Research on factors and performance of solar thermoelectric radiant window

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Abstract. Building energy consumption for cooling in hot climates accounts for about 70\%-80\% of the total energy consumption. It’s interesting that offsetting the energy consumption by the development of new technology. A model of solar thermoelectric radiation window proposed in this paper, combining the concepts of photovoltaic (PV) power generation, thermoelectric cooling and radiant cooling, built a new model of heat transfer about the solar thermoelectric radiation windows. The new structure actively generates electricity for the consumption of cooling by PV module, while passively blocks part of solar radiation for reducing indoor load. Based on the distribution of thermoelectric cooling mode (TEM), the size of the radiator, the form of heat dissipation and other influencing factors, the relationship between the heat gain and cooling capacity, and the balance between power generation and power consumption of the new structure were analysed. The value of this research is to provide a certain reference value for the practical application of the solar thermoelectric radiation window.

1. Introduction

In order to respond to the twin challenges of increasing energy demand and environmental degradation in the world where fossil energy consumption is a major contributor to greenhouse gas emissions and global warming, the development of environmentally friendly energy systems using renewable energy sources is essential [1]. Solar energy, as a representative renewable energy source, has received a lot of attention in recent years as a potential option to meet the growing demand for energy. Solar thermoelectric cooling technology applies photovoltaic power directly to thermoelectric cooling, effectively reducing energy demand without harming the environment. By developing thermoelectric systems and photovoltaic technology to improve building energy efficiency and reduce fossil energy consumption, solar thermoelectric cooling has the potential to be used in zero-energy buildings [2].

He et al. studied the application of building integrated PV (BIPV) in low-carbon buildings to cool rooms via thermoelectric cooling mode (TEM) powered by PV [3]. Shen et al. proposed a new thermoelectric radiant air conditioning system (TE-RAC) that uses thermoelectric modules as radiant panels instead of conventional ones, and studied the performance parameters of the new system [4]. Liu et al. developed and evaluated the performance of an active solar thermoelectric radiant wall system (ASTRW) consisting of a photovoltaic system, an airflow channel, and a thermoelectric radiant cooling system [5]. All of the above studies demonstrate the possibility of thermoelectric cooling in buildings, but due to the limitations of materials development, the current application can only be used
in engineering practice as a supplement to other systems. To this end, this paper proposes a new enclosure structure for solar thermoelectric windows based on the model developed by Liu et al. to improve the transparency of PV modules and appropriately reduce the height of aluminum radiant panels, as shown in Figure 1.

![Figure 1. Structure of solar thermoelectric windows.](image)

2. Mathematical model

In this study, a thermal balance model of the solar thermoelectric radiation window was developed to calculate the temperature of the semi-transparent PV module, transparent glass, TEM, and radiation panels. The semi-transparent PV module consists of multiple layers of material, including front and rear transparent glass layers (each 3 mm thick), and an EVA material layer (containing silicon cells with different PV cell coverage) in the middle layer. The temperature of each layer is calculated by the heat balance equation, and the temperature of the solar cell \( T_{pv} \) is estimated as the average of the temperatures on both sides of the EVA layer. Heat storage in the glass layer is not considered and heat transfer is assumed to be a quasi-steady-state process [6].

\[
G_a = (T_1 - T_e) h_{out,c} + \xi \sigma \left[ (T_1 + 273.15)^4 - (T_e + 273.15)^4 \right] + \frac{\lambda_1}{d_1} (T_1 - T_2) 
\]

\[
G_r \left[ (1 - PVR) \alpha_{EVA} + PVR \alpha_{SC} \right] + \frac{\lambda_2}{d_2} (T_1 - T_2) = \frac{\lambda_2}{d_2} (T_2 - T_3) + P 
\]

\[
G_r \left( 1 - PVR \right) \tau_{EVA} \alpha + \frac{\lambda_2}{d_2} (T_2 - T_3) = \frac{\lambda_2}{d_2} (T_3 - T_4) 
\]

\[
\frac{\lambda_2}{d_2} (T_3 - T_4) = (T_4 - T_{air}) h_{in} + \xi \sigma \left[ (T_4 + 273.15)^4 - (T_{air} + 273.15)^4 \right] 
\]

