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Simulations of floor cooling system capacity

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HIGHLIGHTS

► We have developed numerical model for simulation of floor cooling system.
► We have described floor system capacity depending on its physical parameters.
► We have described floor system capacity depending on type of cooling loads.
► The most important in the obtained cooling capacities is the type of cooling loads.
► The paper sets out the possible maximum cooling floor system capacity.

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ABSTRACT

Floor cooling system capacity depends on its physical and operative parameters. Using numerical simulations, it appears that cooling capacity of the system largely depends on the type of cooling loads occurring in the room. In the case of convective cooling loads capacity of the system is small. However, when radiation flux falls directly on the floor the system significantly increases productivity. The article describes the results of numerical simulations which allow to determine system capacity in steady thermal conditions, depending on the type of physical parameters of the system and the type of cooling load occurring in the room. Moreover, the paper sets out the limits of system capacity while maintaining a minimum temperature of the floor surface equal to 20 °C. The results are helpful for designing system capacity in different type of cooling loads and show maximum system capacity in acceptable thermal comfort condition.

1. Introduction

The radiant floor cooling systems do not belong to the most popular air conditioning systems. They are not new systems but their dynamic performance are not well known. It was commonly thought that cooling capacity of radiant floor systems is rather low and that they should be used more as supporting and complementary systems compared to traditional air conditioning systems. However, in certain conditions, their capacity can be greatly increased. It was previously described that cooling floor system can provide good comfort conditions and energy savings [1,2]. They can be successfully used for cooling in conjunction with a ventilation system which aims to ensure the quality of indoor air [3,4]. But the cooling capacities of the system described in the literature are variable and depends on the location of its application. Simmonds et al. [2] described the performance of the system in the International Airport in Bangkok at about 70–80 W/m^2, but Olesen [1] described it at the level 35–50 W/m^2 in office room conditions emphasizing that with a direct sunshine on the floor it amounts to 100–150 W/m^2. Athienitis and Chen described the effect of solar radiation on dynamic thermal performance of floor heating systems [5]. In conditions of floor cooling the effect of solar radiation on system capacity should be more important [6]. The previous papers concerning cooling floor system did not describe what parameters of the system and room are the most important parameters for reached capacities of floor cooling system and what are the limits of its cooling capacity in condition of direct solar radiation. In this paper it appears that the most important for reached capacities of the floor cooling system is the radiation heat flux which falls directly on the floor surface. When this flux is high, temperature of the floor is similar to the air and the convection flux is quite negligible. In commercial buildings usually two types of radiant flux occur: short wave radiation which comes from direct solar radiation and long wave radiation from internal sources of the

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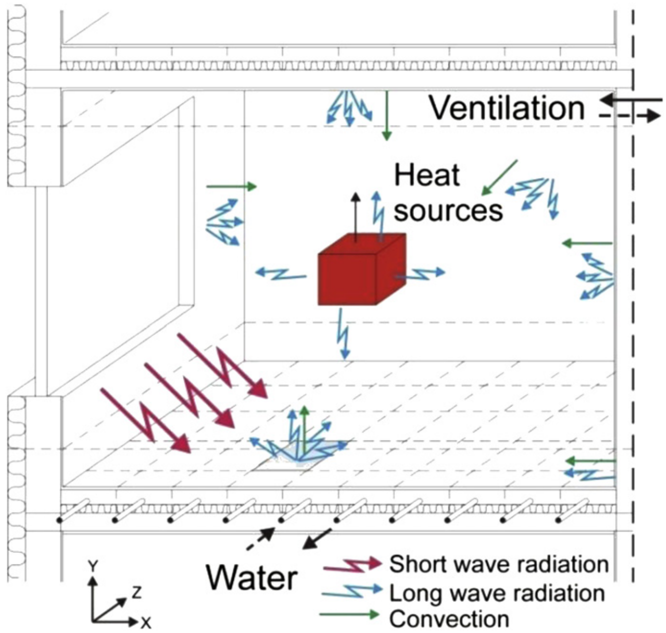

Fig. 1. Schema of the simulated room.

heat, outside surrounding, and surfaces inside the room. In practice, the largest flux of radiation on the floor is the direct solar radiation.

