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ENHANCEMENT OF HEAT DISSIPATION FROM PHOTOVOLTAIC CELLS INSIDE A 3-D CABINET TO AN AMBIENT NATURAL CONVECTIVE AIR STREAM WITH INSTALLATION OF FINS

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ABSTRACT

This study proposes a three-dimensional (3-D) model to investigate the detailed characteristics of conjugate conduction-natural convection heat transfer of photovoltaic cells mounted discretely on the bottom wall of a horizontal cabinet. The influences of thermal interaction between air streams inside and outside the cabinet through the conducting walls are explored. Furthermore, the enhancement of cooling performance of photovoltaic cells by using the fins is conducted. Results show that, for the system with 40 photovoltaic cells and $\dot{Q}$ =10W, the hot spot temperature drop is about 23 ℃ when the fins N_f = 170 are installed onto the cabinet bottom wall.

Keywords: Photovoltaic cell, Thermal interaction, Hot spot temperature, Fin

NONMENCLATURE

k_a	thermal conductivity of air
k_b	thermal conductivity of photovoltaic cell
k_s	thermal conductivity of substrate
k_e	thermal conductivity of electrode layer
k_f	thermal conductivity of fin base and fin
k_g	thermal conductivity of glass lens
k_w	thermal conductivity of cabinet bottom and side wall
N_b	number of photovoltaic cells
N_f	number of fins
p	pressure
$\dot{Q}$	heat generation rate per each photovoltaic cell
T	temperature
T_H	hot spot temperature of photovoltaic cells
T_∞	temperature at region distant to cabinet
ρ	density of air
μ	dynamic viscosity of air

1. INTRODUCTION

The efficiency of photovoltaic cell decreases with increasing cell temperature. The cooling of photovoltaic cells is a major concern for the design and operation of concentrating photovoltaic systems.

The concentrating photovoltaic cell module is mainly composed of solar cell, electrode layers and substrate. The modules are discretely mounted with array arrangement on the bottom wall of a cabinet. In the literature a lot of articles have dealt with the natural convective characteristics for discrete heat sources in closed enclosure. Soni and Gavara [1] studied natural convection in a rectangular cavity with discrete surface-mounted heaters on bottom wall. Effects of three different cooling configurations on maximum component temperature were investigated. Gavara [2] explored the natural convection in a series of thermally interacting cavities with conducting wall mounted heaters. The correlations are presented for maximum dimensionless temperature and average Nusselt number in terms of Rayleigh number. Gray [3] proposed a two-dimensional passive cooling model for the high concentration photovoltaic (HCPV) system. The photovoltaic cells are assumed to be the isothermal heat sources at constant temperature 353K. Cheng et al. [4] examined characteristics of heat transfer from block heat sources mounted on the wall of a closed cabinet to an ambient natural convective air stream.

The main objective of this study is to investigate the characteristics of conjugate conduction-natural convection heat transfer of the photovoltaic cell modules on the bottom wall of a cabinet. The thermal and velocity fields for air streams in the cabinet and surrounding area are solved simultaneously. The temperatures of photovoltaic cells and cabinet walls are obtained from the solution processes. In addition, efforts are performed to examine the enhancement of cooling performance of photovoltaic cells by installing fins onto the cabinet bottom wall.

