FACADE-MOUNTED PV ARRAY

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ABSTRACT

A 20 kW grid-connected PV array was installed at the Queen's University campus in Kingston during the first quarter of 2003. Planning for the project began 18 months earlier with the identification of a candidate building façade. The proposed design included 330 PV panels mounted as awnings above the windows of a 7-storey building. In addition to power generation, this design was intended to provide summer shading and reduced heat gains in the non-air-conditioned offices. Early in the design stage, however, it was determined that the proposed awning geometry could significantly increase the thermal load in the building's offices. In particular, there was a potential for air heated by the PV arrays to flow into the operable windows on the building's façade. To assess this risk, the design team installed and instrumented a small section of solar array in a similar orientation. Measurements obtained, together with the results of numerical modelling, showed that, although unlikely to frequently occur, increased heat gain to the offices was nevertheless a real possibility. Consequently, a number of design changes were proposed to reduce the undesired effects and were incorporated into the final design. These included reducing the panel density, repositioning the arrays and improving the airflow behind the arrays. This paper presents the results of the experimental and numerical analysis performed and discusses the design changes made as a consequence of this study.

INTRODUCTION

A large building integrated photovoltaic (BIPV) system was designed and installed on an existing office building (Goodwin Hall) at Queen's University during the first quarter of 2003. The project was undertaken as a joint demonstration by Queen's University and Natural Resources Canada (NRCan). Arrays of PV panels were installed on the south-facing wall of the seven-story building, Fig. 1.

The rated electrical output of the array is approximately 20 kW. PV panels absorb a significant fraction of the incident solar energy (e.g., 70 to 80%) but convert only between 10-15% to electricity. The balance of the absorbed energy is converted to heat in the PV panels and is rejected to the surrounding environment as waste heat.

An associated benefit of the proposed design was to provide summer shading of the existing windows, thereby reducing solar heat-gain to the building. During the planning phase, however, concerns were expressed with regard to the proposed installation, as the existing building is not climate controlled and has single-glazed, south facing windows. These windows are also equipped with operable awning sections (outward opening) to allow for building ventilation. The proposed design would have located the top of the PV arrays approximately 0.5 m below these windows. It was speculated that air, heated by the PV panels, could enter the building's operable windows and add to its heat load. Rough calculations indicated that a 100 kW of thermal loading could be applied to the building façade as a result of heat rejected by the PV arrays.

Fig. 1. The building integrated photovoltaic (BIPV) system installed at Queen's University.

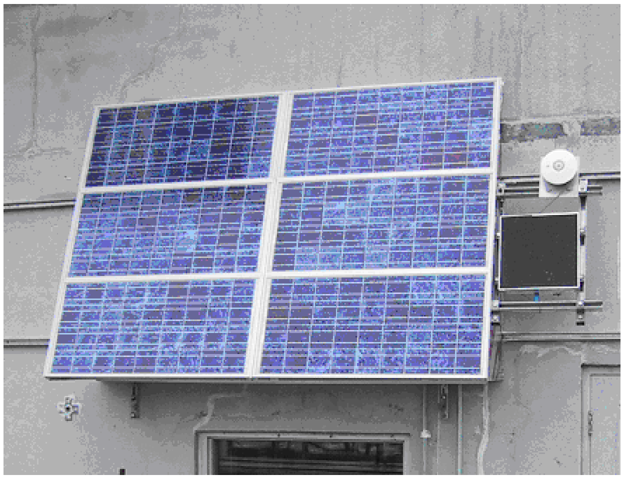


Fig 2. Front view of the "mockup" test section of the proposed BIPV configuration.

An increase in the heat load to the building during the summer period could severely reduce the comfort level for the building's occupants and negate the benefits of the shading from the arrays.

It was therefore decided to investigate the thermal loading caused by the PV system and identify methods to minimize its impact. In particular, this paper describes an investigation of the proposed design configuration with respect to the temperature variation of the PV panel and surrounding air under different weather conditions and mounting details. Results, based on experiment and theoretical modeling, are presented.

