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Application of radiant floor cooling in a large open space building with high-intensity solar radiation

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ABSTRACT

Radiant floor cooling is suitable for environmental control in large space buildings with high-intensity solar radiation caused by a large transparent envelope. A simple method for predicting the performance of radiant floor cooling systems with solar radiation in steady state is proposed in this paper, and the key factors that influence performance are obtained. Cooling capacity of the radiant floor is significantly increased with high-intensity solar radiation and high-temperature building envelope surfaces in large space buildings. The effect of shelter of indoor furniture (such as chairs) on the performance of radiant floors is analyzed. The lowest floor surface temperature is located at the sheltered floor, and the cooling capacity of the sheltered radiant floor is also lower than that of the unsheltered radiant floor. A case study applying radiant floor cooling in a large space building is then analyzed, and the results are compared with those of a conventional all-air jet ventilation system. At the same indoor air temperature, the radiant cooling system can provide better thermal comfort at a lower operative temperature, and it presents a significant improvement in energy efficiency, with total energy demand 20–30% lower than the conventional all-air system.

1. Introduction

Large space buildings, such as airport terminals and railway stations, are developing very quickly in China. For aesthetic purposes and the full use of natural light, this type building is structured with large span without partition, and its envelope is dominated by glass facade/curtain walls. Consequently, its indoor environment is characterized by high-intensity solar radiation and high-temperature internal wall surfaces, which are distinct from the characteristics of common buildings. In addition, apparent thermal stratification in the vertical direction in these buildings has been observed in several studies [1–3].

Currently, all-air jet ventilation is usually adopted in large space buildings, in which handled air is supplied at a speed of 3.0–7.5 m/s at a height of 3–5 m. In this method, the energy consumption of the fans represents a large percentage of the energy consumption of the entire HVAC system (i.e., 30–50%), resulting in high overall energy consumption [4]. Hence, many researchers are working on developing new air-conditioning systems that are suitable for large space buildings. Int-Hout and Kloostra [5] pointed out that stratification is often a useful strategy in large spaces, but displacement ventilation has a limited ability to handle high cooling loads. Several applications have indicated that radiant floor cooling is another effective solution, as it operates using a water temperature that is close to room temperature, with high-efficiency heat pumps and low distributed energy consumption [6–8]. Also, there is the potential for radiant floor cooling systems to achieve higher cooling capacity in large space buildings with high-intensity solar radiation [9]. According to an application in Bangkok International Airport, the cooling capacity of the radiant floor reached 80 W/m^2 when there was high-intensity solar radiation. As a result, radiant floor cooling can be considered appropriate for environmental control in large space buildings with high-intensity solar radiation, such as airport terminals and railway stations.

As for the characteristics of radiant floor cooling systems, several numerical and simplified models have been constructed to illustrate heat flow in the radiant floor and its heat exchange with the indoor environment [10–13]. Design and estimation methods are regulated in standards such as the ASHRAE Handbook and European standards [14–16]. However, previous analyses and calculations of the thermal output of radiant cooling systems only take into account the heat transfer from indoor air and wall surfaces, without considering shortwave radiant heat caused by solar radiation. Athienitis and Chen [17] and Odyjas and Górka [18] studied the influence of direct solar radiation on system

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Nomenclature

a	impact factor of radiant floor surface temperature (dimensionless)
$AUST$	average uncooled surface temperature (°C)
b	impact factor of radiant floor cooling capacity (dimensionless)
c_w	specific heat of water, J/(kg K)
COP	coefficient of performance of chillers (dimensionless)
EER	energy efficiency ratio of air-conditioning system (dimensionless)
F_{s-j}	view factor between floor surface and surface j
$F_{\varepsilon_{s-j}}$	radiation interchange factor between floor surface and surface j
h_c	convective heat exchange coefficient (W/(m^2 K))
h_{lr}	longwave radiant heat exchange coefficient (W/(m^2 K))
$\dot{m}_w$	chilled water flow rate per unit area (kg/(m^2 s))
q	cooling capacity provided to indoor space by radiant floor (W/m^2)
q_c	convective heat flux (W/m^2)
q_{lr}	longwave radiant heat flux (W/m^2)
q_{sr}	shortwave radiant heat flux (W/m^2)
q_{loss}	cooling loss through the lower surface of radiant floor (W/m^2)
q_{tot}	total cooling capacity of radiant floor (W/m^2)
q_{FCU}	cooling supplement by dry fan coil units (W/m^2)
R	equivalent heat resistance of radiant floor ((m^2 K)/W)
T_a	indoor air temperature (°C)
T_j	temperature of internal wall surface j (°C)
T_s	radiant floor surface temperature (°C)
$\bar{T}_w$	mean temperature of chilled water (°C)
$T_{w,s}$	supply temperature of chilled water (°C)
$T_{w,r}$	return temperature of chilled water (°C)
TC	transport coefficient of pumps and fans (dimensionless)
σ	Stefan–Boltzman constant (W/(m^2 K^4))
ε	emissivity of surface (dimensionless)
λ_s	thermal conductivity of the radiant floor surface layer (W/(m K))

capacity using numerical simulations. Nonetheless, a simple method for determining the incremental effect of solar radiation on the cooling capacity of radiant floor remains absent from the literature.

