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Improved Thermal Performance of Combined Convection and Radiation Using Room Air Conditioner

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Abstract. This study aims to evaluate the indoor thermal environment within a detached residence in summer by applying combined convection and radiation air conditioning system using the refrigerant gas of room air conditioners (RACs). First, field measurements were performed in a detached residence at Hiroshima, Japan, in July and August 2021. Consequently, PMV values were generally maintained within the comfortable range during air-conditioning operation. The amount of heat generated by convection (via the RAC indoor unit) Qc and that by radiation (via the radiation panel) Qr were determined as 426 and 259 W, respectively, and the overall heat generated Qtotal was determined as 685 W. Applying the CFD model, thermal environment was compared varying the ratio between Qc and Qr with a constant Qtotal of 685 W. Results showed that the synergistic operation of a RAC and a radiant panel presented more comfortable PMV values than that of a single RAC application. Furthermore, the airflow from the RAC decreased with an increase in Qr ratio, and the chilled radiant panel provided a cooling effect around the dining area, where the airflow of the RAC was inadequate, thereby improving the thermal comfort.

1 Introduction

Radiant air conditioning has been of interest owing to its desirable energy conservation and comfort. Typically, this mechanism is applied with convection air conditioning to meet the requirement of maximal heat load. Several studies have indicated that such convection–radiation hybrid air conditioning provides a comfortable thermal environment with relatively small amounts of energy compared to that of the conventional air conditioning by solely convection [1].

Hybrid air-conditioning systems have been realized in several commercial buildings using hot/chilled water; however, they are less common in residential houses owing to the wide range of application of individual systems, such as room air conditioners (RACs), in residential houses located at the temperate regions in Japan instead of central heating/cooling system using hot/chilled water.

Recently, another hybrid air-conditioning system that utilizes refrigerant gas has been developed [2]. This system is expected to readily improve the thermal comfort in residential houses within the temperate regions.

Thus, the present study aimed to evaluate the thermal environment within a residence with an installed hybrid air-conditioning system. Consequently, we compared the thermal environment under different ratios of heat transfer via convection and radiation using a CFD (Computational Fluid Dynamics) analysis model with measurement-based boundary conditions for summer.

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2 Field measurement in summer

2.1 System overview

As shown in Fig. 1, hybrid air conditioning can be easily realized by connecting an indoor unit and a radiant panel in series with the refrigerant pipes of conventional RACs in this system. In contrast to the conventional central heating/cooling systems, this system requires no hot/chilled water, suggesting that the radiant panels may be preferable even in temperate regions where individual systems are common. The system was basically operated with a remote controller attached to the air conditioner (AC). The refrigerant was partially evaporated in the indoor unit first and then in the radiant panel during cooling.

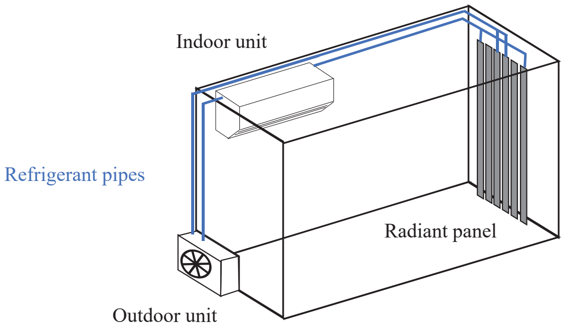

Fig. 1. System diagram

2.2 Building overview

We performed field measurements at a detached residence in Hiroshima, Japan, equipped with a hybrid air-conditioning system. Table 1 and Fig. 2 present information on the residence building and floor plan of the 2nd floor, respectively. The building had an average U-value of 0.37 W/m²/K; an index of the heat transfer coefficient of the outer walls of the building, which was much lower than the standard value in Japan. An indoor unit and a radiant panel (Fig. 3) were installed in the LDK (Living/Dining/Kitchen) room as shown in Fig. 2.

