Experimental Investigation of Thermal Enhancements for a Building Integrated Photovoltaic/Thermal Curtain Wall

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Abstract

Building integrated Photovoltaic/Thermal (BIPV/T) systems provide a cost-effective way of incorporating solar technologies on buildings for the generation of electricity and useful heat, by replacing common building materials. Air-based systems are generally better suited for large façade or roof installations, they are however, less efficient in extracting heat from the PV due to the thermo-physical properties of air and therefore need enhancements for their thermal performance. This study investigates ways of enhancing air-based Building Integrated Photovoltaic/Thermal (BIPV/T) systems, focusing on the use of multiple-inlets and presents the development and initial testing of a BIPV/T curtain wall prototype. The testing of the prototype showed superior performance for the double-inlet versus the single-inlet configuration, thermally (up to 18% higher thermal output), lower peak PV temperatures (reduced by up to 3.6°C) and a marginal increase in electrical output due to enhanced cooling.

Keywords: Building Integrated PV/Thermal, thermal enhancements, experimental performance

1. Introduction

The building sector is responsible for approximately 40% of the global energy consumption (Agathokleous & Kalogirou, 2016). Incorporation of solar technologies for electricity and useful heat production on buildings is essential for the design of net-zero energy buildings and for reducing the energy footprint of retrofits.

Photovoltac/Thermal (PV/T) hybrid systems combine the generation of electricity and useful heat. The photovoltaic layer of such a system also acts as the absorber and a circulating fluid removes part of the excess heat from it, which may be then utilized by various means, depending on the fluid's outlet temperature and delivery rate. PV/T systems have been found more efficient than independent PV or thermal collectors covering the same surface area (Kumar & Rosen, 2011a).

Building-Integrated Photovoltaic/Thermal systems come from the integration of PV/T with the building envelope. This integration may have several advantages over using PV/T systems as stand-alone (Yang & Athienitis, 2016). Apart from the architectural integration and the superior aesthetic result, the PV panels replace the outer shell materials (roof shingles, siding, concrete or masonry panels for façade etc.), increasing the cost effectiveness of the installation and the whole system functions as a building envelope element. A BIPV/T system must fulfill the requirements of the building envelope in terms of heat, air, water and moisture control (Jelle & Breivik, 2012). Integration with the façade or the roof may offer a larger installation area, which would otherwise not be available for use, although BIPV/T systems cannot be optimally oriented and tilted as opposed to stand-alone PV/T systems.

Ventilation and cooling of building integrated PV is essential since they do not have the same wind-driven cooling potential as racked PV (Bloem, 2008; Fossa et al, 2008). An air channel formed between the PV layer and the rest of the wall section for the ventilation of the system may serve two purposes: the cooling of the PV to prevent a decrease in electrical efficiency, and the collection of the preheated air for various purposes. Fan-assisted convection has been found to be more efficient in cooling the PV and extracting heat, in comparison to natural convection, especially in larger systems (Kaiser et al, 2014).

Depending on the coolant, BIPV/T systems are divided into water and air-based systems. Water based systems have greater heat exchange effectiveness. They require special casing and piping and are generally limited to smaller scale roof applications to avoid leakage and freezing issues within the wall section. Air-based systems on the other hand are easier to install and maintain, they do not pose leakage or freezing issues and can be adapted to different kinds

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of facades and roofs. However, due to the thermo-physical properties of air they are less efficient in the extraction of excess heat from the PV. There have been several studies on ways to enhance the thermal performance of PV/T and BIPV/T systems, which are discussed in the next section.

BIPV/T systems currently hold a small share of the PV installations. Usually, a harmonic architectural integration with an existing façade or roof is enough to characterise the system as integrated. However, there are few examples of systems that entirely replace the typical wall or roof structure of a building (Athienitis et al, 2011; Chen et al, 2010). The lack of more examples like those is mainly due to the fact that there is no current BIPV/T standard related to its integrated performance and function as a building envelope element.

