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Thermal regulation of PV façade integrated with thin-film solar cells through a naturally ventilated open air channel

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Abstract

Thermal regulation of photovoltaic façade through passive air channel provides a cost effective measure for improving solar to electrical energy conversion efficiency. This study presents a 2D numerical investigation of the fluid flow and heat transfer characteristics of natural convection driven by buoyancy force inside the passive cooling air channel created by two vertical parallel walls. One wall is heated by absorbed heat by photovoltaic (PV) cells from solar radiation. Numerical solutions for open and closed channel are obtained for the channel of 1.05 m in height and 0.16 m in width, respectively. The natural convective cooling effect on the PV cells for different ventilation strategies were examined considering the surface temperature of PV panels. It is found that the maximum surface temperature reaches 57.1 °C for closed channel, 49.1 °C for opened channel. Opened channel behind the PV panel is an economic way of heat releasing for the benefit of PV power generation. However, other issues such as noise control and cleaning difficulty may also be encountered by façade designers. At the same time, understanding the mechanisms involved in the fluid flow and heat transfer in the channel back the PV panel through examining the pressure distribution along the cavity is required and equally important for the design improvements of PV façade especially for the design of the air channel entrance to lower its pressure drop.

Keywords: Ventilated and closed PV facade; Convective heat transfer; Building integrated photovoltaic (BIPV);

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1. Introduction

PV panels may experience undesirably high temperatures due to part of the absorbed solar radiation that is not converted into electricity. Especially when PV panels are exposed under high solar radiation, the conditions are even worse. This heat input can increase the cells temperatures thus decreasing the conversion efficiency of solar cells. Opened channels beneath PV modules are commonly used to extract the additional heat. The air gap on the back of the PV modules provides natural cooling for the PV cell and reduces its operational temperature. Natural cooling using free convection is a simple method with lower cost to remove heat from the back of the PV modules and to keep the electrical efficiency at an acceptable level. By maintaining reasonable temperature on the PV cells, their efficiency could be enhanced dramatically and their working life extended through a reduction of thermal cycles and stresses. The output electrical generation is, therefore, increased.

Nomenclature			
α	thermal diffusivity, m^2 /s	β_T	coefficient of air thermal expansion, 1/K
g	gravitational acceleration, m/s^2	H	passive cooling channel height, m
L	passive cooling channel length, m	p	pressure, Pa
Nu	Nusselt number	Pr	Prandtle number
Ra	Rayleigh number	u	velocity component in x direction, m/s
v	velocity component in y direction, m/s	υ	Kinematic viscosity,m^2 /s
G	solar intensity, w/m^2	ε	emissivity
Subscript			
c	cold wall	h	hot wall
w	wall	T	temperature
∞	ambient	PV	Photovoltaic panel

Passive cooling air channel beneath the photovoltaic (PV) module has been demonstrated as an economical and effective way for thermal regulation of PV module. It has long been noted and interested by various researchers and described in the literature. Ventilated building integrated PV façade systems involve complicated air flow and natural convective heat transfer phenomena. It is induced by buoyancy forces due to a temperature difference between the inlets and outlets of air channel. There are so many similar structures functioning like this, for example, wind towers, Trombe walls and solar chimneys. There is a growing interest in studying heat and fluid flow in air gaps behind PV panels in order to maximize the utilization of the solar energy from the PV system. These previous works include Brinkworth et al. [1-5], Yang et al [6] and Mittelman et al. [7]. Tonui and Tripanagnostopoulos [8] presented air cooling of a commercial PV module configured as PV/T air solar collector by natural flow. Ibrahim et al. [9] provide a simplified loop analysis for a naturally ventilated channel heated from one side by PV elements. Moshfegh and Sandberg [10] explored the heat transfer and air flow characteristics of buoyancy driven air flow behind PV panel. Analytical expressions for the mass flow rate, velocity, and temperature rise have been developed for air gaps behind solar cells located on vertical facades by Sandberg and Moshfegh [11]. An extension of the familiar heat loss and radiation gain factors (U and g values respectively) has been employed to take account of the energy transfer to the facade ventilation air by Infield et al [12]. Gan [13] investigated the adequate air gap for building integrated photovoltaic system through numerical simulation. Yang and Zhu [14] investigated numerically the transient laminar natural convection in an inclined parallel-walled channel.

In this study, a naturally ventilated photovoltaic façade system with semi-transparent solar cells was introduced. Compared with previous study by same authors of this work [15-16], this study has been intended to cover characteristics of the free ventilation of PV façade system. Two different ventilation strategies i.e. ventilated open channel and non-ventilated close channel were explored. This novel glazing system could not only generate electricity but also achieve potential energy savings by reducing the air conditioning cooling load when applied in subtropical climatic conditions and simultaneously provide visual comfort in the indoor environment. The innovative natural-ventilated PV double-glazing technology could significantly cut down the air-conditioning power consumption when all design parameters are fully considered in the design stage.