2. ANALYSIS

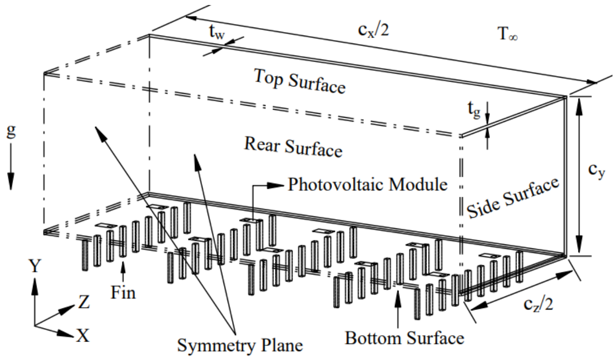


Fig 1 The schematic diagram for 1/4 region of physical system

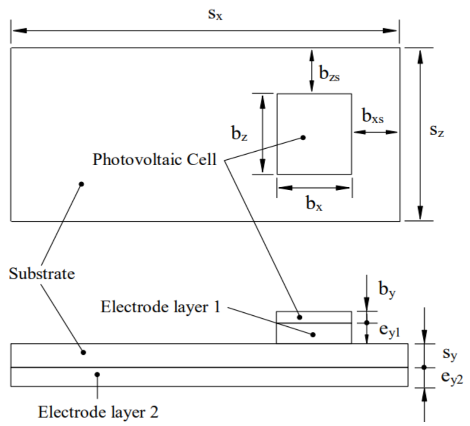


Fig 2 The schematic diagram of photovoltaic cell

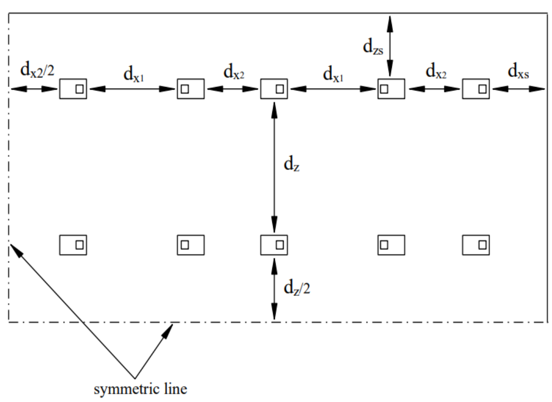


Fig 3 The schematic for the arrangement of photovoltaic cell modules for 1/4 region of physical system

The physical system under consideration, as shown in Fig 1, is a 3-D horizontal cabinet with glass lens for upper wall, and metal plates for all other walls. Multiple photovoltaic cell modules are mounted discretely on the cabinet bottom wall. On the other hand, cooling fins are installed onto the outside surface of the bottom wall. It is mentioned that only 1/4 domain of the system is plotted in Fig 1 because the flow and thermal characteristics are considered to be symmetric to the sectional planes of x-y axis and y-z axis. Figure 2 depicts the structure of photovoltaic cell module. From the viewpoint of heat transfer, the module is simplified

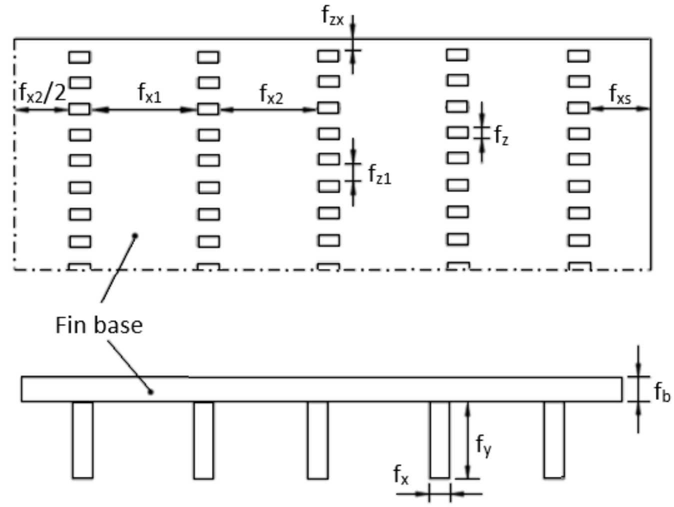


Fig 4 The schematic diagram of fin base and with 40 fins for 1/4 region of physical system

to be comprised of a photovoltaic cell, two electrode layers and a substrate. The heat source is uniformly distributed in the volume of the thin cell. The arrangement of Photovoltaic cell modules is shown in Fig 3. The cabinet is surrounded by air with temperature T_∞ and stationary distant to the cabinet. It is noted that the temperatures and heat fluxes for the outer surface of the cabinet are not previously known. The outer surface temperatures and heat fluxes of cabinet have to be solved in the solution processes. Figure 4 shows the configuration for the cooling fins.

By introducing the Boussinesq approximation, the governing equations describing the steady laminar natural convection for air streams in a 3-D cabinet and the surrounding area are as follow.

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

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)-\rho g \tag{3}$$

$$\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=k_a\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{5}$$

In addition, the energy equation for the photovoltaic cells is

$$k_b\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right)+\frac{\dot{Q}}{b_x b_y b_z}=0 \tag{6}$$

and the energy equation for the electrode layers, substrate, cabinet walls, glass lens, fin base and fins is

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}=0 \tag{7}$$

The governing equations are subjected to the usual no-slip conditions on all the solid walls, and the assumption that the air is stationary at the region distant to the cabinet. The temperatures and heat fluxes are continuous at all the air-solid interfaces and solid-solid interfaces.

