Comparative Study on Comfort and Energy Consumption of Heating Terminal in Hot-summer and Cold-winter Zone in China

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Abstract: In Hot–Summer and Cold–Winter (HSCW) areas, with the improvement of social economy and people's living quality requirements, most residents are installing radiator and floor heating equipment to meet the heating demand. To explore the thermal comfort difference of different heating terminals and their adaptability in HSCW areas, the thermal environment parameters created by different heating terminals and the energy consumption of the heating system were measured in the laboratory, and the thermal comfort, thermal feeling, and physiological parameters of the subjects were investigated. Results showed that under the same energy consumption, the indoor temperature distribution of Floor Heating (FH) was more uniform, which can better meet the needs of the comfort of the feet and legs of the subjects. Using radiator heating (RH), the comfort of the subjects at different distances from the end had obvious differences, and the improvement effect was not good when the indoor heating temperature rises. The actual test finds that with the increase of indoor temperature, the energy consumption of RH exceeded that of FH. The operating cost of FH is lower, and the actual benefit and economy are higher in the HSCW areas where central heating is lacking. FH has better comfort and economic benefits in HSCW areas. The research provides suggestions and reference for residents to choose heating terminals in winter.

Key words: HSCW areas, heating terminal, thermal comfortable, energy consumption

1. Introduction

China's HSCW climate zone covers the Yangtze River coastal areas, and is one of the most economically developed and densely populated areas in China. Relevant scholars investigated the indoor temperature under natural ventilation in winter rooms in HSCW regions [1–4], and found that compared with other regions, the winter in this region is more cold and overcast, with a long duration and insufficient indoor heating. Residents in this region are in a long-term indoor low temperature environment in winter [5]. With the development of social economy and the improvement of residents' heating demand, most users had installed heating terminals at home [6], among which radiator and FH were common heating terminals. Exploring user comfort and system energy consumption under different heating terminals has become a research focus of many scholars.

Through comparative study, many scholars believe that radiant heating equipment is better than convection heating equipment in terms of vertical temperature difference [7, 8], thermal distribution [9,10], thermal comfort and thermal feeling [11, 12]. However, the radiator and FH are still the research hotspots. Some scholars believe that [13, 14] compared with RH, the vertical temperature difference of FH is small, the local thermal comfort is more uniform, and the overall comfort performance of FH is better. Lin *et al.* [15] compared the performance of radiator and FH equipment. Under the temperature of 21.5~22.5℃, the overall environmental satisfaction of radiator is significantly higher than that of FH, and the subjects prefer rooms heated by radiator. Zhou *et al.* [16] believed through research that the low temperature radiator driven by air source heat pump in HSCW areas has low power consumption and can meet room comfort. Through the above research, it is found that there is still no uniform conclusion on the comfort of using RH and FH. And different from the central heating mode in the north, the winter in HSCW areas is longer and colder than other climate areas in the south. Residents in this area have different adaptation to winter through physiological, psychological, behavioral, clothing and other ways [4]. The thermal comfort evaluation of heating equipment in this area cannot directly copy the research conclusions in other regions.

To find the balance between indoor comfort and energy consumption has been a problem for scholars. Lin *et al.* [17] found that household income is the key factor affecting residents' heating demand through field investigation. Zhou *et al.* [18] used the air source heat pump as the heat source in Shanghai to study the performance of radiators in office buildings during intermittent operation, and found that more than 90% of people were satisfied with the thermal and humid environment, but the COP value of the air source heat pump was low. Hu *et al.* [19] conducted a comparative study on the performance of new bimetallic radiator, cast iron radiator and FH under the continuous heating mode. Under the same heating demand, cast iron radiator has the worst comfort and high energy consumption, while FH has the best comfort, but its operating cost is the highest, and the new bimetallic radiator is among them. The above research found that indoor thermal comfort and system energy consumption are different due to different heating terminal types, so it is necessary to compare energy consumption based on comfort.

2. Method

2.1. Experimental environment

The experiment was carried out in two rooms of the radiant heating and cooling platform of Chongqing University, with an external window size of 2800mm × 2100mm wide × Height), the window is aluminum alloy single–layer window, the glass thickness is 6mm, and thick blue curtains are laid inside; The external walls of the building are 240 mm thick solid brick walls, the external insulation is made of 20mm cement mortar, and the internal walls are 200 mm thick solid brick walls. Conventional FH water coil and radiator are laid in the room. Both heating equipment use the same AC constant frequency double compressor air source heat pump unit as the system heat source.

