Modelling of Air-Based Building Integrated Photovoltaic/Thermal (BIPV/T) Systems with Multiple Inlets

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Abstract

This paper studies the modelling of air-based building integrated photovoltaic/thermal (BIPV/T) systems with multiple inlets for solar houses. The experimental investigation of the BIPV/T prototypes with one and two air inlets in a full-scale solar simulator was conducted to develop the correlation for the convective heat transfer coefficient (CHTC) of the air channel with multiple inlets. The mathematical model for air-based BIPV/T systems with multiple inlets is proposed with integration with the CHTC correlation for BIPV/T air channels with multiple inlets, based on which a computer program is developed. The numerical study shows that a typical residential BIPV/T roof with 5 air inlets can increase thermal efficiency by 6.4% compared to a conventional BIPV/T system with 1 inlet.

Keywords: solar; energy; thermal; BIPV/T

1. Introduction

A building integrated photovoltaic/thermal (BIPV/T) system makes use of the building envelope for solar energy collection to produce both electricity and useful heat at the same time, providing an efficient way of reducing building energy consumption. The concept of the BIPV/T started emerging in the 1990s [1], and at this time a demonstrative BIPV/T system was installed on the roof of a restaurant for electricity and hot water production in North Carolina, USA as part of the PV Bonus initiative [2]. An office building of the Aerni Fenster factory in Switzerland was among the first in Europe to have a façade-integrated BIPV/T air system [3]. Similar installations in Europe include the Scheidegger façade-integrated BIPV/T air system, the Brig roof-integrated BIPV/T air system and the Rigi roof-integrated BIPV/T air system [4].

The BIPV/T technology, a promising technology for generating electricity and useful heat, has attracted increasing attention since 2000 due to its potential to promote net-zero energy buildings through enhanced solar energy utilisation. Fujisawa and Tani [5] compared the performance of a hybrid PV/T system and a unit of separate PV and thermal system covering the same area on the basis of exergy efficiency. They found that the hybrid design achieved higher exergy output. Each of the studies of roof-integrated BIPV/T systems by Dupeyrat et al.[6], Fraisse et al. [7], and Kazanci et al. [8] arrived at similar conclusions.

A number of media, including air, water and refrigerants, can be used as the working medium of a BIPV/T system. The BIPV/T system using air as the working medium has lower installation costs, reduced risk of leakage and freezing, and ease of maintenance compared to other liquid-based BIPV/T systems. The air gap of a BIPV/T system is situated between the upper PV modules and the lower insulation layer, allowing fan-driven ambient air flowing through the gap to cool the PV modules, resulting in improved PV electrical efficiency. The hot air may have the potential to assist space heating, domestic hot water heating and even solar cooling.

Generally, the performance of BIPV/T air systems is low due to the inherent physical properties of the air, such as low density, low heat capacity and low heat conductivity, resulting in a need to enhance the performance of air-based BIPV/T systems. Agrawal and Tiwari [9] considered connecting the air channels under each row of PV panels both in series and parallel in order to maximize outlet air temperature, energy gains and exergy gains. Pantic et al. [10] explored the feasibility of connecting a 1.5 m vertical glazed solar air collector in series with the outlet of the conventional BIPV/T system. This system expanded the usable roof area and enabled the vertical section to receive high amounts of solar radiation during the winter when the solar altitude is low. We have proposed an open-loop air-based BIPV/T system enhanced with an additional vertical glazed solar air heater whose channel has multiple air inlets in the PV covered section, and carried preliminary numerical analysis [11]. The results showed that the two-inlet system is superior to its one-inlet counterpart by increasing the thermal efficiency by about 5%.

The objective of this paper is to evaluate the performance of the BIPV/T air system with multiple inlets in a cold climate. By conducting experiments on a two-inlet air-based BIPV/T prototype in a full-scale solar simulator, the effect of the inlets on BIPV/T heat transfer is investigated, and the heat transfer coefficients are proposed. The experimental results are then used to improve the mathematical model for two-inlet air-based BIPV/T systems. With the mathematical model, the energy performance of the multiple-inlet air-based BIPV/T system for a cold climate for a solar house is numerically investigated.