3. SOLUTION METHOD

The governing equations (1) - (7) and boundary conditions are solved by a numerical scheme derived from the SIMPLER algorithm. The solution is considered to be converged when the relative differences of u, v, w and T at each node between two consecutive iterations, as well as the overall energy imbalance of the system are less than a prescribed value of 1×10^{-4}.

The numerical algorithm is validated in two ways. First, different numbers of grid lines in all the x–, y– and z– directions are employed to ensure that the solution is grid independent. In addition, because of the elliptic nature of the present problem, it is necessary to make sure that the boundary conditions at region distant to the cabinet do not artificially constrain the solution. To ensure that the results are not affected by the horizontal and vertical lengths of the computation domain, tests are performed by varying the size of the computation domain around the cabinet. Secondly, the results for the limiting situations with natural convection in an enclosure containing distributed heat sources are compared to the relevant literature. Excellent agreement is found between the present prediction and the results presented by Bazylak et al. [5].

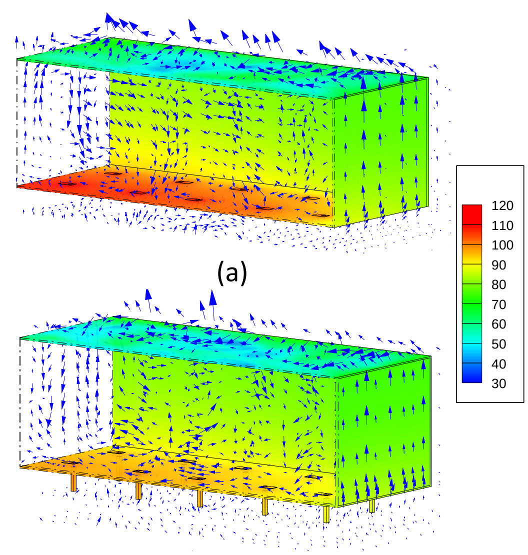
4. RESULTS and DISCUSSIONS

The flow and heat transfer characteristics in the present system depend on a vast number of governing parameters. An analysis of all combinations of problems is not practical. The objective of this study is to present samples of results that can illustrate the effects of $\dot{Q}$, k_e, k_w, on the heat dissipation characteristics of photovoltaic cells mounted on the bottom wall of a horizontal cabinet. In addition, samples of results would also demonstrate the enhancement of cooling performance of photovoltaic cells by installing fins onto the cabinet bottom wall. The values of fixed and variable parameters are listed in Table 1.

Initially, the 3-D flow and thermal fields are portrayed in Fig 5 for cases without and with fin installation. It is clearly seen in Fig 5(a) that, for the bottom wall, the temperatures at the central region are higher than those near the vertical walls, and the temperatures of photovoltaic cells are the local highest. The velocity vectors in Fig 5(a) show that multiple air recirculation cells exist in the cabinet. In addition, the ambient air in the region near the cabinet is induced to

Table 1 The values of fixed and variable parameters

Fixed Parameters
Fluid: air, k_a = 0.0263 W/m-K
Cabinet: c_x = 1331mm, c_y = 210mm, c_z = 548mm, t_w = 3mm, t_g = 3mm, k_w = 166.9 W/m-K, k_g = 0.21 W/m-K
Photovoltaic cell: N_b = 40, b_x = 6.7mm, b_y = 0.16mm, b_z = 5.5mm, b_{xs} =8.5mm, b_{zs} = 4.15mm, k_b = 60 W/m-K
Substrate: s_x = 25mm, s_y = 0.25mm, s_z = 15mm, k_s = 25 W/m-K
electrode layer 1: e_{x1} = 6.7mm, e_{y1} = 0.24mm, e_{z1} = 5.5mm, k_e = 280 W/m-K
electrode layer 2: e_{x2} = 25mm, e_{y2} = 0.24mm, e_{z2} = 15mm, k_e = 280 W/m-K
Arrangement of photovoltaic cell
Modules: d_{x1} = 119.5mm, d_{x2} = 87.5mm, d_z = 110mm, d_{xs} = 59.75mm, d_{zs} = 58.5mm
Fin: f_b = 3mm, f_x = 6.7mm, f_z = 5.5mm, f_y = 40mm, k_f = 167 W/m-K
Surrounding temperature at region far away from cabinet: T_∞ = 27℃
Variable Parameters
Heat generation rate per each photovoltaic cell: $5\leq\dot{Q}\leq10$(W)
Heat conductivity of electrode layers : $100\leq k_e\leq280$ (W/m-K)
Heat conductivity of metal plate wall of cabinet: $26\leq K_w\leq167$ (W/m-K)
Fin number: N_f = 0, 170
Arrangement of fins:
For N_f = 170: f_{x1} = 126.5mm, f_{x2} = 119.5mm, f_{z1} = 24.58mm, f_{zs} = 3mm, f_{xs} = 66.25mm