2. Problem description and modeling

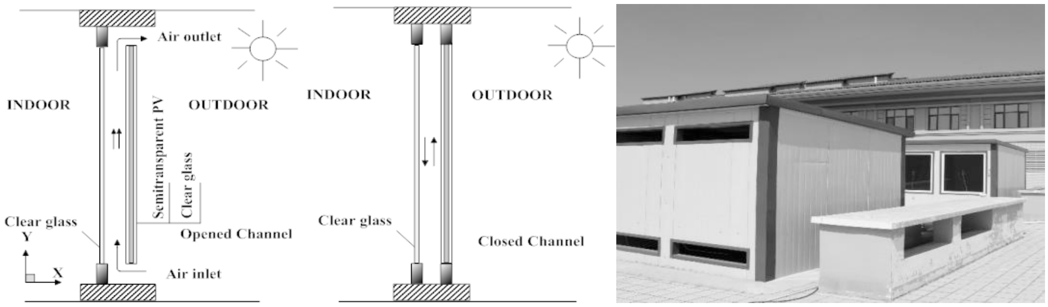

Fig 1 Schematic of the naturally ventilated PV façade (left) and the closed (right) and the test units

The physical problem is buoyancy force induced natural convective heat transfer in air cavity created by two parallel vertical walls. As shown in Fig 1, one surface of the wall is created by semi-transparent photovoltaic glass panel. The problem, at this study, is considered to be steady state and two dimensional (2D). The top and bottom walls are well insulated, whereas the left wall is maintained at a lower temperature (T_c) and the right wall is maintained at a higher temperature (T_h), with $T_h > T_c$. Two air vents are located on the bottom and top of the photovoltaic panel for cool air inlet and warmer air outflow, respectively. It is assumed that the influence of the temperature on density is confined only to the body force term of the momentum equation and that all other fluid properties are independent of temperature and pressure. The flow fields are considered to be steady and fluid is assumed incompressible. Numerical modeling for open and closed channel was considered for the channel of 1.05 m in height and 0.16 m in width. The channel aspect ratio is defined as the ratio of the height H to the plate spacing L (A = H/L). The two dimensional (2D) governing equations for natural convective flow in the air channel back the PV panel can be written as:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{1}$$

$$\frac{\partial uu}{\partial x}+\frac{\partial vu}{\partial y}=-\frac{\partial p}{\partial x}+\left(\frac{\mathrm{Pr}}{Ra}\right)^{1/2}\nabla^2 u \tag{2}$$

$$\frac{\partial uv}{\partial x}+\frac{\partial vv}{\partial y}=-\frac{\partial p}{\partial y}+\left(\frac{\Pr}{Ra}\right)^{1/2}\nabla^2 v \tag{3}$$

$$\frac{\partial u\Theta}{\partial x}+\frac{\partial v\Theta}{\partial y}=\frac{1}{\sqrt{Ra\Pr}}\nabla^2\Theta \tag{4}$$

where Ra is the Rayleigh number, $Ra = g\beta_T(T_w - T_\infty)H^3/\upsilon\alpha$; Θ is the dimensionless temperature, $\Theta = (T - T_\infty)/(T_w - T_\infty)$; β_T is the coefficient of the thermal expansion of fluid; T_∞ and T_w are the ambient and wall temperatures respectively.

The boundary conditions on the walls can be described by:

$$u=0,\ v=0,\ \Theta=0, \text{ for the left vertical wall} \tag{5}$$

and

$$u=0,\ v=0,\ \Theta=1, \text{ for the right vertical wall} \tag{6}$$

The boundary conditions on the inlet and outlet boundaries can be described by:

$$(\Theta)_{in}=0,\ \left[\frac{\partial\Theta}{\partial y}\right]_{out}=0, \tag{7}$$

$$u=0, v=1 \text{ for } x=L \tag{8}$$

The energy balance on the photovoltaic panel is described by:

$$(\tau\alpha)_{PV}G(1-\eta_{PV})=h_o(T_{PV}-T_\infty)+\varepsilon_{PV}\sigma(T^4{}_{PV}-T^4{}_{sky})-k\frac{\partial T}{\partial x}+h_c(T_h-T_c) \tag{9}$$

where η_{PV} is the solar to electrical energy conversion efficiency, and it is determined according to [7]:

$$\eta_{PV}=\eta_o+\beta_{PV}(T_{PV}-298)+\gamma\log\left(\frac{G}{1000}\right) \tag{10}$$

where η_o is the efficiency at standard test temperature of 298K and insolation of 1000 W/m^2, and β_{PV} and γ are the coefficients for operating temperature and solar intensity.

