Experimental study on thermal performance of roof and floor capillary radiant heating systems

Hang Zou¹, Enshen Long²,¹,*, Yin Zhang² and Pei Ding¹

¹Institute for Disaster Management and Reconstruction, Sichuan University, Chengdu, 610207, China
²Key Laboratory of Deep Earth Science and Engineering (Sichuan University), Ministry of Education, Chengdu, 610065, China

*Corresponding email: longes2@163.com

Abstract. This research picks up the bedroom and study of a residential building in Chengdu as the research object. The temperature variations in the supply water of the room, the surface temperature of roof and floor, and the indoor air is analysed when the capillary ends were located on the roof and the floor respectively. Furthermore, the internal mechanism of the different heating environments of the two heating modes is revealed by analysing the heat flux density. The results show that: under the same water supply temperature and flow rate, the thermal response time of the roof radiant heating is shorter and the stability of the surface temperature of the floor radiant heating is better due to the different thickness of the capillary network. The floor heating room has more uniform distribution and better comfort. The heat transfer characteristics of the roof and floor surface are different, and the variation of the radiation and convection heat transfer amount are also different. The heat flux density of the roof increases faster and the maximum value can be reached in only 60 minutes, while the floor needs 156 minutes. The roof heating is about 4.36% higher than the floor heating in the proportion of radiation heat exchange. Thus, roof radiant heating is preferred for intermittent heating. This paper provides a reference when designing the end of the residential heating systems.

1. Introduction

Capillary radiant heating end is gradually popularized and applied for its advantages of comfort, rapid heating, the ability of using low-temperature heat source and a small footprint. The air source heat pump is especially suitable for distributed heating. It uses the air source as a low-grade heat source which can be used for both cooling and heating. It meets the climate requirements of hot summer and cold winter regions and has the characteristics of energy saving and flexible installation. At present, there are many researches on capillary radiant heating. R. K. Stand and K. T. Baumgartner [1] proposed a mathematical model of radiant heating through the study of radiation principle and physical model. S. Sattari and B. Farhanieh [2] established a floor radiant heating model which simulated the influence of different floor radiant heating design parameters on indoor temperature. It is shown that the surface layer material and thickness have the greatest influence on the indoor temperature. Rongling Li, et al [3] conducted a radiant heating performance and thermal environment test on a pilot project using capillary radiation in Japan. It is shown that the upward heat loss accounts for 30-40% of the total heat supply. Borong Lin, et al. [4] compared the thermal comfort of the radiant heating system with the convection heating system through objective measurement and subjective investigation.

Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Published under licence by IOP Publishing Ltd
Most of the existing researches have carried out theoretical research on capillary radiant heating by establishing a radiant heating model [5-9], and some scholars have studied the indoor thermal comfort under radiant heating mode by numerical simulation [10-13]. Experimental research on the indoor thermal environment under different radiant heating modes is less, besides, the influence of outdoor meteorological parameters on the indoor thermal environment is basically ignored. In this experiment, the air source heat pump is combined with the capillary radiant heating ends, and the roof radiant heating is consistent with the outdoor meteorological parameters of the floor radiant heating experiment. The thermal comfort under different heating modes is studied by analyzing the room supply and return water temperature, the radiation surface temperature, unheated surface temperature and indoor air temperature.

2. Experimental set-up

2.1. Experimental room
The experimental platform is located in Shuangliu County, Chengdu, and the experimental platform plan is shown in Figure 1. The bedroom and the study are used for comparison rooms because of the same direction and similar size. The bedroom is 4000×3450×2800mm (length × width × height) and the study is 4100×3150×2800mm (length × width × height).

2.2. Experimental system
An air source heat pump unit was used as cold and heat source in the experimental system (as shown in Figure 2). In the winter, the air source heat pump was utilized to obtain the hot water. The high temperature hot water was supplied to the capillary network ends through the plate heat exchanger, and the water flow of the capillary network was adjusted by the valve on the manifold.

Figure 1. Experimental platform
Figure 2. The experimental system
The ends of the experimental system were divided into two kinds of laying methods: the capillary network was placed on the roof of the bedroom and the floor of the study. The capillary network was made of SB20 type. The layout of the capillary network in the roof is different from it in the floor, and the structure map of the capillary radiation is given in Figure 3.

Figure 3. The structure map of capillary radiation
2.3. Experimental content
The duration time of the experiment was from 2:10 am to 6:55 am. The outdoor air temperature was stable during the experiment and ranged from 8.2 °C to 10.9 °C, and the average temperature was 9.65 °C. The return water temperature of main unit was controlled to 35 °C. In each room, 6 measuring points were set in the building inner envelope (as shown in Figure 4) and 4 indoor air temperature measuring points were set in the space (as shown in Figure 5). 2 of the 4 indoor air temperature measuring points were set in the vertical direction of the room from the ground at 0.1 m (ankle) and 1.7 m (the top of the standing head). At the same height of 1.7 m, 1 measuring point was set on the side close to the door and another close to the window.

