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Cooling capacity prediction of radiant floors in large spaces of an airport

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Abstract

In large space buildings such as check-in halls and departure halls in airports, the envelope is dominated by glass façades, skylights, and metal ceilings. A radiant floor is an effective sensible heat removal terminal due to its direct longwave radiant heat exchange with high-temperature wall surfaces and absorption of solar radiation. The emissivities of metal ceilings and many advanced materials (e.g., low-e coating) in large spaces range from 0.2 to 0.9, markedly different from that of traditional building materials (0.9–0.95), which affects the indoor longwave heat exchange. Moreover, the number of transient solar radiation incidents on the floor surface can vary tremendously, resulting in remarkable differences in cooling capacity of the radiant floor, e.g., from 30 to 40 W/m^2 to more than 100 W/m^2. In this paper, a new simple calculation method for longwave radiant heat exchange that considers emissivity is proposed, and the location and duration of transient solar radiation through skylights and side windows in large spaces are depicted quantitatively. Based on this new method, a typical case study is presented, in which the cooling capacity of a radiant floor in the large spaces of an airport is calculated. The case study also showcases designs of radiant floors in large spaces with different material emissivity and transient solar radiation values.

Keywords: Radiant floor cooling; Large space building; Longwave radiant heat exchange; Emissivity; Solar radiation

1. Introduction

Large space buildings include transportation hubs, convention centers, stadiums, and atriums. The building envelope of these spaces is often dominated by glass façades, skylights, and metal ceilings for aesthetic appearances. Therefore, the indoor environment is typically characterized by high-temperature internal wall surfaces and high-intensity solar radiation in summer. Under such conditions, a radiant floor is an effective sensible heat removal terminal due to its direct absorption of solar radiation and longwave radiant heat exchange with high-temperature wall surfaces (Simmonds et al., 2000; Babiak et al., 2007; Olesen, 2008). Radiant heat, including the absorption of solar radiation and longwave radiant heat exchange with high-temperature wall surfaces, represents a significant proportion of the cooling capacity of the radiant floor, and it varies tremendously under different occasions (Simmonds et al., 2000; Zhao et al., 2013). Therefore, predicting the cooling capacity of the radiant floor is crucial for the application of radiant floor cooling in large spaces.

As for the longwave radiant heat exchange between the radiant floor surface and the other surfaces of the enclosure, several simple calculation methods have been derived from radiosity formulation methods (Walton, 1980; Olesen

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Nomenclature

A	area (m^2)
$AUST$	average uncooled surface temperature (°C)
C	equivalent heat capacity of radiant floor ($kJ/(m^2\ K)$)
D	distance on the horizontal plane (m)
F	view factor (dimensionless)
h	heat exchange coefficient ($W/(m^2\ K)$)
H	height (m)
H'	height of side window (m)
L	length (m)
n	number (dimensionless)
q	cooling capacity or heat flux (W/m^2)
r	resistance of longwave radiant heat exchange (m^{-2})
R	equivalent heat resistance of radiant floor ($(m^2\ K)/W$)
s	moving speed of sunlight on floor (cm/min)
SC	shading coefficient (dimensionless)
t	hour angle (°)
T	temperature (°C)
w	width of sunlight on floor (m)
W	width (m)
α	solar azimuth angle (°)
β	geometry factor (dimensionless)
γ	ratio (dimensionless)
δ	declination of the sun (°)
ε	emissivity of surface (dimensionless)
θ	solar elevation angle (°)
σ	Stefan–Boltzmann constant, 5.67×10^{-8} $W/(m^2\ K^4)$
τ	time (s)
τ_c	time constant (s)
φ	local latitude (°)

Subscripts

a	air
c	convection
EW	transmeridional
f	floor
lr	longwave radiation
NS	meridional
rs	star point
sr	shortwave radiation (solar radiation)
w	chilled water inside radiant floor

et al., 2000; ASHRAE, 2012). In the MRT method, the uncooled surfaces are treated as a fictitious surface with average surface emissivity and temperature. When the emissivities of these uncooled surfaces are similar, this calculation method demonstrates high accuracy; otherwise, it will produce results that deviate from the exact values (Steinman et al., 1989). The linearization equations proposed by Olesen et al. and ASHRAE are based on the precondition that material emissivity is 0.9–0.95, which severely limits their application scope. Indeed, the emissivities of metal and many advanced materials (such as low-e coating) that are commonly employed in large spaces range from 0.2 to 0.9 (Ge and Na, 1989; Lu, 2008); this emissivity range is markedly different from that of traditional building materials. Therefore, a new simple calculation method for predicting the cooling capacity of radiant floors with low-emissivity surface materials would be extremely beneficial.

In terms of shortwave radiant heat, the potential for radiant floor cooling systems to achieve higher cooling capacity with solar radiation has been demonstrated (Olesen, 2008). For example, based on complex calculations with building load simulation tools, the radiant floor in Suvarnabhumi International Airport in Bangkok, Thailand was dimensioned to remove 70–80 W/m^2 of heat, including 50 W/m^2 by radiation (Simmonds et al., 2000). It also has been the subject of numerous studies, and various coefficients representing the improvement of steady-state heat transfer have been proposed (Causone et al., 2010; De Carli and Tonon, 2011; Feng et al., 2013). However, the effect of solar radiation is usually a transient process of limited duration (Athienitis and Chen, 2000). In Xi'an Xianyang International Airport (China), the cooling capacity of the radiant floor increased significantly to 110–140 W/m^2 when there was high-intensity solar radiation on the floor (e.g., 120–170 W/m^2) with a duration of 10–30 min (Zhao et al., 2014b). Theoretical analysis has also revealed that cooling capacity with transient solar radiation is related to both the duration and intensity of radiation (Zhao et al., 2014a).

The cooling capacity of a radiant floor with high-intensity solar radiation may exceed 100 W/m^2, while that without solar radiation might only be 30–40 W/m^2. Due to extreme variation and a lack of comprehensive analysis, cooling capacity is estimated conservatively in most current designs. For example, in European Standard EN 15377 and in the ASHRAE handbook, cooling capacity is dimensioned without consideration of solar radiation, i.e., 30–40 W/m^2 (CEN, 2008; ASHRAE, 2012). In order to predict cooling capacity accurately, it is essential to determine the impact of solar radiation on radiant floor cooling, including the detailed locations of solar radiation and the extent of its impact on these affected regions.

In this paper, the influence of material emissivity on longwave radiant heat exchange between the radiant floor surface and the indoor wall surfaces is estimated, and a new simple calculation method for different emissivity values is investigated. The location and duration of solar