3. Results and discussion

Fig 2 shows temperature distribution of air inside the channel for ventilated (left) and non-ventilated (right). It is found that the bulk temperature in the closed channel is larger than that in opened channel due to no cool air supply from the bottom invent. Natural ventilation is induced by buoyancy forces due to a temperature difference between the inlets and outlets of air channel. This passive cooling measure is a simple method with lower cost to remove heat from the back of the PV modules and to keep the electrical efficiency at an acceptable level. It is found that opened channel behind the PV panel provided an economic way of heat releasing for the benefit of PV power generation. Acknowledgment of detailed temperature distribution of PV façade is useful in the double skin

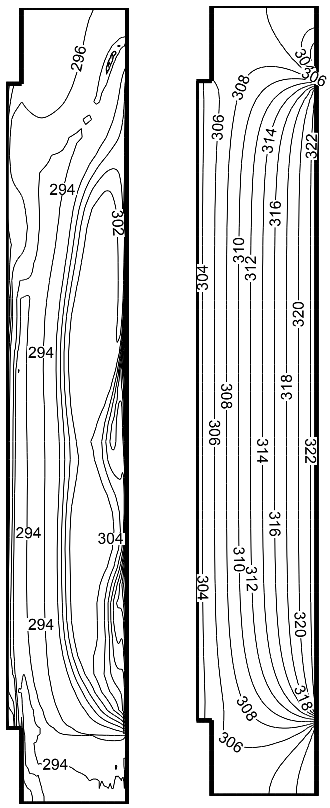

Fig 2. Temperature distribution inside the channel for ventilated (left) and non-ventilated (right)

photovoltaic façade design. In this section, the comparison of the surface temperature distribution for ventilated and non-ventilated PV façade was examined. In the figure, it shows the temperature distribution of PV module for ventilated (upper) and non-ventilated (lower) conditions. It is found that the maximum surface temperature reaches 57.1°C for closed channel, 49.1°C for opened channel. Well-proportioned temperature distribution may benefit better operation of PV module and help to extend its average life-span by eliminating thermal stress as that may destroy solar cells.

Fig 5 shows output of the electricity from the PV façade with variation of the solar radiation. The maximum solar radiation level reaches approximately 550 w/m^2 at that day. The maximum power generation from the PV façade reaches about 23 watts at noon. It is found that the power generation from the thin-film amorphous solar cells is much lower than that from mono-silicon solar cells. However, the manufacture cost of thin-film amorphous solar cells is lower than that of the mono-silicon solar cells. It has much potential for application with building façade integration.

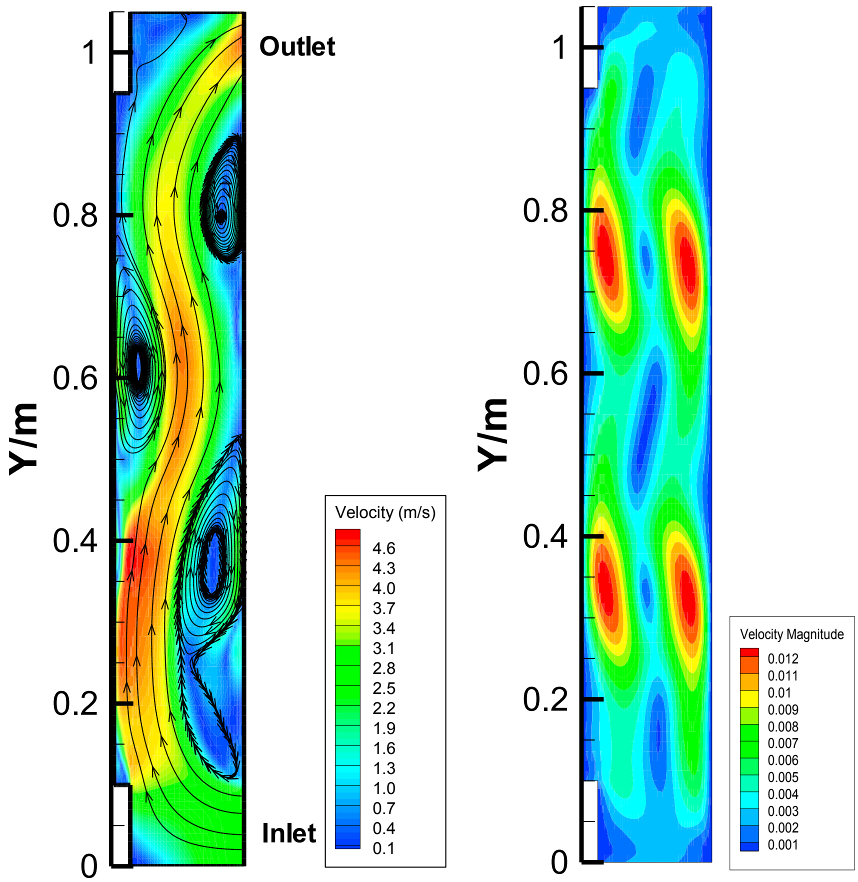

Fig 3. Velocity Contour for open air cavity with inlet air velocity of 3m/s and the closed (right)