2.4. Basic theory
Combined thermal heat transfer between capillary radiant roof and floor \( q_1 \):

\[
q_1 = q_r + q_c
\]

Radiant heat transfer heat flux between roof, floor and indoor air \( q_r \):

\[
q_r = 5 \times 10^{-8} \times \left( t_{pj}^4 - t_{fj}^4 \right)
\]

(2)

Convective heat transfer heat flux between roof, floor and indoor air \( q_c \):

\[
q_c = h \left( t_{pj} - t_a \right)
\]

(3)

(4)

(5)

(6)

Where: \( q_1 \) - total heat flux, W/m²; \( q_r \) - radiant heat flux, W/m²; \( q_c \) - convective heat flux, W/m²; \( t_{pj} \) - radiated surface average temperature, K; \( t_{fj} \) - non-heated surface weighted temperature, K; \( A_i \) - i-th surface area of the room, m²; \( \varepsilon_i \) - emissivity of the i-th surface of the room; \( t_i \) - average temperature of the i-th surface of the room, K; \( n \) - number of non-heated surfaces; \( t_a \) - indoor air temperature, K; \( h_c \) - convective heat transfer coefficient; \( h_{cr} \) - roof convection heat transfer coefficient; \( h_{cf} \) - floor convection heat transfer coefficient.

3. Results and discussion

3.1. Temperature in the vertical and horizontal direction of space
The temperature distribution in the vertical direction under different radiant heating modes is given in Figure 6. The longitudinal temperature difference of the roof and floor radiant heating was 2.0 °C and 1.6 °C respectively when the vertical height was 0.1~1.7 m, and the thermal comfort by adopting floor radiant heating was better. The temperature gradients of the roof and floor radiant heating were respectively 1.25 °C/m and 1.0 °C/m which meet the ASHRAE standard.

The temperature distribution in the horizontal direction of the space under different radiant heating modes is shown in Figure 7. When the vertical height was 1.7 m, the horizontal temperature difference between the roof and the floor radiant heating were respectively 0.7 °C and 0.3 °C (the temperature difference was from the side near the window to the side near the door). The temperature gradients were respectively 0.7 °C/m and 0.3 °C/m, similarly, the thermal comfort of floor radiant heating was better.

3.2. Heat flux of radiant roof and floor

In order to analyze the heat transfer form and variation law of the roof and floor surface, the test data are brought into the equations (1) ~ (6). It can be seen from figure 8 and 9 that the process of comprehensive heat flux density, radiant heat flux density and convective heat flux density can be divided into two stages: increasing and oscillating in a certain range. With the increase of the surface temperature of the roof and the floor, the radiant heat flux density and the convective heat transfer heat flux density increase rapidly. After 60 minutes, the radiant heat flux density and convective heat flux density reach the maximum value of 84.2 W/m² and 56.7 W/m² respectively. And the integrated heat flux density reached 140.9 W/m². After 156 minutes, the radiant heat flux density and convective heat flux density reached 53.8 W/m² and 36.2 W/m², respectively, and the integrated heat flux reached 90.1 W/m². The top plate ends the increase phase at 60 minutes, while the floor ends the increase phase at 72 minutes, after which it enters a range of oscillations within a certain range.
3.3. Analysis of surface heat transfer characteristics of radiant roof and floor

In order to analyse the contribution rate of ground net radiation heat transfer and convective heat transfer in the floor comprehensive heat transfer, Figure 10 and Figure 11 show the variation of the radiation heat transfer and convective heat transfer percentage of the roof and the floor, respectively.

It can be seen from Figure 10 that the percentage of roof radiation heat transfer in roof comprehensive heat transfer decreases first with the change of water supply temperature, and then oscillates with the change of water supply temperature within a certain range. The percentage of convective heat transfer first increased and then changed with the water supply temperature in a certain range. At the initial stage of 63 minutes, the radiative heat transfer percentage decreased from 97.7% to 61.8%, and the convective heat transfer percentage increased from 2.3% to 38.2%.

As shown in Figure 11, the percentage of floor radiation heat transfer in the comprehensive floor heat transfer decreases first, and then gradually decreases to a stable level after increasing. The percentage of convective heat transfer first increased, then increased to stable after decreasing. In the initial stage of heating for 9 minutes, the radiative heat transfer percentage decreased from 97.5% to 54.38%, and the convective heat transfer percentage increased from 2.5% to 45.6%. When the water supply temperature continues to rise, the radiative heat transfer percentage gradually increases to 64.5%, and the convective heat transfer percentage gradually decreases to 35.5%.

Comparing Figure 10 and 11, the variation of the proportion of radiation heat exchange is different. The proportion of radiation heat exchange is larger because the heating surface temperature of the two heating modes increases rapidly. The difference is that radiation heat exchange of roof and floor heating accounted for 64.74% and 60.38%, and roof heating was about 4.36% higher than floor heating. When the water supply temperature reaches the set value, the radiation heat transfer amount of the roof has a certain fluctuation trend with the change of the water supply temperature. The reason for the slight increase of the overall radiation heat exchange amount is that: the proportion of radiation heat transfer increases slightly, because the hot air floats more obviously in the roof heating and the amount and rate of convection heat transfer decrease faster. The reason why the floor radiant heating curve is stable is that the floor surface temperature and indoor air temperature change little in steady heating, and the radiation and convection heat exchange amount are changed little.

