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Multiple-inlet Building Integrated Photovoltaic/Thermal system modelling under varying wind and temperature conditions

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ABSTRACT

Air-based, open-loop Building Integrated Photovoltaic/Thermal (BIPV/T) systems are an efficient means for generating electricity and useful heat from incident solar energy. However, due to the low heat exchange efficiency of air, overheating issues may occur that can reduce the electrical production of the system, as well as its durability. With the introduction of multiple intakes of air along the PV string, the goal is to improve the heat extraction from all PV panels, while achieving lower and more uniform PV temperatures.

This study presents the results of a numerical investigation on the comparison of the performance of single and multiple-inlet BIPV/T systems for a possible retrofit or new buildings, with an example of a potential large scale installation on an office building. The comparison was carried out considering a cold winter and a hot summer day, under varying wind conditions, in terms of electrical and thermal performance, and PV temperature distributions. For the modelling of a multiple-inlet BIPV/T system, a flow distribution model was developed utilizing pressure drop and flow correlations, as well as wind tunnel pressure measurements representing the wind effects on the flow distributions, and a modified energy balance model for the multiple-inlet system.

It was found that a multiple-inlet BIPV/T system may have up to 1% higher electrical efficiency corresponding to 7% additional power to the total output of a 120 kW system and up to 24% higher thermal efficiency, while resulting in the lowest and most uniform PV temperatures.

1. Introduction

Solar technologies integrated with the building envelope can be efficiently used for electricity generation and ventilation air preheating, while replacing common building materials, thus increasing the cost effectiveness of the installation (Athienitis et al., 2010). In a BIPV/T system, photovoltaic panels (PV) form the external layer of the building envelope (replacing shingles, rain-screen cladding, etc.) and a channel is formed between the PV layer and the internal skin of the building. In that channel a fluid medium may circulate in an open (only for air) or closed-loop configuration (normally water), extracting excess heat from the PV panels via convection, while part of this heat can be recovered and used through various means. Apart from the potential thermal gains, heat extraction from the PV layer results in electrical production enhancement, since, according to Florschuetz (1979), the electrical efficiency of the PV module is a function of its temperature. Thus, low operating PV temperatures can be beneficial for the performance of the systems, especially in large installations.

Water-based systems generally have higher heat exchange efficiency, due to the higher specific heat capacity and density of water. These systems are more suitable for climates with high levels of solar irradiation and ambient temperature. In a review of the state of the art PV/T technology, Chow (2010) referred to experimental and outdoors studies, which showed that water-based PV/T systems may have a thermal performance equivalent to a conventional solar thermal collector, with the added electricity production. However, due to their weight, cost and required ducting for the liquid coolant, water-based systems are mainly limited to roof applications. Air-based systems, on the other hand, are more practical for large roof and façade applications in a cold climate since they pose no leakage issues through ducts and joints, there is no need for the addition of anti-freezing additives, they are lighter, easier to install and maintain, while being far less complicated (Bambara et al., 2012; Tyagi et al., 2012).

Heat transfer enhancement techniques for air-based systems have been the subject of several studies. Hegazy (1999) studied variations of glazed and double pass PV/T collectors, with the PV