As a result of this investigation, a number of design changes were proposed to mitigate the undesired effects of the PV array on the building and its occupants. The revisions were incorporated into the final installation.

Preliminary BIPV System Specification

It was initially proposed to configure individual 75 W PV panels in the form of awnings mounted above the building's south-facing windows. The "awnings" were to be installed on each of the top four floor levels, and were to consist of three rows of PV panels, in "landscape" orientation, except the top floor, which only had space for two rows.

Individual modules were to be mounted on an aluminum support structure (tilted outwards 20° from vertical) that was attached to the building by expandable wall-anchors. Wire mesh was specified to close-in the underside of the arrays and to keep out birds while allowing ambient air to cool the backside of the arrays.

A small (20 mm) gap between the edge of the PV panels and the wall was specified to allow heated air to escape from the top of the arrays. Under low wind-speed conditions, hot air rising from the arrays could enter the operable awning windows used for ventilation of the buildings offices.

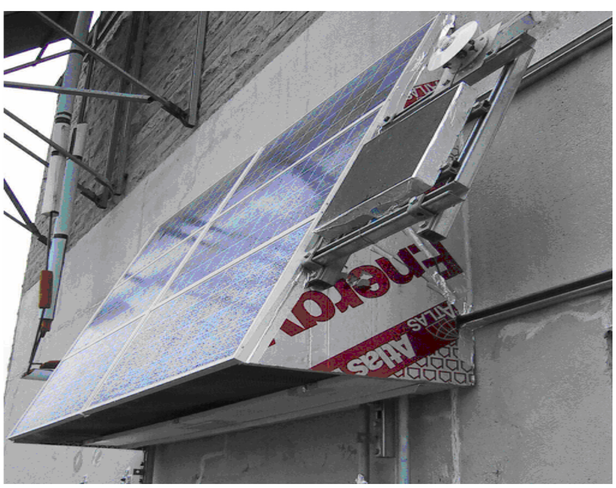


Fig. 3. Test section showing the insulation of the sides used to mimic a continuous array.

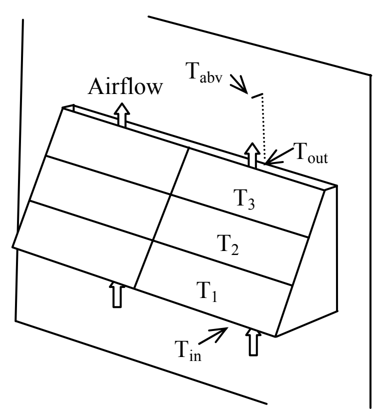


Fig. 4. Location of measurement points, (T_1, T_2, and T_3 measured on the backside of the PV panels).

EXPERIMENTAL INVESTIGATION

To evaluate the thermal aspects of the proposed design, an experimental investigation of the temperatures and airflow adjacent to the PV array was undertaken. Based on the proposed design, an experimental “mockup” of the array, consisting of six PV panels, was installed on a south-facing wall at Solar Calorimetry Laboratory (SCL), Queen’s University. Individual panels (each 1.23 m by 0.56 m) were grouped into two sections and installed at a 70° tilt angle (to the horizontal), Fig. 2. To simulate the continuous array of the panels, the sides of the array were closed-in with 20 mm-thick insulation foam board, Fig. 3.

Testing was carried out from May 10th, 2002. The temperatures of the PV panels and the ambient air below and 0.3 m above the array were measured with thermo-couples, Fig. 4. Thermo-couples were also placed on the back of each PV panel, and at the exit of the gap formed between the top of the PV array and the wall, Fig. 4. This gap was initially set to 20 mm for the tests. The outdoor ambient temperature, solar radiation on the PV surface and wind speed were also measured and recorded.

Experimental Results

The temperature of PV panels and surrounding air were measured and recorded under different solar and wind conditions. For illustration purposes, data for May 28, 2002 is shown, but similar trends were found on other monitored days.