Table 1. Building overview

Local	Hiroshima-city
Building area	79m²
Total floor area	236m²
Floor	Three-story
Measurement period	July 16, 2021～August 24, 2021

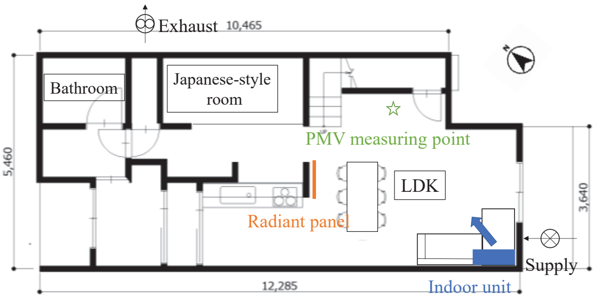

Fig. 2. 2nd floor plan

2.3 Measurement method

The field measurements were performed from July 16 to August 24, 2021. We measured the air temperature, globe temperature, air humidity, and air velocity at a height of 1.1 m above the floor at the reference point in Fig. 2 and obtained the PMV (Predicted Mean Vote) values considering 0.5 clo and 0.9 met. A representation of the measurement is shown in Fig. 3. The blowing air temperature from the indoor unit and the surface temperature on the radiant panel were estimated using pictures captured by a thermal camera. The power consumption of the RAC was obtained using a HEMS (Home Energy Management System).

Fig. 3. Radiant panel (Left)
PMV measuring equipment (Right)

2.4 Measurement results

Fig. 4 shows the variations in the energy consumption (integration for 30-min) and PMV on August 5 and 6, which were among the hottest days in the period with daily maximum outdoor temperatures above 35 °C. The PMV typically remained within the comfortable range (-0.5–0.5) between 12:00 and 18:00 on August 5 and between 8:00 and 24:00 on August 6, during which energy consumption was generated and the AC seemingly working. The results showed that the system provided a comfortable thermal environment, even on the hottest days, which may be attributed to the high insulation performance of the building and relatively large capacity of the RAC. In the next section, we described thermal environment via CFD analysis applying the data obtained on August 5 at 16:00 as a representative time with a stable environment.

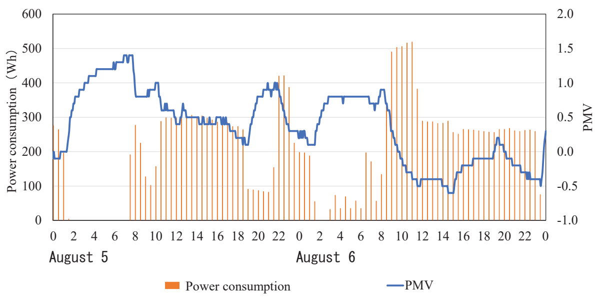

Fig. 4. Power consumption and PMV

3 CFD analysis overview

3.1 CFD analysis conditions

CFD analysis was performed using Flow Designer 2021 by Advanced Knowledge. The analysis conditions are listed in Table 2. Analysis was carried out at steady-state with measured temperatures on the inner wall surfaces (28ºC) and at the AC (17ºC) as boundary conditions. Blowing air emanating from the AC was inclined at 45º horizontally and 30º vertically to simulate the actual operating situations. For ventilation, an ideal outdoor air conditioning of 35 ºC and 30 m³/h was provided at the

Table 2. CFD analysis conditions

Simulation area	12.26m(X) × 5.46m(Y) × 2.4m(Z)		
Mesh	498,400 = 178(X) × 80(Y) × 35(Z)		
Simulation mode	Steady-state		
Turbulence model	Standard k-ε model		
Boundary conditions	Outlet air	Air conditioner	17°C
		Outdoor supply	35°C 30m³/h
	Inlet air	Exhaust	30m³/h
	Ceiling・floor・wall surface	Surface temperature：28°C	
Heat loads	Occupants	100 W/human	
	Lights	10 W/m²	

air inlets as shown in Table 2. Additionally, we gave heat loads for occupants (four people) and provided lighting. As shown in Fig. 5, the analysis was performed on the entire 2nd floor of the building. Furthermore, we established a "dining area" of 1.30 m x 3.64 m around the dining table and a "living area" of 3.56 m x 3.64 m in the living space for discussions in the next chapter. We also set cross-sections of X1 across the radiant panel and X2 across the sofa. Heat loads due to solar radiation were eliminated from this analysis as the residence was surrounded by buildings and hardly influenced by solar heat. Fig. 6 shows an elevated view of the simulated analysis area from the south direction. The radiant panel was positioned at the center of the space, as shown in Fig. 6. The radiant panel was simulated as six panels, 10 cm wide and 10 cm apart, at the same angle.