This study presents the development and initial testing of a BIPV/T prototype, which was designed based on existing curtain wall practices and intended for full building integration. The main purpose was to be able to test and compare different thermal enhancements on the same experimental prototype, and provide design insight on fully integrated air-based BIPV/T systems. The initial experimental test set-up focuses on the effect of different PV module transparencies, the introduction of an additional air intake and the use of a flow director on the electrical and thermal performance of the prototype. The use of fins and varying channel depth will also be incorporated and studied in the future.

2. BIPV/T Thermal Enhancements

2.1 Air based systems thermal enhancements

Air-based systems are generally more suitable for envelope integration and large-scale applications, but less efficient in heat extraction than water-based systems. Several researchers have looked into ways of enhancing the thermal performance of air-based systems. These enhancements may only involve geometric and/or flow optimization, or the addition of material elements such as double glazing, fins or other porous media. Most of the proposed enhancements were applied to a reference PV/T system (Fig.1), while others refer to specific prototypes.

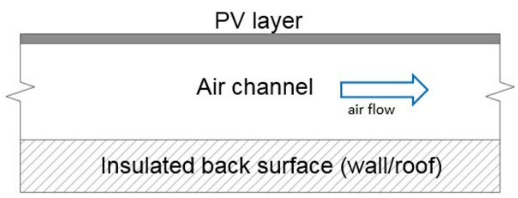

Fig. 1: Typical PV/T configuration

The criteria for enhancement vary among studies. For naturally ventilated systems with no heat collection the goal is to enhance the electrical output and PV durability by reducing the PV temperatures. This is generally achieved by optimizing the collector's aspect ratio (length over depth) for which the velocity of the buoyancy driven flow is maximized, but it may also involve the optimum tilt angle (Brinkworth, 2000; Brinkworth et al, 2000; Brinkworth & Sandberg, 2006; Brinkworth, 2006; Gan, 2009). In general, studies on naturally ventilated systems agree on a 10-15 cm optimum channel gap and a 45^o-55^o tilt angle.

The enhancement of mechanically ventilated systems varies considerably, depending on whether the priority is given to either the electrical output, or the thermal output, or a balance between the two and whether the consumption of the cooling system is also considered. Several researchers have investigated the optimal aspect ratio of the collector length to the collector depth and the optimal flow for air-based PV/T systems (Kaiser et al, 2014; Bambrook & Sproul, 2012; Zogou & Stapountzis, 2011). In addition, some studies include the effect of pressure drop within the collector (Bambrook & Sproul, 2012) and within the ducting that connects the PV/T to the HVAC system (Farshchimonfared et al, 2015). The suggested optimal flows vary between 0.026-0.050 kg/m2s, and the optimal channel depth between 0.025-0.090 m.

The practice of adding one or more glazing layers over the PV layer has been studied as a means to increase the thermal output of the system by reducing the wind induced heat losses (Hegazy, 2000; Tiwari et al, 2006; Sopian et al, 2000). The boosted thermal performance comes at the cost of the electrical, due to the higher PV temperature and the reduced solar radiation transmitted through the extra glazing (occasionally due to the formation of condensation on the outer glazing). The PV temperatures can be decreased with a double-pass configuration, by placing the PV layer between two air channels, independent or connected. Tripanagnostopoulos (2007) suggested that, unless the system is optimized for thermal output, glazed PV/T systems are not recommended, due to PV overheating and poor electrical performance.

Heat extraction from the PV layer can be further enhanced with the use of material elements inside the air channel. These elements could either be fins in contact with the absorber that act as heat sinks (Othman et al, 2007), or fins set on the back surface which induce turbulence and boost the convective heat transfer (Kumar & Rosen, 2011b; Tonui & Tripanagnostopoulos, 2006). Other elements can be porous media, such as a metallic mesh (Pantic et al, 2010; Yang & Athienitis, 2014), honeycomb heat exchanger (Hussain et al, 2015), and suspended thin metal sheet [24] which further increase the radiative and convective area. These techniques have been proven very effective in removing heat from the PV, as opposed to the reference design (Fig. 1). However, a major limitation is that they cannot be used for systems with long channels due to the added flow resistance in the air channel and consequent increase of fan consumption.