2. Experimental of convective heat transfer in two-inlet air channel of BIPV/T system

2.1 Experimental BIPV/T prototype

The schematic of the experimental BIPV/T prototype consists of two custom-designed and manufactured PV panels. The one with mono-crystalline PV panels is shown in Figure 1. Each PV panel contains three columns of six solar cells, with length × width × thickness of 1030mm × 548mm × 4mm. The two sides of the air channel were made of 31 mm thick solid pine wood with grooves for installing the PV panels. The PV panels were slit along the grooves and then fixed with 9.5 mm of the panel width embedded in the groove on each side, leaving the air channel width of 529 mm. The bottom of the channel consists of 25.4 mm thick (1 inch) rigid polystyrene insulation with an RSI value of 0.88 m2·K/W and an 11 mm (7/16 inch) thick oriented strand board.

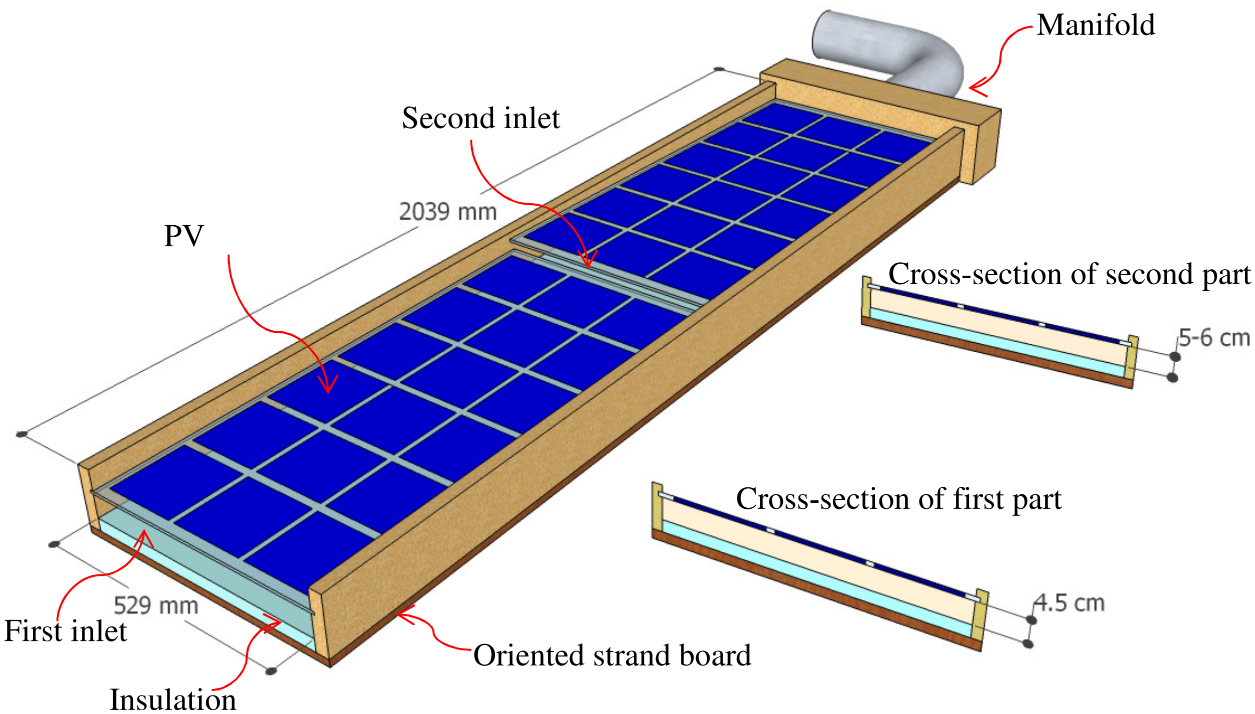

Figure 1. Schematic of the semi-transparent BIPV/T system prototype with two inlets.

