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RADIANT AND CONVECTIVE SPLIT OF INTERNAL HEAT GAIN IN BUILDINGS WITH RADIANT COOLING SYSTEMS

Baisong Ning[1*], Yulong Fang [1], Weilin Li[1]

1 Zhengzhou University, NO. 100 Science Avenue, Zhengzhou 450001

(Email address:bsning@foxmail.com; Tel: +86-0371 67781680)

ABSTRACT

Radiant cooling system is a promising technology in saving building energy consumption as well as achieving better thermal comfort. However, in design and simulation of radiant systems, there is a lack of information on one basic parameter: the radiant and convective split of internal heat gain. This study established the dynamic heat transfer model of rooms with radiant cooling systems and internal heat gain components like equipment, lighting and occupant. Through the parametric simulation results, we found the mean radiant temperature of rooms with radiant system could be decreased by 1.0 ^{0}C. The radiant splits of internal heat gain are increased: from 0.50 to 0.56 for equipment, from 0.50 to 0.54 for lighting, while from 0.40 to 0.48 for occupant.

Keywords: radiant cooling system, radiant and convective heat split, internal heat gain

NONMENCLATURE

Abbreviations	
Q	Heat transfer rate
H	Heat transfer coefficient
T	Temperature
r	Fraction of radiant heat
F	Angle factor
Symbols	
r	Radiant
c	Convective
i	Number of room surface

1. INTRODUCTION

Water-based radiant cooling system has been increasingly being used thanks to its potential of energy saving, better thermal comfort, as well as improved indoor air quality [1,2]. In general, radiant cooling system can be defined as a system that radiant heat transfer covers more than 50% of heat exchange within a conditioned space [3], while conventional all-air system use cooled air to remove all the room heat gain. A recent field study showed that, after two years of operation, the radiant system has used 34% less energy as compared to the VAV system [4]. When compared to conventional all-air system, the main reason of radiant system for energy saving could be attributed to the following aspects : a) the higher water temperature required for cooling can improve the plant efficiency, which contributes to reducing primary energy consumption; (b) the transportation energy for the thermal medium (using water) can be significantly reduced compared to conventional air systems (using air); c) similar to phase change material, radiant slab cooling system has the ability of load shifting from daytime to nighttime.

As the presence of activated radiant surface have changes the building thermal dynamics (especially the radiant temperature of the room), design and simulation of radiant systems should consider these changes. There are a few simulation and experiment studies on the cooling load of radiant systems [5-7] to help better understand the design and control of the system. However, the changes of radiant/convection split from internal heat gain, which mainly includes the equipment, lighting and occupant heat gain, has not been taken into account in these studies. The

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radiant/convection split is a basic parameter in design and simulation of any air conditioning systems. Currently, this parameter is based on testing or calculation with all-air system. For radiant system, no such parameter is available. This study tries to explore the change of room side temperature change, and their impact on the radiant/convection split from internal heat gain for radiant systems. A heat transfer model with the room, radiant system, and the internal heat gain sources will be developed, the impact of various parameters on the radiant and convective heat gain split will be explored.

2. METHODS

2.1 Heat transfer dynamics of radiant cooling room

To investigate the impacts of the presence of activated cooled surface on the internal heat gain split, we developed a dynamic heat transfer model for the room components and the internal heat gain sources, equipment, lighting and occupant, as shown in Fig 1. The heat transfer of RCP includes heat exchange with solar radiation Q_{solar}, internal heat gain Q_{int}, convective heat transfer with air Q_{conv}, long wave radiation heat exchange with other surfaces Q_{lwr}, and the cooling provided by the RCP Q_{rcp}. While the heat transfer for the internal heat source (equipment, occupant, and lighting) include radiant heat exchange with other surfaces Q_{rad}, and convective heat exchange with the air Q_{conv}.

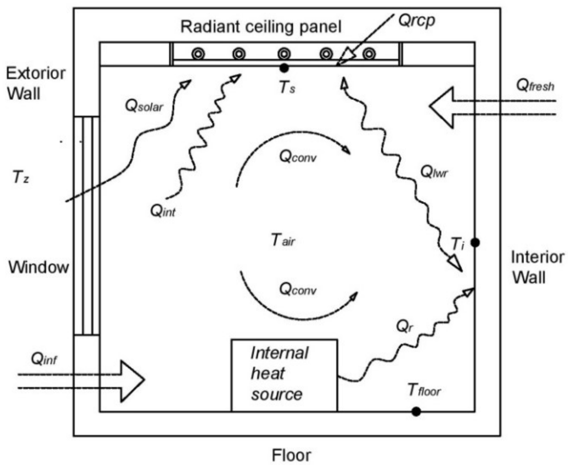


Fig. 1 Heat transfer dynamics for a radiant system

To set up the model, dynamic heat transfer and heat gain calculation of walls, windows, internal heat gain, radiant system component, fresh air system et. al should be taken into consideration. Take the heat transfer of the wall (a typical component in the model) as an example, as shown in Figure 2, the dynamic heat transfer process can be expressed by Eq. (1).

