Journal of Building Engineering 8 (2016) 48–57

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: www.elsevier.com/locate/jobe

Evaluation of thermal characteristics on a multi-sheet-type radiant panel heating system

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ARTICLE INFO

Article history:
Received 10 May 2016
Received in revised form
5 September 2016
Accepted 15 September 2016
Available online 16 September 2016

Keywords:
Radiant panel
Thermal environment
Heat transfer
U-value
Computational fluid dynamics (CFD)

ABSTRACT

The purpose of this study is to examine the thermal characteristics of a multi-sheet-type radiant panel heating system and its effect on the indoor thermal environment. To examine the thermal characteristics using computational fluid dynamic (CFD) simulations, simulation of a radiant panel model that considers actual usage condition combined with convection and radiation is very important. We analyze the indoor thermal environment of a real-scale space, heated by a radiant heating system, using full-scale measurement and CFD simulation. In a multi-sheet-type radiant panel, the convective heat transfer is greater than the radiative heat transfer. The multi-sheet-type radiant panel is actually not a real "radiant panel." It is named as such by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers because its radiative heat transfer is more than 50%. We also determine the effects of indoor setup location of the radiant panel and panel shape on the heat-discharge characteristics. Compared with a single-sheet-type with the same heat discharge, a multi-sheet type has a larger surface area and area of contact with air. Thus, the convective heat transfer is greater, and the radiative heat transfer is smaller.

1. Introduction

To address the energy and environmental problems associated with global warming, increasing attention is being focused on the use of radiant heating systems combined with natural ventilation as energy-saving systems. Radiant heating systems such as floor, ceiling, wall, and panel heating systems are now regarded as energy efficient and comfortable heating systems compared with conventional heating systems [1–7]. The radiant heating system offers many advantages. It is more efficient than conventional air-conditioning system, and it directly delivers heat from the hot panel surface to the people skins and in the room via infrared radiation. Further, it does not produce noise or cause drafts and does not use ducts. Moreover, the system provides uniform temperature distribution, which is suitable for improving personal convenience. Hydronic (liquid-based) radiant heating systems can use a wide variety of energy sources to heat the liquid, including standard gas-fired boilers, oil-fired boilers, solar water heaters, geothermal heat pumps, or a combination of these sources. Additionally, many energy-efficient building technologies with increased thermal insulation and airtightness have also been applied in buildings with radiant heating systems, which could contribute to low building heat loss and reduce energy consumption [8].

The computational fluid dynamic (CFD) technology has been extensively used to predict indoor heat transfer and thermal comfort environment in a radiant panel heating system. Myhren and Holmberg [9] and Chen [10] discussed different heating systems using CFD simulations (a surface-to-surface radiation model and a low-Re number k–ε turbulence model) to investigate draught problems, differences in vertical temperature gradients, air-speed levels, and energy consumption in their work areas. Karadag et al. [11] used the standard k–ε turbulence model to study ceiling-panel systems. They found that when the room dimensions and temperature difference between the ceiling and interior air increase, the Nusselt number over the floor also increases. Song and Kato [12] performed a simple analysis of an indoor thermal environment of a radiant panel system using CFD simulation. They demonstrated that a hybrid air-conditioning system with a radiant panel system could realize better energy efficiency than ordinary systems in a hot and humid climate. However, verification using full-blown experiments has not been performed. In addition, although the radiant panels used were the multi-sheet-type in which thin panels were lined up to more

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http://dx.doi.org/10.1016/j.jobe.2016.09.006
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effectively exploit the dehumidifying effect of surface condensation, evaluation of the simulations was done using a simple model with a single sheet.

The CFD simulation must be verified through detailed modeling that simulates the actually used panel because this is the only means of accurately ascertaining the heat-discharge characteristics of a radiant panel while separating the radiated and convected heat components. In particular, multi-sheet-type panels have a useful function to adjust humidity environment that they easily cause surface condensation at a low surface temperature owing to their increased contact with air in the cooling mode. However, significant potential for a high level of convective heat transfer is expected due to the increase in the heat exchange area with air. Naturally, when panels consisting of multiple thin sheets are modeled using the CFD simulation, the calculated load increases with a finer mesh partition. However, with the present development in computer performance, this problem is not expected to be a major issue. To ascertain the heat-discharge characteristics of the panels, examining the heating operation at night is appropriate to eliminate the thermal load elements (solar radiation and latent heat) that complicate the simulation.

