Thermal Performance Simulation of PV Insulating Windows with Different Arrangement of PV Cells

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Abstract. In order to explore the influence of the arrangement of PV cells on the heat transfer performance of the PV insulating window, this paper uses the finite element calculation software to conduct the heat transfer process of the PV insulating window using the bulk-shaped, square-shaped and stripe-shaped PV cell arrangements respectively. Simulation analysis and calculation. The results show that the surface temperature of the PV window using the stripe-shaped PV cells is the lowest, and the surface temperature of the PV window using the bulk-shaped PV cells is the highest. The temperature difference between winter and summer is 4°C and 2.5°C. The former has the smallest comprehensive heat transfer coefficient in summer, which can reduce the adverse effect of PV cells on the building cooling load.

1. Introduction

With the improvement of people's living standards in modern society, people's requirements for indoor comfort have also increased, which has caused building energy consumption to increase year by year. In order to reduce building energy consumption as much as possible, more and more PV materials are applied to the building envelope. PV windows are one of these applications. V. B. Dinh et al. [1] presents a sizing method of PV panels for maximizing the match between the building’s load profile and the solar energy generation shape. Zhang W et al. [2] compared the overall energy performance between STPV windows and commonly used energy-efficient windows. Wang M et al. [3] studied the overall energy performance of a PV double skin facade (PV-DSF) and a PV insulating glass unit (PV-IGU). Chen M et al. [4] evaluated the effects of the air gap on window thermal performance, window orientation, different window-to-wall ratio and coverage ratio of PV cells. There are many studies related to PV windows, but few studies have explored the effect of the arrangement of PV cells on the heat transfer performance of PV windows. This paper will numerically simulate the steady-state heat transfer process of PV windows with different PV cell arrangements at the 3D level, so as to explore the effect of different arrangements on the heat transfer performance of PV windows.

2. Physical model

Establish a photovoltaic window model with a front size of 1000 mm × 1000 mm and a side layered size of 2 mm photovoltaic cells, 6 mm glass layers, 12 mm air layers, and 6 mm glass layers from outside to inside. In order to explore the influence of the arrangement of PV cells on the surface temperature and heat transfer performance of PV cells in PV Windows, the PV cell layout of case 1 (bulk-shaped PV cells), case 2 (square-shaped PV cells) and case 3 (strip-shaped PV cells) are set up respectively, as shown in figure 1. By controlling the area ratio of photovoltaic cells, the 3D models...
with coverage rates of 30%, 50% and 70% are established according to the layouts in figures 1, respectively. At the same time, a 3D model with no PV cells coverage and 100% PV cells coverage is established as the control group 1 and the control group 2 respectively. The calculation grids of 3D models are all divided by free tetrahedral grids.

![Figure 1. Schematic diagram of PV cells layout.](image)

3. Mathematical model
In this paper, the numerical calculation uses the finite element method to simulate the heat transfer and heat radiation of PV window on a 3D level.

3.1. Calculation of thermal radiation
The heat radiation calculation uses the Hemicube Model to calculate the heat radiation transfer. And use Linear Model to discretize the calculation model. The differential equation of the heat radiation process is shown in equations 1 to 4.

\[ J = \varepsilon e_b(T) + \rho_a G \]
\[ G = G_m(J) + G_{amb} + G_{ext} \]
\[ G_{amb} = F_{amb}e_b(T_{amb}) \]
\[ e_b(T) = \sigma T^4 \]

3.2. Calculation of heat transfer
It is assumed that the thermal parameters of the simulated material are isotropic. In this paper, Fourier's law is used to calculate the heat transfer. The linear element is used for discretization. The differential equations of the heat transfer process are shown in equations 5 and 6.

\[ \rho c_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q \]
\[ \mathbf{q} = -k \nabla T \]

3.3. Coupling calculation of thermal radiation and heat conduction
Since the simulation process is a steady-state simulation, the two processes of heat radiation and heat transfer can be coupled through the equilibrium condition. As shown in equation 7.

\[ -\mathbf{n} \cdot \mathbf{q} = \varepsilon (G - e_b(T)) \]

4. Calculation condition
4.1. Boundary condition
The convective heat transfer boundary conditions and radiation boundary conditions are set in this calculation. Convective heat transfer boundaries are set on the outer and inner surfaces of PV windows.
A vertical wall surface solar radiation is set on the outer surface of the photovoltaic window as the radiation boundary condition.

### 4.2. Calculation Parameters

The thermal property parameters and boundary condition parameters of various materials in the mathematical model are shown in table 1 and table 2. Among them, the indoor and outdoor calculation parameters in the boundary conditions in table 2 are derived from *Design code for heating ventilation and air conditioning of civil buildings* [5]. The average radiation temperature is approximated by the air temperature.