Where \( G_a \), \( G_r \) are the intensity of solar radiation absorbed and transmitted by PV (W/m²). \( T_1 \) and \( T_2 \) are the outer surface temperature of PV and EVA layer (°C). \( T_3 \) and \( T_4 \) are the inner surface temperature of EVA layer and PV (°C). \( T_{air} \) and \( T_e \) are ambient temperature and average temperature in the air channel (°C). \( h_{out,c} \) and \( h_{in} \) are convection heat transfer coefficient of outer and inner surface of PV (W/(m²·K)). \( \xi \), \( \sigma \) and \( \alpha \) are emissivity of glass, Boltzmann constant (W/(m²·K⁴)) and absorption of glass. \( d_1 \), \( d_2 \), \( \lambda_1 \) and \( \lambda_2 \) are thickness and thermal conductivity of glass and EVA layer. P is electricity generation of PV (W/m²).
The semi-transparent PV module with a peak power of 150W, width of 0.95m, height of 1.65m, total thickness of 8mm is adopted from Solar Module Company, where photovoltaic cell coverage (PVR) is 46.3%. The parameters of the semi-transparent PV module are shown in Table 1.

**Table 1.** The nameplate parameters of the semi-transparent PV module.

| Thickness (mm) | Thermal conductivity (W/m·K) | Absorption | Transmission | Reflection |
|---------------|-------------------------------|------------|--------------|------------|
| glass         | 6                             | 0.760      | 0.108        | 0.810      | 0.082      |
| EVA           | 2                             | 0.116      | 0.060        | 0.900      | 0.040      |
| solar cell(SC) | 0.3                           | 168.0      | 0.970        | 0            | 0.030      |

The heat transfer process in the air channel between PV module and the new thermoelectric radiant window structure can be viewed as a one-dimensional heat transfer problem, and ignoring the non-stationary changes in the air, there is:

$$\rho_{a}C_{a}V_{a}A_{a}(T_{\text{out}} - T_{\text{in}}) + Q_{\text{dis}} = A_{\text{pv}}(T_{\text{a}} - T_{\text{air}})h_{a} + \left(A_{\text{pv}} - A_{\text{panel}}\right)(T_{w} - T_{\text{air}})h_{w}$$ (5)

Where $\rho_{a}$, $C_{a}$ and $V_{a}$ are the density (kg/m³), constant pressure specific heat (J/(kg·K)), average velocity (m/s) of air in the air channel. $A_{a}$, $A_{\text{pv}}$ and $A_{\text{panel}}$ are the area of the air channel, PV module and radiant aluminum plate (m²). $h_{w}$ is the convective heat transfer coefficient of the outer surface of the glass (W/(m²·K)). $T_{w}$ is the temperature of glass (°C). $Q_{\text{dis}}$ is the heat emitted by hot side of TEM (W).

The energy balance equation for the envelope structure of the new thermoelectric radiant window is divided into two blocks for analysis, with the upper part being a transparent glass structure, and the heat storage of the glass structure is not considered, assuming that the heat transfer is a quasi-steady-state process, and the heat transfer equation for the glass structure is as follows:

$$h_{a}(T_{\text{air}} - T_{w}) + G r_{\text{glass}}^{2}(1 - P\text{V}R)\tau_{EVA}\alpha_{\text{glass}} = h_{\text{in}}(T_{w} - T_{r})$$ (6)

Where $h_{a}$ is the convective heat transfer coefficient of the inner surface of the glass (W/ (m²·K)). $r_{\text{glass}}$ and $r_{EVA}$ are the transmittance of glass to solar radiation and EVA material to solar radiation. $T_{r}$ is indoor air temperature (°C).

The lower part is the thermoelectric radiation part, the surface of the radiation plate on the outside of the room are coated with thermal insulation material, so the heat transfer between indoor and outdoor is 0, the heat dissipation on the outside of the room is the heat dissipation process of the hot side [7]. The equation of thermal balance with the air channel is:

$$\left(T_{h} - T_{\text{air}}\right)/R_{z} = N\left[\alpha IT_{h} + 0.5I^{2}R - K(T_{h} - T_{c})\right]$$ (7)

Where $T_{h}$ and $T_{c}$ are the temperature of TEM at hot and cold side (°C). $R_{z}$ is the overall heat dissipation resistance of the radiator (K/W). $N$ is number of TEC in TEM. $\alpha$, $R$ and $K$ are seebeck coefficient (V/K), thermal conductivity (W/(m·K)) and resistance (Ω) of TEM.