The first PV panel is parallel to the bottom insulation surface, creating a uniform channel height of 45 mm. Considering that the BIPV/T system is intended to be used as the building envelope and should reduce rain/snow/dust penetration, the second PV module overlaps the first one at the conjunction and leaves a gap of 12 mm in height as the second air inlet. Along the air flow path, the second PV module tilts down so that in a large-scale project more PV panels could be set at the same elevation as the second module and maintains a uniform look. The BIPV/T channel covered by the parallel PV is called the first section, and that covered by the tilted PV is named the second section.

2.2 Test Rig

The test BIPV/T prototype was mounted onto the collector support of the solar simulator and placed under the solar simulator in the Solar Simulator – Environmental Chamber Laboratory at Concordia University, Montreal, Canada. The solar simulator offers accurate and repeatable test conditions in terms of solar radiation, wind speed and ambient temperature, allowing for the prototype being tested under a stable environment close to room temperature. The sunlight-simulating lamps provide radiation close to the solar spectrum at a stable. The fan creates different wind speeds parallel to the PV surface in the same direction as the flow in the cavity. At the same time, there are some special requirements. The intensity and location of each lamp (8 in total) need to be adjusted so that the irradiance on the test surface is in an acceptable uniformity range. The uniformity achieved was 3%. The lab temperature was set around 20 ºC, which was maintained by a cooling unit controlled by the lab thermostat. The solar simulator had an uncertainty of ±1%.

The test BIPV/T prototype can be tilted between 0° and 90° to produce different roof/façade slopes. Figure 2 shows a photo taken during the testing of the black opaque BIPV/T system at a 45° tilt angle.

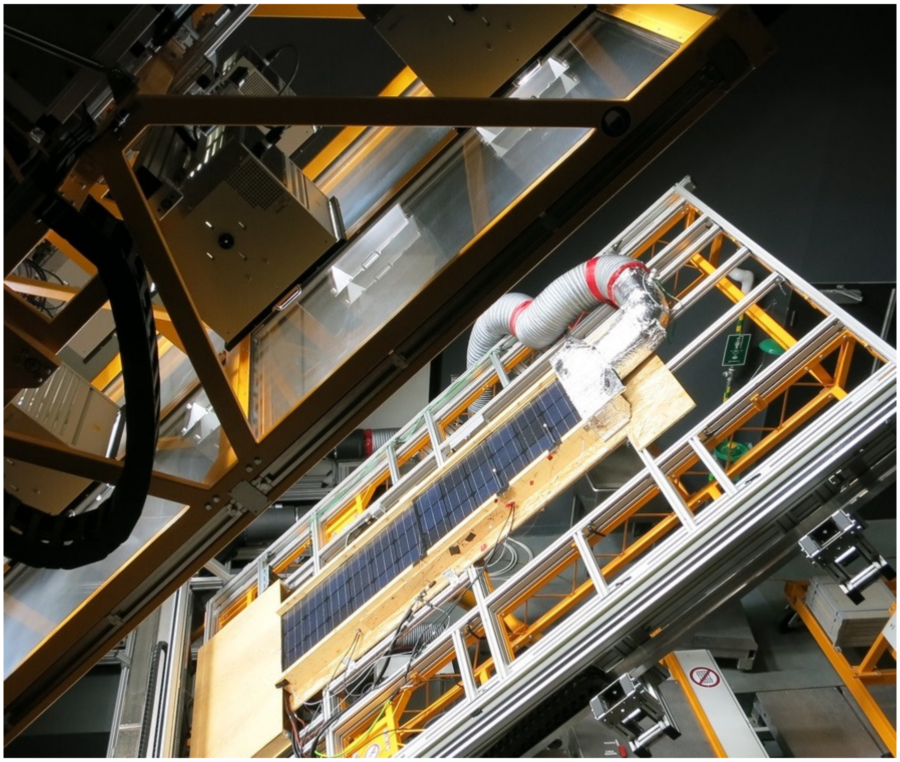

Figure 2. Photo of the BIPV/T system using black opaque PV panels being tested at a tilt angle of 45°.

Fifty-five type-T thermocouples and three RTD temperature sensors were distributed throughout the system. Four system parameters were measured: the bottom surface temperature of the PV module, the channel air temperature, the inner surface temperature of the insulation and the artificial wind temperature just above the top surface of the PV module (the simulator creates an artificial wind along the length of the collector). The temperature sensors had an uncertainty of ±0.2 °C.

