ELSEVIER

Energy and Buildings 30 (1999) 167–175

ENERGY AND BUILDINGS

Thermal comfort and energy consumption of the radiant ceiling panel system. Comparison with the conventional all-air system

Takehito Imanari [a,*], Toshiaki Omori [a], Kazuaki Bogaki [b]

[a] *Energy Technology Research Institute, Tokyo Gas, 16-25, Shibaura 1-chome, Minato-ku, Tokyo 105, Japan*
[b] *Building Research Institute, Ministry of Construction, Japan*

Abstract

The purpose of this study is to investigate the various characteristics of a radiant ceiling panel system and their practical application to office buildings. The radiant ceiling panel system and conventional air-conditioning system were compared in terms of thermal comfort, energy consumption, and cost. Thermal environment, along with human response, was tested by using a small meeting room equipped with radiant ceiling panels. The responses were collected by questionnaires given to the male subjects in the room. The experiment for the female subjects was conducted separately. Results show that the radiant ceiling panel system is capable of creating smaller vertical variation of air temperature and a more comfortable environment than conventional systems. When using a cooled ceiling, a small volume of supplied air creates a less draught environment, which reduced the discomfort of feeling cold in the lower part of the body. Numerical simulation of yearly energy consumption and cost estimation were conducted. Typical office rooms located on the 3rd, 4th, and 5th floor of a six-floor building in the Tokyo area were simulated. Since part of the sensible heat load is handled by radiant ceiling panels, the volume of supplied air can be reduced, leading to lower energy consumption for air transport. By using the radiant ceiling panel system in one of the three floors of the simulated building, energy consumption can be reduced by 10%. Estimated pay back time was from 1 to 17 years depending on the market price of the radiant ceiling panel.

Keywords: Thermal; Energy consumption; Radiant ceiling panel system

1. Introduction

In Japan, a forced convection air-conditioning system, which controls room temperature by supplying cold or hot air, has been the most commonly applied to office buildings. While the system has been popular in view of merely cooling or heating rooms, some discomfort factors have been claimed. The system is likely to create uncomfortable environment caused by draught and air temperature differences between the human head and foot. Many complaints about air-conditioning systems have been claimed, especially in summer by female occupants. The required level for air-conditioning quality in office buildings has gotten higher recently. It could be possible to create an ideal thermal environment with a very expensive system that consumes large amount of energy. In reality, we need to develop a practical system that creates a more comfortable thermal environment than conventional all-air systems with lower energy consumption. One of these solutions is the radiant ceiling panel system. This system utilises a thermal radiation effect for air-conditioning with radiant panels mounted on the ceiling. The system is believed to create a superior thermal environment than conventional all-air systems. Since part of the heat load is handled by radiant ceiling panels, the volume of supplied air can be reduced, leading to lower energy costs for air transport power. The system was released into the European market recently [1].

Despite the number of advantages reported in Europe, some problems have been identified for its application in the Japanese market. The first point is the climate in Japan, which greatly differs from that of Europe. In summer, it is not only hot but also humid with the average dew point in August exceeding 22°C; in winter, it is relatively dry. Radiant ceiling panel systems in Japan definitely require dehumidification to avoid water condensation on the pan-

* Corresponding author. Fax: +81-3-34532674; E-mail: imanari@tokyo-gas.co.jp

0378-7788/99/$ - see front matter
PII: S0378-7788(98)00084-X

els while cooling. The system also needs ventilation to maintain indoor air quality, for which an air handling unit should be incorporated. Optimal system and operating conditions must be investigated in order to reduce energy consumption [2,3]. Furthermore, if used for heating, the system allegedly causes discomfort created by the warmed ceiling panels.

The purpose of this study is to investigate various characteristics of the radiant ceiling panel system and its practical applications. This paper describes the experimental investigation of thermal comfort and the numerical simulation of energy consumption.

