Experimental of natural ventilation in a semi-transparent photovoltaic double skin façade in summer

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Abstract Semi-transparent photovoltaic double skin façade (STPV-DSF) is a novel structure which integrates photoelectric, photothermal, ventilation and energy-saving features, which proves to be extremely attractive and promising. In this study, a full-scale experimental system was built, airflow and heat transfer in a rectangular cavity with different transmittance (τ) and different ventilation modes in summer that studies a STPV-DSF and includes natural ventilation were examined experimentally. The Rayleigh number and Nusselt number of STPV-DSF is significantly higher than that of traditional DSF. This also means stronger intense flow. And the maximum temperature difference at night between mode 1 and mode 2 can reach 7.3°C. When the external air circulation mode is switched to the external and internal mode, the indoor temperature drops by 2.88°C in ten minutes. Therefore, making fully use of natural ventilation can effectively reduce the cooling load of air conditioning in summer. The solar radiation intensity is proved to have the greatest influence on the cavity temperature, followed by the transmittance, and the the ventilation mode least influence. Applying naturally ventilated STPV-DSF would be a new efficient way for the curtain wall buildings to meet the task of sustainable building design.

1 Introduction

Building envelope plays a vital role in reducing air conditioning energy consumption. Reasonable use of natural ventilation can improve indoor air quality and reduce air conditioning energy consumption to a certain extent. One of the advantages of ventilated double skin façade (DSF) is that it promotes natural ventilation without any power demand, which provides good indoor air quality and improves thermal comfort ([1,2]). However, the design of natural ventilation of DSF is delicate due to the interactions between heat transfer and the ventilation process, which depends on the characteristics of each component of the building structure ([3]). Therefore, predicting the performance of a DSF requires more considerations of natural ventilation characteristics. For solar facades installed with photovoltaics, it is very important to be ventilated for the photovoltaic cladding layer, otherwise the high temperature of photovoltaic module will cause efficiency losses and unnecessary heat for buildings, especially in summer time. In order to solve this problem, the design effective forced or natural ventilation to extract heat is necessary. There are many factors affecting the natural ventilation of semi-transparent photovoltaic double skin façade (STPV-DSF), such as cavity width ([4]), inner and outer skin materials ([5]), façade structure ([6]) and cavity opening size ([7]), which needs to be further studied.

2 Method and experiment

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The experimental chamber was located in Qingdao, China, with a size of 2.44 m (width) × 2.44 m (length) × 2.85 m (height), as shown in Fig. 1. Three façades with different transmittances (τ) from left to right are STPV-DSF of τ 40%, transparent DSF and STPV-DSF with τ of 20%, respectively. Materials and types of façade structures are shown in Table 1.

![Fig. 1. Front view of experimental system.](image)

The façade is 15° south to east, and it will be shaded by the shadow of a higher building behind each day after 14:00. The size of experimental system and measuring points are shown in Fig. 2. The experimental parameters and equipment used are listed in Table 2. Two different modes of natural ventilation operation were conducted in this study, as shown in Table 3, where EAC is external air circulation, EIC is external and internal circulation.

### Table 1. Materials and types of structures.

<table>
<thead>
<tr>
<th>Structure name</th>
<th>Materials and type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outer skin of STPV-DSF</td>
<td>CdTe photovoltaic glass</td>
</tr>
<tr>
<td>Inner skin and outer skin of DSF</td>
<td>double-layer insulating glass (6 + 12A + 6)</td>
</tr>
<tr>
<td>Vents of outer skin</td>
<td>parallel open windows</td>
</tr>
<tr>
<td>Vents of inner skin</td>
<td>side open windows</td>
</tr>
</tbody>
</table>

In order to determine the effect of buoyancy of airflow in the cavity of STPV-DSF, the Archimedes number (Ar) is introduced:

\[
Ar = \frac{Gr}{Re^2} = \frac{g \beta \Delta T L}{v^2} \quad (1)
\]

where \( Gr \) is the Grashof number; \( Re \) is the Reynolds number; \( g \) is the gravity acceleration; \( \beta \) is the thermal expansion coefficient; \( \Delta T \) is the average temperature difference between the fluid and the skin; \( L \) is the characteristic size; and \( v \) is the air flow velocity.

When \( Ar < 0.1 \), the flow is pure forced convection; when \( 0.1 \leq Ar < 10 \), the flow is mixed convection; when \( Ar \geq 10 \), the flow is pure natural convection.