2.2. Subjects

Based on the type of experiment, the nature of testing indicators, the cost of the experiment and the reliability of the experimental results, a total of 18 subjects (9 men and 9 women) were recruited in the experiment. All of them were college students, who were healthy, aged between 20 and 25, and lived in the local area for more than two years. See Table 1 for summary of basic physiological information of subjects.

During the test, the subjects uniformly wore the basic indoor clothing of residents in the area under natural ventilation environment: autumn clothes, sweaters, coats, trousers and cotton slippers. According to ASHRAE standard 55, the thermal resistance of their clothing was 1.3clo.

Table 1. Subject information.

Gender	Age	Heigh(cm)	Weigh(kg)
Male	23.9±1.4	172.3±5.8	64.1±9.9
Female	24.4±1.1	161.7±2.9	51.0±6.5

2.3. Thermal comfort evaluation

During the experiment, the subjects need to fill in a subjective questionnaire at a certain time point to give feedback on the thermal environment at this time. Subjective questionnaires include: thermal sensation, thermal comfort, air flu, environmental acceptability, etc. Thermal sensation evaluation refers to ASHRAE [20] scale, and its scale is shown in Table 2.

Table 2. Thermal responses voting scale

Voting scale	Thermal sensation	Thermal comfort	Humidity sensation
−3	Very cold	Very uncomfortable	Very humid
−2	Cold	Uncomfortable	Humid
−1	Slightly cold	Slightly uncomfortable	Slightly humid
0	Neutral	Neutral	Neutral
1	Slightly warm	Slightly comfortable	Slightly dry
2	Warm	Comfortable	Dry
3	Hot	Very comfortable	Very dry

2.4. Parameter measurement

In this experiment, 12 measuring plumb lines are arranged. Temperature and humidity probes are arranged at the heights of 0.1m (ankle), 0.6m (knee), 1.1m (sitting head) and 1.7m (standing head) on each plumb line.

The instruments, precision and frequency tested in the experiment are shown in Table 3.

Table 3. Instruments used in the experiment

Instrument	Test content	Measuring range	Measure precision
METREL MI6401	globe temperature	10–120℃	±0.5% (10–49.9℃)
HOBO UX100-011	Air temperature	−20℃~70℃	±0.21℃(0℃~50℃)
	Relative humidity	1%~95%	±2.5%(10%~90%)
KIMO VT100	Wind speed	0.15m/s~30.0m/s	±3%
DS1922L-F5	skin temperature	−10℃~+65℃	±0.5℃

2.5. Test conditions and process

According to GB50736–2012 Code for Design of Heating Ventilation and Air Conditioning of Civil Buildings, the indoor design temperature range of civil buildings in HSCW climate zone in winter is 16~22℃. Three temperature levels of 18, 20 and 22℃ are selected for the experiment. Two radiant heating terminals, radiator and conventional water coil, are used to discuss the thermal comfort of personnel at different terminals and energy consumption based on thermal comfort performance.

Each working condition lasts for 90 minutes, and the subjects wear standard clothes. First, they stabilize for 30 minutes without heating in the laboratory. During this period, they fill in a comfort questionnaire every 5 minutes to investigate the thermal comfort without heating. At the 30th minute, enter the room where the heating equipment has been turned on and the thermal environment has been stabilized, conduct a 60 minute heating thermal comfort experiment, and fill in the questionnaire at 1, 3, 5, 10, 15 minutes at this time, and then fill in the questionnaire every 15 minutes.