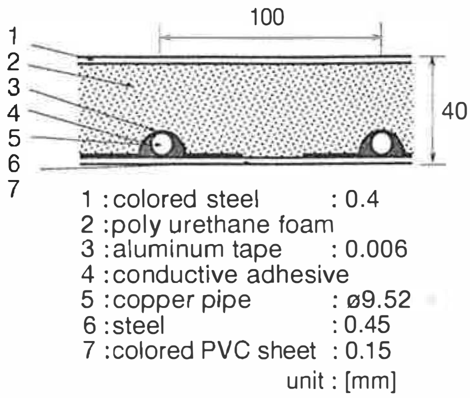


Fig. 2. Cross-section of the ceiling panel.

2. Thermal comfort

2.1. Experimental system and method

Thermal environments, along with human responses were investigated by using a meeting room equipped with radiant ceiling panels (Fig. 1). The meeting room has about 33 m^2 floor area with the ceiling 2700 mm above the floor. Radiant ceiling panels cover 56% of the total ceiling area. The structure of the ceiling panel originally developed is shown in Fig. 2. The surface of the ceiling panels was cooled or heated by cold or hot water supplied into the copper pipe. Air Handling Unit (AHU) was equipped to handle latent load and ventilation. It was also used to simulate the conventional all-air system. Fresh air was introduced into the room through the sensible and latent heat recovery unit (total heat exchanger).

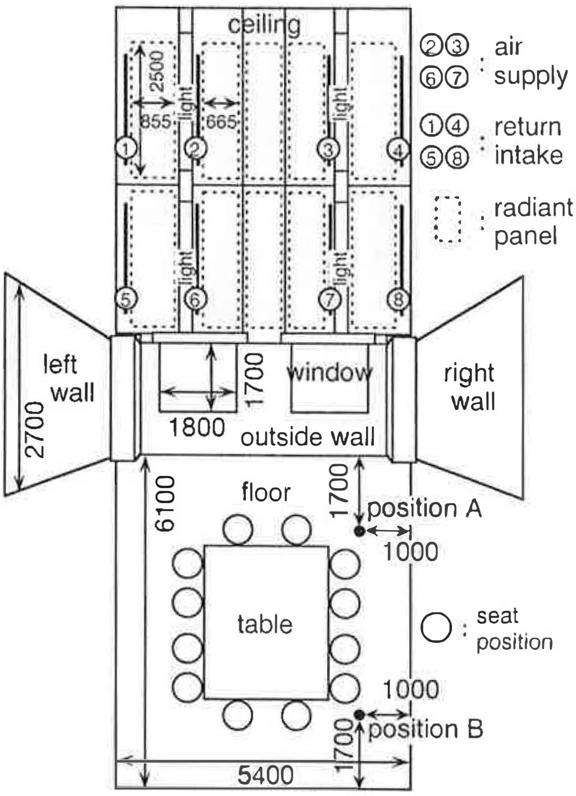


Fig. 1. Diagram of the meeting room.

To compare thermal environments and comforts, seven subjective experiments were carried out. Table 1 shows the summary of experimental conditions. Temperatures and humidities showed here are average during experiments. Experiments 1, 4, and 6 simulated the radiant ceiling panel system and experiments 3, 5, and 7 simulated the conventional system. Experiment 2 simulated a humidity controlled cooling system, which is believed to be a more comfortable but expensive system than conventional system in Japan. Experiments 1–5 were conducted for male subjects, most of them being office workers of Tokyo Gas. After that, experiments 6 and 7 were carried out for female subjects.

The experimental conditions were determined to maintain PMV (predicted mean vote) at two representative positions in the room (position A and B in Fig. 1) within ± 0.5 for male subjects and ± 0.3 for female subjects. PMV was calculated at the height of 600 mm. Since most of the sensible heat load was handled by the radiant ceiling panels, the volume of supplied air into the room could be reduced to the rate of introduced fresh air. The temperature of the ceiling panels and supplied air was controlled to meet the thermal load of the room without causing water condensation on the panels. To avoid discomfort caused by radiant temperature asymmetry [4], the surface temperature of the ceiling panels was limited to the range of 18–22°C while cooling and 27–30°C while heating.

