Influence of External Surface Radiation Properties on Thermal Performance of Walls——Take a typical office building in Chengdu as an example

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Abstract. In this paper, taking a typical office building in Chengdu as an example, the coupling relationship between the radiation properties (short-wave absorption coefficient and long-wave emission coefficient) of the external surface materials of the wall and the insulation types and the insulation performance is studied by using software simulation method. The results show that the internal insulation wall is beneficial to reduce the heating load while the external insulation wall is beneficial to reduce the cooling load. And the external surface material's radiative properties hardly affect the wall insulation type choice. Still, in the case of Chengdu office buildings, internally insulated walls are more conducive to year-round building energy efficiency. In summer, the radiation characteristics of the outer surface material will affect the choice of the best heat transfer coefficient (U-value) of the wall. When the short-wave radiation absorption coefficient is small, the wall with good insulation performance will appear anti-energy-saving phenomenon. Therefore, it is recommended that the regions with high cooling loads fully consider the influence of the external surface material's radiation properties on the wall's thermal performance in the design of the thermal performance of the wall.

1 Introduction

The rational design and selection of the building envelope and its components is the most direct and effective way to improve the energy performance of buildings and is one of the most commonly used passive design strategies. In recent years, more and more researchers have focused on analyzing the dynamic thermal behavior of building envelopes, and rational optimization and management of the building envelope can significantly reduce the additional air conditioning energy consumption caused by outdoor environmental thermal disturbances through the envelope. The opaque envelopes account for 60%-70% of the total energy loss of the envelope[1], and insulation forms and new materials play a key role in improving the energy-saving technology of the envelope.

One of the important reasons for the significant differences in the optimization paths of current studies for opaque building envelopes is the different climatic conditions and operating modes of the buildings. For example, for regions with hot summers and cold winters, the thermal insulation performance of externally insulated walls is optimal under intermittent cooling conditions[2], while the energy efficiency of internally insulated walls is optimal[3]; under continuous cooling conditions, the energy efficiency of externally insulated walls is optimal[4]; and under free-running conditions in summer, the thermal insulation performance of internally insulated walls is optimal[5]. In most of these studies, the estimation of buildings’ heating and cooling loads is based on the degree-day concept. This approach provides a simple estimate of the year-round load but does not consider the effect of the radiant properties of the external surfaces Solar radiation absorption coefficient (ρₖ) and Thermal emissivity coefficient (Tₑ) on the energy balance of the building envelope[6]. Another part uses dynamic analysis models, but most only consider fixed external surface radiation characteristics[7].

In recent years, the emergence of various types of reflective and long-wave emitting materials has provided new ideas for studying energy efficiency and improving indoor thermal comfort in buildings. Guo et al.[8] found that using highly reflective roofs in the Xiamen area could make the outer surface of the roof 27.2°C lower than that of a low-reflective roof. For long-wave cooling materials, experimental studies have shown that long-wave radiative cooling can keep the surface temperature nearly 5°C below the ambient air temperature, even in direct sunlight[9]. Investigations of the sensitivity of the radiative properties of external surfaces have shown that long-wave emissivity and short-wave absorption play an essential role in the heat balance of the external surfaces of the envelope[10], as well as in the heat gain and heat loss through the envelope.

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Existing literature rarely considers the effects of both long-wave emissivity and short-wave reflection on the choice of insulation methods and thicknesses of opaque envelopes. Therefore, this paper uses a typical building simulation approach to investigate the effect of short-wave absorption and long-wave emission of exterior surface materials on building energy consumption at different insulation thicknesses within the external insulation method within the wall, using Chengdu as an example.

2 Method

2.1 Building model and related building service data

The reference building used in this paper is a standard three-story office building with a north-south orientation. The plan of the model space is shown in Figure 1. The reference building is a model of a medium-sized freestanding office building developed by the Pacific Northwest National Laboratory (PNNL). It was initially designed for the U.S. Department of Energy's Building Energy Code Program and has been used extensively in simulation studies. The dimensions of each floor are 50 m (L) × 33 m (W) × 3.5 m (H). The model space includes four exterior areas (facing four different directions) for office use, with a depth of 4.5 m, and one interior area for non-office use without heating and cooling equipment.

![Fig. 1. Plans of the reference building.](image)


-Envelope parameters are shown in Table 1.
-Window-to-wall ratio: 31% for all exterior walls, and the solar heat gain coefficient (SHGC) for the window is 0.45.
-Personnel density: 10 m²/person, with hourly occupancy set according to the standards [11].
-Heat production of lighting and equipment: 9 W/m² and 15 W/m², respectively, with hourly occupancy set according to the standards [11].
-The number of air changes: 30 m³/(h·people) during working hours
-Working schedule: from 7:00 a.m. to 7:00 p.m. on weekdays, the hour-by-hour utilization rate of lighting, electrical and air-conditioning HVAC equipment, temperature, and room-by-room occupancy rate of personnel are shown in Figure 2

![Fig. 2. Schedule of occupancy, lighting and equipment usage, and the heating and cooling setpoint temperatures.](image)

- Ventilation schedule (if required): To optimize the ventilation effect, the ventilation is carried out in a temperature-controlled manner, i.e., ventilation is carried out when the indoor temperature is higher than the outdoor temperature, and the minimum control temperature is 20°C.

