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Part II: Thermal analysis of naturally ventilated BIPV system: Modeling and Simulation

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ABSTRACT

This is the second part of a two-part study based on the thermal behaviour of a naturally ventilated BIPV systems. In the first part an experimental analysis of the thermal behaviour of a naturally ventilated BIPV system is presented and two new correlations for the estimation of the convective heat transfer coefficients in the air gap between the PV panel and a second skin are given, for windy and non-windy conditions. The present study (second part) presents a simulation based thermal analysis of a naturally ventilated vertical BIPV system. The simulation model is created using the developed equations for the estimation of the convective heat transfer coefficients presented in the first part of the present study, and the model is validated with the use of experimental data shown in the first part as well. The experimental based correlations are imported in the mathematical model, in order to be able to investigate the effect of other parameters on the thermal behaviour of the system such as the height of the system, the size of the air gap and the air velocity in the duct. These parameters are not easy to be investigated experimentally and their investigation would be very time consuming. The simulation model has a good agreement with the experimental results. The results shown that an air gap of 0.1 m can create adequate air flow on naturally ventilated systems and can ensure low PV temperatures to avoid efficiency decrease. This can be done when the air gap has bottom and top openings to allow air circulation. In taller systems, the temperatures are higher and there is a drop of the efficiency of the system.

1. Introduction

Photovoltaics (PVs) make use of the main renewable resource available on our planet, solar radiation, to produce electrical energy directly, silently, with no moving parts. Additionally, they are light and have a long life. Photovoltaics break one limit after the other and the total installed capacity at the end of 2015 was 227 GW with more than 50 GW installed just in 2015, breaking the threshold of 200 GW for the first time (REN21 Steering Committee, 2016). Despite this growth only about 1.3% of the worlds electricity is produced by PV. According to the latest IEA report 23 countries have at least 1 GW of cumulative PV capacity by the end of 2015 and 7 countries installed at least 1 GW in 2015. This growth is expected to continue in the years to come. At the end of 2016 the total installed capacity reached 303 GW which is much higher than in 2015, breaking this time the 300 GW limit (REN21 Steering Committee, 2017).

During the last years building integrated photovoltaic (BIPV) systems are used extensively in building applications. In BIPV systems, PVs replace conventional construction materials of the building's envelope such as facades, glazing, roof tiles, curtain walls and shading elements.

However, apart from the increase in the applications of the BIPV systems, there is a special interest in the associated research. BIPV systems integrated on the envelope of the building (opaque surfaces) such as the external walls or roof, are very popular in the research world during the last years. Those systems consist of two skins, one is the PV panel and the second is the outer skin of the building which is the brick wall in façade applications or the insulation in roof applications. However, in order to avoid overheating of the PV panels when they are integrated to a second skin, usually an air gap is left between the PV and the back skin. The air gap can be open ended duct or closed cavity, it can have different width sizes and can be ventilated naturally or mechanically with the use of mechanical means like fans. The design of the air gap is very important parameter that affects the performance of the system.

While there are many papers in the literature on the forced circulation systems, very few researchers studied the systems operating by natural convection. This is probably because their thermal performances are lower than those with forced flow. Thermal performance is

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Nomenclature

E	error
C_p	specific heat of the fluid (J/kg K)
d	distance between the two flat plates (m)
D_h	hydraulic diameter of the duct (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)
p	perimeter (m)
Pr	Prandlt number
$\dot{Q}$	heat transfer rate (W/m^3)
$\dot{q}$	heat flux (W/m^2)
Ra''	channel Rayleigh number
Ra^*	modified channel Rayleigh number
T	temperature (°C)
u	air velocity (m/s)

Abbreviations

ARE	Absolute relative error
BIPV	Building Integrated Photovoltaic
BIPV/T	Building Integrated Photovoltaic/Thermal
CFD	Computational Fluid Dynamics
CHTC	Convective Heat Transfer Coefficients
DSF	Double skin façade
PRE	Percentage relative error
PV	Photovoltaic
PV/T	Photovoltaic/Thermal