Most of the aforementioned studies has been based on small scale experimental models (collector length generally 1-1.5 m), the behaviour of which could be different in larger scale applications. This is primarily due to the formation of a thermal boundary layer and a consequent temperature rise of the PV layer along the collector, leading to non-uniform PV temperature distribution and lower performance of the collector.

One major issue that is raised is the lack of common criteria for the enhancement and optimization of the systems. Usually the enhancement refers to the PV/T system without considering the integration with the mechanical system (heat pump, direct heat supply, heat exchanger, desiccant cooling etc.) and the corresponding requirements in terms of flow and fluid temperature, along with limitations for allowed PV temperatures. Furthermore, it is difficult to have a clear comparison between the various proposed systems due to the difference in dimensions and testing conditions, while the proposed numerical models are usually case specific and the convective correlations are not generally applicable.

2.2 Multiple-inlet BIPV/T

A more recent method of thermal enhancement is the introduction of more than one air intakes along the collector's channel. This technique is based upon the breaking of the thermal boundary layer and taking advantage of the introduced entrance effects. The convective heat exchange from the PV layer to the air stream is enhanced and more uniform PV temperatures can be achieved by regulation of the inlet flow distribution. The concept of a multiple-inlet BIPV/T evolved from the hybrid unglazed transpired collector (UTC) - PV/T system introduced by Athienitis et al (2011), which is installed at the mechanical penthouse of the John Molson School of Business (JMSB) building of Concordia University in Montreal. This system consists of custom PV modules attached onto a layer of UTC.

A double-inlet system was numerically investigated by Yang & Athienitis (2014). Convective heat transfer correlations were developed based on the testing of an experimental single-inlet prototype in an indoors solar simulator facility, which were used for the simulations of the performance of a two-inlet system. The addition of a second inlet increased the thermal efficiency of the system by 5%, reduced the maximum PV temperatures and marginally increased the electrical efficiency. Rounis et al (2016) proposed a method of modelling multiple-inlet BIPV/T systems and simulated the performance of a single and a multiple-inlet BIPV/T system for a large-scale office building application. Results showed that the multiple-inlet system had the lowest and most uniform PV temperatures, as well as higher electrical and thermal efficiency. Mirzaei et al. (2014) investigated experimentally the role of cavity flow on the performance of naturally ventilated BIPVs placed on inclined roofs. The experimental configurations included a flat and a stepped arrangement, which was essentially a multiple-inlet formation. It was found that the PV temperatures were significantly lower for the stepped configuration (multiple-inlet) cases, as opposed to the flat roof.

3. BIPV/T Prototype Development

A BIPV/T prototype was designed at Concordia University and developed in collaboration with Unicel Architectural and Canadian Solar, based on the curtain wall façade system. The prototype (Fig. 2) represents part of a full BIPV/T curtain wall façade. The purpose of the prototype was to address issues of architectural and structural integration, but also to investigate and compare experimentally different configurations and performance enhancement methods. The objective of this effort would be to provide insight on the development of a BIPV/T design and performance standard.