<table>
<thead>
<tr>
<th>Type of envelope structure</th>
<th>U-value W/(m²·K)</th>
<th>ρs</th>
<th>Ts</th>
</tr>
</thead>
<tbody>
<tr>
<td>External wall</td>
<td>0.25, 0.5, 1.0, 1.5</td>
<td>0.1, 0.5, 0.9</td>
<td>0.45, 0.7, 0.9</td>
</tr>
<tr>
<td>Roof</td>
<td>0.18</td>
<td>0.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Floor slabs</td>
<td>0.25</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Internal partition wall</td>
<td>1.18</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Windows</td>
<td>1.2</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Ground floor</td>
<td>0.25</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

2.2 Simulation software and meteorological data

The simulations were performed in DesignBuilder software, which is based on the EnergyPlus engine and has excellent reliability. The solar absorption coefficient and long-wave absorption coefficient of the material on the exterior surface of the envelope are entered separately in EnergyPlus. These two parameters are used in calculating the amount of incident solar radiation absorbed by various surfaces and the exchange of long-wave radiation with multiple surfaces, affecting the surface's heat balance process. Among them, the long-wave absorption coefficient indicates the proportion of radiation bands with incident wavelengths >2.5 μm that is absorbed by the material, and solar radiation includes the visible spectrum as well as the near-infrared and near-ultraviolet bands (wavelengths from 0.3 to 2.537 μm).

The meteorological data used for the simulations are Chinese Standard Weather Data (CSWD), including hour-by-hour air temperature, air humidity, solar radiation, and wind speed. The city chosen for the study is Chengdu. According to the secondary zoning index of building thermal design, Chengdu is a hot summer and...
cold winter zone A (3A), and the design requirements of this region should meet the heat insulation and thermal insulation design requirements and pay attention to natural ventilation and sun shading design. According to statistics[13], the most occurring hours of direct solar radiation intensity in Chengdu city throughout the year are 100-200 W/m², with 282 h; the second most occurring hours are 0-100 W/m², with 277 h; the intensity of direct solar radiation between 200 and 700 W/m² are less than 200 h, and the number of hours of direct solar radiation intensity above 700 W/m² is 50 h.

3 Results

To investigate the effect of the wall insulation type and the way of combining short-wave absorption coefficient and long-wave emission coefficient on the building heating and cooling loads on the exterior surface of the wall, the cumulative heating load per unit area, cumulative cooling load per unit area and total annual load per unit area of the interior and exterior insulated wall buildings were compared separately in the following analysis. It is worth noting that the zone of non-heating and cooling areas is not included in the calculation of the unit area load.

3.1 Heating loads

Figures 3(a) and 3(b) show the cumulative heating loads of the interior and exterior insulated wall buildings, respectively.

![Fig. 3. The cumulative heating load of the building: (a) internal thermal insulation wall; (b) external thermal insulation wall](image)

Generally, the heating load is more influenced by the U-value and less affected by ρs and Ts, regardless of whether it is internally or externally insulated. When the wall U-value is small (U=0.25 W/(m²·K)), Ts increases from 0.45 to 0.9 only makes the heating load increase by 0.4%, and ρs increases from 0.1 to 0.9 when the heating load is only reduced by 0.4%; even when the U-value is large (U=1.5 W/(m²·K)), the effect of Ts on the heating load is only about 1.5%, and ρs on the heating load has a slightly more significant impact of about 3.5%.

Although the effects of ρs and Ts on the thermal performance of the wall are more pronounced at larger U-values of the wall, this leads to an increase in the heating load. When the U-value increases from 0.25 W/(m²·K) to 1.5 W/(m²·K), the heating load increases by an average of 26.1% and 22.4% for the internal and external insulation, respectively. In addition, in terms of the comparison between internal and external insulation, the heating load of the walls with the internal insulation method is lower, and the cumulative heating load of the walls with internal insulation is approximately 5.2%, 4.9%, 3.4%, and 2.4% lower relative to the building with external insulation walls when the U-values of the walls are 0.25, 0.5, 1.0 and 1.5 W/(m²·K), respectively.

Therefore, it can be seen from the above analysis that ρs and Ts do not significantly affect the heating load of the building for the Chengdu area. Although a higher U-value is beneficial for surface materials to exert their radiant properties to affect the heating load, the amount of heating load increased by increasing the U-value is much larger than the amount of load reduction brought about by decreasing Ts or increasing ρs or their combined effects.