As anticipated, the results indicate that the air-temperature rise associated with the PV panels was mainly dependent on the solar radiation level and wind speed. On the day shown (May 28th) the wind speed was low, typically in the range from 0-1.5m/s. At an incident solar radiation level of 700 W/m² and an ambient air temperature of 28°C, the back surface of the PV panels reached 65°C, Fig. 5. It should also be noted that portions of the PV array were shaded after 12:00 noon on this day.

Under these conditions, air leaving the panel, and at a position 0.3 m above the panel (close to building wall), reached 18°C and 9.5°C above the ambient air temperature, respectively, Fig. 6. Figure 7 shows the air temperature 0.3 m above the PV array over the day.

Figure 8 shows the increase in air temperature measured at the top of the PV array in the gap between the PV module frame and the wall. Values recorded on a number of test days are shown on the plot as a function of incident solar radiation intensity, grouped by wind speed range. Trend lines are fitted to the data sets to illustrate the impact of the solar radiation level on the observed air temperature increase. The data clearly shows that as wind speed is decreased, the air temperature exiting the back of the array increases. It may be seen that as the wind speed increases to values near 3 m/s, the temperature rise is significantly reduced. Under these conditions, corresponding measurements made 0.3 m above the array indicted negligible increases in the air temperature.

The experimental results confirm, however, that on days with low wind conditions, air heated by the PV arrays may enter window openings above the arrays. To gain an insight in to the airflow field associated with the placement of the PV arrays, a preliminary flow analysis was conducted by computer simulation.

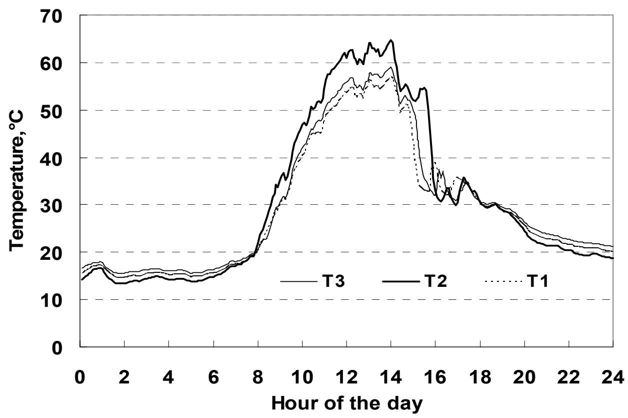


Fig. 5. Temperatures measured on the back surfaces of the PV panels (28/05/2002).

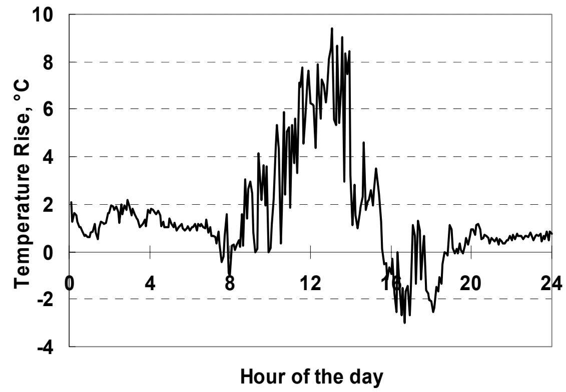


Fig. 7. Increase in air temperature above the ambient at a location 0.3 above PV panel (28/05/2002).

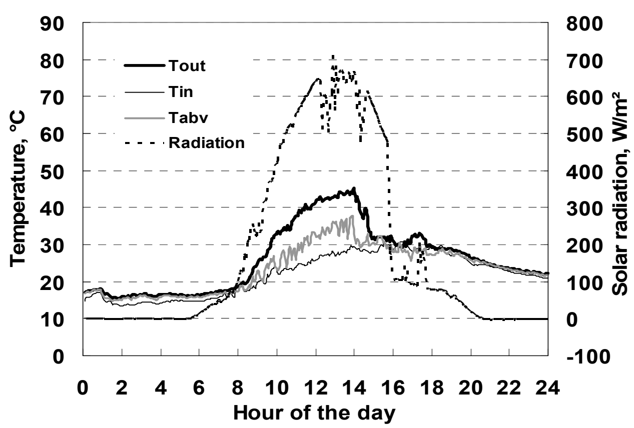


Fig. 6. Air temperature adjacent to the PV array and solar radiation levels on 28/05/2002.