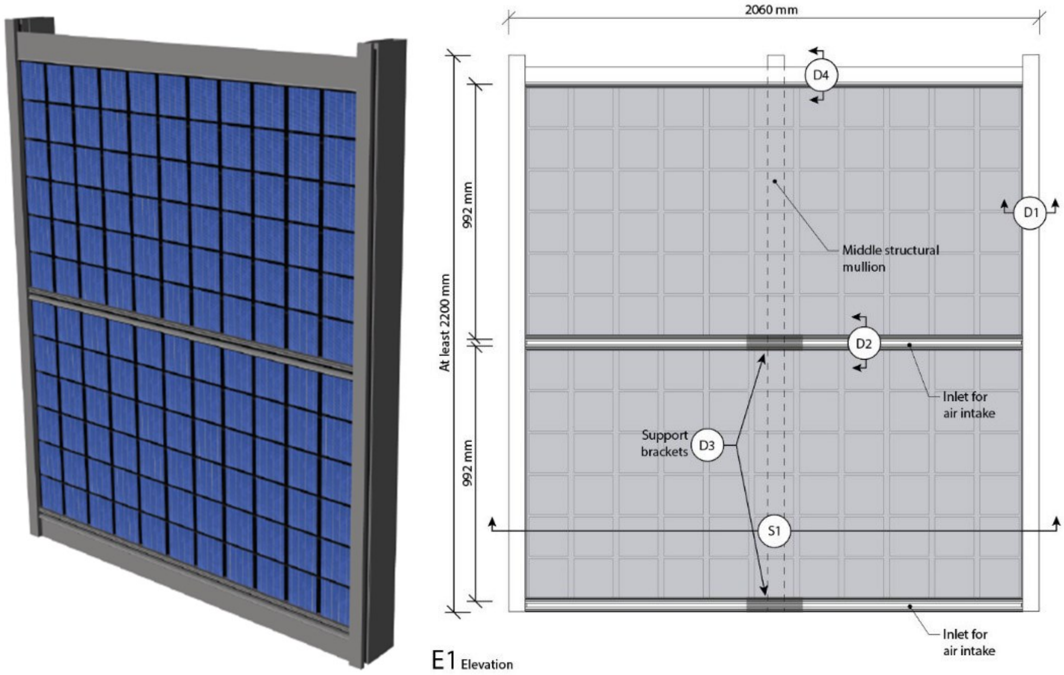

Fig. 2: BIPV/T curtain wall concept

The BIPV/T curtain wall prototype consists of a metal frame, two frameless PV modules and a 2-inch rigid insulation sandwiched between aluminum sheets. The metal frame was fabricated by Unicel Architectural using commercial mullion extrusions. The frameless, semi-transparent PV modules were provided by Canadian Solar. Two sets of semi-transparent PV modules were used, one with 66 cells and one with 72 cells, in order to investigate the effect of different transparencies on the prototype's performance.

A second inlet was introduced between the two PV modules, while the PV panels were placed horizontally to take advantage of the entrance effects of the second inlet flow. The panels were fixed with pressure plates at the side and top mullions and a shorter middle mullion was used to reduce counter deflection and provide extra support for the dead load of the panels.

Figure 3 demonstrates the cross side section of the prototype and the building envelope functions of its layers.