Table 2 shows the summary of subjects' statistics. Subjective experiments with male subjects were carried out while the meeting room was used normally, for the purpose of the meetings. The experiments were conducted as follows: subjects, who were not informed of the type of air-conditioning system being operated, were asked to fill in a question form at the end of the meeting. Answers from subjects who stayed no longer than 1 h or who claimed improper health conditions (having colds, hangover, etc.) were eliminated. A small amount of (¥300) token tickets

Table 1
Summary of experimental conditions

Experiment	System	Mode	Gender of subjects	Volume of supplied air (m^3/h)[b]	Room temperature (°C)	Relative humidity (%)	Outside temperature (°C)
1	Ceiling + AHU	Cooling	Male	300	24.0	61.2	29.0
2	AHU with reheater	Cooling	Male	600	23.9	60.2	32.7
3	AHU	Cooling	Male	600	24.2	66.6	26.6
4	Ceiling + AHU[a]	Heating	Male	300	21.9	33.4	8.9
5	AHU	Heating	Male	600	20.3	32.6	8.7
6	Ceiling + AHU	Cooling	Female	300	25.7	61.2	34.3
7	AHU	Cooling	Female	600	25.9	59.8	34.8

[a]Only for ventilation (not heated).
[b]Set value.

Table 2
Summary of subjects

Experiment	Gender	Number of subjects	Age					Height		Weight	
			10s	20s	30s	40s	50s	Av	SD	Av	SD
1	Male	36	0	24	8	2	2	171.3	4.8	64.5	11.4
2	Male	15	0	10	3	1	1	170.6	4.7	65.2	15.3
3	Male	11	0	7	2	1	1	172.8	3.2	70.2	13.7
4	Male	66	0	20	21	16	9	170.5	5.9	66.0	9.2
5	Male	23	0	13	8	1	1	172.3	5.5	65.4	8.7
6, 7	Female	74	6	63	5	0	0	158.6	4.4	48.9[a]	–[a]

Av: average.
SD: standard deviation.
[a]Questioned with category.

for books were given to the subjects as gratitude. Most of the subjects were office workers of Tokyo Gas and wearing uniform about 0.6 clo.

Questionnaires for female subjects were carried out for the purpose of subjective experiments, hence, under more strictly controlled conditions. Subjects were instructed to attend the experiment twice; one for cooled ceiling and the other for AHU. Subjects were not informed as to which air-conditioning system was being operated. To insure nearly constant thermal and physiological condition, subjects occupied the meeting room for 2 h. Before entering the meeting room, subjects stayed for half an hour in the pre-test room where the temperature maintained was moderate. During experiments, subjects voted on thermal comfort and sensations every 15 min. Additionally, work efficiency tests, which were intended to compare the achievement and accuracy of the simple work under the environment created by different type of air-conditioning system were conducted after 105 min elapsed since subjects entered the meeting room. The test involved counting the number of specific figures in a row, from a paper filled with random numbers within 1 min. Tests were conducted three times with a 1 min rest period between them. During the experiments, subjects were asked to wear the clothing of ordinary female office workers. The average clothing of the subjects was estimated at 0.4 clo. A total of 74 subjects participated in two sets of experiments. Most of them were hired for the experiments and remunerated.

