Solar Energy 170 (2018) 885–895

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Novel method for the design of radiant floor cooling systems through homogenizing spatial solar radiation distribution

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ARTICLE INFO

Keywords:
Radiant floor cooling
Solar radiation
Cooling capacity
Homogenizing treatment

ABSTRACT

The local and mobile incident sunlight from skylight and side windows shining on the floor surface increases the cooling capacity of the radiant floor cooling system. In this study, a novel method of homogenizing spatial solar radiation distribution over the entire radiant floor surface is proposed to the design of the radiant floor with a conventional circuit pattern of counter flow. A verified three-dimensional numerical radiant floor model is utilized to evaluate the deviation of the novel method in steady and transient states. The simulation results indicate that the relative error for local sunlight with a width over two pipe spacing is less than 1.0%. With a solar radiation intensity of 300 W/m^2, the deviation of the simulated floor surface heat flux via the novel method is less than 0.3 W/m^2 for any sunlight size in steady states. Furthermore, under transient and mobile sunlight, the simulated water side and floor surface heat fluxes via the novel method agrees well with the 3D model. As a result, the homogenizing treatment significantly simplifies the dynamic analysis of radiant floor system under temporal and spatial solar radiation distribution with enough accuracy in engineering applications.

1. Introduction

A radiant floor cooling system presents the potential to improve the indoor thermal comfort (Le Dréau and Heiselberg, 2014; Tian and Love, 2008) and achieve energy saving by increasing the required cooling water temperature and reducing transmission energy consumption (Feustel and Stetiu, 1995; Hu and Niu, 2012; Saber et al., 2016; Rhee et al., 2017). The application of radiant floor cooling has been extended to large space buildings, e.g., airport terminals, entrance halls and atriums (Hu and Niu, 2012; Rhee and Kim, 2015; Rhee et al., 2017). The cooling capacity of the radiant floor is restricted by the minimum floor surface temperature due to the condensation and comfort concern (Tang et al., 2016). For typical applications of radiant floor cooling systems, the rule of thumb is that the maximum cooling capacity is only 30–40 W/m^2 without incident solar radiation on the floor surface (Olesen et al., 2000; De Carli and Olesen, 2002).

Natural lighting and physical connection to our environment are integral to the design of commercial and public buildings. To access natural lighting and the visual comfortable effect, skylights and side windows are designed in the large space building and glass curtain walls are designed in office buildings. As a result, direct solar radiation enters the indoor space and shines on the floor surface. For conditions that the sun illuminates the radiant floor surface, the cooling capacity can increase significantly up to 130–140 W/m^2 (Zhao et al., 2014a). The cooling capacity of the radiant floor with direct solar radiation differs greatly from that without solar radiation. Thus, Causone et al. (2010) proposed a simplified procedure to calculate the magnitude of the direct solar load that is directly converted to cooling load by the radiant floor cooling. Zhao et al. (2014a, 2014b) defines a dynamic equivalent heat resistance to reflect the thermal behavior of radiant floor with transient solar radiation. ISO-11855 (2012) characterizes the effect of solar radiation on the built environment using the improvement of the radiant heat transfer coefficient on surfaces under solar radiation. Feng et al. (2016) established a new model calculating the enhanced cooling capacity as a function of window transmitted solar radiation and a mean temperature differences between the hydronic loop and room operative temperature. However, these calculation methods are all based on the assumption that the incident sunlight covers the entire radiant floor surface.

In reality, sun shading is designed to reduce building cooling load induced by incident solar radiation. For instance, deep overhangs are utilized in the checking hall and the entrance hall of the airport terminal as external sunshades. Color glazed glasses occupy parts of the side windows in the departing hall to reduce direct solar radiation. Therefore, the incident solar radiation from discontinuous skylight and transparent part of side windows presents discrete and non-uniform

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https://doi.org/10.1016/j.solener.2018.06.039
Received 25 January 2018; Received in revised form 8 June 2018; Accepted 10 June 2018