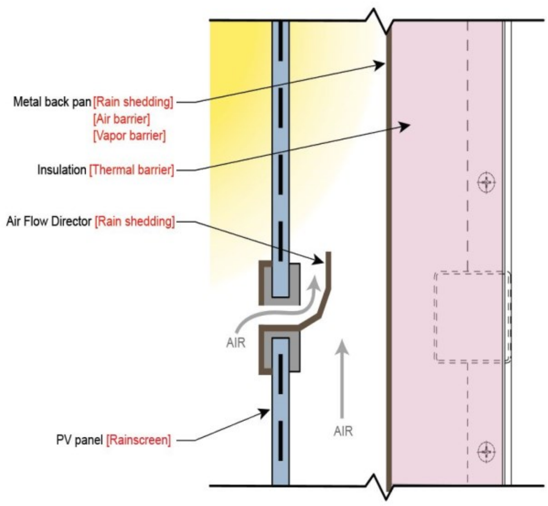

Fig. 3: BIPV/T curtain wall cross section

The prototype was designed with a reduced height to fit the test platform, but is considered as part of a story-high, or taller, system. Regarding the flow of the air channel, several aspects were considered. The primary factor that dictated the overall flow design was the introduction of a second inlet between the PV panels. The opening of the inlet was roughly estimated by previous analysis (Rounis et al, 2016) to approximately provide one third of the total flow when fully open. Furthermore, air flow directors were used (Fig. 3) to direct the air stream of the second inlet closer to the surface of the top PV module. This also acted as a measure against rain penetration. Finally, a custom manifold was built and connected to holes opened on the top mullion, at the top side of the collector. This consisted of four take-offs from the collector connected to the main duct of the air collection unit. The number of take-offs was a compromise between flow uniformity and reduction of the structural integrity of the top mullion.

4. Experimental Process and Preliminary Results

The experimental prototype was tested in the Concordia University indoor Solar Simulator (Fig. 4). The Solar Simulator consists of a lamp field which emulates the sun light and a test bench upon which the test specimens are placed. The 8 metal halide lamps that comprise the lamp field can be moved individually in the horizontal and vertical axis and can produce irradiance intensities from 500 to 1200 W/m2 with a uniformity of up to 97% (Kapsis et al, 2016). The spectral quality of the lamps fulfills the specifications of ISO 9806. Both the lamp field and the test platform can rotate between a horizontal and vertical orientation to accommodate testing cases varying between flat roofs, tilted roofs and vertical facades. The experiments carried out for the experimental process presented here was in the vertical position, corresponding to a façade integrated BIPV/T.

This paper includes the results from testing conditions similar to the Nominal Operating Cell Temperature (NOCT) conditions, namely:

- Average solar radiation, G=842 W/m2
- External wind velocity, Vwind=1 m/s
- Ambient temperature, Tamb=20^{o}C

Two sets of PV modules were used (66 and 72 cell) and for each set, three configurations were tested: single inlet (with the middle inlet covered), double-inlet without the flow director and double inlet with the flow director installed. For each configuration, three total mass flow rates were investigated, namely, 400 kg/hr, 500 kg/hr and 600 kg/hr, with corresponding average channel velocities of 0.5 m/s, 0.62 m/s and 0.74 m/s. The most important results from this first set of experiments are presented in the following sections.

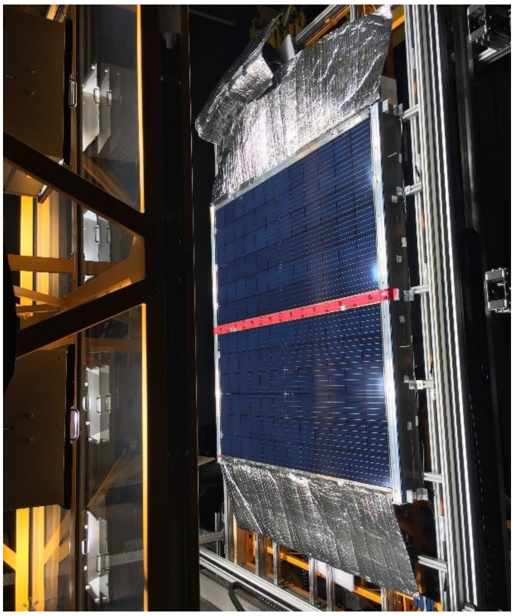

Figure 4: The BIPV/T prototype during testing in a vertical position at the Concordia University Solar Simulator

4.1 Effect of transparency

As expected the set of more transparent modules (66-cell) had lower electrical output of about 10-11% versus the 72-cell set, but the higher amount of radiation transmitted to the back absorber resulted in a 5-10% higher thermal output and slightly higher outlet temperature (up to 0.7^{o}C). The peak PV temperatures for the 72-cell set were higher by 0.6°C - 3.6°C, due to the higher radiation absorbed by a larger PV cell area. These results agree with previous investigations (Bloem, 2008; Vats et al, 2012). The choice of packing factor in a real application would depend on the desired electrical and thermal output.