**Table 1.** The thermal parameters of each material in the simulation calculation of PV windows.

| Material     | Density (kg/m³) | Specific heat capacity (J/(kg·K)) | Thermal conductivity (W/(m·K)) | Absorption coefficient (%) | Radiance (%) |
|--------------|-----------------|----------------------------------|-------------------------------|----------------------------|--------------|
| Glass        | 2210            | 730                              | 1.4                           | 0.05                       | 0.85         |
| Air          | 1.16            | 1006                             |                               | \                          | \            |
| PV cells     | 2300            | 800                              | 150                           | 0.9                        | 0.4          |

**Table 2.** Boundary condition parameters in the simulation calculation of PV windows.

|                          | Summer | Winter |
|--------------------------|--------|--------|
| Outdoor                  |        |        |
| Air temperature °C       | 34.8   | -4.1   |
| Convective heat-transfer coefficient W/(m²·K) | 16     | 16     |
| Mean radiant temperature °C | 34.8   | -4.1   |
| Solar radiation W/m²    | 500    | 300    |
| Air temperature °C       | 26     | 20     |
| Indoor                   |        |        |
| Convective heat-transfer coefficient W/(m²·K) | 2.5    | 3.6    |
| Mean radiant temperature °C | 26     | 20     |

### 5. Simulation results and analysis

#### 5.1. Analysis of surface temperature distribution

In order to analyze the temperature situation of PV cells in summer, according to the summer simulation calculation results of PV windows in different cases, the temperature distribution of PV windows from bottom to top and through PV cells was counted. The results are shown in figure 2 and figure 3.

**Figure 2.** Wall temperature distribution in summer.

a. 50% PV cell coverage  
   b. Three types of photovoltaic cell coverage
From the vertical distribution of temperature in figure 2 (a) and figure 3 (a), it can be seen that in the three cases of PV cell layout in the PV window, no matter in summer or winter, the highest temperature at the PV cell location is case 1 (bulk-shaped PV cell), with the highest temperature being 316 K and 276 K respectively. The lowest temperature is case 3 (strip-shaped PV cell), and the highest temperature is 312 K and 273.5 K. The arrangement of the strip-shaped PV cells is easier to disperse the heat generated by the PV cases, and the generated heat can be dissipated in time. Therefore, the cooling effect is better than in other cases. The higher the temperature of PV cells, the less efficient it is in generating electricity. Therefore, in these cases, the layout of PV cells in case 3 can minimize the negative impact of PV calls heating on the premise of ensuring the coverage ratio of PV cells, which is beneficial to the improvement of PV window’s power generation performance.

From the vertical distribution of temperature in figure 2 (b) and figure 3 (b), it can be seen that in either case, the temperature outside the PV window increases with the increase of the coverage of PV cells in winter and summer. In case 1, the change of PV cells coverage has a very small impact on temperature. Even if the PV coverage reaches 100%, the maximum temperature is not much different from other coverage. For every 20% increase in PV cells coverage in case 2 and 3, the temperature increases roughly by 2℃ in summer and 1.5℃ in winter. Therefore, the higher the PV cell coverage rate is, the higher the surface temperature of the PV cell will be, which will adversely affect the power generation efficiency of the PV cell.

5.2. Analysis of heat transfer performance
The simulation results of heat transfer performance of photovoltaic Windows in winter and summer under different schemes are shown in figure 4.

As can be seen from figure 4, the total heat flow of PV window in summer is from large to small: the control group 2, case 1, case 2, case 3, the control group 1. However, the trend of total heat flow in winter is just the opposite. In winter, the indoor temperature is higher than the outdoor temperature, and the heat flow caused by the temperature difference is from the inside to the outside, while the heat flow caused by the solar radiation is from the outside to the inside, which cancels each other out. The summers are mutually reinforcing, so when the heat flow due to solar radiation is relatively large, it can result in the opposite trend of heat flow.
In terms of the comprehensive heat transfer coefficient of the PV window, it can be seen from figure 4 that the comprehensive heat transfer coefficient of the PV window will be significantly improved after the PV cells are added. However, according to the simulation results, the comprehensive heat transfer coefficient of PV window does not increase with the increase of PV cells coverage. In winter, the overall heat transfer coefficient increases roughly with the increase of PV cells coverage. In summer, the change of the comprehensive heat transfer coefficient of different cases is not consistent. For example, in case 2, the heat transfer coefficient at 50% PV cells coverage is slightly higher than at 70% PV cells coverage. In case 3, the heat transfer coefficient of 30% PV cells coverage is a little higher than that of 50% PV cells coverage. In addition, the comprehensive heat transfer coefficient of case 3 is also the lowest in summer. After the simulation analysis, the integrated heat transfer coefficient of the PV windows with strip-shaped layout in case 3 is lower in summer, which can reduce the additional cooling load that may be brought to the room due to the heating of PV cells. Although the heat transfer coefficient is higher in winter, it will reduce the indoor heat brought by PV cells. But compared with ordinary Windows without PV cells, they can still reduce indoor heat load in winter. Therefore, in terms of the impact on the indoor load, the PV cells layout in case 3 is more advantageous than other cases.

6. Conclusion
The strip-shaped layout can enhance the heat dissipation of PV cells on PV windows and effectively reduce their surface temperature. Therefore, case 3 can make the PV cells work at a higher temperature of power generation efficiency and improve the power generation performance of the PV cells.

On the other hand, the overall heat transfer coefficient of PV windows with a strip-shaped layout is lower than that of other cases in summer. Therefore, case 3 can reduce the adverse effect of heat generated by photovoltaic cells on indoor cooling load in summer to a certain extent.

According to the simulation results in this paper, in the summer, the cooling load of windows in the case using strip-shaped PV cells is reduced by up to 5.5% compared with other cases, and the coverage rate of PV cells is 50% at this time. During the winter, the case using strip-shaped PV cells with a PV cell coverage of 50% reduced the thermal load by 9.4% compared with windows without PV cells. From this result, when the PV window adopts strip-shaped PV cells and the coverage rate of PV cells is 50%, the thermal performance effect will be better.

7. Reference
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