3.2 Identification of heat balance of the system

First, to identify the balance between convective and radiant heat transfer, combination of unknown parameters of air flow rate of the AC (Vc) and heat amounts released by the radiant panel (Qr) were determined by CFD analysis to calculate the thermal environment (0.5 of PMV) and surface temperature of the radiant panel (15.8 ºC). Table 3 presents the simulation cases. Vc and Qr varied from 50 to 300 m^3/h and 250 to 360 W, respectively. Fig. 7 shows the calculated PMV and surface temperature for each case. In these five cases, both the measured PMV and surface temperatures were reproduced simultaneously in case 2 with Vc and Qr of 100 m^3/h and 259 W, respectively. Lastly, the amount of heat released in the AC was calculated as 426 W using the following equation:

$$Qc=(t_R-t_r)\times\frac{1.2V_c}{3600\times0.83} \quad (1)$$

Qc= heat amount released in the AC [kW]
t_R=return air temperature to the AC [°C]
t_r=blowing air temperature from the AC [°C]
V_c=blowing air volume [m^3/s]

Therefore, the overall heat generated was determined as 685 W by adding 259 W to 426 W, where the balance between the convective and radiant components was identified as approximately 6:4. Notably, we considered this boundary condition as "present case" in the following sections.

3.3 Simulation cases

We conducted a case study with different balances between the convective and radiant heat transfer, as shown in Table 4, where the total heat amount was 685 W. Table 4 presents the simulation cases. Illustratively, cases A, B, and C represent the present case, case solely using an AC, and case assuming a convection and radiation balance of 1:9, respectively. For each condition, the blowing air volume of the AC is provided, as shown in Table 4, with the blowing air and return temperatures evaluated as 17.0 and 27.6 ºC, respectively.

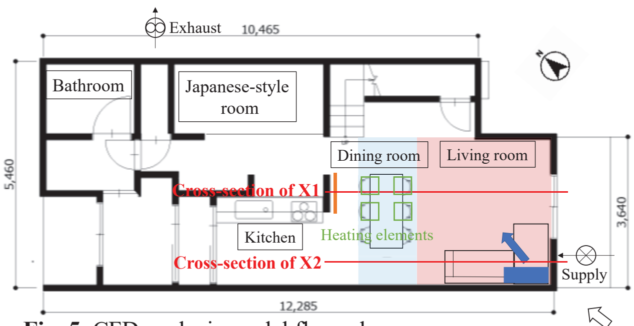

Fig. 5. CFD analysis model floor plan

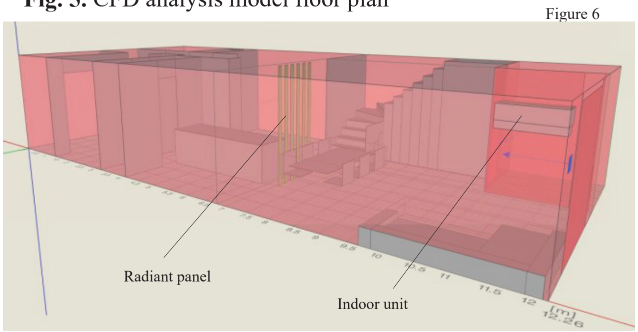

Fig. 6. CFD analysis model perspective

Table 3. Identification of Vc and Qr

		case1	case2	case3	case4	case5
Input	Vc : Air conditioner blowing air volume[m^3/h]	50	100	100	200	300
	Qr : Heat dissipation of radiant panel[W]	252	259	288	324	360
Output	Panel surface temperature[°C]	16.6	15.8	14.8	12.4	9.5
	PMV	0.8	0.5	0.4	-0.2	-0.6

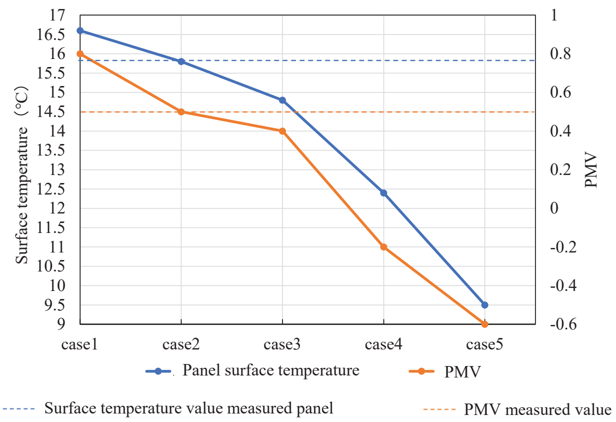

Fig. 7. Identification of Vc and Qr

Table 4. Ratio change simulation case

	Simulation case	case A	case B	case C
	Convection : Radiation (Ratio of heat dissipation)	6 : 4	10 : 0	1 : 9
Convection	Qc : Heat dissipation[W] (Air volume[m^3/h])	426(100)	685(161)	68(16)
Radiation	Qr : Heat dissipation[W]	259	0	617