$$\frac{\partial^2 T}{\partial x^2} = \alpha \frac{\partial T}{\partial \iota} \qquad (1)$$

The indoor and outdoor boundary conditions are:

$$\frac{\partial T}{\partial x}\Big|_{x=0} = h_z\left(T_z - T\right) \qquad (2)$$

$$\frac{\partial T}{\partial x}\Big|_{x=l} = h_c\left(T_{air} - T\right) + \sum_{i=1}^{m} h_{r,i}\left(T_i - T\right) + q_{int} + q_{dir} + q_{indir} \qquad (3)$$

Where, α is the thermal diffusion coefficient of material, m^2/s, h_z is the comprehensive heat transfer coefficient between exterior surface and the outdoor thermal environment, W/(m^2·K), T_z is the solar-air temperature, ^{0}C, h_c is convective heat transfer coefficient between the interior surface temperature and the room air temperature, T_i is the interior surface temperature of other surfaces, h_r is the radiation heat transfer coefficient between different interior surfaces, W/(m^2·K), q_{int} is the part of heat gain received from internal heat sources, W/m^2, q_{sol} is the part of heat gain received from solar radiation, W/m^2.

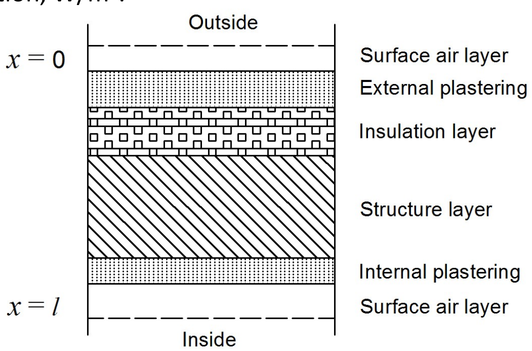


Fig. 2 Diagram of a multi-layer wall

After setting up the equation for window, exterior walls, interior walls, floor, ceiling, radiant system, equipment, occupant, lighting, a set of equations will be established.

2.2 Radiant/convective split for internal heat source

Through solving of the heat balance equation set of different building components, we could get the radiant heat transfer Q_r between room components and internal heat sources.

$$\mathrm{Q}_r = \varepsilon F_i \sum_{i=1}^{n}\left((T_s + 273)^4 - (T_i + 273)^4\right) \qquad (4)$$

Since the total heat released by the internal heat components could be treated the same in rooms with different air conditioning systems, we could calculate the radiant split with equation (4).

$$r = \frac{Q_r}{Q_{tot}} \qquad (5)$$

The convective heat splits equals *1-r*.

2.3 Impact of different parameters

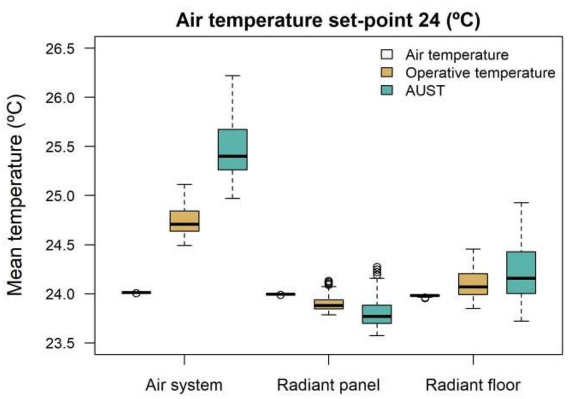
Many factors may impact the radiant and convective heat gain split of internal heat source. To get the quantitative index, a sufficient large database taking into account these impact factors should be developed. In this study, we choose the possible impact factors based on ISO ISO 11855 2012 standard [8], Chinese standard JGJ 142-2012[9], GB 50736-2012[10] and GB 50189 -2015[11]. Night possible impact factors are taken into account, as follows:

(1) Room type: lightweight, heavyweight;
(2) Design temperature: 24 ° C, 25 ° C, 26 ° C;
(3) Location: Beijing, Xi'an, Shanghai, Guangzhou;
(4) Direction: east, west, south, north;
(5) Window to wall ratio: 0.2, 0.4, 0.6;
(6) Radiant types: radiant ceiling panel, radiant floor
(7) Pipe embedded layer material: cement motor, lightweight concrete, medium weight concrete;
(8) Thickness of pipe embedded layer: 0.45 m, 0.65 m, 0.85 m
(9) Pipe spacing: 0.1 m, 0.2 m, 0.3 m.