3.2 Cooling loads

Figures 4(a) and 4(b) show the cumulative cooling loads of the interior and exterior insulated wall buildings, respectively.

As can be seen from Figure 4, ρs and Ts affect the cooling load, especially when the wall U-value is large. When the wall U value is small (U=0.25 W/(m²·K)), the cooling load decreases about 0.5% as Ts increases from 0.45 to 0.9, and the cooling load decreases about 2% as ρs decreases from 0.9 to 0.1; when the U-value is large (U=1.5 W/(m²·K)), the effect of Ts on the cooling load is about 1.5%~3.3%. The effect of ρs on the cooling load is more apparent, and the effect is around 10.7%~12.2% when the wall is internally insulated and around 11.6%~13.2% when it is externally insulated.

In addition, it can also be seen from Figure 4 that the cooling load of the externally insulated walls is lower, about 5.0% lower relative to the cumulative cooling load of the internally insulated wall building,
respectively, but the difference between the different heat transfer coefficients are not significant. However, in terms of cooling load, the ps and Ts of the wall exterior surface material will influence the choice of wall U-value.

For buildings with internally insulated walls, when \( \rho_s = 0.9 \), smaller U-values are more favorable to reduce the cooling load, and when the wall U-value is reduced from 1.5 W/(m²·K) to 0.25 W/(m²·K), the cooling load is reduced by 3.9% to 6.6%. And when \( \rho_s = 0.1 \), it is instead the walls with larger U-values that favor the cooling load reduction. For example, when \( \rho_s = 0.1 \) and \( T_s = 0.9 \), the cooling load of a wall with a U-value of 1.5 W/(m²·K) is 5.2% lower than that of a wall with a U-value of 0.25 W/(m²·K). When \( \rho_s = 0.5 \), the value of Ts will influence the choice of the optimal U-value of the wall, but the difference between them is slight, with a maximum difference of about 2.6%. For example, when \( T_s = 0.9 \), the wall U-value of 1.5 W/(m²·K) has the lowest cooling load; when \( T_s = 0.7 \) and 0.45, the wall U-value of 0.25 W/(m²·K) has the lowest cooling load. For buildings with externally insulated walls, the laws when \( \rho_s = 0.9 \) and 0.5 are similar to those for internally insulated walls with \( \rho_s = 0.9 \) and \( \rho_s = 0.1 \) are similar to those for internally insulated walls with \( \rho_s = 0.1 \).

Therefore, for Chengdu city, the short-wave radiation absorption coefficient and the long-wave radiation emission coefficient of the external surface material have little influence on the optimal insulation method of the building wall but have a more significant impact on the selection of the optimal U-value. When the short-wave radiation absorption coefficient is large, the smaller U-value is more beneficial to reduce the cooling load. Still, when the short-wave radiation absorption coefficient is smaller, the smaller U-value of the wall will instead be anti-energy saving.

### 3.3 Total cumulative annual loads

Figures 5(a) and 5(b) show the buildings' total annual loads with internal and external insulated walls, respectively.

![Fig. 5. The cumulative total load of the building: (a) internal thermal insulation wall; (b) external thermal insulation wall](image)

For Chengdu, a comprehensive year-round view shows that since the annual heating load accounts for about two-thirds of the total load, even though walls with smaller U-values run the risk of increasing the cooling load, the total load still follows the law that the smaller the U-value of the wall the lower the total load, and a total load of a wall with a U-value of 0.25 W/(m²·K) is lower than that of a U-value of 1.5 W/(m²·K). The total load is reduced by 14.5% to 15.7%. Since higher Ts or lower ps is beneficial to reduce the cooling load in summer, but increase the heating load in winter. Therefore, the effect of \( T_s \) and ps on the total annual load is very low, only about 0.5%.

### 4 Conclusions

In this paper, the effects of short-wave absorption coefficients and long-wave emission coefficients of exterior surface materials on building energy consumption at different insulation thicknesses of walls with varying types of insulation are studied using a typical building simulation approach, taking Chengdu as an example. The conclusions are as follows.

1. The radiative properties of the external surface materials do not affect the choice of internal or external insulation type of the wall, but for the Chengdu area, internal insulation walls are more conducive to building energy efficiency.

2. For the Chengdu area, the short-wave radiation absorption coefficient and long-wave radiation emission coefficient do not have much influence on the heating load of the building. Still, the impact on the cooling load cannot be neglected. However, since the cooling load only accounts for about one-third of the total load, the exterior surface materials' radiative properties do not significantly impact the total annual load.

3. In summer, the external surface material's radiation characteristics will affect the best U-value of the wall. When the short-wave radiation absorption coefficient is large, the smaller the U-value is, the more beneficial to reduce the cooling load. Still, when the short-wave radiation absorption coefficient is small, the smaller the U-value of the wall will instead appear as an anti-energy-saving phenomenon, while the larger the U-value of the wall, the lower the cooling load.

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