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# Part I: Thermal analysis of naturally ventilated BIPV system: Experimental investigation and convective heat transfer coefficients estimation

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ABSTRACT

The purpose of this two-part study is to present the experimental analysis carried out on a naturally ventilated Building Integrated Photovoltaic (BIPV) system and the new correlations developed for the estimation of the convective heat transfer coefficients (CHTC) in the air gap, and use the developed correlations to construct a simulation model which is validated with the experimental data. In BIPV systems the air gap is responsible to cool the PVs and remove excess heat to avoid building overheating. The ventilation of the air gap can be natural or mechanical. However, naturally ventilated systems are less studied although they have important advantages over the mechanically ventilated ones, such as the avoidance of extra energy of the fans, maintenance and noise. The present Part I of this study presents an experimental based thermal analysis of a naturally ventilated vertical BIPV system. A series of experiments on a custom made BIPV system were carried in real outdoor conditions as well as indoors with the use of a large scale solar simulator to measure the thermal characteristics of the system and its thermal behaviour. Indoor experiments were performed to avoid external disturbances from wind that may occur outside. The results show that an open-ended air gap of 0.1 m can create adequate air flow on naturally ventilated systems and can ensure low PV temperatures to avoid PV efficiency decrease. The experimental data are then used to estimate the convective heat transfer coefficients to fit the real conditions of the BIPV systems. Then two correlations are proposed for the estimation of the Nusselt number that fits best the thermal characteristics of a naturally ventilated BIPV system.

## 1. Introduction

During the last few years photovoltaic (PV) panels are increasingly incorporated (or integrated) into the construction of buildings for generating electrical power. These are called Building Integrated Photovoltaic (BIPV) systems.

The integration of PV panels in a second skin creates heat behind the PVs. However, in order to prevent overheating of the PVs and accordingly loss of their efficiency, the two skins are separated by an air gap. The air gap can reduce the PVs overheating and also building cooling load which occur due to the presence of hot surfaces around the skin. Fresh air passes through the air gap and cools the PVs. The heated air then can be either thrown to the environment or be used to heat the interior of the building. When the heated air is used to heat the building, then the system is called Building Integrated Photovoltaic/Thermal (BIPV/T). The ventilation of the air gap can be natural or mechanical. The system investigated in this study is a naturally ventilated BIPV system. This has a number of advantages, the most important of which is the avoidance of energy to power the fans, the operation with no noise and the avoidance of overheating which can happen when the fan stops in an active system as well as the higher initial cost of the system due to the fans and special installation.

The design of the system and the sizing of the air gap is very important for the performance of the building. The air in the duct affects the system whether it is a Double Skin Façade (DSF) or a BIPV. In DSF the air may overheat the façade if is not treated appropriately and thus add unwanted thermal loads to the building, and in BIPV systems the overheating of the PVs decreases the efficiency of the PVs but also overheat the building. Gan (2009) used a computational fluid dynamics (CFD) method to assess the effect of the air gap between PV modules and the building envelope on the performance of the system in terms of the cell temperature for a range of roof pitches and panel lengths and to determine the minimum air gap that is required to minimize the PV overheating. Initially, the air flow patterns and the images of the temperature distribution around the module, shows that while the roof inclination increases, the velocity of the air increases but the PV temperature decreases.

Various researchers tried to understand the heat transfer and the air

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**Nomenclature**

| | |
|---|---|
| $A$ | area ($m^2$) |
| $C_p$ | specific heat of the fluid (J/kg K) |
| $d$ | distance between the two flat plates (m) |
| $g$ | acceleration of the gravity ($m/s^2$) |
| $h$ | convective heat transfer coeff. ($W/m^2$ K) |
| $k$ | thermal conductivity (W/m K) |
| $L$ | length (m) |
| $m$ | mass (kg) |
| $Pr$ | Prandlt number |
| $\dot{Q}$ | heat transfer rate ($W/m^3$) |
| $\dot{q}$ | heat flux ($W/m^2$) |
| $Ra^*$ | modified channel Rayleigh number |
| $T$ | temperature (°C) |

*Abbreviations*

| | |
|---|---|
| *BIPV* | Building Integrated Photovoltaic |
| *BIPV/T* | Building Integrated Photovoltaic/Thermal |
| *CFD* | Computational Fluid Dynamics |
| *CHTC* | Convective Heat Transfer Coefficients |
| *DSF* | double skin façade |
| *SE* | standard error |
| *PRE* | percentage relative error |
| *PV* | photovoltaic |
| *PV/T* | Photovoltaic/Thermal |

