A field study on the effect of cold radiation on human thermal comfort in winter

Yunyan Xu1, Zhaojun Wang1,2,*, Xiaowen Su1, Wenjing Lu1

1 School of Architecture, Harbin Institute of Technology
2 Key laboratory of science and technology of human settlements in cold region, ministry of industry and information technology, Harbin 150001, China

* wangzhaojun@hit.edu.cn

Abstract. A field survey of indoor thermal environment was conducted on four office buildings in Harbin. It aims to research the effect of cold radiation on human thermal comfort in winter. The results showed that the average indoor temperature of buildings with floor heating (FH) systems was as high as 27.53 °C, which was 3.2 °C higher than that of the buildings with radiator heating (RH) systems. And thus indoor environment was too warm in FH rooms which seriously affected occupants' thermal comfort. In addition, FH building was less affected by cold radiation from the external windows and walls. However, people complained local thermal discomfort of legs and feet under the overheated environment. In RH buildings, among the votes of local thermal sensation, a large amount of subjects who were within 2m from external windows voted "cold" and complained "shoulder" and "back" were significantly suffered by the cold radiation from exterior envelope.

1. Introduction

Harbin is in the severe cold climate zone in China, where the outdoor air temperature is low and the heating period is long in winter. Therefore, central heating systems with radiator heating (RH) or floor heating (FH) have been used in the North of China in winter.

In the severe cold area, cold radiation of the external windows and walls interacting with heat radiation of the RH and FH contributes to an asymmetrical radiation and an uneven thermal environment [1]. As a result, the occupants who are close to the external envelope often feel uncomfortable [2]. At the same time, due to the high floor temperature of FH, the local thermal sensation of the feet is higher than the overall thermal sensation, and it has a great influence on the overall thermal comfort [3]. It is obvious that occupants show great different thermal sensation in buildings with various heating modes.

Some researchers have focused on the simulation of asymmetric radiation environment in experimental cabins with cooling/heating ceiling, side wall or floor [4, 5]. These studies had shown that discrepancy of occupants' thermal states and local thermal sensations results in difference of their overall thermal comfort. And the thermal discomfort was mainly caused by asymmetrical body temperature, which means one side of the body is hotter or colder than the other sides [6]. The overall thermal comfort response is not the accumulation of local thermal comfort responses, but it follows the "complaint" model, that is, the most uncomfortable parts of the body play a decisive role in the overall thermal comfort response [3]. However, in experimental researches, subjects are asked to wear the unified clothes under the controlled environment with stable indoor environmental parameters. But there are much uncertainty in reality, so it is necessary to study the effect of asymmetric radiation environment on human thermal comfort through field studies. In this paper, a field survey was conducted in four office buildings recently to research the influence of asymmetric radiation on human thermal comfort.
2. Research Methods

2.1. Samples
In January 2019 before winter vacation, a field survey of indoor thermal environment in four office buildings was conducted together with subjective investigation in the coldest month of Harbin. Besides, the location of indoor staff in the room needs to be considered in the survey, so only 168 questionnaires were selected. One of the buildings was the teacher's private offices, which used FH system and totally 14 valid questionnaires were obtained, including 6 males and 8 females. The other three buildings were multi-person offices, which used RH and totally 144 valid questionnaires were collected with gender ratio of about 1:1. More details about the office buildings are shown in Table 1.

Table 1. Sample Information

| Sample Information |
|--------------------|
| Building codes     | 1#     | 2#     | 3#     | 4#     |
| Heating method     | FH     | RH     | RH     | RH     |
| Number of rooms    | 10     | 15     | 12     | 5      |
| Floor numbers      | 5      | 4      | 5      | 5      |

2.2. Objective investigation
We measured the environmental parameters, including indoor air temperature (AT), relative humidity (RH), air speed (AS), globe temperature (GT), and inner surface temperature.
In order to study the effect of cold radiation on human thermal comfort, the indoor air temperature, globe temperature and air speed were measured at the center of the room and 2 m from external windows respectively. According to the requirements of ASHRAE Standard 55-2013[7], the indoor air temperature and air speed were measured at 0.1 m, 0.6 m and 1.1 m from the ground, and then calculated the average value. The relative humidity was measured at 1.1 m above the floor. The surface temperatures were measured at five points in each wall and window, and the average value is considered as the surface temperature. Only the temperature at the center point of floor and ceiling was measured.
In the study, a self-recorded thermometer (WSZY-1A), a self-recorded globe thermometer (HWZY-1), and a hot- wire anemometer (Testo 425) and an infrared thermometer (Testo 830-T1) were used. The test instruments and precision refer to Wang et al [8].