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Nomenclature

Symbols

A	orifice area (m^2)
$A_{b.frame}$	back frame opening area (m^2)
A_{inlet}	inlet area (m^2)
c_p	specific heat of air (J/kg °C)
C_p	pressure coefficient
D_h	hydraulic diameter (m)
f	the Darcy friction factor
h_{c1}	convective heat transfer coefficient for the PV layer (W/m^2 °C)
h_{c2}	convective heat transfer coefficient for the insulation layer (W/m^2 °C)
h_o	exterior film coefficient (combined radiation and convection) (W/m^2 °C)
h_{rad}	radiative heat transfer coefficient (W/m^2 °C)
h_{wind}	wind-induced heat transfer coefficient (W/m^2 °C)
K	local loss coefficient for flow through an orifice
$K_{b.frame}$	local loss coefficient for flow through the back frame opening
K_{inlet}	local loss coefficient for flow through an inlet
L	characteristic length of the flow (m)
M	mass flow rate of the air collector (kg/h)
Nu	Nusselt number
P	pressure (Pa)
P_i	wind induced external static pressure (Pa)
Q	volumetric flow rate (m^3/s)
$Q_{channel}$	air channel volumetric flow (m^3/s)
Q_{inlet}	inlet volumetric flow (m^3/s)
Q_n	n-th channel volumetric flow (m^3/s)
$Q_{opening(i)}$	flow through the i-th opening (m^3/s)
Q_{tot}	total flow of the air collector (m^3/s)
Q_u	heat transferred to the air stream (J)
R	flow resistance ($kg/(m^4\,s)$)
$R_{channel}$	channel flow resistance ($kg/(m^4\,s)$)
R_{inlet}	inlet flow resistance ($kg/(m^4\,s)$)
Re	Reynolds number
S_{PV}	radiation absorbed by the PV layer (W)
T_{air}	ambient air temperature (°C)
T_i	entrance air temperature (°C)
T_{ins}	temperature of the insulation on the back wall of the BIPV/T (°C)
T_{ma}	temperature of air inside the BIPV/T air channel (°C)
T_n	n-th channel air temperature (°C)
T_o	external temperature (°C)
T_{PV}	temperature of the PV module (°C)
T_R	temperature of the adjacent room to the BIPV/T (°C)
U_{ins}	insulation layer conductance (W/m^2 °C)
V_{loc}	wind velocity at the height of measurements (m/s)

Greek letters

ΔP	pressure drop (Pa)
$\Delta P_{channel(i)}$	pressure drop within i-th channel
$\Delta P_{opening(i)}$	pressure drop across the i-th inlet
ρ	air density (kg/m^3)

Abbreviations

BIPV/T	Building Integrated Photovoltaic/Thermal
COP	Coefficient of Performance for heat pump
PV	Photovoltaic
UTC	Unglazed Transpired Collector

layer set behind a glazing to reduce wind induced heat losses, increasing the thermal efficiency of the system, but also resulting in higher PV temperatures and reduced electrical production. By increasing the air mass flow rate, the PV temperature dropped, at the cost of increased fan consumption. Tonui and Tripanagnostopoulos (2006) investigated additionally the use of fins and a thin metal plate within the air channel. Both techniques improved the performance of the system, the fin system being superior. The incorporation of a solar air heater in series with an air-based BIPV/T system as a means to enhance the thermal output of the system and the outlet air temperature, has also been investigated (Yang and Athienitis, 2014).

The above methods achieved higher thermal efficiencies of the studied systems, but also produced higher PV temperatures. The employment of a continuous air channel causes a vertical temperature stratification of the PV layer. The non-uniform PV temperatures may affect the electrical production, depending on the PV array's connection configuration. For example, if the PV modules of the string are connected in series in the vertical sense, then the PV strings performance will be determined by the performance of the hottest panel. If the PV modules are connected in series horizontally and therefore have similar temperature, then the PV array will consist of strings that perform differently and, naturally, not optimally.

1.1. Multiple-inlet BIPV/T

A potential method that could counter the effect of temperature stratification and yield lower PV temperatures employs more than one opening on the PV system along the flow path of the air channel (Fig. 1).

Separate channels are created, one for each PV module, which are interconnected, forming a multiple-inlet system. This system aims to enhance heat extraction from each of the PV modules, by regulation of the flow, as well as the boundary temperature of air entering each channel, which is a mixture of air from the previous channel and outside air at ambient temperature. This concept evolved from the hybrid UTC-PV/T system designed by Athienitis et al. (2010), consisting of a layer of UTC bearing custom made PV modules fixed with supports, covering 70% of the total UTC area. The concept of that system was that the solar collector could also produce electrical energy, increasing its cost-effectiveness, especially in the summer months, when space heating is not needed (except for domestic water heating use). While the overall thermal performance of the hybrid system was lower than that of a UTC, its overall efficiency was found to be 7–17% higher, based on a coefficient of performance (COP) of a heat pump to convert electricity into equivalent heat, assumed to be equal to four (Athienitis et al., 2010; Bambara et al., 2012). The system was modelled assuming uniform suction from the UTC perforations, according to Kutscher (1994), considering the mass flow entering the exposed UTC area and the PV covered area for the energy balance.

Yang and Athienitis (2014) investigated experimentally a two-inlet BIPV/T variation of a single-inlet prototype, previously studied by Candanedo et al. (2010). Yang developed Nusselt correlations for the laminar and the turbulent region of the PV and the insulation layer of the collector, which were used to model the improved design with two inlets, intended for inclined roof applications. The thermal performance of the system was further