2.2. Experimental results

2.2.1. Thermal environment

Fig. 3 shows typical t_{pr} (plane radiant temperature) and t_{mr} (mean radiant temperature) at a height of 600 mm at positions A and B while cooling. These parameters were processed from the surface temperatures of walls, floor and

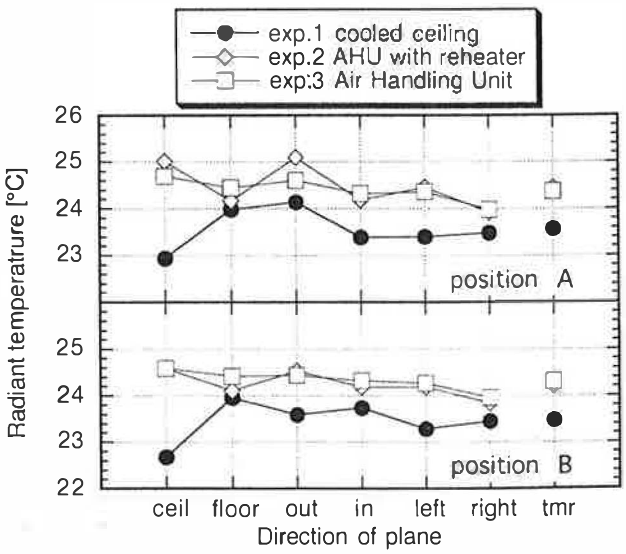


Fig. 3. Typical t_{pr} and t_{mr} at the height of 600 mm of position A and B while cooling.

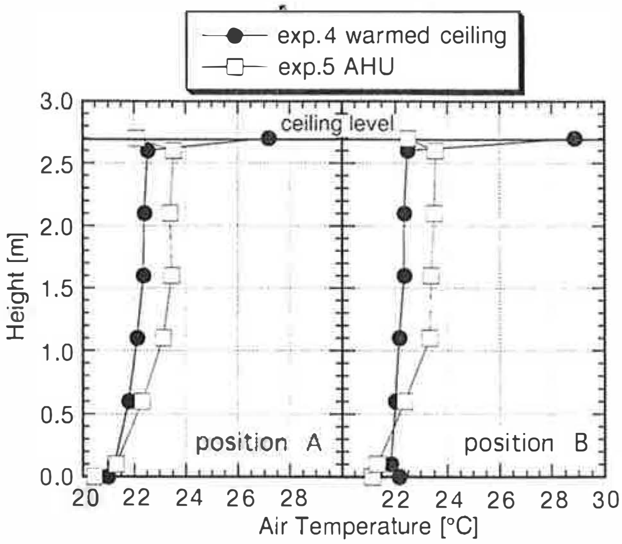


Fig. 4. Typical vertical variations of air temperature while heating.

ceiling by using numerically calculated view factors between a small cube at the considered positions and the room surfaces. The radiant ceiling panel system (Expt. 1) showed lower t_{pr} in all directions than other two systems, presumably because the walls and the floor were cooled by direct radiation exchange with the cooled ceiling. Fig. 3 clearly demonstrates that the radiant ceiling panel system created a 'cool head and warm feet' radiant environment, whereas conventional AHU systems created a slightly 'warm head and cool feet' environment.

Fig. 4 shows typical vertical variations of air temperature while heating. The conventional system created a higher air temperature in the upper part of the room. This result shows that the radiant ceiling panel system created a smaller vertical temperature difference than the conventional system, while heating. Conversely, while cooling, significant difference in the vertical variations of air temperature were not observed in the three air-conditioning systems tested. Temperature distribution under the centre of the table was also monitored. Both of the systems showed similar temperature distributions at floor level, 100 mm and 300 mm above the floor.

Table 3 shows evaluation of the thermal environment created by the warmed ceiling. This table shows a comparison with the recommended comfort index of ISO7730. None of the factors exceeds the recommended limit in experiments 4 and 5. In terms of vertical temperature difference and floor temperature, experiment 4 seemed to give more comfort than experiment 5.

Table 4 shows mean air velocities and percentage of dissatisfied (PD) [5], calculated from averaged air velocity, temperature and turbulence intensity at the height of 600 mm of positions A and B during the experiments. Due to smaller supply air volume, the radiant ceiling system (Expts. 1, 4 and 7) showed lower mean air velocity and smaller PDs than the conventional system using AHU (Expts. 2, 3, 5 and 7). This observation also clearly shows another favourable effect of the radiant ceiling panel system to thermal environment.