![Fig. 2. The experimental temperature and wind speed measuring points (left: EAC mode, right: EIC mode).](image)

### Table 2. Experimental parameters and equipment

<table>
<thead>
<tr>
<th>Measured parameters</th>
<th>Equipment and specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>thermal resistance</td>
</tr>
<tr>
<td>Vertical solar radiation</td>
<td>Delta OHM (LP PYRA02) pyranometer</td>
</tr>
<tr>
<td>Data acquisition instrument</td>
<td>Agilent (34970A)</td>
</tr>
<tr>
<td>Wind speed of ventilation</td>
<td>Swema 03 + micro anemometer</td>
</tr>
</tbody>
</table>

### Table 3. Three modes of experiment

<table>
<thead>
<tr>
<th>Mode</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mode 1 (EAC)</td>
<td>All day</td>
</tr>
<tr>
<td>Mode 2 (EAC &amp; EIC)</td>
<td>EAC: 8:00-12:00; EIC: other time</td>
</tr>
</tbody>
</table>

For pure natural convection, buoyancy-induced flow intensity can be determined by Rayleigh number (Ra):

\[
Ra = Pr \cdot Gr = \frac{v}{\alpha} \cdot \frac{g \beta \Delta T L^3}{v^3} \quad (2)
\]

where \( Gr \) is the Grashof number; \( Pr \) is the Prandtl number; \( \alpha \) is thermal diffusivity; \( v \) is the kinematic viscosity of air; \( g \) is the gravity acceleration; \( \beta \) is the thermal expansion coefficient; \( \Delta T \) is the average temperature.
difference between the fluid and the skin; \( L \) is the characteristic size.

If \( Ra \) is less than \( 10^8 \), buoyancy driven convection is laminar; when \( Ra \) is \( 10^8-10^{10} \), it is a transitional stage between laminar flow and turbulence.\(^9\)

The Nusselt number \( (Nu) \) can be used to represent the intensity of convective heat transfer, and the larger the \( Nu \) is, the stronger the convective heat transfer is. It can be used in DSF to determine the heat transfer and ventilation effect of airflow in the cavity.

The empirical formula of Nusselt number obtained by Catton et al. \(^{10} \) is commonly used:

\[
Nu = 0.18 \left( \frac{Pr}{0.2 + Pr} \right)^{0.29} \tag{3}
\]

where \( 1 < H/L < 2; \) any \( Pr \) number; \( RaPr/(0.2 + Pr) > 10^3 \).

\[
Nu = 0.22 \left( \frac{Pr}{0.2 + Pr} Ra \right)^{0.29} \left( \frac{H}{L} \right)^{0.25} \tag{4}
\]

where \( 2 < H/L < 10; \) any \( Pr \) number; \( Ra < 10^{10} \).

3. Results

The natural ventilation of STPV-DSF in this experiment is mainly caused by thermal pressure. According to the experimental results, it was found that the effect of thermal pressure can be explicitly shown by the stratification of temperature in the cavity.

Fig. 3 shows the average temperature ( \( T_{ac,avg} \) ) of air in the cavity and the temperature difference (\( \Delta T \)) between the upper and lower wind outlets of the three façades under different solar radiation intensities in mode 1 and mode 2. The \( T_{ac,avg} \) of the three façades changes with the intensity of solar radiation. The difference of \( T_{ac,avg} \) between different façades is affected by solar radiation intensity, and the transmittance has no significant impact on the \( T_{ac,avg} \) under low radiation. Higher \( T_{ac,avg} \) also results in larger \( \Delta T \), which means that the cavity has a risk of overheating. It can be seen that solar radiation intensity is the main factor affecting the cavity temperature regardless of different ventilation modes. Under stronger solar radiation in mode 2, \( T_{ac,avg} \) are just higher 1-2°C than that in mode 1, which shows that making full use of EIC mode has the potential to reduce the cooling load.

Fig. 4 illustrates the change of the average \( Ar \) number in the cavity. The change of \( Ar \) number in the two modes is not in an equivalent order of magnitude. The \( Ar \) number in both modes is much larger than 10 in a day, and it is much higher with mode 2. This is closely related to the air velocity of through the opening of the cavity. During night time, its shows small temperature difference between indoor and outdoor, resulting in poor effect of thermal pressure and low air velocity through the cavity openings.
with $Nu$. The influence of transmittance on $Nu$ number is greater than different ventilation modes. The outer skin of transparent DSF absorbs more heat, and the heat transferred into the cavity also increases. Compared with STPV-DSF, transparent DSF has weaker convective heat transfer and more heat is accumulated in the cavity without being discharged timely, resulting in more significant temperature stratification.

![Fig. 5. The average Ra number in the cavity.](image1)

Fig. 5. The average $Ra$ number in the cavity. The two photovoltaic facade with a transmittance of $\tau=20\%$ and $\tau=40\%$ have similar degree of convective heat transfer. And lower transmittance rate causes higher $Nu$, which is beneficial in summer time.

Fig. 7 shows indoor temperature in mode 1 and mode 2, respectively. When EAC mode was converted to EIC mode at 12: 00, the indoor temperature decreased by 2.88°C within 10 min, indicating that the ventilation mode of DSF has a significant effect on the indoor temperature. When it is not affected by solar radiation at night, the maximum indoor temperature difference between the two modes is 7.3°C, which also indicates that making full use of the EIC mode at night in summer can effectively reduce the cooling load and increase fresh air supply to the room.

4. Conclusions

Solar radiation intensity, transmittance rate of outer glass and ventilation mode are main factors affecting natural ventilation and heat transfer of the façade. The significance of these influence factors decreases sequentially.

The air flow in natural ventilated STPV-DSF cavity is pure free convection, regardless of the ventilation modes. Low transmittance results in high $Ra$ and $Nu$, and stronger natural ventilation in summer. Fully use of EIC mode at night can not only introduce outdoor fresh air, but also effectively reduce indoor temperature.

Reference