The heated air from the first section and ambient air from the second inlet mixes in the second section of the system. To examine the mixed air temperature profile, three thermocouples were grouped at different heights and five such groups were distributed along the air flow direction in the second section of the BIPV/T system. The tip of the thermocouple is shielded by aluminum foil in order to block the radiation from the PV and insulation hot surfaces.

With the second air inlet closed, the flow rate in the first section equals the total flow rate which was known from the fan controlling program. The uncertainty of the air mass flow rate measurement was less than ±2%. A TSI VelociCalc meter 8346 was used to measure air velocity through the hole. The anemometer had an accuracy of ±3.0% of reading or ±0.015 m/s, and its measurement showed a deviation of ±1.25% when calibrated in a wind tunnel against a 4-hole cobra probe.

2.3 Experimental Results

For mass flow rates of 0.03, 0.064 and 0.095 kg/(m^2·s), the tested two-inlet BIPV/T system achieved thermal efficiencies of about 36%, 50% and 58%, respectively. The test conditions are 1040 W/m^2 of solar radiation, wind speed of 2.1 m/s and ambient temperature of 19 °C.

For the first and second sections of a two-inlet BIPV/T system, the Nusselt number between the PV panel and the channel air, fitted with a coefficient of determination of around 99%, can be expressed as:

$Nu = 0.0149Re^{0.9}Pr^{0.43}$ for the first section (1)

$Nu = 1.451Re^{0.44}Pr^{0.4}$ for the second section (2)

where Pr is the Prandtl number and Re is the Reynolds number.

It is evident that the convective heat transfer is more effective in the second section, which is due to the broken boundary layer and local heat transfer enhancement by the extra air inlet. It should be noted that although the above correlations were derived from a 2-inlet BIPV/T system, they can also possibly be applied in a BIPV/T system with multiple inlets due to the similar nature of heat transfer and fluid flow.

3. Modeling of multiple-inlet air-based BIPV/T system

3.1 Mathematical model

The mathematical model for multiple-inlet air-based BIPV/T systems is constructed based on the energy balance of the components participating in the heat transfer process. Figure 3 shows the temperature nodes in a typical control volume of a BIPV/T system. The layers of the PV panel are combined and are represented with a single temperature node with no significant thermal capacity.

The following assumptions have been applied to the model: (1) the system is in quasi steady state, (2) the bottom insulation and the side walls are adiabatic, (3) heat flow is assumed to be one-dimensional perpendicular to the PV, (4) the cover glass, anti-reflective coating, EVA sheet, and backing sheet can be considered as a lump sum body with a temperature of T_{pv}.

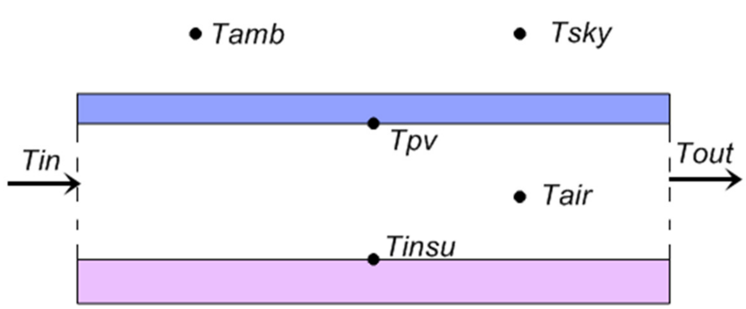

Figure 3. Temperature nodes of a typical control volume of a BIPV/T system.

A set of energy balance equations is written for the components in the BIPV/T system. In the PV air channel, the CHTC is calculated using Eqs. 1 and 2.

For the temperature node of Tpv, the energy balance equation is

$$\alpha G = \eta G + \frac{\sigma\left(T_{pv}^4 - T_{ins}^4\right)}{\frac{1}{\varepsilon_{pv}} + \frac{1}{\varepsilon_{ins}} - 1} + h_{amb}\left(T_{pv} - T_{amb}\right) + \varepsilon\sigma\left(T_{pv}^4 - T_{sky}^4\right) + h_{top}\left(T_{pv} - \overline{T}_{air}\right) \quad (3)$$

where η is the electrical efficiency of the PV panel. From left to right, the items in equation 3 represent absorbed solar energy, converted electricity, radiative heat transfer to the insulation, convective heat transfer to the ambient air, radiative heat transfer to the sky and convective heat transfer to the channel air.