Table 4
Mean air velocity and calculated percentage of dissatisfied caused by draught at the height of 600 mm

Experiment	Position A		Position B	
	Mean air velocity (m/s)	PD (%)	Mean air velocity (m/s)	PD (%)
1	0.073	4.4	0.068	4.0
2	0.125	12.7	0.099	8.5
3	0.101	8.2	0.105	8.7
4	0.076	5.6	0.073	4.6
5	0.098	7.8	0.099	7.7
6	0.087	4.6	0.078	4.9
7	0.159	10.7	0.117	8.7

2.2.2. Thermal comfort

Fig. 5 shows the result of votes on thermal comfort, from an all male group. Considering the method of questionnaire, the trend of the result is better shown, rather than detailed analysis. While cooling, nearly 80% of the votes favoured the radiant ceiling panel system with either 'comfortable' or 'slightly comfortable' votes. This clearly suggests that the radiant ceiling panel system is capable of creating a more comfortable environment than the conventional system with humidity control (Expt. 2). While heating, the radiant ceiling panel system (Expt. 4) obtained even more votes of 'comfortable' or 'slightly comfortable'.

Fig. 6 shows the summary of thermal comfort votes from female subjects. Though the total percentage of votes for 'comfortable' or 'slightly comfortable' looks similar, the comfort margin of the cooled ceiling (Expt. 6) increased as time elapsed during the experiment. On the

Table 3
Comparison with recommended comfortable factors of ISO7730

Factors	PMV		Vertical temperature difference 0.1–1.1 m		Vertical t_{pr} asymmetry		Surface temperature of floor		Operative temperature	
Recommendation	−0.5 to +0.5		Less than 3°C		Less than 5°C		19°C–26°C		20°C–24°C	
Position	A	B	A	B	A	B	A	B	A	B
Experiment 4	−0.4	−0.4	0.9	0.3	3.3	3.9	21.0	22.2	22.2	22.4
Experiment 5	−0.4	−0.4	1.8	2.0	1.5	1.9	20.5	21.2	21.9	22.1

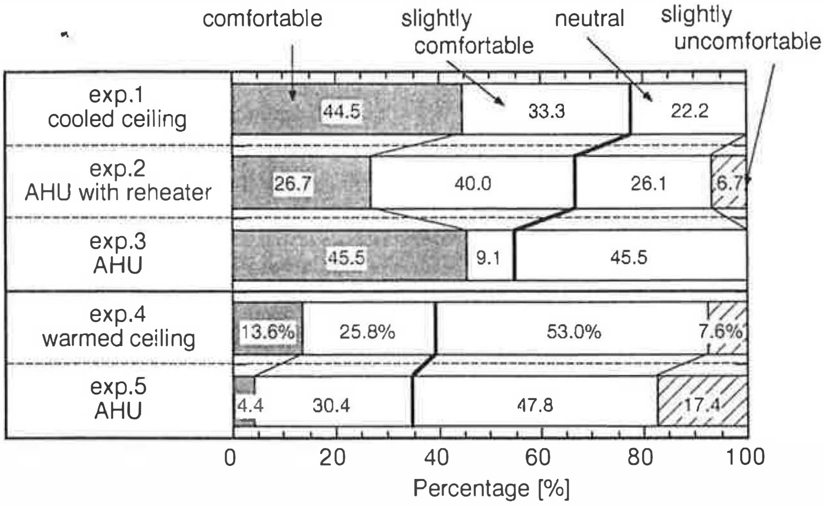


Fig. 5. Summary of votes from male subjects on thermal comfort.

other hand, the percentage of votes for 'slightly uncomfortable' or 'uncomfortable' for AHU has been higher than that of cooled ceiling through the experiments. These results can be explained by Fig. 7, time variation of mean thermal sensation votes of subject's thighs. No significant difference was observed between two systems initially. After the first 45 min, the subjects in Expt. 7 felt cooler, whereas subjects in Expt. 6 felt no change. Fewer subjects felt comfortable when feeling cooler in the lower parts of the body. As seen in Table 4, when the radiant ceiling panel system was operated, a small volume of supplied air creates a less draughty environment.