Greek symbols

β	the volumetric coefficient of thermal expansion (1/K)
ε	emissivity
μ	dynamic viscosity of air (kg/m s)
ν	kinematic viscosity of air (kg/m s)
ρ	fluid density (kg/m^3)
σ	Stefan-Boltzmann constant (W/m^2 K^4)

Subscripts and superscripts

amb	ambient
b	bottom
m	middle
out	outside or outlet
pv	photovoltaic
s	surface
surr	surroundings
t	top

important for the BIPV/T (building integrated photovoltaic/ thermal) systems where the heated air in the air duct is used for space heating. However, this should not be a barrier to their application because naturally ventilated systems have numerous advantages over the systems with forced ventilation. First of all, they do not use electrical energy to circulate the air and this minimizes the operation cost, and the maintenance cost as well. In addition, naturally ventilated systems do not require a control system, special structure to install the fans, and they do not cause noise (which is caused by the fans in forced ventilation systems). In this study, the system under investigation is a BIPV system because it makes no use of the heated air for space heating.

Various studies attempted to investigate the PV facades and the DSF with simulation tools such as Eicker et al. (1999), Xamán et al. (2005) and Brinkworth et al. (2000).

Mei et al. (2003) presented a dynamic thermal model in TRNSYS to assess the heating and cooling loads of an integrated ventilated PV façade. Gan (2009) carried out a CFD (computational fluid dynamics) simulation analysis on BIPV system to investigate the effect of the air gap size on the PV performance in terms of cell temperature for different roof pitches and panel lengths and to determine the minimum air gap that is required to minimise PV overheating. Hailu et al. (2014) carried out a CFD analysis on the BIPV/T systems considering forced convection. Another CFD study is carried out by Manz (2003) on the heat transfer of the naturally ventilated cavities on the façade elements. Manz and Frank (2005) presented a study with thermal simulation of buildings with double skin facades. Faggembauu et al. (2003) presented a numerical simulation analysis of ventilated and conventional facades. Zogou and Stapountzis (2012) studied the flow and heat transfer inside a PV/T collector for building applications. In the study of Zogou and Stapountzis (2012), the experimental results are combined with CFD computations to calculate heat transfer coefficients of the specific PV/T system.

However, according to Versteeg and Malalasekera (1995), the combination of a fluid flow and heat transfer modeling cannot be sufficient without reference to experimental validations. According to Linfield and Mudry (2008) CFD simulations is the only option for complex temperature problems involving conduction, convection or radiation heat transfer mechanisms. CFD models in heat transfer field can run for temperature variations and take into account changes in fluid density, viscosity, thermal conductivity and heat transfer coefficient.

Roeleveld et al. (2015) presented a validation study of a CFD model of a BIPV/T system, with experiments conducted in Concordia University. The system is tested in three orientations 0°, 45° and 90° at two different flow rates, focused on the thermal behaviour of the system. The system in this study is not naturally ventilated. The simulation results had a good agreement with the experimental data. Another study with experimental validation of a simulation model is presented by Syamimi et al. (2016). A naturally ventilated BIPV/T system is investigated, and various parameters are estimated, such as the PV surface temperature, the air temperature, the mass flow rate as well as the power output.

Shahrestani et al. (2017) carried out experimental and numerical analysis to assess the energy performance of naturally ventilated PV façade systems. A numerical model is developed in TRNSYS software which is validated with experimental data obtained from a prototype ventilated PV façade system. Apart from the estimation of the annual performance of the system, it is concluded that ventilation improves the efficiency of the system.

The aim of this study is to present a thermal analysis of a naturally ventilated BIPV system with simulations. A simulation model is created in COMSOL Multiphysics and with the appropriate mathematical approach, which is validated with the use of measured experimental data. 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). Consequently, COMSOL Multiphysics 4.3b software was used, with 3D geometry, in order to simulate the model which was already experimentally assessed as shown in Agathokleous and Kalogirou (2018). A BIPV model was created in the same size with the experimental apparatus and equations from the theory are applied through the model in order to simulate the heat transfer mechanisms and the air flow in the duct. The analysis is based on the effect of the air velocity, duct height and gap width and their effect on the thermal behaviour of the system.