4. Conclusions

In this paper, the indoor thermal environment of the roof and floor capillary radiant heating is analyzed comparatively. Conclusions are as follows:

1) The radiation surface temperature has a great relationship with the structural layer of the capillary network. When the roof radiant heating is adopted, the radiation surface temperature is higher and the thermal response time is shorter which reach the indoor set temperature. When the floor radiant heating is adopted, the temperature of the radiation surface is low and the thermal response time is longer. After reaching the heating stabilization phase, the bedroom roof radiant surface temperature fluctuates greatly
with the start-stop of the main unit. While the floor radiation surface temperature stably increases because of the flooding and releasing heat of the structural layer.

2) Comparing the spatial temperature distribution under the two radiant heating modes, the vertical temperature difference and the horizontal temperature difference of the floor radiant heating are lower than the roof radiant heating, and the floor radiant heating has higher comfort.

3) The heat transfer characteristics of the roof and floor surfaces are different. The process of comprehensive heat flux density, radiant heat flux density and convective heat flux density can be divided into two stages: increasing and oscillating in a certain range. However, the rate of increase of the roof is faster and reach the maximum in only 60 minutes, and the floor increases slowly and reach the maximum in 156 minutes.

4) The radiation and convection heat transfer characteristics are related to the thickness of the convection heat. The radiation and convection heat transfer ratio of the two heating modes are different. The roof heating is about 4.36% higher than the floor heating in the proportion of radiation heat exchange during steady heating.

5) Roof radiant heating should be preferred for intermittent heating. Roof radiant heating has the characteristics of low thermal inertia and fast response speed. Thus, the indoor air temperature increased rapidly, and the heating system will be more energy efficient.

Acknowledgements
This work was supported by the National Key Research and Development Program of China [2016YFC0700400]; the National Natural Science Foundation of China [No.51778382].

References
[1] Strand, R. K. , & Baumgartner, K. T. . (2005). Modeling radiant heating and cooling systems: integration with a whole-building simulation program. Energy and Buildings, 37(4), 389-397.
[2] Sattari, S. , & Farhanieh, B. . (2006). A parametric study on radiant floor heating system performance. Renewable Energy, 31(10), 1617-1626.
[3] Li, R. , Yoshidomi, T. , Ooka, R. , & Olesen, B. W. . (2015). Field evaluation of performance of radiant heating/cooling ceiling panel system. Energy and Buildings, 86, 58-65.
[4] Lin, B. , Wang, Z. , Sun, H. , Zhu, Y. , & Ouyang, Q. . (2016). Evaluation and comparison of thermal comfort of convective and radiant heating terminals in office buildings. Building and Environment, 106, 91-102.
[5] Miriel, J. , Serres, L. , & Trombe, A. . (2002). Radiant ceiling panel heating-cooling systems: experimental and simulated study of the performances, thermal comfort and energy consumptions. Applied Thermal Engineering, Volume 22(issue 16), 1861-1873.
[6] Weitzmann, P. , Kragh, J. , Roots, P. , & Svendsen, S. . (2005). Modelling floor heating systems using a validated two-dimensional ground-coupled numerical model. Building & Environment, 40(2), 153-163.
[7] Richard K. Strand, Curtis O. (2002). Pedersen. Modeling Radiant Systems in an Integrated Heat Balance Based Energy Simulation Program. ASHRAE Trans, 97998.
[8] Mikeska, T. , & Svendsen, S. . (2012). Heating and cooling with capillary micro tubes integrated in a thin-shale concrete sandwich element. Passivhusnorden.
[9] Mikeska, T. , & Svendsen, S. . (2013). Study of thermal performance of capillary micro tubes integrated into the building sandwich element made of high performance concrete. Applied Thermal Engineering, 52(2), 576-584.
[10] Myhren, A. , Jonn, HOLMBERG, & Sture. (2008). Flow patterns and thermal comfort in a room with panel, floor and wall heating. Energy & Buildings, 40(4), 524-536.
[11] Schellen, L. L. , Timmers, S. S. , Loomans, M. M. , Nelissen, E. E. , Hensen, J. J. , & Marken Lichtenbelt, V. W. W. . (2012). Downdraught assessment during design: experimental and numerical evaluation of a rule of thumb. Building & Environment, 57(4), 290-301.
[12] Fathollahzadeh, M. H., Heidarinejad, G., & Pasdarshahri, H. (2016). Producing a better performance for the under floor air distribution system in a dense occupancy space. Energy & Buildings, 126, 230-238.

[13] Holmberg, S., & Chen, Q. (2003). Air flow and particle control with different ventilation systems in a classroom. Indoor Air, 13(2), 200-204.