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Cooling performance comparison of radiant floor system and all-air system with solar radiation

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Abstract

In large space buildings such as airports, convention centers and entrance halls, the envelope is dominated by glass facades and skylights, and the indoor thermal environment is characterized by high-intensity solar radiation. The heat transfer process of radiant floor and air system are compared in this paper. During the cooling process, radiant floor removes indoor heat not only by convection but also by radiation, while air system handles all the heat by circulating air. It means that radiant floor can absorb the solar radiation directly. A case study comparing radiant floor and air system is analyzed, and the results show that with transient high-density solar radiation, radiant cooling system can enlarge the terminal cooling capacity more remarkably than air system. The adaptivity of radiant cooling system can help avoiding temperature fluctuations and prevent unnecessary indoor adjustment requirements.

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Keywords: radiant floor; cooling ability; solar radiation

1. Introduction

Nowadays, large space buildings such as transportation hubs are developing quickly, the envelope of these buildings are often dominated by glass facade and curtain walls with high-intensity solar radiation. Currently, all-air jet ventilation is the most common air-conditioning form adopted in large space buildings. Compared with all-air ventilation systems, radiant floor cooling systems express to be an energy saving mode. Energy consumption of transportation and distribution system will decrease as water is the main cold media. Radiant floor systems can improve indoor thermal comfort due to lower surface temperature. This positive effect allows higher air

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temperatures for identical comfort conditions so that cooling load will decrease. The cooling ability of radiant floor is closely related to the condition of heat sources, such as envelope inner surface and solar radiation, which is different from other air-conditioning terminals of heat convection. With this characteristic, radiant floor can deal better with the change of heat sources, such as instantaneous solar radiation.

The self-modify characteristic of radiant floor is attracting more attention of researchers. Babiak and Olesen indicated that solar radiation can improve the cooling capacity of radiant cooling systems [1,2]. Zhao estimates the dynamic performance of different radiant floors with solar radiation [3]. Causone presents a method for evaluate cooling loads of radiant system with solar radiation [4]. Several calculation models have been constructed to illustrate the heat transfer process of radiant cooling[5,6].

In this paper, typical heat transfer characteristics of radiant floor cooling system will be analyzed. A physical model is established to compare the cooling capacity between heavy radiant floor cooling system and all-air system with high-density solar radiation.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$h_c$</td>
<td>coefficient of convective heat transfer (W/m²·K)</td>
</tr>
<tr>
<td>$h_{lr}$</td>
<td>coefficient of long wave radiation heat transfer (W/m²·K)</td>
</tr>
<tr>
<td>$q_{air}$</td>
<td>cooling supplement by cold air (W/m²)</td>
</tr>
<tr>
<td>$q_c$</td>
<td>convective heat flux on the surface of the floor (W/m²)</td>
</tr>
<tr>
<td>$q_l$</td>
<td>longwave radiant heat flux on the surface of the floor (W/m²)</td>
</tr>
<tr>
<td>$q_s$</td>
<td>shortwave radiant heat flux on the surface of the floor (W/m²)</td>
</tr>
<tr>
<td>$q_{s,in}$</td>
<td>cooling supplement by radiant floor or cooling capacity provided to indoor space by radiant floor (W/m²)</td>
</tr>
<tr>
<td>$q_{sr}$</td>
<td>shortwave radiant heat flux (W/m²)</td>
</tr>
<tr>
<td>$q_w$</td>
<td>cooling supplement by chilled water (W/m²)</td>
</tr>
<tr>
<td>$R$</td>
<td>equivalent heat resistance of radiant floor ((m²·K)/W)</td>
</tr>
<tr>
<td>$T_a$</td>
<td>indoor air temperature (°C)</td>
</tr>
<tr>
<td>$T_{fs}$</td>
<td>radiant floor surface temperature (°C)</td>
</tr>
<tr>
<td>$T_{w,avg}$</td>
<td>average temperature of chilled water (°C)</td>
</tr>
<tr>
<td>$T_{wall}$</td>
<td>average uncooled surface temperature /AUST (°C)</td>
</tr>
</tbody>
</table>