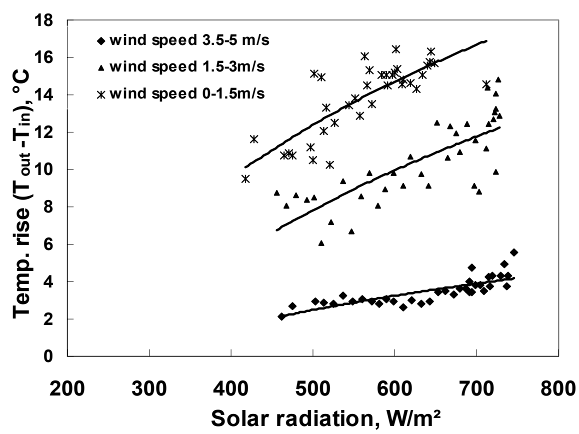


Fig. 8. Air temperature rise, (T_{out}-T_{in}), as a function of solar radiation and wind speed.

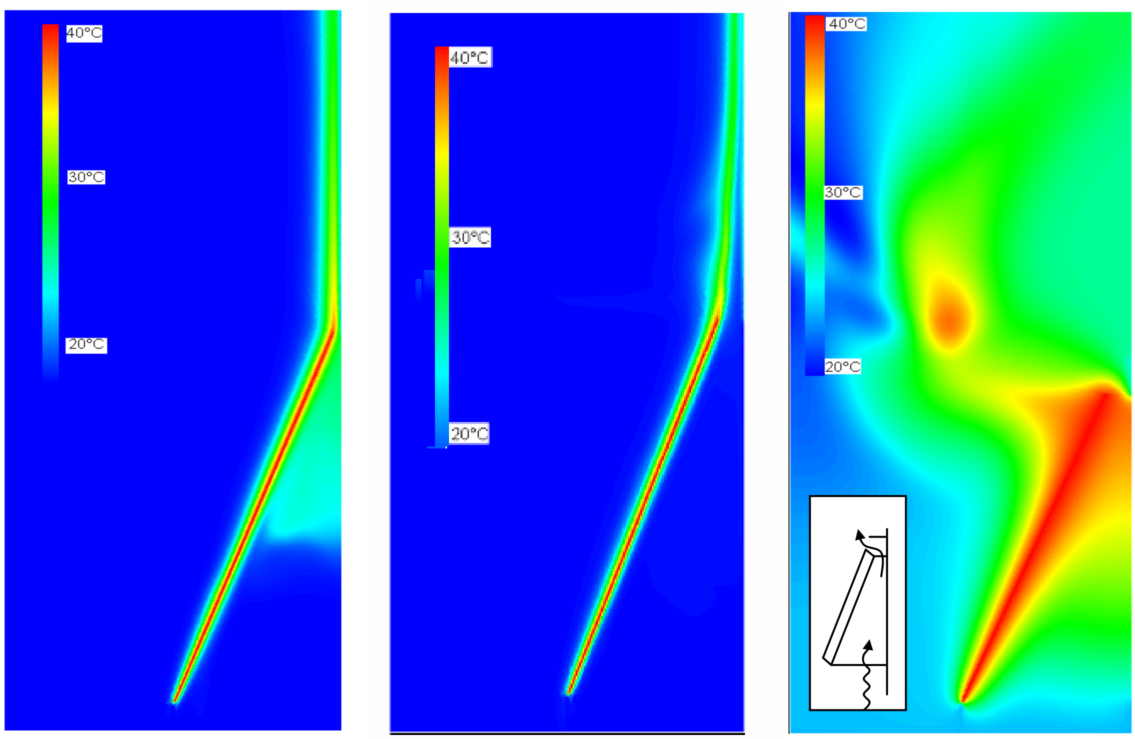
COMPUTER MODELING

To predict the airflow and temperature field adjacent to the PV panels for different installation configurations, computer simulations were carried out using a commercial Computational Fluid Dynamics (CFD) program [1].