2.3. Subjective survey
Electronic questionnaires were adopted. The subjective survey included the following:

Table 2. Vote scales of thermal response

| Vote                     | Scale                                      |
|--------------------------|--------------------------------------------|
| Overall Thermal Sensation| -3 cold, -2 cool, -1 slightly cool, 0 neutral, +1 slightly warm, +2 warm, +3 hot |
| Local Thermal Sensation  | -1 cold, 0 neutral, +1 warm                |
| Thermal Expectation      | -1 cooler, 0 no change, +1 warmer          |
| Thermal Comfort          | 0 comfortable, +1 slightly uncomfortable, +2 uncomfortable, +3 very uncomfortable, +4 unbearable |

1) Background information of subjects (gender, age, height, weight, etc.);
2) Subject's clothes and their activities during the survey;
3) Thermal responses of subjects, such as overall thermal sensation, local thermal sensation, thermal comfort, thermal expectation and acceptability. The vote scales of thermal response are shown in Table 2.
3. Results

3.1. Thermal environment

The objective investigation results are shown in Table 3. The indoor comfort temperature range in winter is 20–24°C, while the lower limit drops to 18°C in the Chinese code [9]. The indoor air temperature of the FH building was high to 27.53°C, which overwhelmingly exceeded the upper limit of comfort temperature. The average indoor temperature of the RH buildings was 24.27°C, slightly higher than the requirements of the standard. However, the average relative humidity of the FH building was only 15.56% and the RH buildings was only 22.82%, which were considerably lower than the minimum confined. The air speed met the thermal comfort standard (≤0.15 m/s). It is seen that indoor environment in FH buildings was not pleasant where the indoor temperature should be reduced and the relative humidity should be increased.

In addition, the average indoor air temperature and the globe temperature within 2 m from external windows were lower than that at central of the room. The internal surface temperatures of the windows and exterior walls of FH buildings were 9.25°C and 7.18°C in FH buildings lower respectively than the average indoor air temperature. And that were 7.27°C and 3.54°C respectively lower than the indoor average temperature in RH buildings. Thus cold radiation of the exterior walls and windows can cause a non-uniform thermal environment.

Table 3. Environmental parameters

| indoor climates       | The FH buildings | The RH buildings |
|-----------------------|------------------|------------------|
|                       | Mean  | Max  | Min  | S.D. | Mean  | Max  | Min  | S.D. |
| AT(℃)                 |       |      |      |      |       |      |      |      |
| 2m                    | 27.0  | 29.2 | 23.8 | 1.5  | 24.3  | 28.2 | 21.3 | 1.5  |
| center                | 27.5  | 29.4 | 23.6 | 1.6  | 24.3  | 27.6 | 21.6 | 1.4  |
| AS (m/s)              |       |      |      |      |       |      |      |      |
| 2m                    | 0.1   | 0.4  | 0.1  | 0.1  | 0.1   | 0.2  | 0.1  | 0.3  |
| center                | 0.1   | 0.1  | 0.1  | 0.0  | 0.1   | 0.1  | 0.1  | 0.0  |
| GT (℃)                |       |      |      |      |       |      |      |      |
| 2m                    | 26.8  | 28.5 | 24.2 | 1.4  | 24.1  | 23.8 | 11.4 | 2.2  |
| center                | 27.3  | 28.6 | 24.4 | 1.3  | 24.5  | 27.2 | 21.5 | 1.3  |
| RH (%)                |       |      |      |      |       |      |      |      |
| windows (℃)           | 15.6  | 25.1 | 10.0 | 4.7  | 22.8  | 37.0 | 14.2 | 6.0  |
| exterior walls (℃)    | 18.3  | 26.2 | 14.4 | 3.6  | 17.1  | 26.9 | 11.4 | 3.5  |
| inner walls (℃)       | 20.4  | 23.1 | 16.2 | 2.0  | 20.8  | 26.9 | 17.0 | 2.2  |
| ceilings (℃)          | 26.1  | 28.6 | 20.6 | 1.6  | 22.7  | 31.4 | 18.4 | 1.9  |
| floor (℃)             | 31.0  | 34.0 | 25.4 | 2.6  | 22.4  | 20.6 | 35.0 | 2.9  |

3.2. Thermal sensation

The distributions of actual thermal sensation votes (TSV) in Figure 2. From figure 1, it is shown that the percentage of voting for "hot" and "warm" was 71.43% in FH buildings. No one felt "cool" or "slightly cool", which means overheating in this building subjectively. In RH buildings, the votes for "neutral" was 43.75%, and the percentage of voting for "slightly warmer", “warm” and “hot” was 45.85%, In particular, there are also a few of subjects felt “slightly cool”. Overall, the occupants in RH buildings felt more comfortable than FH buildings.

Figure 1. Distribution of residents’ thermal sensation vote
4. Discussion

4.1. Local thermal sensation

Whether subjects feel comfortable, not only depends on the overall thermal sensation of the subjects, but also on the local thermal sensation. Therefore, the subjects' local thermal sensation votes such as "shoulder", "back", "hand", "leg" and "foot" were investigated. The statistical results are showed in Figure 2. As can be seen that in FH buildings, 50% subjects voted "warm" and complained "leg" uncomfortable, and 35.71% subjects voted "warm" for "foot". It can be seen that the floor temperature is too high that the subjects felt hot for their lower part of the body. In addition, a few subjects complained their "shoulder" and "back" were significantly suffered by the cold radiation from exterior envelope.