*Greek symbols*

| | |
|---|---|
| $\beta$ | the volumetric coefficient of thermal expansion (1/K) |
| $\varepsilon$ | emissivity |
| $\nu$ | kinematic viscosity of air (kg/m s) |
| $\rho$ | fluid density ($kg/m^3$) |

*Subscripts and superscripts*

| | |
|---|---|
| *amb* | ambient |
| *a* | air |
| *b* | bottom |
| *c* | cell |
| *ch* | channel |
| *f* | fluid |
| *i* | inlet |
| *o* | outlet |
| *m* | middle |
| *out* | outside or outlet |
| *pv* | photovoltaic |
| *s* | surface |
| *surr* | surroundings |
| *t* | top |

flow between the two skins of the DSF and BIPV systems. Numerous studies approached the analysis experimentally (Brinkworth, 2000; Brinkworth et al., 1997, 2000; Brinkworth and Sandberg, 2006; Kaiser et al., 2014; Mei et al., 2003) or numerically with simulations (Eicker et al., 1999; Gan, 2009; Manz, 2003; Xamán et al., 2005).

Studies can be also categorized between those who studied the forced ventilated systems and those who studied the naturally ventilated systems. An extensive review by Agathokleous and Kalogirou (2016) presented the various studies carried out for BIPV systems separated into naturally and mechanically ventilated systems, and studies which analysed the system experimentally or theoretically. It was concluded that most researchers studied the systems with mechanical ventilation because of the flexibility to adjust the air flow in the duct to remove the heated air or drive it into the building. Additionally, natural ventilation systems are more complex in terms of the air flow behaviour in the duct which is difficult to be predicted. ElSayed (2016) carried out simulations for a BIPV model, and the results showed that the air flow behind PV modules in a ventilated gap and cell temperatures are complicated due to the compilation of the internal space of the air gap and dynamics of heat transfer.

According to Wang et al. (2006), BIPV has significant influence on the heat transfer through the building envelope because of the change of the thermal resistance of the various building elements. Consequently, it is important to find the configuration of the system that will increase the efficiency of the PVs and do not increase the cooling loads of the building in summer. For the BIPV/T systems it is important to keep both electrical and thermal efficiencies high throughout the year. According to Brinkworth and Sandberg (2006) the most important variable to be fixed in the design of a PV cooling duct is the depth, and hence the hydraulic diameter of its cross section. As concluded by Agathokleous and Kalogirou (2016), researchers seem to agree that the optimum air gap between the PVs and the building façade ranges between 10 and 15 cm in order to keep the PVs temperature at low levels.

The aim of this study is to present a thermal analysis of a naturally ventilated vertical BIPV system with experimental analysis. A further objective of this study is to develop new correlations to estimate the convective heat transfer coefficients (CHTC) in the air gap of the naturally ventilated BIPV systems. It is important to investigate the behaviour of naturally ventilated BIPV systems in order to show that naturally ventilated systems can be efficient when correct design is done and the overheating can be avoided. The correct estimation of the CHTC will give a better prediction of the system's behaviour and performance. Both indoor and outdoor experiments are carried out with the use of custom made experimental BIPV apparatuses. For the indoor experiments, a solar simulator is used for artificial solar radiation in controlled environmental conditions without wind or clouds.

## 2. System description

The experimental procedures to investigate the temperature distribution of the various parts of a naturally ventilated BIPV system were carried out in Limassol, Cyprus (34.70°N, 33.02°E). As already mentioned, both outdoor and indoor experiments were carried out, to examine the thermal behaviour of a naturally ventilated vertical façade BIPV system.

The indoor experiments were performed in a laboratory with controlled conditions with the use of a solar simulator. The aim of the indoor experiments was to carry out experiments with uniform and constant amount of solar radiation for a certain amount of time without external disturbances like wind to affect the air flow in the air channel of the system or clouds, dust and rain to affect the thermal behaviour of the system, while the aim of the outdoor experiments was to test the system in different orientations under real operating conditions. Orientation is very important when testing a vertical system in order to exploit as much radiation possible, in amount that it does not cause overheating effects to the system.

For the experimental procedures, two custom made experimental apparatuses are designed and built, one for outdoor experiments and one for indoor testing. Both apparatuses represent a single PV panel BIPV system with air gap between the PV panel and a second skin, forming an open-ended duct. The duct is naturally ventilated without the use of a fan to circulate the air. The basic schematic representation of the tested BIPV system is shown in Fig. 1.

The system consists of a primary skin (building envelope) and