3. RESULTS

3.1 Room side temperature change

With the presence of cooled surface in the room, the surface temperature of walls, floor and ceilings should be different from the cases with all-all systems. These temperatures will be the main impact factors on the radiant heat transfer rate of the internal heat sources. The main indexes of these temperatures are: room air temperature, area weighted radiant temperature (AUST), and operative temperature, which considers both air temperature and radiant temperature. Figure 3 shows the analyzed the results of thousands of cases.



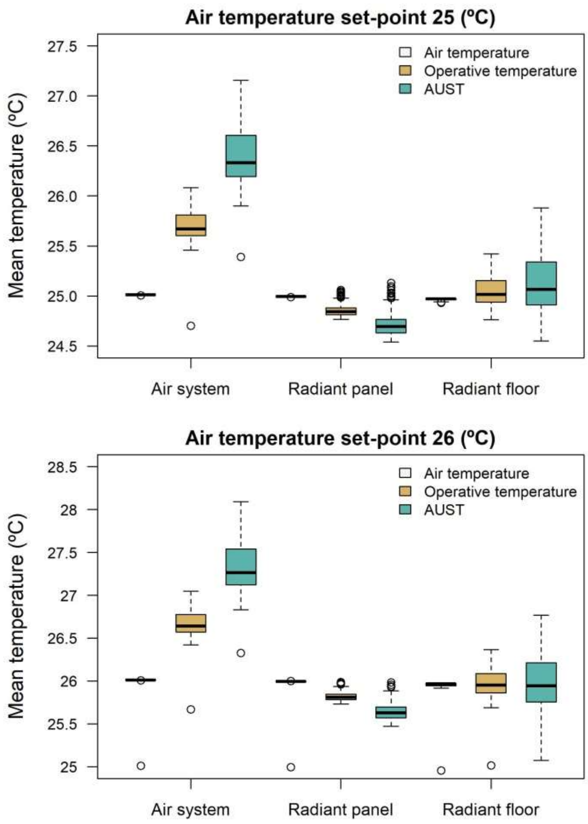


Fig. 3 Room air, operative and radiant temperature distribution for different temperature step points

We can see that, with radiant system, the area weighted radiant temperature (AUST) could be ~1° C lower than all air systems at different room temperature set point. In addition, the difference between the air temperature, operative temperature and radiant temperature with radiant systems are smaller than all-air system. In fact, we could simply use air temperature to represent the radiant temperature if the information is unknown.

3.2 Calculated radiant and convective heat gain split

Through calculation using equation (4), and taking into account the impact factor shown in section 2.3, the mean value and the range of radiant heat splits are shown in Table 1.

Note that, when calculating the radiant heat transfer between internal components and room condition, instead of using AUST, we separately calculate the heat transfer with walls, ceilings and floors, to reduce the calculation errors.

Table 1 Calculated radiant fraction of internal heat gain

	Types	All-air system	Radiant panel	Radiant floor
Equipment	Mean value	0.5	0.55	0.57
	Range		(0.52,0.57)	(0.53,0.61)
Lighting	Mean value	0.5	0.53	0.54
	Range		(0.52~0.55)	(0.53~0.57)
Occupant	Mean value	0.4	0.46	0.48
	Range		(0.43,0.48)	(0.45,0.52)

In Table 1, the radiant splits of heat for all-air system are set as 0.5, 0.5 and 0.4 for equipment, lighting and equipment. We can see that the radiant and convective splits are increase as follows: from 0.5 to 0.56 for equipment, from 0.5 to 0.54 for lighting, from 0.4 to 0.48.

We found the increments of radiant heat split is 8~16% compared to all air system. The impact on occupant and equipment are larger than lighting. It should be noted that, the results are based on calculation, in practice, the heat transfer parameter like heat transfer coefficients and thermal storage might be different from the calculation, experimental studies are needed to verify these results.

4. CONCLUSIONS

Through number of cases simulation, we arrived at the following conclusions:

(1) The area weighted radiant temperature (AUST) could be ~1°C lower than all air systems. Besides, the air temperature and radiant temperature are similar in radiant cooling environment.

(2) The radiant heat gain splits are increased in radiant cooling room: from 0.5 to 0.56 for equipment, from 0.5 to 0.54 for lighting, from 0.4 to 0.48. Experiment studies are needed to verify these conclusions.

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