Nomenclature

A_i	surface area of the *ith* wall (m^2)
$AUST$	area weighted average surface temperature (°C)
c_p	specific heat (J/(kg·K))
d_i	inner diameter of pipe (m)
d_o	outer diameter of pipe (m)
H	thickness of radiant floor (m)
H_1	distance from the pipe center to the floor surface (m)
H_2	distance from the pipe center to the slab bottom surface (m)
h_c	convective heat transfer coefficient (W/(m^2·K))
h_l	longwave radiative heat transfer coefficient (W/(m^2·K))
h_w	convective heat transfer coefficient in pipes (W/(m^2·K))
L	sunlight length in z direction (m)
L_1	pipe spacing in Fig. 2 (m)
L_2	width of a single radiant floor in Fig. 2 (m)
L_3	pipe length per row in Fig. 2 (m)
L'	pipe length of the radiant floor (m)
m_w	water mass flow rate (kg/s)
NTU	number of transfer unit of the radiant floor (–)
Nu	Nusselt number of the forced convection heat transfer in the pipe (–)
P_i	external perimeter of the *i*th water pipe (–)
Pr	Prandtl number of the water (–)
q_{sol}	temporal and spatial solar radiation intensity distribution (W/m^2)
$q_{sol,ave}$	average solar radiation intensity over the entire floor surface (W/m^2)
q_s	average floor surface heat flux (W/m^2)
q_{water}	water side heat flux of the radiant floor cooling (W/m^2)
R_d	thermal resistance per area of the pipe wall ((m^2·K)/W)
Re	Reynolds number of the forced convection flow in the pipe (–)
R_f	thermal resistance per area of the radiant floor ((m^2·K)/W)
S	floor surface area (m^2)
T	slab temperature inside the radiant floor (°C)
T_a	indoor air temperature (°C)
T_s	average floor surface temperature (°C)
$T_{w,i}$	cooling water temperature in the *i*th water pipe (°C)
$T_{w,s}$	supply water temperature (°C)
$T_{w,r}$	return water temperature (°C)
$T_{wall,i}$	inner surface temperature of the *ith* wall (°C)
T_z	indoor equivalent heat transfer temperature (°C)
v_w	water velocity in pipes (m/s)
W	sunlight width in x direction (m)

Greek symbols

α	thermal diffusivity (m^2/s)
ε	relative error of the novel method (–)
ρ	density (kg/m^3)
λ	thermal conductivity of slab (W/(m·K))
λ_w	thermal conductivity of water (W/(m·K))
υ_w	dynamic viscosity of the water (N·s/m^2)

sunlight rather than covers the entire radiant floor area. Inside furniture also plays a role of keeping out the sun to the floor surface. The cooling capacity increment of the radiant floor is determined by the spatial solar radiation distribution on the floor surface. Furthermore, the varying solar altitude angle results in sunlight movement and changing solar radiation intensity. Experimental and simulation results reported in literature reveal that solar beam radiation can cause a local floor surface temperature in the illuminated area 8 °C higher than other areas (Athienitis and Chen, 2000; De Carli and Tonon, 2011). Therefore, the sunlight on the floor surface presents locality, mobility and intensity variety and plays a significant role on the floor surface temperature and heat flux distribution. However, the simulation models of the radiant floor cooling in literature including heat conduction transfer function (Holopainen et al., 2007), RC-network model (Tian et al., 2014), bi-dimensional radiant floor model (Wang et al., 2014), and the whole building energy simulation programs, i.e., EnergyPlus 8.2.0 and TRNSYS 18.0, all assume a uniform solar radiation distribution on the entire radiant floor surface. Nevertheless, the sunlight only covers part of a single radiant floor in reality, which demonstrates inadequacy of the existing radiant floor models.

For designers, prediction of the radiant floor cooling capacity is crucial both for sizing the radiant cooling system but also for sizing the associated air system. In this paper, a novel method of homogenizing the spatial solar radiation over the entire floor surface is proposed to quantify the dynamic average floor surface temperature and heat flux of the radiant floor cooling system. The homogenizing treatment is verified against the results calculated through a three-dimensional finite difference model. The error analysis of the novel method is performed

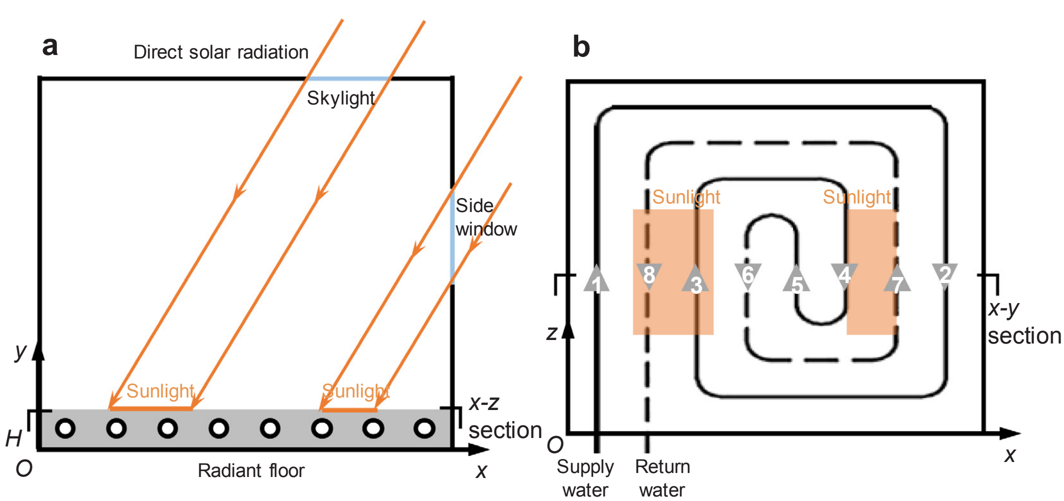

Fig. 1. Local sunlight shining on radiant floor: (a) Schematic of spatial solar distribution introduced by the skylight and side windows (side view); and (b) a circuit layout pattern of counter flow applied in the water pipe loop (top view).