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Evaluation and comparison of thermal comfort of convective and radiant heating terminals in office buildings

Borong Lin [a, b, *], Zhe Wang [a, b, c], Hongli Sun [a, b, c], Yingxin Zhu [a, b], Qin Ouyang [a, b]

[a] Department of Building Science, Tsinghua University, Beijing 100084, China
[b] Key Laboratory of Eco Planning & Green Building, Ministry of Education, Tsinghua University, China
[c] Beijing Key Laboratory of Indoor Air Quality Evaluation and Control, Tsinghua University, Beijing, China

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ABSTRACT

Radiant heating systems are increasingly widely utilized in buildings for its energy conservation potential and enhanced thermal comfort. This paper presented an experiment to compare the thermal comfort performance of radiant heating system with convective heating system through objective measurement and subjective survey. Six physical parameters which might influence occupants' thermal satisfaction, including the Mean Radiant Temperature (MRT), humidity, air movement, A-weighted sound level, temperature fluctuation and vertical temperature difference, were measured. In addition, 97 subjects participated in the subjective survey part of this experiment, experiencing all the three environments heated by air source heat pump, radiator and floor heating. And they were asked to vote in six thermal comfort related aspects, i.e. thermal sensation, humidity, draught, local discomfort, overall thermal satisfaction and overall preferences, plus the acoustic environment, since the operation noise of heating system might lead to complains of the occupants. It was found that in continuous heating, no significant difference between radiant and convective heating system was observed in the Mean Radiant Temperature (MRT), indoor humidity and noise issue. Though radiant heating systems resulted in lower draught risk and less local discomfort complains in the feet region due to the less significant temperature fluctuations and vertical temperature gradients, radiant heating did not have significantly higher overall thermal satisfaction votes and was not significantly more preferred by occupants.

1. Introduction

Most residential buildings have to be heated in northern China, and domestic heating is significant energy consumer, accounting for 5% of the total energy consumption in China [1]. Heating terminals significantly influence heating energy consumption and indoor thermal comfort. Recently the comparison between convective and radiant heating terminals is hotly debated. Convective heating terminals control indoor thermal environment by supplying hot air. Radiant heating terminals control the indoor temperature by providing hot surfaces. For radiant heating terminals, heat is exchanged through two way, firstly, natural convection between the hot surface and air, and secondly, radiation between the hot surface and other interior surfaces as well as the occupant. Therefore both convective and radiant heat exchange exist in radiant heating system. ASHRAE handbook defined radiant heating system as a system that radiant heat transfer covers more than 50% of the total heat exchange within a conditioned space [2].

1.1. Literature review

During the past two decades, radiant heating terminals are widely utilized in commercial and residential buildings for its energy saving potential and enhanced thermal comfort performance. Like for instance, almost all residential buildings in Korea [3], a wide range of buildings in Japan [4] and 30%–50% of new residential buildings in Germany, Austria and Denmark [5] are equipped with floor heating system. The merits of Radiant Heating and Cooling (RHC) system are as follows.

- Energy saving potential

* Corresponding author. Department of Building Science, Tsinghua University, Beijing 100084, China.
E-mail address: linbr@tsinghua.edu.cn (B. Lin).

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- Reduce heating/cooling load since do not need to warm or cool the entire space and the low heat loss[1].
- Reduce fan power consumption [6]
- Lower pumping energy due to the high thermal capacity of water [7,8]
- Higher chiller efficiency due to the high temperature cooling or low temperature heating [7,8]
- Possibility to utilize renewable energy due to the high temperature cooling or low temperature heating [9,10]
- Reduce peak time energy consumption due to the utilization of building thermal mass [11].

● Improved comfort
- Quiet operation [12]
- Less air movement, hence less draught risk, [13,14] and less transportation of dust [5].
- Reduced vertical temperature gradient [6,14].

As for the floor heating system, in addition to the advantages mentioned above, Zhang [15] pointed out that floor heating is able to create a more comfortable thermal environment for sedentary occupants. Since sedentary occupants are likely to feel coldest in the foot region, due to the less blood circulation accompanied by less movement than the rest of the body, sedentary occupants would feel more comfortable if the foot region was warmed to a higher temperature, which is exactly the case in the space heated by floor heating.