A baseline, 2-dimensional, CFD model was developed for the array configuration tested, assuming a zero wind speed and only buoyancy-induced natural convection airflow. Typical surface temperatures measured during the experimental study were used to establish the boundary conditions for the computer simulation. For the analysis, it was assumed that the PV panel and ambient temperatures were 40°C and 20°C, respectively. The surface temperature of the exposed wall above the array was fixed at 24°C. Two initial cases were investigated to determine the effect of the width of the gap between the PV array and the building's wall on the airflow and temperature field. The results of this analysis are shown for the case of a 20 mm gap, Fig. 9(a), and for a 90 mm gap, Fig. 9(b).

These results indicate that the air temperature near the top of the panel is higher in case (a) than in case (b). In both cases, hot air from the PV panel moves up and towards the building wall. For the same height above the PV panels, the air temperature is slightly lower for the larger gap. It is anticipated that the larger air-gap will also promote mixing of the hot air-stream with cooler ambient air. The results for both cases, however, still indicate the potential of heated air entering the awning windows above the arrays.

In an effort to deflect this air movement and to promote mixing, a third case was considered where a horizontal baffle was attached to the building wall. It was located 90 mm above the top of the PV array and protruded 100 mm horizontally from the wall. The simulation results are shown, Fig. 9(c). They indicate that the airflow is deflected away from the building, promoting mixing and lowering temperatures near the wall. The baffle does have the effect of restricting the airflow through the space behind the panel resulting in slightly higher local temperatures in that region.



(a) 20 mm spacing (b) 90 mm spacing (c) 90 mm with baffle

Fig. 9. Relative temperatures and flow field around the PV array for an assumed PV panel temperature of 40°C, an ambient temperature of 20°C, and a 24°C wall temperature above the array. Results are shown for cases: (a) panel to wall distance = 20 mm; (b) panel to wall distance = 90 mm and; (c) 90 mm gap with deflector baffle located 90 mm above the array.

REVISED SYSTEM SPECIFICATION

As a result of the previously described investigation a number of changes to the PV systems specifications were recommended to minimize the detrimental effects of the thermal loading on the building. These included reducing the panel density, repositioning the arrays and redirecting the airflow behind the arrays. Specifically:

i) the configuration of each of the PV "awnings" was changed from three rows of PV panels in "landscape" orientation to a single row of PV modules in "portrait" orientation;

ii) the gap between the top of the PV panels and the wall was increased from 20 to 100 mm to promote airflow behind the array;

iii) a custom baffle and weather flashing was designed to direct the airflow away from the wall and to restrict the access through the larger gap by birds, etc.

Item (i), reduced the total number of PV panels from 330 to 264. This change also reduced the effective height of each PV awning allowing the arrays to be located farther below the operable windows, thereby providing a larger distance for the diffusion of the heated air, Fig. 10.

A photo of the aluminum support structure is shown in Fig. 11, taken during the installation.