3. Result

3.1. Subjective voting

Due to the different characteristics of the thermal environment created by the two types of heating equipment, in the experimental room, three different subject positions are divided by the distance from the radiator to conduct a comparative study on the thermal comfort and thermal sensation of the subjects in different areas. As shown in Fig. 1 and Fig. 2, door area is farthest from the radiator and window area is close to the radiator. It can be seen from Fig. 2 that when the ambient temperature is 18 ℃, at door area, both types of radiant heating equipment cannot meet the comfort of the feet and legs of the subjects. At middle area, the overall comfort of FH is significantly higher than that of FH (p=0.029). Under the working condition of 20 °C, the comfort of using two kinds of heating equipment is improved. The average voting value of floor panel heating comfort is higher than that of RH. In door area, the comfort of feet and legs of floor panel heating is significantly higher than that of RH (p =0.029, p =0.037). When the working condition is 22 °C, the thermal comfort vote of RH in middle area and window area is higher than that of FH, but there is no significant difference between the two, while in door area, the thermal comfort vote of FH is significantly higher than that of RH (p =0.03). When using RH, the comfort vote of door area, middle area and window area is significantly different (p =0.008, p =0.04).

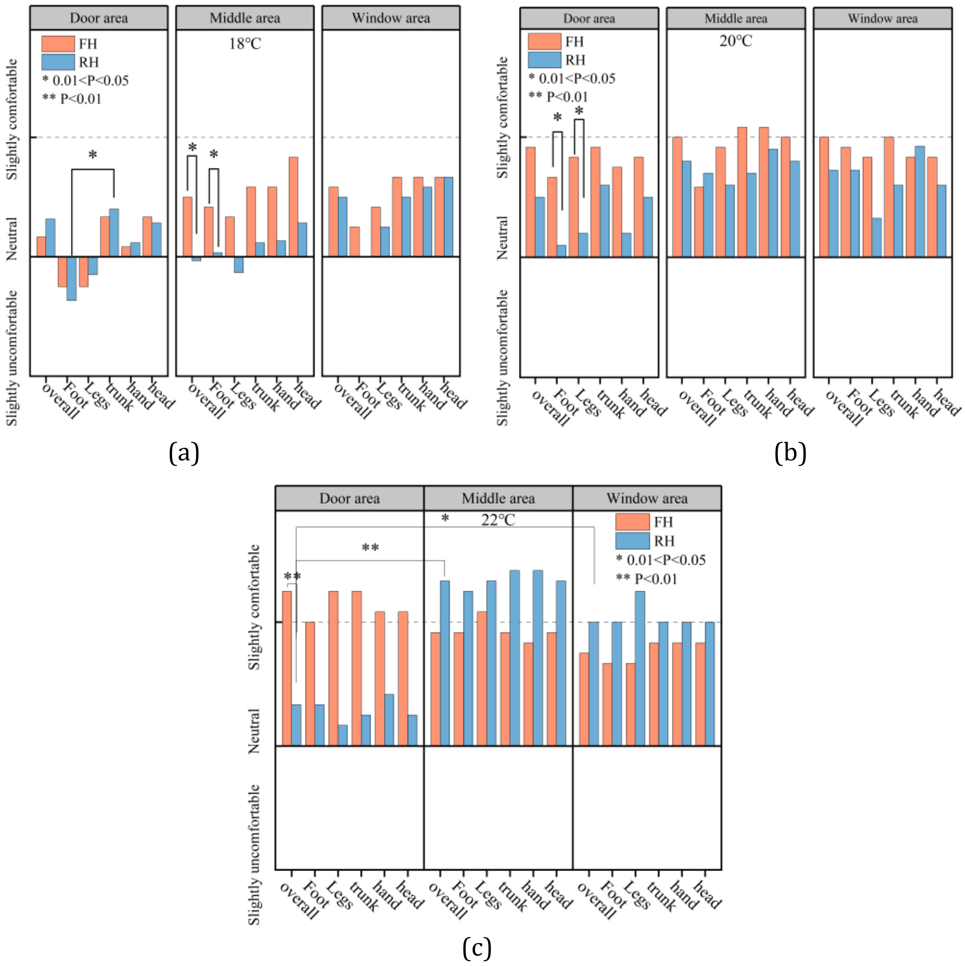
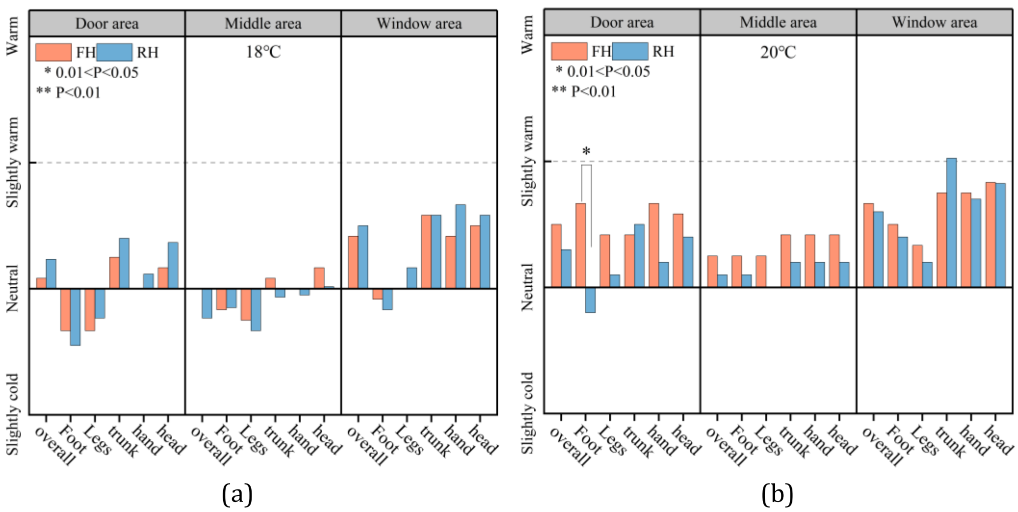
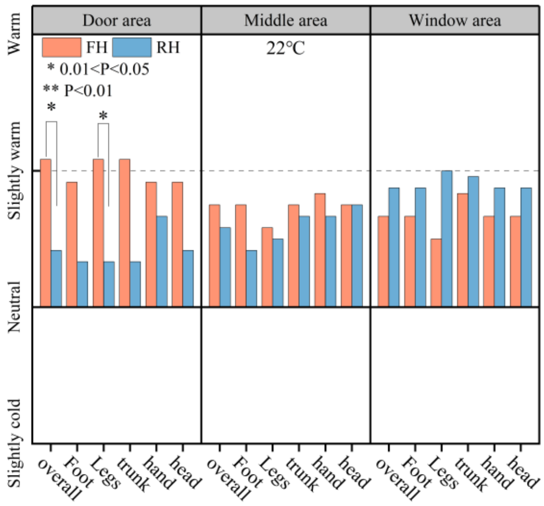