However, some researchers doubted the benefits of improved perceived comfort the radiant heating system is able to achieve. Kitagawa et al.'s [4] chamber experiment found that the environment with small air movement, especially with velocity changes, had higher thermal comfort votes than other environments with almost still air movement. This finding was confirmed by Tian and Love's [16] field investigation. Tian and Love's [16] research found that the slow air movement of radiant heating system led to more complaints and more air movement is preferred since the air velocity is related to ventilation and air freshness by many occupants. In addition, Conceição and Lúcio's [17] and Chung et al.'s [18] found that decreased air velocity of radiant heating system resulted in increasing thermal stratification and asymmetry, and more local discomfort complaints, especially in densely populated area, for instance the classroom. Furthermore, radiant ceiling system is expected to cause local discomfort when used for heating, and similarly radiant floor system might cause local discomfort when used for cooling [6].

The indoor thermal environment of radiant heating system is also assessed by field investigation, collecting both objective physical environment data and subjective occupant response data. Tian and Love [16] performed an on-site thermal environment investigation of a university office building in Canada, which is heated by radiant slab heating system. The measured operative temperature is controlled with the range of 20.3 and 23.6 °C in winter. The discrepancy between PMV and AMV (actual mean vote) is less than 0.1 scale unit. The main merit of radiant heating terminals is found to be its ability to reduce air temperature difference and draft rate in this research. Zeiler and Boxem [19] compared the thermal comfort level of 3 Dutch primary schools heated by radiant floor heating system and that of 11 other primary schools heated by convection heating system through measurements and questionnaires. A slight, but not significant, advantage in the perceived comfort was found for those schools heated by radiant floor heating system. One explanation for this advantage is the overheating problem. In the 2 schools heated by convective system, overheating was observed. However, in the schools heated by radiant floor heating system, no overheating problems were reported. Imanari et al. [6] compared the thermal comfort of radiant heating panel system with that of conventional all-air system, i.e. convective terminals, through collecting subjective responses and measuring objective parameters. It was found that compared with convective terminals, radiant ceiling panel system obtained more votes for comfort from the subjects. However the reason why subjects preferred radiant ceiling panel system than all-air system was still unclear.

From the literature review, it can be seen that on the evaluation of thermal comfort of convective and radiant terminals, the results of previous research are far from consistent and sometimes conflict with each other [20]. Like for instance in literature [13] and [14], radiant heating system led to more thermal comfortable votes due to the less air movement. However literature [4] and [16] reports that subjects complained more in spaces heated by radiant system because they might doubt the freshness of the air since they cannot feel the air movement. Besides, previous research focused on one or several specific thermal comfort parameters however the overall thermal satisfactory of radiant and convective heating terminals and the occupants' preference were not clear.

1.2. Objectives

The goal of this research is to shed light on the comparison of radiant and convective heating terminals from the aspect of thermal comfort, investigating whether different heating terminals lead to different thermal satisfactory levels and to explain the reasons for this difference, which might be able to help choose the proper heating terminals when designing HVAC system. To achieve this goal, both the subjective response and the objective parameters was measured and collected. Firstly, the overall thermal satisfactory of radiant and convective heating terminals were investigated through subjective survey. Three typical heating terminals were compared in this research, i.e. Air Source Heat Pump (ASHP), radiator and Floor Heating (FH). Occupants' preference between these three terminals were also studied. Statistical analysis was employed to validate whether different heating terminals lead to significantly different thermal satisfactory level. Secondly, the reasons behind the overall thermal satisfactory level and occupants' preference between these three typical terminals were explored through the measurement of physical parameters.

2. Methods

The thermal environments heated by Air Source Heat Pump (ASHP), radiator and Floor Heating (FH) were compared under three experimental conditions, the warm, moderate and cool condition. Both subjective survey and objective measurement were conducted in this research.

The experiment was performed in three individual but consecutive office rooms (around 20 m^2 floor area with the ceiling 2700 mm above the floor) located in the northeast part of the Architecture Building of Tsinghua University. The Architecture Building is a six-floor office building, with total floor area of 3000 m^2, located inside the Tsinghua campus. The layout of these three rooms are shown in Fig. 1. These three rooms were heated by different heating facilities: Room 1 by ASHP, Room 2 by radiator and Room 3 by FH. The Air Source Heat Pump was installed 2.4 m above the ground and the radiator was installed under the North window. Both locations were shown in Fig. 1. Detailed information of the

[1] In the space heated by radiant systems, the environment air temperature can be a little lower since the average radiant temperature is higher than spaces heated by convective systems. Therefore, the heat loss through infiltration and exterior envelope is expected to be lower.