Study on the heat transfer performance of the ceiling radiant panel

Yuki Ichikawa¹*, Ryoichi Kuwahara¹, Hideki Sato¹
¹ Tokiwadai, Ube, Yamaguchi, Japan
* i011ve@yamaguchi-u.ac.jp

Abstract. The purpose of this study is to acquire data to examine the design method of radiant air conditioning in Japan. The radiant panels were installed in the population weather chamber, and the convective heat transfer coefficient and the radiant heat transfer coefficient on the upper side and the lower side of the radiant panel were experimentally calculated. As a result of this experiment, the radiant heat transfer coefficient was larger than the convective heat transfer coefficient during cooling and heating. In addition, CFD simulation of the thermal environment and airflow in the environmental control chamber was conducted. From the simulation results, it found that there was almost no temperature unevenness in the environmental control chamber, and the air flow was very small. There were differences in the comparison between the experimental values and the analysis values of the vertical temperature distribution.

1. Introduction
In Japan, the radiant cooling and heating has been introduced as an air conditioning system of Zero Energy Building because of its superior comfort and energy saving. However, there is no clear design method as it is hot and humid in Japan. Therefore, in order to examine a clear design method of the radiant air conditioning, it is necessary to calculate the heat transfer coefficient of the radiant panel. Radiant cooling and heating has different heat transfer coefficient depending on the shape of the radiant panel. In this study, the R-shaped radiant panel was used and the total heat transfer coefficient was experimentally obtained by dividing it into components of convective heat transfer and radiant heat transfer in the environmental control chamber. Also, the air flow and thermal environment simulation were conducted based on the experimental values obtained in consideration of the characteristics of the radiation panel.

2. Experimental method
2.1. Experimental condition
Table 1 shows the Experimental conditions. Experimental conditions during cooling were set to an indoor set temperature of 26°C, the water supply temperature of 18°C, and the water supply rate of 3L/min. Experimental conditions during heating were set to an indoor set temperature of 22°C, a feed water temperature of 31°C, and a water feed rate of 3L/min.

| Table 1. Experimental conditions |
|----------------------------------|
| **Experimental condition** | **Cooling** | **Heating** |
| Indoor set temperature | 26°C | 22°C |
| Water supply temperature | 18°C | 31°C |
| Water supply rate | 3L/min | 3L/min |

*Content from this work may be used under the terms of the 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
2.2. Experimental point
Figure 1 shows the A-A’ cross section and measurement points in the environmental control chamber. Measurement points were at air temperature of 600mm and 1,450mm height from the floor surface. The surface temperature was on the floor surface, the radiant panel surface, the total of 7 points including the ceiling surface and the wall surface (2 points at the height of 600mm, 2 points at the height of 1,450mm)

![Figure 1. A-A’ cross section and measurement points](image)

2.3. Measurement method of radiant heat transfer coefficient
The wall surface temperature of the steady state and the surface temperature of the radiant panel were measured. The radiant heat transfer rate was obtained from equation (1).

\[
\alpha_r = \sum \varphi \varepsilon_p \varepsilon_w \frac{\sigma}{|\theta_w - \theta_p|} [\text{W/(m}^2\text{K)}] \tag{1}
\]

sharp factor is \(\varphi\), radiation emission rate of the radiant panel is \(\varepsilon_p(=0.93)\), radiation emission rate of each wall is \(\varepsilon_w(=0.7)\), Stefan-Boltzmann constant is \(\sigma\), wall surface temperature is \(\theta_w\), panel surface temperature is \(\theta_p\), indoor temperature is \(\theta\).

