9th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) and the 3rd International Conference on Building Energy and Environment (COBEE)

Experimental Study of Heat Performance on Ceiling Radiant Cooling Panel

Yong-Li Yuan\textsuperscript{a}, Xiang Zhou\textsuperscript{a}, Xu Zhang\textsuperscript{a,*}

\textsuperscript{a}School of Mechanical Engineering, Tongji University, 204 Jiyang Building, 1239 Siping Road, Shanghai, 200092, China

Abstract

The main thrust of this research is to develop a simplified correlation between the heat flux density and temperature difference firstly. To obtain the limited values of the total heat transfer coefficients based on the experimental data secondly. The climatic test chamber with a cooled ceiling radiant panel composed by three different construct ways are constructed. Based on the experimental data, a linear regression equation is derived. Besides, a comparison with previous correlation and data given in reference literature is conducted. The result shows that the heat flux destiny can be quantified independently in different radiant panel structures. The total heat transfer coefficients are fluctuated in some ranges. The experimental results can provide guidance for engineering application.

Keywords: Capillary tube mats; Graphite plates; Metal plates; Temperature difference; Heat transfer coefficients

1. Introduction

The radiation heat transfer performance parameters are varied with different materials and installation of radiant panel. The heat transfer coefficients as fundamental parameters play an essential role in calculating heating/cooling load and dimensioning of radiant systems. The heat transfer performance affected by the radiant panel surface temperature prominently [1].

In the last few decades, many researchers focused their attentions on heat transfer coefficients for heating/cooling panels. The work of Min et al. [2] was an early paper researched heat transfer coefficients, they considered the effect of room sizes and determined natural-convection coefficients by using three different sized testing chambers, then...
obtained a series of equations for calculating heat flux density from radiant panels by convective heat transfer coefficients shown as

\[
h_c = 2.13(T_a - T_p)^{0.31} \quad \text{(for cooled ceiling and heated floor)} \quad (1)
\]

EN 15377-1 and ASHRAE Standard are also provided \( h_{\text{total}} \) and \( h_c \) fluctuated in 10-11.1 W m\(^{-2}\) K\(^{-1}\) and 3.1-4.3 W m\(^{-2}\) K\(^{-1}\) respectively. In conclusion, it is important to establish a characteristic curve to estimate heat flux density of radiant systems. The present study is mainly concrete to deepen the understanding of the heat transfer process in radiant system. Most researchers were experimental research the heat flux density and total heat transfer coefficients under the natural convective and thermal radiation condition in a climate chamber. Partly experimental data could not be quantified the correlation deeply. In this study, three categories of radiant panels are conducted and dozens of experimental data are obtained to predict heat flux density and the total heat transfer coefficients for the general radiant system.

### Nomenclature

- \( A_p \): surface area of the cooling panel, m\(^2\)
- \( \text{AUST} \): average unheated (uncooled) surface temperature, °C
- \( h_c \): convective heat transfer coefficient, W m\(^{-2}\) K\(^{-1}\)
- \( h_{\text{total}} \): total heat transfer coefficient, W m\(^{-2}\) K\(^{-1}\)
- \( q_c \): natural convective heat flux, W m\(^{-2}\)
- \( q_r \): radiation heat flux, W m\(^{-2}\)
- \( q_{\text{total}} \): total heat flux density, W m\(^{-2}\)
- \( T_a \): indoor air dry bulb temperature, °C
- \( T_p \): radiant surface temperature, °C
- \( T_{\text{return}} \): return water temperature, °C
- \( T_{\text{supply}} \): supply water temperature, °C
- \( c_p \): specific heat capacity, J kg\(^{-1}\) K\(^{-1}\)
- \( \rho \): mass density, kg m\(^{-3}\)
- \( V \): volumetric flow rate, m\(^3\) s\(^{-1}\)

### 2. Experimental methods

#### 2.1. The climate chamber

The radiant ceiling panels have been subjected to do the experiments in a climber chamber that is located in the test room of Tongji University [3]. The climate chamber is composed of walls, floor and ceiling, all surfaces were made from the stainless steel plates and only the south wall was insulated by 100 mm thick XPS insulation board, at the center of the south wall, there is a 2.76 m\(^2\) double-glazed observation window shown as Fig.1. The floor area of the test chamber is 15.12 m\(^2\), the inside height is 2.6 m. All the inside surface temperatures are controlled by the water panels that covering all the outside surfaces with circulating temperature controlled water except the south wall, and the temperatures can be ranged from 10 to 40 °C separately. In the study, during the chilled ceilings experiment, thermally effective panel surfaces exchanged heat only by natural convection and thermal radiation according to the ASHRAE Standard [4].
In the study, several electric heats are set in a climate chamber according to EN14240 [5] with the circulating temperature controlled water wall to keep the stable indoor air temperature that is shown in Fig. 2.