![Figure 2. Distribution of residents' local thermal sensation votes](image)

In order to study the influence of cold radiation from the external walls and windows, the position of the subjects in the room was collected during the objective investigation. The statistical result of subjects' local cold sensation at different locations in the room are shown in Table 4. As can be seen from the table, the local cold sensation of subjects within 2 m from the windows was higher than that in other locations, especially in the "shoulder" and "back", which were just at the same level with the windows. The result was consistent with Wang et al. [10]. It can be seen that the cold radiation of the external walls and windows will affect the local thermal sensation, and the closer to the windows, the greater the impact.

| Location         | Shoulder | Back | Hand | Leg | Foot |
|------------------|----------|------|------|-----|------|
| 2m from the door | 0.00     | 0.00 | 0.69 | 1.39| 0.69 |
| Middle of the room | 1.39    | 1.39 | 1.39 | 2.08| 2.78 |
| 2m from the window | 6.25   | 4.17 | 3.47 | 4.17| 3.47 |

4.2. Local thermal sensation and thermal sensation

Because the indoor temperature was quite different in different room, the mean overall thermal sensation and the mean local thermal sensation were also different. So then mean thermal sensation (MTS) votes with mean local thermal sensation (MLTS) were linearly fitted. The fitting results are showed in Figure 3 and the relationships were given in Equations (1) ~ (5).
Figure 3. Fitting results of MTS and MLTS

shoulder: \( MTS_s = 0.2106 \times MLTS - 0.1384, \ R^2 = 0.407 \); (1)
back: \( MTS_b = 0.1038 \times MLTS + 0.0376, \ R^2 = 0.0902 \); (2)
hand: \( MTS_h = -0.0397 \times MLTS - 0.0488, \ R^2 = 0.0129 \); (3)
leg: \( MTS_l = 0.1639 \times MLTS + 0.0016, \ R^2 = 0.7697 \); (4)
foot: \( MTS_f = 0.2835 \times MLTS - 0.0782, \ R^2 = 0.88 \). (5)

Where MTS is the mean thermal sensation vote, and MLTS is the mean local thermal sensation vote. By the results analysis, the local thermal sensation of "foot" and "leg" had the highest fitting degree to the overall thermal sensation, indicating that in the asymmetric radiation environment, the uneven indoor temperature will aggravate the local thermal sensation of "leg" and "foot", and then affect the thermal sensation. In an inhomogeneous environment, because the clothing insulation of the shoe is low and the blood circulation in the leg is poor, the foot could intuitively feel the temperature fluctuation near the ground, resulting the lowest local thermal sensation of the foot. Besides, the goodness between the thermal sensation and the local thermal sensation of leg was the highest, which is in accordance with Wang et al. [2]. It is clear that the most uncomfortable part of the body will affect the thermal sensation, and the thermal comfort is close to the most uncomfortable part of the body, that is, the "complaining" mode is followed.

T-test of two independent samples was used to calculate the local and overall thermal sensation votes of subjects within 2 m from the windows and other locations respectively. The results of T-test results for thermal sensation votes were shown in Table 5.

Table 5. T-test results of thermal sensation vote

|     | overall | shoulder | back  | hand  | leg   | foot  |
|-----|---------|----------|-------|-------|-------|-------|
| P   | 0.255   | 0.034    | 0.45  | 0.288 | 0.464 | 0.308 |
| >0.05 | <0.05  | >0.05    | >0.05 | >0.05 | >0.05 | >0.05 |

From the table, only the P of thermal comfort vote on the shoulder is less than the significant level of 0.05, which indicated that the location had a significant impact on the local thermal comfort vote of "shoulder". Because most subjects sit with their back to the window, so the shoulder is more easily affected by the external windows and walls of cold radiation.

5. Conclusion
(1) The average room temperature of the radiant floor heating buildings is 3.2 °C higher than that of the radiator heating buildings. Therefore, when the water supply has the same temperature, the FH buildings need to be equipped with bypass mixed flow devices.

(2) In buildings with floor radiation heating, when the indoor temperature is overheated, the subjects are less affected by cold radiation of the external walls and windows; while the buildings with radiator heating the subjects felt cold radiation when they sat although within 2 m to the windows. However,
they were generally satisfied with the environment by taking appropriate measures or adjusting themselves.

(3) In the asymmetric radiation environment, there is a difference between the local thermal sensation and the thermal sensation, in which the thermal sensation is close to the most uncomfortable part of the body, the leg, and the thermal sensation follows the "complaining" mode. It shows that the thermal sensation can be improved by changing the most uncomfortable part of the body in the asymmetric radiation environment.

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