2.4. Measurement method of convective heat transfer coefficient
Figure 2 shows the outline of measurement of convective heat transfer coefficient. Two pairs of type K fine thermocouples not susceptible to radiant heat transfer were used, and one was fixed at a position sufficiently away from the ceiling radiant panel surface and was taken as the reference temperature(\(\theta_{ref}\)). At the lower side of the radiant panel, another set of thermocouple was attached to the tip of the traverse device and the digital voltameter was measured. At the upper side of the radiant panel, measurements were taken at the position 21mm and 24mm from the center of the radiant panel. The temperature difference(\(d\theta\)) was measured. Theremopower from 0.1mm to 5mm from the ceiling radiant panel surface was measured at 0.1mm pitch and obtain the temperature gradient \(d\theta/dx\) from the obtained theremopower date regression line to calculate the equations (2) and (3).

\[
q_c = \lambda \frac{d\theta}{dx} [\text{W/m}^2] \tag{2}
\]

\[
\alpha_c = \frac{q_c}{\theta_w - \theta_{ref}} [\text{W/(m}^2\text{K)}] \tag{3}
\]

Convective heat transfer coefficient in the mechanical engineering field, convective heat transfer coefficient of the lower surface of the horizontal panel is 2.60W/(m²K) at cooling and 0.95W/(m²K) at heating.
NOTE
The time constant ($\tau$) of the Kr bare wire used was 0.056 $\mu$ sec. Assuming that the form factor of the radiant panel from the bare wire is 0.7, the influence of the radiant heat transfer from the radiant panel during heating is about 0.0063 K, and the temperature can be measured well.

Figure 2. Measurement of convective heat transfer coefficient

3. Experimental results
Figures 3 to 5 show the correlation between the distance from the radiant panel and the temperature difference.

3.1. Experimental results during cooling
Table 2 shows the measurement results of the convective heat transfer coefficient during cooling. From the experimental results, the convective heat transfer coefficient of the lower side of the radiant panel was 2.46 W/(m²K) and the upper side was 2.44 W/(m²K) at the distance of 21 mm from the center of the radiant panel, 2.77 W/(m²K) at 24 mm. And the average value of the convective heat transfer coefficient of the two measurement points was 2.61 W/(m²K). The indoor temperature in the environmental control chamber was 24.9°C and the radiant panel surface temperature was 20.8°C. From this result, the radiant heat transfer coefficient was 6.56 W/(m²K) at the upper side of the radiant panel and 5.75 W/(m²K) at the lower side of the radiant panel.

3.2. Experimental results during heating
Table 2 shows the measurement results of the convective heat transfer coefficient during heating. From the experimental results, the convective heat transfer coefficient of the lower side of the radiant panel was 1.52 W/(m²K) and the upper side was 0.72 W/(m²K) at the distance of 21 mm from the center of the radiant panel, 0.96 W/(m²K) at 24 mm. And the average value of the convective heat transfer coefficient of the two measurement points was 0.84 W/(m²K). The indoor temperature in the environmental control chamber was 19.7°C and the radiant panel surface temperature was 27.7°C. From this result, the radiant heat transfer coefficient was 4.47 W/(m²K) at the upper side of the radiant panel and 5.17 W/(m²K) at the lower side of the radiant panel.
\[ y = -0.3794x + 3.4677 \quad R^2 = 0.9858 \]

\[ y = -0.2221x + 2.9826 \quad R^2 = 0.5495 \]

**Figure 3.** Lower side of panel

**Figure 4.** Upper side of panel (21.5mm)

**Figure 5.** Upper side of panel (24mm)

**Table 2.** Heat transfer coefficient during cooling

| Measurement item                      | Lower side | Upper side |
|---------------------------------------|------------|------------|
|                                       |            |            |
| Temperature gradient [K/m]            | 448.1      | 379.4      | 428.6      |
| Convective heat transfer coefficient [W/(m²K)] | 2.46       | 2.44       | 2.77       |
| Radiant heat transfer coefficient [W/(m²K)] | 6.56       | 5.75       |

**Table 3.** Heat transfer coefficient during heating

| Measurement item                      | Lower side | Upper side |
|---------------------------------------|------------|------------|
|                                       |            |            |
| Temperature gradient [K/m]            | 463.6      | 222.1      | 295.6      |
| Convective heat transfer coefficient [W/(m²K)] | 1.52       | 0.75       | 0.96       |
| Radiant heat transfer coefficient [W/(m²K)] | 4.47       | 5.17       |
4. Outline of the Simulation