Fig. 1. Thermal comfort voting of subjects at different positions: (a) 18℃, (b) 20℃ and (c) 22℃.





(c)

Fig. 2. Thermal sensation voting of subjects at different positions: (a) 18°C, (b) 20°C and (c) 22°C.

3.2. Heating energy consumption

During the thermal comfort experiment, in order to evaluate the energy consumption of using different heating equipment to create a heating environment, the building energy consumption monitoring system is used to record the heating energy consumption under various working conditions. As shown in Fig. 3. The system records the energy consumption data every 20 minutes, and the final total heating energy consumption is the cumulative value of each time. The system energy consumption diagram under different heating modes is made. According to the data calculation, under the working condition of 18 °C, the 24–hour cumulative energy consumption of radiator is 21.40 KW·h, and the FH energy consumption is 20.10 KW·h; Under the working condition of 20 °C, the 24–hour cumulative energy consumption of radiator is 29.01 KW·h, and the FH energy consumption is 31.25 KW·h; Under the condition of 22 °C, the 24-hour cumulative energy consumption of radiator is 49.36 KW·h, and the FH energy consumption is 39.82 KW·h. According to the data, under the same temperature of 18 °C and 20 °C, the energy consumption of FH is close to that of RH. At 22°C, the energy consumption of RH is significantly higher than that of FH. And during the whole experiment. The outdoor temperature is similar, so it can be considered that the outdoor temperature has the same impact on the system operation performance.