2.2. The radiant panels

The radiant panels were composed of three different structure panels: the first panel was composed by insulating material, capillary tube mats embedded into the gypsum plaster and plaster. The second panel was used the plastic tube mats instead of the capillary, and embedded in the graphite plate. The third one was composed by insulation, metal plate and gypsum plaster.

Six capillary tube mats were connected in parallel and composed of the ceiling radiant cooling panel. The ceiling was placed at a height of 2.4m above the floor. The plaster panel area of capillary tube mats was almost accounted for 79% of the indoor ceiling area of the climate chamber. The detailed material parameters of capillary tube mats were shown in Table 1 and Fig. 3.

Table 1. Detailed capillary tube mats specification.

| Specification                                                                 |
|-------------------------------------------------------------------------------|
| Panel                                                                         |
| Single capillary tube mat length 3000 mm,                                     |
| wide 660 mm, gypsum plaster height 9 mm, plaster height 10 mm,                 |
| insulation height 35 mm                                                       |
Six groups of graphite plates were connected in parallel and composed of the ceiling radiant cooling panel. Each group was contained of six boards that connected in series. The plaster panel area was almost accounted for 71% of the indoor ceiling area of the climate chamber. The detailed material parameters of the graphite plates were shown in Table 2 and Fig.4.

**Table 2. Detailed graphite plate specification.**

| Specification                                                      |
|-------------------------------------------------------------------|
| **Panel**                                                         |
| Single graphite plate length 1050 mm, wide 285 mm, plaster height 3 mm, insulation height 36 mm, graphite plate height 12 mm |
| **Pipe**                                                          |
| Pipe external diameter 10 mm, internal diameter 8.5 mm             |

Twelve metal plates were connected in parallel and composed of the ceiling radiant cooling panel. The plaster panel area of metal plates was almost accounted for 77% of the indoor ceiling area of the climate chamber. The detailed material parameters of metal plates were shown in Table 3 and Fig.5.

**Table 3. Detailed metal plate specification.**

| Specification                                                      |
|-------------------------------------------------------------------|
| **Panel**                                                         |
| Single metal plate length 2500 mm, wide 275 mm, plaster height 10 mm, insulation height 8 mm, metal plate height 4 mm |
| **Pipe**                                                          |
| Pipe external diameter 10 mm, internal diameter 8.5 mm             |
3. The measurement equipment

In the climate chamber, K-type thermocouples were used to measure the inner surface temperatures. There were several test points fixed on the inner surface in each wall to measure and record the temperatures. Some radiant system parameters were measured, such as the supply water flow rate, supply and return water temperatures and the ceiling surface average temperatures. All process of the experiment was measured under a steady state condition. There were six K-type thermocouples average distribution on the surface of the radiant panel and record every 60 s during the entire test. There were also two temperature sensors fixed in the supply and return water pipes separately to monitor the average water temperatures. The heat flux density was calculated by the temperature difference between supply and return water. All of temperature sensors were used to analyze the relationship between the heat flux density and \((T_{a}-T_{s})\) in ceiling radiant cooling panel.

4. The experimental conditions

The designed indoor air temperatures were changed from 24 to 30 °C in the experiment, all of inner surface temperatures were kept equal to the air temperatures. The study was not considered the effect of changing humidity load of cooling capacity of radiant systems, when the supply water temperatures ranged from 14 to 20 °C. The whole experimentation was controlled the constant water volume of the radiant ceiling system. Therefore, during the experiment, the air within the test chamber was not influenced by any forced air flow, the heat sources kept the test chamber at an average dry-bulb air temperature ranged from 24 to 30 ± 0.5 °C. There was not any humidity load during the experimental processes.

5. Mathematical description

The experiment was measured on the condition of thermal balance, because of the heavy insulation of the test chamber envelop, the heat gains through thermally ineffective panel surfaces were ignored during the test and the heat flux density measurements in the hydronic circuit was considered as the same value to the thermally effective panel surfaces, and the heat flux density measured through the hydronic circuit is calculated by the following equation [6]

\[
q_{\text{total}} = \sum_{j=1}^{m} \left[ \rho V C_p \left( T_{\text{return}} - T_{\text{supply}} \right) \right] \sum_{j=1}^{m} \left[ A_p \right]_j
\]  

During the test of the radiant cooling panels, on the surfaces of the radiant panels, heat exchanged though natural convectively with the room air and thermal radiation with other inner surfaces. So the total sensible heat gain of the panel is sum of natural convective \(q_c\) by Equation (3) and radiation heat flux density \(q_r\) that exchanged to walls inner surfaces and floors by Equation (4).
\[ q_c = 2.13(T_a - T_p)^{0.31}(T_a - T_p) \]  
\[ q_c = 5 \times 10^{-8} \left[ (AUST + 273)^4 - (T_p + 273)^4 \right] \]

6. Results and discussion

6.1. Cooling capacity

For this study, the specific cooling capacity experimental and literature [7] results are presented in Fig. 6. A series of experimental results showing that the correlation is

\[ q_{total} = 7.24(T_a - T_p)^{1.09} \]

It is obvious that each group of data follows the similarly trend and \( q_{total} \) increases with growing \( (T_a - T_s) \) as expected. The empirical correlations can well predict the specific cooling capacity of ceiling radiant cooling panel in the climate chamber.