For the above reasons, the present study focused on a space heated by a radiant panel, and the heat-discharge characteristics of the radiant panel were ascertained by analyzing the room airflow and temperature distributions according to actual measurements and numerical analysis. Prediction precision sufficient for practical numerical analysis was confirmed for an indoor environment using a radiant panel by comparing and examining the results of both numerical analysis and actual measurement. This study also determines the extent to which the indoor setup location of the radiant panel and panel shape affect the heat-discharge characteristics of the radiant panel.

2. Experimental study

2.1. Full-scale room model description

Fig. 1 shows the space where the measurements were conducted [4.50 m (W) × 3.60 m (D) × 2.30 m (H)], which was in an experimental house at the Chiba Experiment Station (N 35° 36′ 18″, E 140° 7′ 24″), Institute of Industrial Science, University of Tokyo, Japan, as well as the radiant panel heating system. The west-side wall was connected to the adjoining preparation room, and the other walls were adjacent to the outside. In addition, the space has also two horizontal slider windows with dimensions of 1.60 m (W) × 0.80 m (H) and two vertical swing windows with dimensions of 1.60 m (W) × 0.40 m (H) in the north- and south-side walls. In the room, heating was provided using a multi-sheet-type radiant panel only [Table 1, two columns × 35 sheets (one sheet: 0.07 m (W) × 0.005 m (D) × 2.0 m (H); spacing distance between sheets = 0.035 m; spacing distance between columns = 0.02 m)]. The surface area of the radiation panel was 21.049 m^2, and 15 L/min of heated water was supplied to the radiation panel. No air inlet/outlet for ventilation or air conditioning was present. Thus, the only airflow in the room was natural convection due to buoyancy.

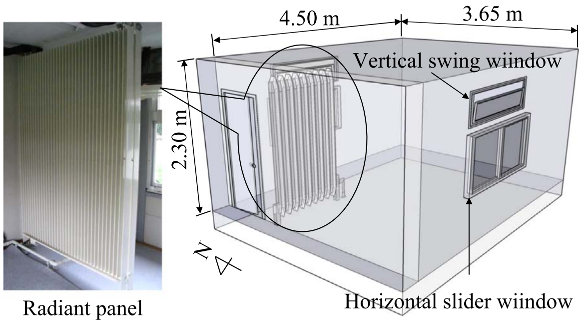

Fig. 1. Schematic room model with a radiant panel heating system.

Table 1
Specification of the multi-sheet-type radiant panel.

Item	Contents
Configuration of radiation panel	Two columns × 35 sheets (one sheet: 0.07 m (W) × 0.005 m (D) × 2 m (H)) Spacing distance between sheets: 0.035 m Spacing distance between columns: 0.020 m Size of flow path in a sheet: 0.068 × 0.003 m
Surface area of radiation panel	21.049 m^2
Supply water flow rate	15 L/min

2.2. Measurement of thermal insulation and infiltration performance in the room model

To determine the thermal insulation and infiltration performance from the cracks in the room model, the U-value of the walls and windows and the infiltration rate were measured. The measurement of the U-value (thermal transmittance) at the walls and windows was conducted using the infrared thermography method [13]. In the thermograph method, the heat flow through a component in contact with the outdoor air at a building site was calculated based on the indoor-side surface temperature (measured by an infrared camera), the total heat transfer coefficient, and the environmental temperature. Then, the U-value in a quasi-stationary state of the component was determined from the inside and outside environmental temperature difference. This method allows possible measurement of the insulation performance of the entire architectural component and demonstrate to the residents of the building the temperature distribution of the indoor walls in contact with the outdoor air. In addition, to determine the infiltration rate of the room model, tracer-gas measurement was used to quantify the infiltration rate on the natural ventilation state. The decay method, known as the step-down method, was used to calculate the infiltration rate through the cracks in the room because this method only requires relative concentrations; the tracer-gas injection rate need not be measured [14]. The infiltration rate was measured by uniformly dispersing sulfur hexafluoride (SF_6) as a tracer gas in the room. A desk fan in the room ensured proper mixing. Samples were drawn into a multi-gas monitor (INNOVA 1312) through plastic tubes at five different locations in the room at 30-s intervals. Eq. (1) was used to solve for I by periodically measuring the tracer-gas concentration during the decay and fitting the data in a logarithmic form. The ratio of airflow rate Q to volume V being tested has a unit of 1/time and considered as infiltration rate I [Eq. (2)] of the measured room.

$$C(t) = C_0 \cdot e^{-It} \tag{1}$$

$$I = \frac{Q}{V} \tag{2}$$

In these equations, t [h] is the time, C_0 [ppm] is the concentration of the tracer gas in the room at $t=0$, $C(t)$ [ppm] is the tracer-gas concentration at time t, I [h^{-1}] is the infiltration rate, Q [m^3/h] is the airflow rate out of the room, and V [m^3] is the room volume.