(b)

Fig 5 Effects of $\dot{Q}$ and N_f on the velocity vector and temperature distributions of 1/4 cabinet and neighboring of cabinet for cases with k_e = 280 W/m-K, k_w = 167 W/m-K, (a) $\dot{Q}$ = 10W, N_f = 0; (b) $\dot{Q}$ = 10W, N_f = 170

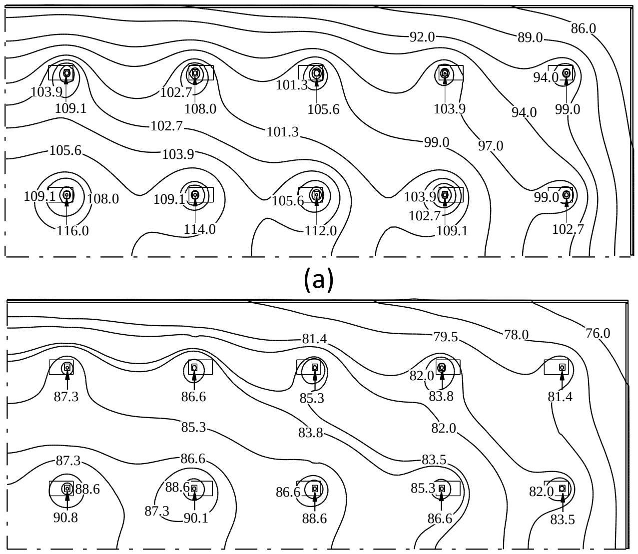


Fig 6 Effect of fin on the temperature distribution of the inner surface of cabinet bottom wall for $\dot{Q}$ = 10W, k_e = 280 W/m-K, k_w = 167 W/m-K, (a) N_f = 0; (b) N_f = 170

Table 2 The hot spot temperatures of photovoltaic cells for cases with k_e = 280 W/m-K; k_w = 167 W/m-K, and various $\dot{Q}$ and N_f

N_f	T_H (℃)		
	$\dot{Q}$ =5W	$\dot{Q}$ =8W	$\dot{Q}$ =10W
0	78.5	101.85	119.6
170	66.8	85.2	96.7

Table 3 The hot spot temperature of photovoltaic cells for case with $\dot{Q}$ = 10W, N_f = 0, and various k_w and k_e

k_w (W/m-K)	T_H (℃)		
	k_e = 100	k_e = 200	k_e = 280
167	120.0	119.8	119.6
52	158.2	150.1	143.0
26	183.3	174.2	166.3

flow upward owing to the heat dissipation from the cabinet to the surrounding. The flow separations and separation bubbles of the ambient air stream can be evidently observed in the region above the upper lens. Fig 5(b) represents the temperature and velocity distributions for the system that 170 fins are installed onto the bottom wall. It is seen that the temperatures in Fig 5(b) are evidently lower than those in Fig 5(a).

It is seen in Fig 6 that the photovoltaic cell temperatures are the local highest at positions vicinity to the cell modules. The temperatures are higher at the central region, and decrease in the directions toward the side edge and rear edge of bottom wall.

The temperatures of photovoltaic cells are important in engineering applications. Table 2 lists hot spot temperature of the system for the cases with various $\dot{Q}$ and N_f. When the system is without the installation of fin (N_f = 0), the T_H for $\dot{Q}_w$ = 10W is 119.6 ℃ which is much higher than that for $\dot{Q}$ = 5W. Furthermore, the installation of fin can significantly enhance the cooling performance of photovoltaic cells. For $\dot{Q}$ = 10W, the T_H drops from 119.6 ℃ to 96.7 ℃ when N_f varies from 0 to 170. Finally, the results in Table 3 illustrate the effects of k_e and k_w on the T_H. It is seen that the rise in T_H is 63.7 ℃ when k_w = 167 W/m-K and k_e = 280 W/m-K decrease to k_w = 26 W/m-K and k_e = 100 W/m-K.

5. CONCLUSIONS

This study investigates the characteristic of conjugate conduction-natural convection of photovoltaic cells mounted discretely on the bottom wall of a horizontal cabinet. The results show that the $\dot{Q}$, k_w, k_e, and N_f can significantly affect the hot spot temperature of cells.

ACKNOWLEDGEMENT

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