4.2 Effect of second inlet and flow director

The introduction of the second inlet may increase the thermal output by up to 18% and the outlet temperature by 1°C (for a collector of 2 m height). The system's performance was further enhanced with use of a flow director, which directed the flow entering from the second inlet closer to the surface of the upper PV module, extracting more heat and further reducing its temperature. The electrical efficiency was marginally increased and the peak PV temperatures are lower by up to 1.6°C, depending on the flow rate. These results are in accordance with the experimental work of Yang & Athienitis (2014)

Figure 5 presents the electrical and thermal efficiencies and the peak PV temperatures for the three configurations at the 600 kg/hr flow air collection rate. The results were similar for the other flow rates tested, as well as for the 66-cell set.

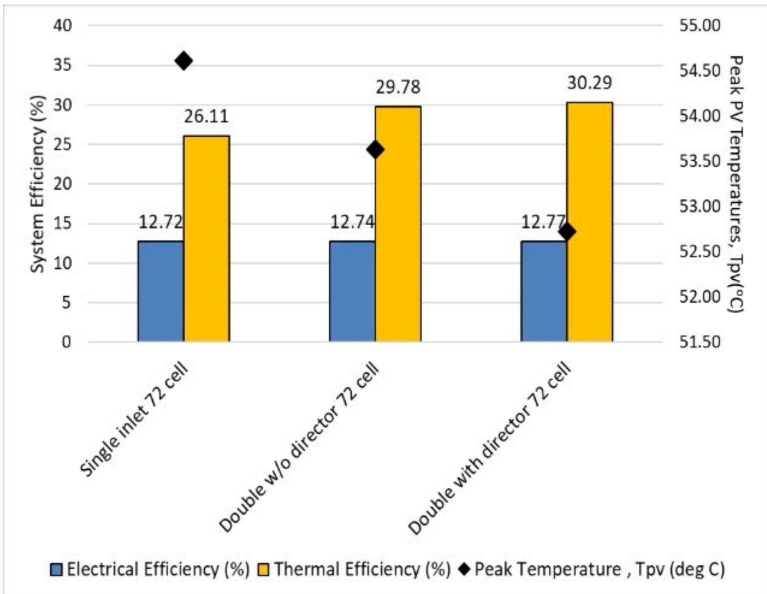

Figure 5: Electrical efficiency, thermal efficiency and peak PV temperature for the three configurations of the 72-cell set, at 600 kg/hr total mass flow rate (0.75 m/s average channel velocity)

5. Conclusion

This study focused on thermal enhancement techniques for air-based BIPV/T systems and presented the initial testing of a BIPV/T curtain wall prototype, with semi-transparent PV and multiple-inlets. The prototype has been developed to both provide design guidelines for fully integrated façade and roof BIPV/T systems and investigate the performance and applicability of various thermal enhancement techniques.

The initial testing of the prototype has shown that the introduction of a second inlet may increase the thermal output by up to 18%, decrease the peak PV temperatures by up to 3°C and marginally increase the electrical output, as opposed to the case of a reference single-inlet system. The double-inlet system's performance was further boosted by an air flow director element, which directed the flow closer to the surface of the second PV module. The use of higher transparency PV modules increased the thermal output, by 5-10% and the outlet air temperature but the electrical output was decreased by 10-11%. The differences in performance for the single and double-inlet systems are expected to be more prominent in larger scale applications.

This is part of a larger study involving the comparison of different enhancement techniques for air-based systems as well as the development of design guidelines for BIPV/T that may lead to a BIPV/T performance standard. Future work includes the investigation of more thermal enhancement techniques applied to the prototype, such as the use of fins and varying channel depth. A collective comparison of the tested methods will be carried at the end of the experimental procedure. Furthermore, models will be developed and validated according to the experimental results for the simulation of full scale systems and the suitability of already developed convective coefficient relations will be evaluated.

6. Acknowledgements

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