From these results, it is clearly demonstrated that the radiant ceiling panel system creates a more comfortable environment for both male and female occupants.

2.2.3. Work efficiency

Fig. 8 shows the result of work efficiency tests. The examination result from the *T*-distribution with 98% reliability, derived that the work 1 showed significant difference. Generally speaking, both accuracy and achievements of the work seem to be higher under the environment created by cooled ceiling (Expt. 6), than conventional all-air system (Expt. 7). It may be concluded that there is a possibility to provide high work efficiency by using radiant ceiling panel system though further research is necessary.

3. Energy consumption

3.1. Numerical simulation model

To compare the energy consumption and cost efficiency of the different air-conditioning systems, typical office rooms located on the 3rd, 4th, and 5th floor of a six-floor building in Tokyo were simulated as a case study. Total

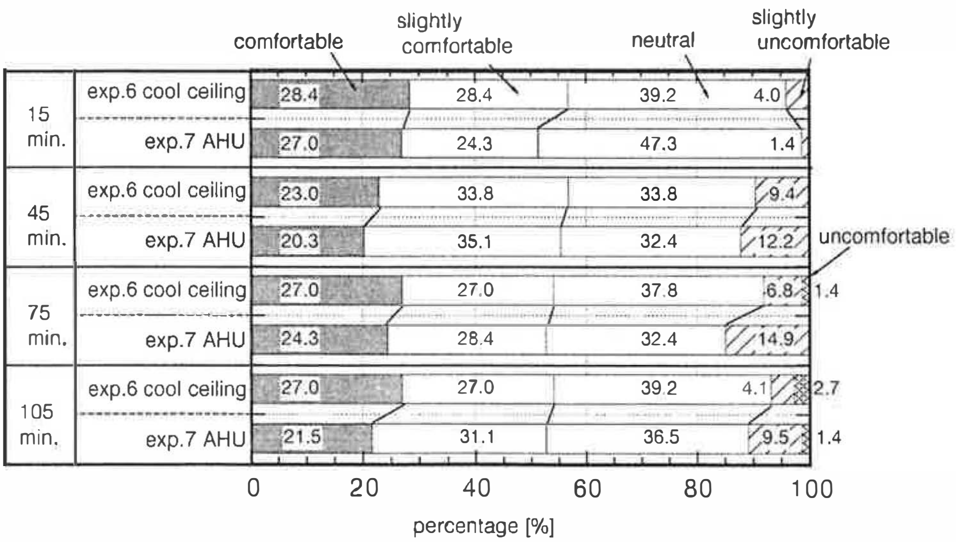


Fig. 6. Thermal comfort vote from female subjects with elapsed time.

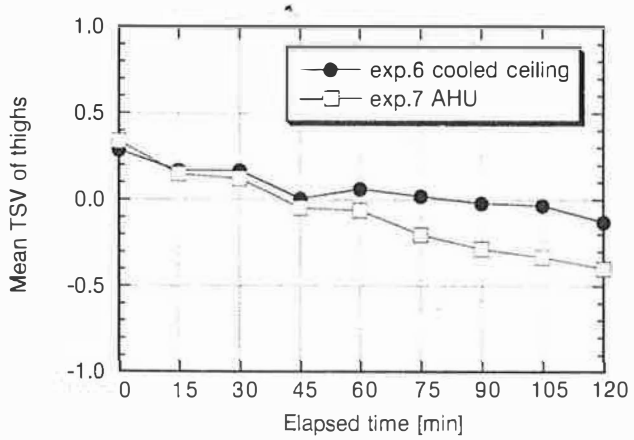


Fig. 7. Mean thermal sensation votes of thighs.

area of air-conditioned space was set at 1764 m^2. It was determined that about 70% of the ceiling was covered by radiant ceiling panels when the radiant ceiling panel system was applied. Calculated conditions relating to the thermal load are as follows: floor area per occupant was 7 m^2 with room occupancy rate of 70%; heat generation by lights and appliances (i.e., computers, copy machines, etc.) was 37.5 W/m^2 of floor area.