2. **Comparison of heat transfer process between radiant floor cooling and air system**

2.1. **The heat transfer characteristics of radiant floor cooling and air system**

During the cooling process, radiant floor removes indoor heat not only by convection but also by radiation, which is shown in Fig. 1. Radiation heat transfer includes the directly absorption of shortwave radiation (such as solar radiation) and the long-wave radiation with indoor wall surfaces. Then the heat transferred into radiant floor is taken away by chilled water inside radiant panel. By comparison, in conventional convection process such as all-air system, all the heat is handled by circulating air. Hereinto, the convective heat is removed by air directly, while the shortwave radiant heat and the long-wave radiant heat are absorbed by surfaces firstly, cause the temperature rise of floor/wall, and then diffused into indoor air.

2.2. **Model and analysis on radiant floor cooling system**

This paper analyzes the concrete core radiant floor system, whose structure is shown in in Fig. 2(a). In this type of radiant floor, water pipes are encased in a concrete core with a floor covering above it. The concrete slab acts as a heat accumulator in the heat transport mechanism. As concrete slab has the characteristic of large thermal capacity, concrete core radiant floor is also called “heavy floor”. The simplified two dimensional model is used to estimate the heat transfer process inside the floor, as shown in Fig. 2(b) [3].
The formula for calculating cooling capacity provided to indoor space by radiant floor $q_{s,\text{in}}$ is shown in Eqs. (1).

$$q_{s,\text{in}} = q_c + q_l + q_s = h_c (T_a - T_{s,f}) + h_{lR} (T_{wall} - T_{s,f}) + q_s$$ \hspace{1cm} (1)

Outdoor conditions have a significant impact on the cooling ability of radiant floor. When the sunlight reach the surface of radiant floor, solar radiation would be absorbed directly and transfer to the chilled water in the pipe, which increases the cooling capacity of radiant panel per unit area. That’s to say, radiant cooling system has the ability of self-regulating, it can adjust itself based on the changes in cooling load and strengthen its adaptability for various operation conditions.

3. Case study

3.1. Basic information

In order to make a prediction to the cooling capacity of radiant floor cooling system and air system, we can take the following case as an example. The indoor air temperature is set to 26°C as the average uncooled surface temperature is 28.5°C. Heat flux of indoor source remains constant at 50.8 W/m². The following items are simplified for the convenience of calculation: shortwave radiant heat flux and air infiltration are not in consideration; the minimum fresh air requirement is not essential while forced ventilation is only for cooling.

The heavy radiant floor with a heat resistance of 0.094 (m²·K)/W is employed for cooling in the building. The coefficient of convective heat transfer $h_c$ is 1.5 W/(m²·K) and the coefficient of long wave radiation heat transfer $h_{lR}$ is 5.5W/(m²·K). Fig. 3(a) shows the steady-state condition without solar radiation. All the heat of indoor source (50.8 W/m²) is absorbed by the radiant floor in equilibrium while the surface temperature of radiant floor stabilized at...
20.7°C. For Eqs. (1), the convective heat flux $q_c$ is 7.9 W/m² and longwave radiant heat flux $q_l$ is 42.9 W/m². The cooling supplement by chilled water $q_w$ is identical with the cooling supplement by radiant floor $q_{s,in}$.

In other situations that the radiant floor can’t deal with all the indoor heat, cold air can get rid of the rest as supplementary. As for the model of all-air system, the floor structure, indoor condition and heat source are the same with the radiant floor system, while cold air is the only cold media to take all the indoor heat away (Fig. 3(b)).

![Fig. 3. Sketch of heat transfer without solar radiation in equilibrium (a) Radiant floor system; (b) Air system.](image)

### 3.2. Cooling capacity comparison between RF system and air system with solar radiation

Three conditions with different duration time of solar radiation are selected for comparing. When the system achieves stability, solar radiation (100W/m²) is set to the system with duration time of 10 min, 30 min and 3 h respectively. Indoor air temperature $T_a$ and average uncooled surface temperature $T_{wall}$ keep constant during the entire process. Fig. 4 shows the cooling capacity of floor and the temperature of floor surface.