This paper introduces a simple method for calculating the cooling capacity of radiant floor in steady state with regard to heat resistance, in which the influence of solar radiation is considered. A significant improvement in the cooling capacity of the radiant floor in a large space building is illustrated, and the effect of indoor furniture (such as chairs) shelter on the performance of the radiant floor is analyzed. The surface temperature of the sheltered radiant floor is much lower than that of the radiant floor without shading, especially when there is high-intensity solar radiation; the formation of moisture condensation is also much more likely to occur for the former compared to the latter. A case study applying a radiant floor cooling system in a large space building is then analyzed, and the results are compared with those of a conventional all-air jet air-conditioning system.

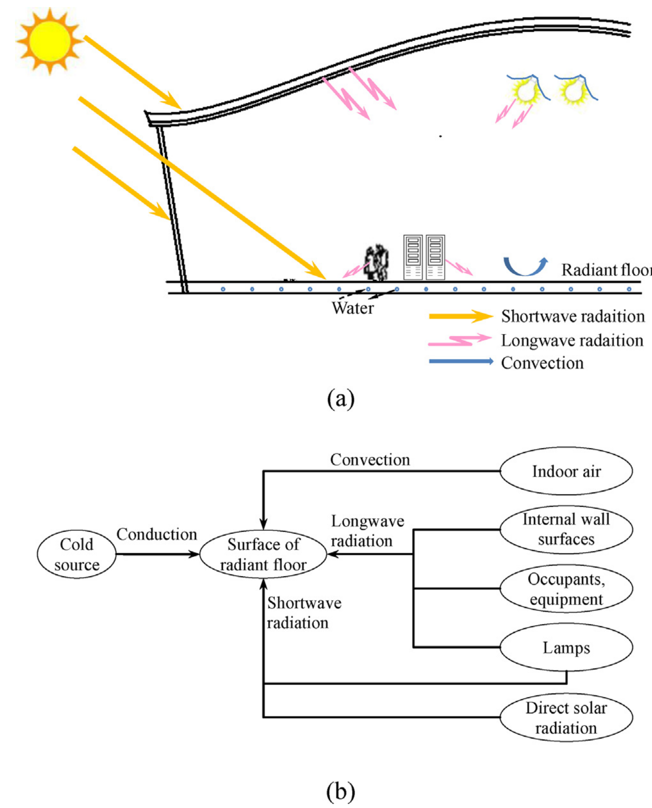

Fig. 1. Heat transfer of radiant floor with surroundings: (a) simple graph and (b) schematic diagram.

2. Heat transfer process of radiant floor systems

2.1. A simple analytical method

In radiant floor cooling systems, chilled water is supplied by embedded circular pipes in a concrete layer or extruded sheet, which forms a low-temperature surface at the floor. Then the floor surface exchanges heat with the indoor air, internal wall surfaces, occupants, equipment, etc. by convection or longwave radiation, as shown in Fig. 1. In addition, shortwave radiation (such as solar radiation) arrives at the floor surface and can be absorbed by the radiant floor directly. Therefore, the cooling capacity of the radiant floor is not a fixed value; it depends on the conditions of the chilled water, indoor heat sources, and the structure of the radiant floor itself.

The heat transfer processes from the indoor space to the chilled water can be depicted as Fig. 2 with classical equivalent circuit model. In steady state, the thermal mass effect is negligible, and the cooling capacity of the radiant floor is decided by the indoor heat sources temperature/intensity, chilled water temperature and the heat transfer resistance at each link. The heat transfer processes can be divided into two parts. The first part refers to heat transfer from the indoor space to the radiant floor surface, which is dependent on the radiant floor surface temperature (T_s) and indoor conditions such as the indoor air temperature (T_a), internal wall surface temperature ($AUST$), surface properties (emissivity/absorptivity), view factors, and shortwave radiation absorbed by the radiant floor (q_{sr}). The second part refers to heat transfer from the floor surface to the chilled water, which is determined by the construction parameters of the radiant floor and the difference between the chilled water temperature ($\bar{T}_w$) and the radiant floor surface temperature (T_s).

The total heat flux between the floor surface and the indoor space is the sum of the heat exchange capacity through convective