![Fig. 6. the specific cooling capacity for ceiling radiant cooling panel.](image)

6.2. Heat transfer coefficients

As stated in previous paragraphs, total heat transfer coefficient - temperature difference curve can be described as shown in Fig.7. The values range from 10 to 11.1 \( \text{Wm}^{-2} \text{K}^{-1} \) in the specific climate chamber [7]. The correlation is described as

\[ h_{total} = 7.24(T_a - T_p)^{0.09} \]

The experimental results shown that total heat transfer coefficients in ceiling radiant cooling panel ranged from 6.5 to 9.7 \( \text{W m}^{-2} \text{K}^{-1} \) with \( (T_a - T_s) \) moves from 1.3 to 9.7 °C. Compared to values of Karadağ [8] and EN15377-1 [7], lower values of the total heat transfer coefficient, were noticed.

Heat flux density and the heat transfer coefficients for radiant panel are influenced by some parameters like heat gain from the solar radiation that entering rooms through the window, changing heat gain in rooms and different inner surface colors. Total coefficients included emissivity are obtained by Karadağ, values as a function of temperature.
difference \( (T_u - T_i) \) and emissivity. This difference can be explained mainly due to the choice of the reference temperature.

![Fig. 7. comparison between literatures and measured heat transfer coefficients.](image)

7. CONCLUSIONS

An experimental test developed in the climate could effectively predict the heat flux density of ceiling radiant cooling system. Operating temperatures are similarly equal to air temperatures during the experiment. The characteristic curve can be described as a correlation between total heat flux and temperature difference under the experimental condition.

Total heat transfer coefficients have few fluctuated when inner heat sources are uniform distribution and there are not forceful solar radiation. The values are stable in the rooms which respect limitations stated in the standards. The results also shown as a correlation mentioned above. The total heat transfer coefficient is fluctuating from 6.5 to 9.7 W m\(^{-2}\) K\(^{-1}\) and the average value is 8.5 W m\(^{-2}\) K\(^{-1}\).

The reference temperature is basic of calculating total heat transfer coefficients. The operative temperatures are influenced by different values of the average radiation temperatures and air temperatures. Air temperatures can be reliably used in calculations in place of operative temperatures in those rooms which the average radiation temperatures are similarly equal to air temperatures.

Acknowledgements

This research has been supported by the National Natural Science Foundation of China under Grant No. 51308396. Authors are very grateful to the reviewers for their valuable comments for improving this article for publication.

References

[1] P. Weitzmann, J. Krugha, P. Rootsb, S. Svendsena, Modelling floor heating systems using a validated two dimensional ground- coupled numerical model, Building and Environment. 40 (2005) 153-163.
[2] T.C. Min, L.F. Schutrum, G.V. Parmelee, J.D. Vouris, Natural convection and radiation in a panel heated room, ASHRAE Transactions. (1956) 337-358.
[3] Y.L. Yuan, X. Zhou, and X. Zhang, Experimental Research on Ceiling Radiant Panel Combined with Different Air Distribution System, in: 13th International Conference on Indoor Air Quality and Climate, Hong Kong, 2014, pp. 856-860.
[4] ASHRAE, ANSI/ASHRAE 138-2013, Method of Testing for Rated Ceiling Panels for Sensible Heating and Cooling. American Society of Heating, Refrigerating and Air Conditioning Engineers Inc. Atlanta, 2013.
[5] EN, EN-14240, Ventilation for Buildings—Chilled Ceilings—Testing and Rating, European Committee for Standardization. Brussels, Belgium, 2004.
[6] J.-W. Jeong, S.A. Mumma, Ceiling radiant cooling panel capacity enhanced by mixed convection in mechanically ventilated spaces, Applied Thermal Engineering. (2003) 2293-2306.
[7] EN, EN 15377-1, Heating systems in buildings-Design of embedded water based surface heating and cooling systems-Part 1: Determination of the design heating and cooling capacity. BSI, 2008.
[8] Karadağ, R., New approach relevant to total heat transfer coefficient including the effect of radiation and convection at the ceiling in a cooled ceiling room, Applied Thermal Engineering. (2009) 1561-1565.