Take the condition in which the duration time of solar radiation is 3 hours for example(Fig. 4(c)). At the beginning of solar radiation (at the time of 60 min), the heat absorbed by the floor increases immediately. Radiant floor can remove all the cooling load, including indoor heat and solar radiation heat ($q_s=150.8$ W/m²). As time elapses, the temperature of floor surface gradually rises from 20.7°C to about 25°C, and the heat removed by floor surface decreases while chilled water takes more heat away. 17 minutes after the end of solar radiation, cooling capacity of chilled water reaches a maximum. For air system, the concrete floor can absorb all the solar radiation heat ($q_s=100$ W/m²) at beginning and then heated to about 33°C, only part of radiation heat can be removed.

The heat flow rate in the moment when solar radiation ends is shown in Table 1. For air system, surface temperture of floor $T_{f,s}$ is higher than air temperture, floor gives off heat. For radiant floor, $T_{f,s}$ stays lower and takes on part of indoor cooling load while cold air takes on the rest.

<table>
<thead>
<tr>
<th>Solar radiation duration time</th>
<th>0min(No solar radiation)</th>
<th>10min</th>
<th>30min</th>
<th>3h</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_a$ (°C)</td>
<td>RF system 20.7</td>
<td>28.0</td>
<td>21.9</td>
<td>29.1</td>
</tr>
<tr>
<td>$q_{s,in}$ (W/m²)</td>
<td>50.8</td>
<td>0</td>
<td>42.7</td>
<td>-8.0</td>
</tr>
<tr>
<td>$q_{air}$ (W/m²)</td>
<td>0</td>
<td>50.8</td>
<td>8.1</td>
<td>58.8</td>
</tr>
<tr>
<td>$q_w$ (W/m²)</td>
<td>50.8 \ \ \ \ \ \ \ \ \</td>
<td>\</td>
<td>51.0</td>
<td>\</td>
</tr>
</tbody>
</table>

Fig. 5 compares the cooling capacity of the three conditions. When indoor air temperature $T_a$ and average uncooled surface temperature $T_{wall}$ keep constant, radiant floor can remove more heat under the influence of solar radiation. The cooling capacity of radiant floor system includes cooling by chilled water(green line) and cold air(purple line). Total cooling capacity is listed in Table 1, it can be seen that with the supplement of cold air, the cooling capacity of radiant floor system under transient high-density solar radiation is much higher than air system. A test of radiant floor system in Tianjin railway station shows the similar results[7].
Fig. 4. Cooling capacity of floor and the temperature of floor surface (a) 10min; (b) 30min; (c) 3h of solar radiation.
4. Conclusions and future work

In this paper, the cooling capacity of radiant floor and air system with solar radiation is analyzed. The conclusions are summarized as follows:

- Based on the heat transfer characteristics, the cooling capacity of the radiant floor system would increase with high-intensity solar radiation.
- A simulation of radiant floor cooling and air system is analyzed, and the results show that when indoor air temperature $T_a$ and average uncooled surface temperature $T_{wall}$ keep constant, the cooling capacity of heavy radiant floors increases significantly compared to air system when exposed to high-density solar radiation. In other words, more heat is taken away by chilled water in the pipe to keep the same $T_a$ and $T_{wall}$. In addition, radiant floor cooling can keep the temperature of floor surface at lower levels.
- Compared with air system, the radiant floor cooling system can enhance the terminal cooling ability largely than air system, especially with high-density solar radiation. With the characteristic, radiant floor system can prevent unnecessary indoor adjustment requirements.

In the future we plan to optimize the model in order to be closer to the actual conditions. The comparison in this paper is under the same indoor air temperature. Under the same condition of identical thermal comfort, the air temperature of radiant systems will be higher. On the other hand, radiant system is usually applied together with fresh air system. These features will be in consideration in the future research.

Acknowledgements

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References