The expressions of heat transfer in cold side and power of TEM are:

$$Q_{c} = N\left[\alpha IT_{h} - \frac{1}{2}I^{2}R - K(T_{h} - T_{c})\right]$$ (8)

$$P = \alpha I(T_{h} - T_{c}) + I^{2}R$$ (9)

The cooling capacity of the thermoelectric radiant window can be calculated by the following formula. The total heat transfer coefficient ($h_{\text{comb}}$) between the metal aluminum panel surface and the room is composed of the radiant heat transfer coefficient ($h_{\text{rad}}$) and the convective heat transfer coefficient ($h_{\text{conv}}$). For ease of calculation, the total heat transfer coefficient $h_{\text{comb}}$ between the radiant surface and the room is assumed to be constant according to the literature [8-10], with a constant value of 11.3 W/ (m²·K) for the cooling condition.

$$Q_{\text{panel}} = (h_{\text{conv}} + h_{\text{rad}})A_{\text{panel}}(T_{r} - T_{\text{panel}}) = h_{\text{comb}}A_{\text{panel}}(T_{r} - T_{\text{panel}})$$ (10)
3. Results and discussion

The selected site is located in the hot summer and cold winter region of China, with more cooling in summer, and the hotter summer moments were chosen, being at 13:00, when the irradiance of the sun on the PV module is 691W/m², the outdoor dry bulb temperature is 34.2°C, the dew point temperature is 24.9°C, and the outdoor wind speed is 7m/s.

In this paper, a new thermoelectric radiant window is proposed to discuss the future application possibilities of the new enclosure by clarifying the relationship between the cold load transmitted by the window, the power generation of the PV modules, the cooling capacity of the radiant panels, and the cooling capacity of the TEM.

In order to ensure that the temperature of the radiant panels does not have other effects on the room, the surface temperature of the panels is controlled at 17-20°C for cooling [11]. To ensure that the cooling capacity provided by the radiant panels is not too low, four different radiant panel heights (H_{panel} = 0.7m, 0.8m, 0.9m, 1.0m) were selected for the study. According to allowable voltage and current of TEC, ten different combinations were selected. The combination forms and types of TEC are shown in Table 2.

| Case  | case0 | case1 | case2 | case3 | case4 | case5 | case6 | case7 | case8 | case9 |
|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| n1    | 2     | 3     | 2     | 3     | 2     | 3     | 2     | 3     | 2     | 3     |
| n1    | 3     | 3     | 4     | 4     | 5     | 5     | 6     | 6     | 7     | 7     |
| U     | 4     | 4     | 3     | 3     | 2.4   | 2.4   | 2     | 2     | 1.71  | 1.71  |
| Type  | α     | K     | R     | ΔT_{max} | V_{max} | I_{max} | Q_{max} |
| TEC1-12706 | 0.051 | 0.5177 | 1.9558 | 68    | 15.2  | 6     | 56.5  |

Note: n1 indicates how many parallel circuits there are; n2 indicates how many TECs are connected in series.

3.1. Influence of the combination forms of TEC on thermoelectric radiation window

The combination forms of TEC determine the additional voltage and current passed by TEM. The voltage and current of a single TEC are shown in Table 1. It can be seen from Figure 2 and Figure 3 that the smaller the current of TEM, the smaller the temperature difference between the hot and cold side, and the cooling capacity gradually decreases, while COP shows an increasing trend as the current decreases. Adding TEC parallel branches, the cooling capacity and the temperature difference between the two sides of TEM will show an increasing trend in Figure 4 and Figure 5. However, the more the number of branch of TEC, the less the increase in cooling capacity. The increase of the branch makes the current through TEM larger, while COP will significantly decrease. In terms of cooling capacity
and the cold load generated by the radiant window, the cooling capacity of the radiant window can only remove 30-80% of the cold load due to the cooling effect of the TEM itself. It is obvious from Figure 6 and Figure 7 that the power generated by the three parallel branch circuit PV modules themselves can hardly offset the power consumed by the TEM.