In order to determine the efficiency of the cooling floor system in the rooms numerical model was developed. It allows to simulate dynamic thermal conditions. The numerical model takes into account the short-wave radiation (sunlight) depending on time, falling directly on the floor, as well as long wave radiation emitted by internal heat sources and radiation flux exchanged between surfaces of the room. The model was adjusted to simulate the operation of the system in enclosure heat exchange conditions (e.g., office room). The aim of this research was to determine the limits of floor system capacity in steady state conditions.

2. Simulation model

The numerical model describes a rectangular room, which has one outer wall with a window, a floor equipped with a cooling installation, ceiling and three interior walls separating the inner space from other areas (Fig. 1). The numerical model is based on the method of elementary balances, in an open schema. The model is designed to simulate the unsteady flow of heat in the room. It's similar to presented by Athienitis and Chen [5], but with few modifications. It describes the floor with a simplified, three-dimensional heat flow, and other divisions using one-dimensional heat flow. In one dimensional heat flow calculation the temperature of the layer at the end of time step is given by:

$$T_i' = T_i + a\frac{\Delta\tau}{d^2}(T_{i-1} + T_{i+1} - 2{*}T_i) \tag{1}$$

where T_i [K] is the temperature of the "i" layer at the beginning and T_i' at the end of current time step, T_{i-1}, T_{i+1} [K] are the temperatures of the "i−1" and "i+1" layers at the beginning of the time step, $\Delta\tau$ [s] is the length of current time step, d [m] is the thickness of the layer and a [m^2 s^{-1}] is the thermal diffusivity of the layer.

Due to the "lighting" of the floor by the direct solar radiation, thermal states of the dark and the light parts of the floor will be significantly different. To accommodate this, the floor is divided into 100 rectangular fields, the degree of illumination of each field by the solar radiation is calculated individually (Fig. 2).

To calculate the degree of illumination, each field was divided again into 100 sub-fields. Calculations of each sub-field were done separately to determine whether the centre of the sub-field is illuminated at current time step. The sub-field was recognized as illuminated, if the current vertical angle of the sun beam was between lower and upper angle of visibility of the frame of the window

$$\alpha_{V\ \min} < \alpha_V < \alpha_{V\ \max} \tag{2}$$

$$\alpha_{V\ \min} = \arctan\left(\frac{H_L}{L}\right) \tag{3}$$

$$\alpha_{V\ \max} = \arctan\left(\frac{H_U}{L}\right) \tag{4}$$

where α_V [rad] is the angle between sun beams and horizontal plane, H_L, H_U [m] are the distances between the lower and upper frame of the window and L [m] is the distance between the centre of calculated sub-field and the plane of the window. Similar conditions were applied for right and left frame of the window. Exemplary sunlight illumination is shown on Fig. 2.

The model calculates separately direct solar radiation (short wave), solar diffuse radiation (short wave), and issued by the internal heat source and exchanged between walls (long wave). In the model, for these calculations short-wave radiation emissivity coefficient for the floor was assumed to be 0.8, while for the long-wave emissivity coefficient of all the surfaces equalled 0.9. A simplified diagram of heat exchange in the room is shown in Fig. 1. In the model, the typical building heating/cooling floor was used, consisting of a layer of thermal insulation, a layer of concrete with the sunken tubes and a layer of finishing (Table 1). The floor model is composed of 10 sections, perpendicular to the tubes. In each of the sections two-dimensional heat flow in XY plane is calculated, as follows

$$\dot{Q} = \mathrm{d}x\frac{k}{\mathrm{d}y}(T_{i,j-1} - T_{i,j}) + \mathrm{d}x\frac{k}{\mathrm{d}y}(T_{i,j+1} - T_{i,j}) + \mathrm{d}y\frac{k}{\mathrm{d}y}(T_{i-1,j} - T_{i,j}) + \mathrm{d}y\frac{k}{\mathrm{d}x}(T_{i+1,j} - T_{i,j}) \tag{5}$$

$$\dot{Q}\cdot\Delta\tau = \mathrm{d}x\cdot\mathrm{d}y\cdot\rho\cdot c\left(T_{i,j}' - T_{i,j}\right) \tag{6}$$

0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.09	0.20	0.20
0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.81	1.00	1.00
0.00	0.00	0.00	0.00	0.00	0.00	0.50	1.00	1.00	1.00
0.00	0.00	0.00	0.00	0.00	0.19	0.98	1.00	1.00	1.00
0.00	0.00	0.00	0.00	0.02	0.81	1.00	1.00	1.00	1.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Fig. 2. Exemplary sunlight distribution coefficients on the floor SE window, 15 August, 11:30.