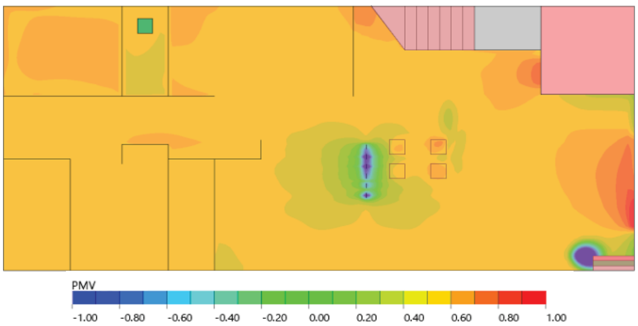

Fig. 8. 2nd floor horizontal PMV distribution

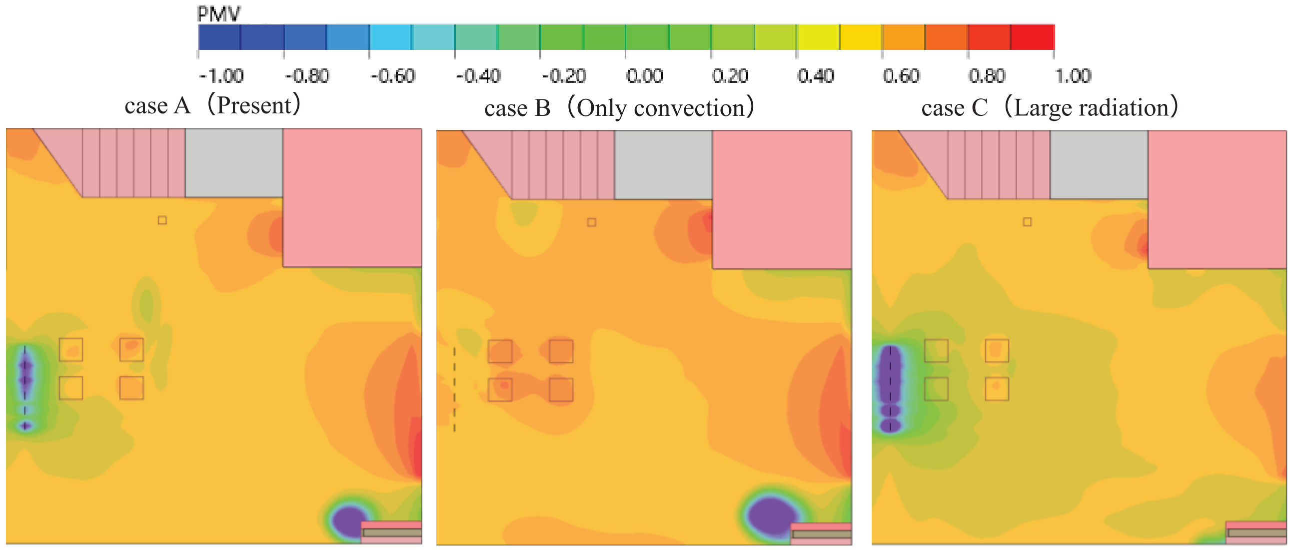

Fig. 9. Dining/Living area horizontal PMV distribution

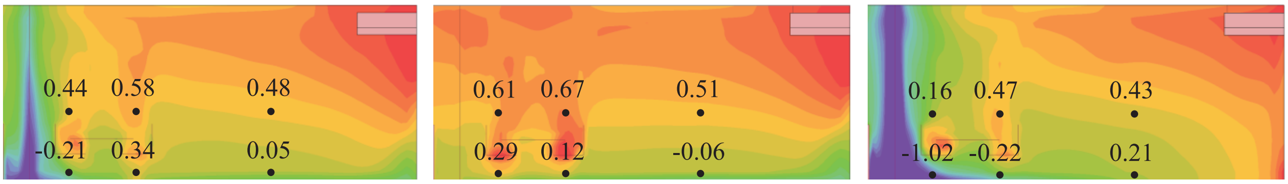

Fig. 10. X1 section vertical PMV distribution

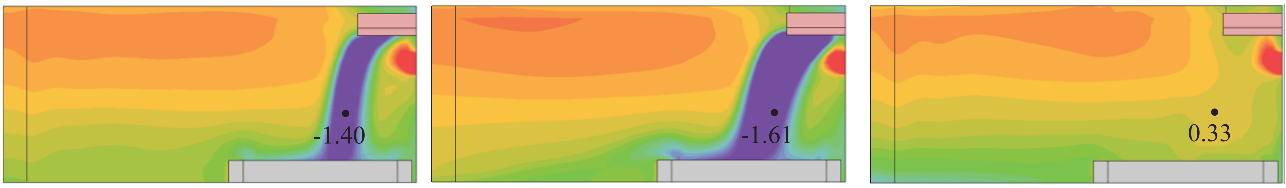

Fig. 11. X2 section vertical PMV distribution

4 Results and discussion

4.1 Horizontal PMV distribution

Fig. 8 shows the horizontal PMV distributions for the entire 2nd floor at an elevated height of 1.1 m from the floor in the present case (case A). Cold heat supply from the radiant panel and AC indoor unit resulted in low values of PMV, as shown at the center and lower right corner of the figure, respectively. Cooling effect was observed at both sides of the radiant panel; both the living/dining room and kitchen directions. Moreover, Fig. 9 shows the horizontal PMV distribution data extracted solely from the dining and living rooms at an elevated height of 1.1 m from the floor in each case. Horizontally averaged values of PMV are presented in Table 5. By comparison, case A presents lower values of average PMV than case B at both areas. Particularly, the average PMV of the dining area was 0.52 in case B and decreased to 0.41 in case A. Thus, it can be inferred that the radiant panel synergistically provides cold heat sufficiently to the area where cooling air flow from the AC indoor unit was initially inadequate. The average PMV was further decreased to a thermally neutral zone in case C with a larger ratio of radiation than that in case A, and this may be attributed to the low surface temperature on the radiation panel resulting in an improved thermal environment in case C.

Table 5. Dining/Living Area Horizontal PMV Distribution

	Dining Area Average PMV	Living Area Average PMV
caseA	0.41	0.43
caseB	0.52	0.44
caseC	0.32	0.40

4.2 Vertical PMV distribution

Fig. 10 shows the vertical PMV distributions of the X1 section in each case at representative height values of 0.1 and 1.1 m from the floor. Further, six representative points are shown; two in the dining area and one in the living room, for heights of 0.1 and 1.1 m. Excessive cold area was observed near the radiant panel in cases A and C, which resulted from the downdraft of cooled