3.2. Effect of the height of radiant panel on thermoelectric radiation window

It can be seen from Figure 2 and Figure 3 that the change in the height of the radiant panel has little or no effect on the temperature of the hot side and a large effect on the temperature of the cold side, with the higher the radiant plate, the greater the temperature of the cold side. The main reason may be that the cooling effect of the TEM can’t affect the entire radiant panel. It can be seen from Figure 4 and Figure 5 that the cooling capacity of the radiant window increases as the height of the radiant panel increases, but the growth trend is not obvious. The COP of the system decreases as the height of the radiant panel increases. From Figure 6 and Figure 7, as the height of the radiant panel increases, the heat transferred from the outdoors to the indoors through radiation decreases significantly, and there is a significant increase in the proportion of cooling capacity in the cold load. In Figure 6 and Figure 7, the points of the ratio of electricity consumption (P) to electricity generation (E) almost overlap, indicating that the change in the area of the radiant panels have little effect on electricity consumption. The change in air layer temperature is consistent with the change in electricity consumption and is less affected by the change in the height of the radiant panel.
3.3. Influence of heat dissipation form on thermoelectric radiation window

The dissipation of heat from the hot side of TEM into the air channel and the heat generated by PV module when generating electricity causes an increase in the air temperature in the channel. Therefore, the way in which the air channel dissipates heat can have a significant impact on the performance of the thermoelectric window. This paper considers the effects of both natural convection and forced convection cooling on the performance of thermoelectric radiation windows. As can be seen in Figure 8, the average temperature of the air in the channel fluctuates between 40-42.5°C under the condition of natural convection, while the average temperature of the air in the channel remains between 37-38 °C under the condition of forced convection. It’s shown that the use of forced convection can significantly improve the heat dissipation performance of the entire radiant window. From Figure 2 to Figure 5, it can be seen that COP of the thermoelectric window under natural convection is less than 1.3 while COP of the thermoelectric window under forced convection is higher than that of natural convection, up to about 1.6.

![The combination forms of TEC](image)

**Figure 8.** The average temperature of the air in the air channel.

Considering the effects of the combination forms of TEC, the height of radiant panel, heat dissipation form on the thermoelectric radiant window, when the heat dissipation form is forced convection and the height of the radiation plate is 1.0m, the cooling capacity and COP of the thermoelectric radiant window are the highest. Although the cooling capacity of three branches in parallel is higher than the cooling capacity of two branches in parallel, the electricity consumption will be larger than the electricity generation. If the solar thermoelectric radiant window is operated under such conditions for a long period, insufficient power generation from PV module is inevitable. Therefore, it is more appropriate to choose two branches in parallel. As the number of TEC in series increases, the cooling capacity will drop slightly, and COP will continue to increase. From three TEC in series to five TEC in series, the growth trend of COP is more obvious than that from five TEC to seven TEC in series. Considering the effects of cooling capacity, COP and power consumption, it is more suitable to choose a combination form with five TEC in series and two branches in parallel.

4. Conclusions

This paper studied the thermal performance of the improved solar thermoelectric radiant window structure under the conditions of the combination forms of TEC, the height of radiant panel, the heat dissipation form. After the above discussion and analysis, the following conclusions are obtained:

1) The combination form of case4 (five TEC in series and two branches in parallel) has better performance. The electricity generation of PV module under ideal conditions can meet the consumption of this combination, and COP can be maintained between 1.0-1.2 under summer cooling conditions.
(2) After the width of radiant panel is fixed, the height of radiant panel is changed to compare the four different heights of 0.7-1.0m. As the height of radiant panel increases, cooling capacity of the thermoelectric radiant window increases by 10.8%, and the cooling load decreases by 34.5%, and COP increased by 12.1%. Therefore, radiant panel with a height of 1.0m is considered.

(3) If the air duct adopts forced convection to dissipate heat, the average temperature of the air in the duct drops from 40.4℃ to 37.0℃, but it has almost no effect on power generation of PV. However, from the perspective of the cooling performance of the thermoelectric radiation window, there is a great improvement: the cooling capacity of the thermoelectric radiation window has increased by 18.7%, and COP has increased by 22.1%.

Acknowledgments
The study supported by the National Natural Science Foundation of China (Grant No. 51908287) and the National Natural Science Foundation of Jiangsu Province (Grant No. BK20180484).

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