For the air passing through the control volume,

$$\dot{m}c_p\left(T_{out} - T_{in}\right) = Ah_{top}\left(T_{pv} - \overline{T}_{air}\right) + Ah_{bot}\left(T_{ins} - \overline{T}_{air}\right) \quad (4)$$

For the temperature node on the insulation inner surface,

$$\frac{A\sigma\left(T_{pv}^4 - T_{ins}^4\right)}{\frac{1}{\varepsilon_{pv}} + \frac{1}{\varepsilon_{ins}} - 1} = Ah_{bot}\left(T_{ins} - \overline{T}_{air}\right) \quad (5)$$

The electrical efficiency of the PV module is expressed as a function of temperature as follows

$$\eta_e = \eta_{ref}\left(1 - 0.4\%\left(T_{pv} - 25\right)\right) \quad (6)$$

3.2 Performance evaluation of a typical BIPV/T system with five inlets

Based on the above mathematical model, a computer program is developed in Matlab. This Matlab program is used to study the performance of BIPV/T air systems with five inlets installed in a typical residential application with a total length of 8 m. The operation condition is a typical winter condition in a cold climate: -10 °C of temperature, 800 W/m^2 of solar radiation, 2 m/s of average wind speed. Two different configurations of air channels (single inlet and five inlets) are compared. For both cases, the total mass flow rate in the air channels is 0.1072 kg/s. For the cases with five inlets, we assume that equal air flow is drawn through each inlet.

The air outlet temperatures of each section of the 5-inlet BIPV/T system are compared with the air temperature profile in the 1-inlet system in Figure 4. With the same inlet temperature of -10 ℃ the outlet temperatures are 9.4 °C and 10.6 °C for the single-inlet and 5-inlet air channel configurations. The 5-inlet system achieved an enhanced thermal efficiency of 34.7% and an electrical efficiency of approximately 16.5%. By using the 5-inlet BIPV/T system instead of the single-inlet one, the thermal efficiency is increased by 6.4%.