air. Particularly, a low PMV of -1.02 was observed in case C at 0.1 m above the floor, which succeeded the comfortable range. Although the increased ratio of heat radiation was effective for cooling the whole space, the extremely cold surface of radiant panels should be considered as it may result in uncomfortable environment locally around the floor. Additionally, Fig.

11 shows the vertical PMV distributions of the X2 section in each case. The AC indoor unit and sofa were positioned at the upper and lower right corners, respectively, in each figure. Specifically, cases A and B presented excessive cold areas (blue zones) according to streamline from the AC indoor unit, unlike case C with a high ratio of radiation and mild air flux. As shown in the Fig. 11, negative values of -1.40 and -1.61 were presented in cases A and B, respectively, while the value was 0.33 in case C within a comfortable range. This represents the effect of low-temperature flow from the AC indoor unit. From the result, it can be inferred that case C is most suitable to prevent local discomfort posed by strong air current and can achieve uniform heat distribution. Thus, we suggest that the hybrid system performs at "low air flow" modes, which results in large amounts of heat radiation, for the actual operation.

Conclusion

In this study, we evaluated the indoor thermal environment in summer in a residential building equipped with a hybrid air-conditioning system using refrigerant gas. The balance between the convective and radiant heat transfer was identified based on measurement. The thermal environment in the room space was determined via CFD analysis using the measured values as boundary conditions. The hybrid air-conditioning system presented a more efficient heat distribution in the horizontal direction than the conventional air-conditioning, which operates solely by convection. The value of PMV was almost zero, indicating a thermally neutral environment, as the ratio of the radiant heat transfer increased with low convection.

Operation on low convection resulted in a comfortable environment, even around the sofa directly under the AC indoor unit; however, downdraft from the cooled radiant panel should be considered.

References

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