Figure 6 shows the outline of the environmental control chamber, figure 7 shows the radiant panel surface, and table 4 shows the simulation conditions. The environmental control chamber reproduced the experiment. The simulation conditions were set the same as the experimental conditions. The experimental data were used.

| Simulation condition     | Cooling | Heating |
|-------------------------|---------|---------|
| Set temperature         | 26°C    | 22°C    |
| Panel surface temperature| 20.8°C  | 27.7°C  |
| Total heat transfer coefficient | Upper : 5.75W/(m²K) | Upper : 5.17W/(m²K) |
|                         | Lower : 6.56W/(m²K) | Lower : 4.47W/(m²K) |
| diffuser                | 26.0°C  | 19.7°C  |
|                         | 0.5m/sec(Ceiling-supply displacement air-conditioning) |
| Surface characteristics (radiation emission rate) | Chamber : Stainless steel plate (0.7) |
|                         | Radiant Panel : Aluminum (0.93) |
| Air vent                | 1,025mm×180mm |
| Mesh division           | 250(X)×400(Y)×100(Z) |
| Simulation model        | Standard k-ε model |

5. Simulation results

5.1. Simulation result during cooling

Figure 8 shows the thermal environment simulation result, figure 9 shows the air flow simulation result, and figure 10 shows the vertical air temperature distributions. As a result of the thermal environment simulation, the indoor temperature was from 25°C to 26°C, and 24°C to 25°C in the vicinity of the radiation panel. It was confirmed that the indoor temperature was almost uniform. Also, as a result of air flow simulation, it was a slight air flow of less than 0.2m/sec. In the comparison of the vertical air temperature distributions, there were differences at the lower side of radiant panel.

5.2. Simulation result during heating

Figure 11 shows the thermal environment simulation result, figure 12 shows the air flow simulation result, and figure 13 shows the vertical air temperature distributions. As a result of the thermal environment simulation, the indoor temperature was from 19°C to 20°C, and 21°C to 22°C in the vicinity of the radiation panel. It was confirmed that the indoor temperature was almost uniform. Also, as a result of air flow simulation, it was a slight air flow of less than 0.2m/sec. In the comparison of the vertical air temperature distributions, there were differences, especially in the vicinity of radiant panel.
6. Discussion
As a result of comparing the vertical air temperature distributions of the experimental values and the simulation values, there were differences. It was thought that the reason was that the simulation could not sufficiently take account of the radiant effect.
In the following study, CFD simulation shall be conducted in consideration of the radiation effect to obtain more accurate results. Also, the design method of radiant air conditioning shall be examined based on the results.

Conclusions
In this study, the purpose was to experimentally measure the convective heat transfer coefficient and the radiation heat transfer coefficient during cooling and heating in the environmental control chamber. Experimental results showed that the radiant effect is larger than the convection effect in both cooling and heating. In addition, CFD simulation in the environmental control chamber was also conducted. From the simulation results, there was no large temperature irregularity and slight air flow in the environmental control chamber during cooling and heating.

References
[1] ISO, EN14240. (2004). Ventilation for buildings, Chilled ceiling, Testing and rating
[2] The Association of Radiant Cooling and Heating systems of Japan, Cooling and Heating - Testing and Rating Standard, ARCH2017 CHTRS Ver.1
[3] Ogasawara T, et al. (2012). Study on Measurement of Convective Heat Transfer Rate in a Room Architectural Institute of Japan2012, 41005
[4] Sakaguchi J, et al. (2018). Study on the heat transfer performance of a ceiling radiant panel – Architectural Institute of Japan2018, 41386
[5] Maruzen publishing. (2005), Heat transfer, The Japan Society of Mechanical Engineer

Figure 8. Thermal environment
Figure 9. Air flow
Figure 10. Temperature distribution

Figure 11. Thermal environment
Figure 12. Air flow
Figure 13. Temperature distribution