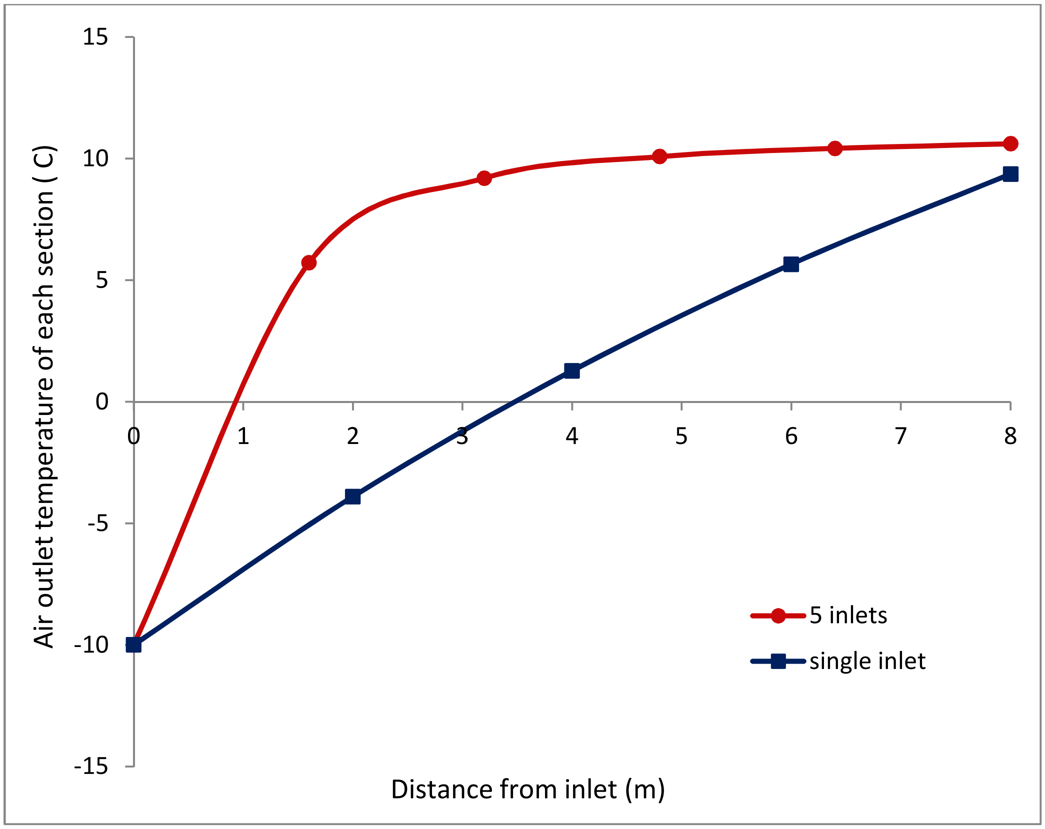

Figure 4. Comparison of the air temperature development of the 1-inlet and 5-inlet BIPV/T systems.

4. Conclusion

A prototype BIPV/T system having two-inlets was experimentally studied in a full-scale solar simulator. The Nusselt number correlations for the first and second sections of the two-inlet BIPV/T air system are proposed. Those correlations can also be used for multiple-inlet BIPV/T air systems.

A mathematical model, which incorporates the experimental Nusselt number correlations, is built, based on which a computer program with the Matlab is developed. This Matlab program can be used to evaluate the performance of BIPV/T system with multiple inlets under typical weather conditions.

5. References

[1] Clarke, J.A., Hand, J.W., Johnstone, C.M., Kelly, N., Strachan, P.A., "Photovoltaic-integrated building facades". *Renewable Energy* 8, 196, 475-479.

[2] Hayter, S.J., Martin, R.L., "Photovoltaics for buildings: Cutting-edge PV". Presented at UPVG Utility PV Experience (UPEx) '98, San Diego, California, Septermber 28-30,1998.

[3] Eiffert, P., "U.S. guidelines for the economic analysis of building-integrated photovoltaic power system". National Renewable Energy Laboratory: Colorado (USA) 2000. NREL/TP-710-25266.

[4] Posnansky, M., Gnos, S., Coonen, S., "The importance of hybrid PV-building integration". Paper presented at the IEEE Photovoltaic Specialists Conference, Hawaii, 1994.

[5] Fujisawa, T., Tani, T., "Annual exergy evaluation on photovoltaic-thermal hybrid collector". *Solar Energy Materials and Solar Cells* 47, 1997, 135-148.

[6] Dupeyrat, P., Menezo, C., Fortuin, S., "Study of the thermal and electrical performances of PVT solar hot water system". *Energy and Buildings* 68, 2014, 751-755.

[7] Fraisse, G., Menezo, C., Johannes, K., "Energy performance of water hybrid PV/T collectors applied to combisystems of Direct Solar Floor type". *Solar Energy* 81, 2007, 1426-1438.

[8] Kazanci, O.B., Skrupskelis, M., Sevela, P., Pavlov, G.K., Olesen, B.W., "Sustainable heating, cooling and ventilation of a plus-energy house via photovoltaic/thermal panels". *Energy and Buildings*, 2014, http://dx.doi.org/10.1016/j.enbuild.2013.12.064

[9] Agrawal, B., Tiwari, G.N., "Optimizing the energy and exergy of building integrated photovoltaic thermal (BIPVT) systems under cold climatic conditions". *Applied Energy* 87, 2010, 417-426.

[10] Pantic, S., Candanedo, L., Athienitis, A.K., "Modeling of energy performance of a house with three configurations of building-integrated photovoltaic/thermal systems". *Energy and Buildings* 42, 2010, 1779-1789.

[11] Yang, T.T., Athienitis, A.K., "A study of design options for a building integrated photovoltaic/thermal (BIPV/T) system with glazed air collector and multiple inlets". *Solar Energy* 104, 2014, 82-92.

6. Acknowledgements

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