The velocity magnitudes for open air cavity with inlet air velocity of 3m/s and closed channel are presented in Fig 3. There are several regions where reverse flow occurred due to sharp turns. It is therefore important to consider appropriate air intake design allowing to reduce the pressure drop. This will be further considered in the future investigation. In the lower speed region for open air cavity, temperatures are found significantly higher than other regions.

The air inlet has an important effect on the velocity field. Significant pressure drops at the sharp turn of the open air cavity is observed as shown in the Fig 4. There is a significant pressure drop near the entrance. It was found via the numerical experiment, the pressure drop is about 0.778 pa when cavity height raises to 0.1m at the location x = 0.12m on the horizontal surface when inlet velocity is 0.3 m/s. The pressure drop reduced to 0.679 pa at the location x = 0.04 m.

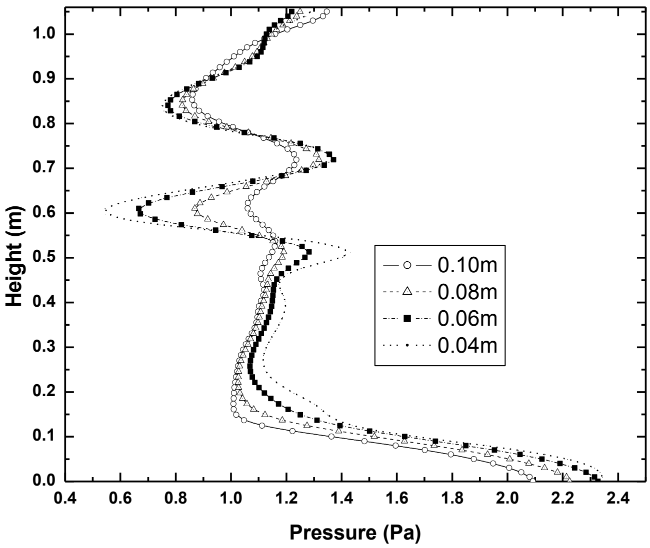

Fig 4. Pressrue variation along height at different locations on bottom surface.

4. Conclusions

Passive cooling air channel beneath the photovoltaic (PV) module is an effective way for thermal regulation of PV module. The air gap on the back of the PV modules provides natural cooling for the PV cell and reduces its operational temperature. Natural cooling using free convection is a simple method with lower cost to remove heat from the back of the PV modules and to keep the electrical efficiency at an acceptable level. This paper presents a 2D numerical investigation of the fluid flow and heat transfer characteristics of natural convection driven by buoyancy force inside the passive cooling air channel created by two vertical parallel walls. One wall is heated by absorbed heat by photovoltaic (PV) cells from solar radiation. Numerical solutions for open and closed channel are obtained for the channel of 1.05 m in height and 0.16 m in width. The natural convective cooling effect on the PV cells for different ventilation strategies were examined considering the surface temperature of PV panels. It is found that the maximum surface temperature reaches 57.1ºC for closed channel, 49.1ºC for opened channel. Opened channel behind the PV panel is an economic way of heat releasing for the benefit of PV power generation. However, other issues such as noise control and cleaning difficulty may also be encountered by façade designers. Understanding the mechanisms involved in the fluid flow and heat transfer in the channel back the PV panel is required and equally important for the design improvements of PV facade. In addition, acknowledgment of detailed temperature distribution of PV façade is useful in the photovoltaic façade design and help to extend its average lift-span by eliminating thermal stress as that may destroy solar cells.

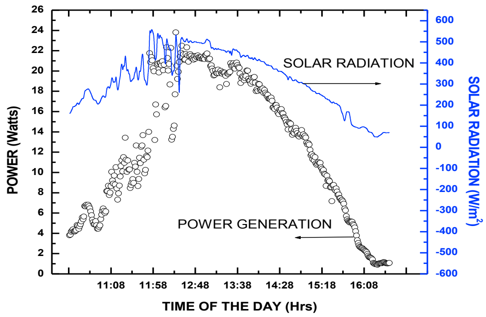

Fig 5 Variation of power generation from PV with solar radiation

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