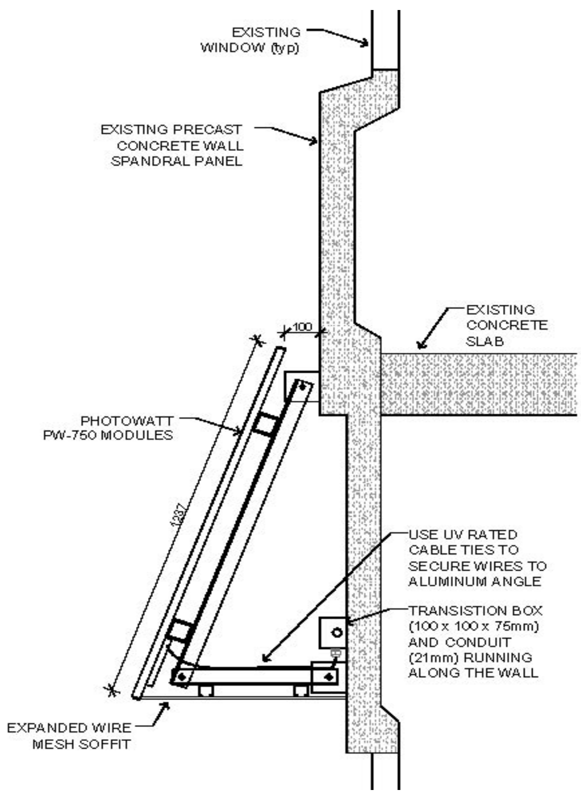


Fig. 10. Revised specification for attachment of the PV modules to the building wall [2].

Fig. 11. Aluminum support structure used to attach the PV awnings to the building.

The configuration of the custom baffle and flashing installed above the arrays is shown in Figs. 12 and 13. It was fabricated from sheet-metal stock. It includes a perforated section on the front face to allow hot air to vent from behind the PV arrays. The perorations consist of six rows of oval openings (9.5 mm by 25 mm), giving about 55% opening area on the vertical face. A wire mesh is also used to close-in the underside of the arrays while allowing air to flow into the space behind the arrays.

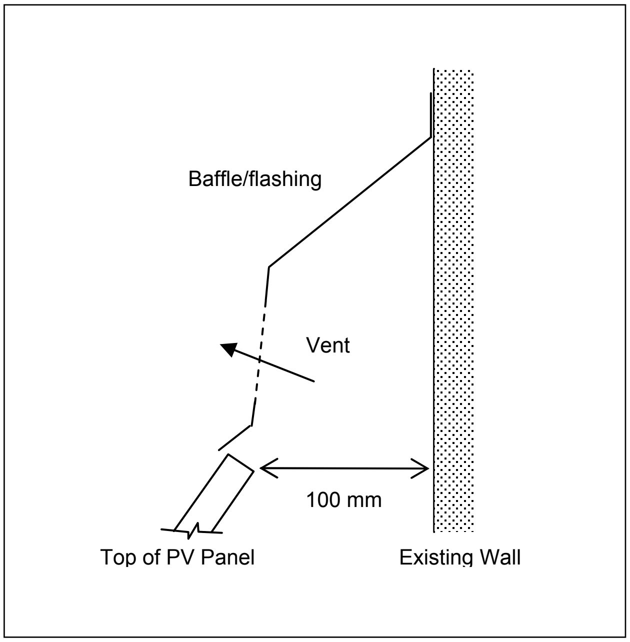


Fig. 12. Configuration of the baffle/flashing used above the PV arrays, (side view, not to scale).

Fig. 13. Photo of the baffle/flashing used above the PV arrays.

CONCLUSIONS

Thermal analysis on the wall-mounted BIPV system was carried out by experiment and numerical simulation. The test results show that with solar radiation of 700 W/m² and an ambient temperature 28°C, the temperature of PV panels reached 65°C. The monitored results showed that the air temperature rise across the PV panels was mainly dependent on solar radiation and wind speed. At low wind speed conditions, air exiting the panel and at 0.3 m above the panel reached 18°C and 9.5°C above the ambient, respectively. At wind speeds greater than 3 m/s, the air temperatures were close to the ambient.

CFD simulation showed that by increasing the space between the PV panel and the wall, air temperatures above the PV panel could be reduced. By adding a baffle 90 mm above of the panel, hot air could be directed away from the wall allowing it to further mix with ambient air.

FUTURE WORK

These results represent a limited investigation of the thermal effects of adding wall-mounted PV arrays to the south side of an existing building. This study did not account for the additive effect of multiple arrays located one-above-another. Simulations of the full south side of the building under no-wind conditions would be valuable, although difficult to implement.

Only limited experimental data was available at the time of this report and further monitoring on the full array, as installed, would be useful in assessing the effectiveness of the design revisions. Extensive instrumentation has been integrated into the full-scale array and both thermal and electrical aspects will be monitored continuously as part of the demonstration and educational program of Queen’s University’s Integrated Learning Center, (http://ilc.queensu.ca/)

REFERENCES

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