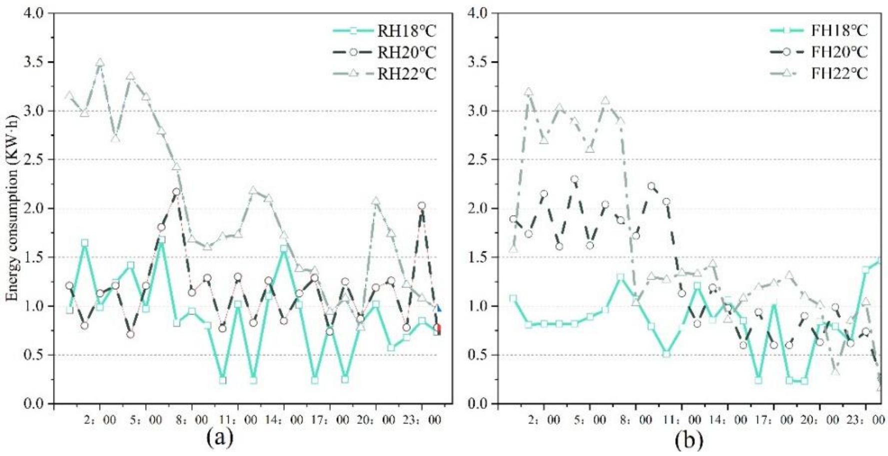


Fig. 3. Energy consumption of different heating equipment

4. Discussion

4.1. Comfort analysis

Under the working condition of 18 °C, the proportion of discomfort of the subjects in the area near the door furthest from the radiator was the largest, and the voting value of foot and overall thermal comfort and thermal sensation was the lowest. The reason is that, when using radiator for heating, No. 1 is the farthest from radiator, and its heat flux is the lowest; For FH, because the area near the door is at the end of the water coil, the water temperature at this location is low, and the heat exchange is low, so the heat flow density at this location is the lowest. In the middle area, using FH, the thermal sensation of the subjects' feet is significantly higher than that of RH, so the overall comfort of the subjects is significantly higher than that of RH. Under low temperature heating, FH can ensure the foot comfort of more subjects, and its comfort effect is better. Under the working condition of 20 °C, the comfort voting of the feet and legs of the subjects using FH near the door area was still significantly higher than that using RH. Under the working condition of 22 °C, the foot comfort of RH is better than that of FH in the area near the window, while the FH is better than that of RH in the area near the door. When using radiators for heating, it is found that there is a significant difference in thermal comfort voting between the area near the door, the middle area and the area near the window. The study found that increasing the heating environment temperature could not improve the thermal comfort difference at different distances under RH, and the thermal comfort uniformity of FH was better than that of RH.

To sum up, the FH terminal has a large effective heating area, which can ensure the comfort of the feet and legs of the subjects at various locations.

4.2. Energy consumption analysis

Based on the analysis of the environmental satisfaction of the subjects, the radiator is not suitable for low-temperature heating, and its lower limit of heating temperature is higher than that of FH. According to the actual measurement of energy consumption, the energy consumption of FH at 18 °C is lower than that of radiator at 20 °C. At 20 °C, the energy consumption of the two types of heating equipment is similar. When the heating temperature continues to rise, the energy consumption of RH increases significantly. On the premise of environmental satisfaction, the use of FH will broaden the range of user temperature settings and energy consumption, which can better adjust comfort and economy. Energy conservation and consumption reduction are widely concerned by scholars all over the world. At present, countries are also vigorously developing low-temperature radiant heating systems, so the operating energy consumption level of the heating system should be reduced as much as possible. One of the measures is to reduce the indoor heating environment temperature. From the point of view of user's economic conditions and energy saving and consumption reduction, it is considered that the operating cost of FH is lower than that of RH, which has certain economic advantages.

5. Conclusion

To explore the suitability of different heating equipment in HSCW areas, comparative experiments were conducted in the laboratory. Through objective evaluation and analysis of experimental data, the following conclusions were drawn:

1) Under the same energy consumption, the FH equipment has a large effective heating area, and it can better ensure the comfort of different locations; The RH appeared on the far side of the radiator, and there was a significant difference between the comfort of the whole body and the legs and the comfort of the nearby parts;
2) Under low temperature conditions, RH cannot meet the comfort requirements of most subjects, and cannot effectively guarantee the thermal comfort and thermal sensation of the legs and feet of subjects.
3) For low temperature heating, the energy consumption of the two heating equipment systems is close. With the increase of heating temperature, the energy consumption of radiator increases more obviously compared with that of FH.

To sum up, FH has advantages in thermal comfort and operating cost, and has better suitability in HSCW areas.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Zelong Tian, Hong Liu concuted the research; Zelong Tian analyzed the data and wrote the paper. All authors had approved the final version.

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