Table 5 shows four different air-conditioning systems of which the performance has been numerically simulated. Case 1: conventional all-air system, case 2: humidity controlled all-air system (AHU with reheater), case 3: radiant ceiling panel system with AHU and case 4: radiant ceiling panel system with AHU and desiccant dehumidifier. Considering reasonable initial costs, these air-conditioning systems were regarded to be applied to only the 5th floor of a six-floor office building. Cases 2 and 4 required a water boiler while cooling because reheating of overcooled air or regeneration (drying) of the adsorption wheel is necessary. In all cases, the 3rd and 4th floor were air-conditioned by a conventional all-air system, which were identical to case 1. Room humidity condition has also been tabulated in Table 5. To avoid condensation on cooled ceiling panels, surface temperature of the panel was kept 2°C higher than the room dew point temperature in cases 3 and 4 while cooling. All systems supplied constant volume of air and an identical volume of fresh air 8.2 m^3/hm^2 floor area (ventilation rate: 3.0/h) was maintained. Two gas absorption chiller–heaters were used as heat source.

3.2. Calculation procedure

To investigate the effect of radiant ceiling panels on thermal environment, a three-dimensional steady state radiative heat transfer analysis was conducted [6]. External boundary conditions for the building such as ambient temperature, humidity and solar radiation were obtained from the standard weather data of Tokyo, which provides monthly averaged values of each hour. Along with the monthly averaged data, two peak conditions representing the most severe environment were applied to estimate the peak load and to design the maximal capacity of air-conditioning appliances. In total, 14 different days at every hour from 8:00 am to 6:00 pm were selected. These 14 days included 12 days of monthly average and winter and summer peak days.

Fig. 9 shows the flow chart of the calculation. Firstly, direct interchange areas and total exchange areas for radiative heat transfer analysis were calculated. Energy balance equations for the rooms were then solved. When solving the energy equation, PMV at the height of 600 mm in the centre of the room was maintained within ± 0.3. Parameters of calculating PMV were given as follows: air velocity, 0.1 m/s; metabolic rate of occupants, 1.1 MET; clothing, 0.5 clo in summer, 1.0 clo in winter, 0.75 clo for other seasons. Requirements for the supplied air temperature and ceiling panel temperature were then calculated, from which the heat load was predicted. Variation of the heat load at every hour from 8:00 am to 6:00 pm each month was calculated. Based on the predicted peak load, the maximal capacity of the air-conditioning system was

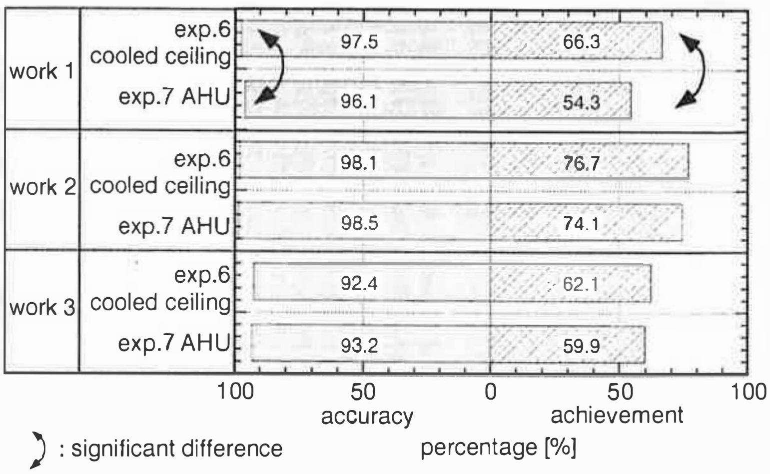
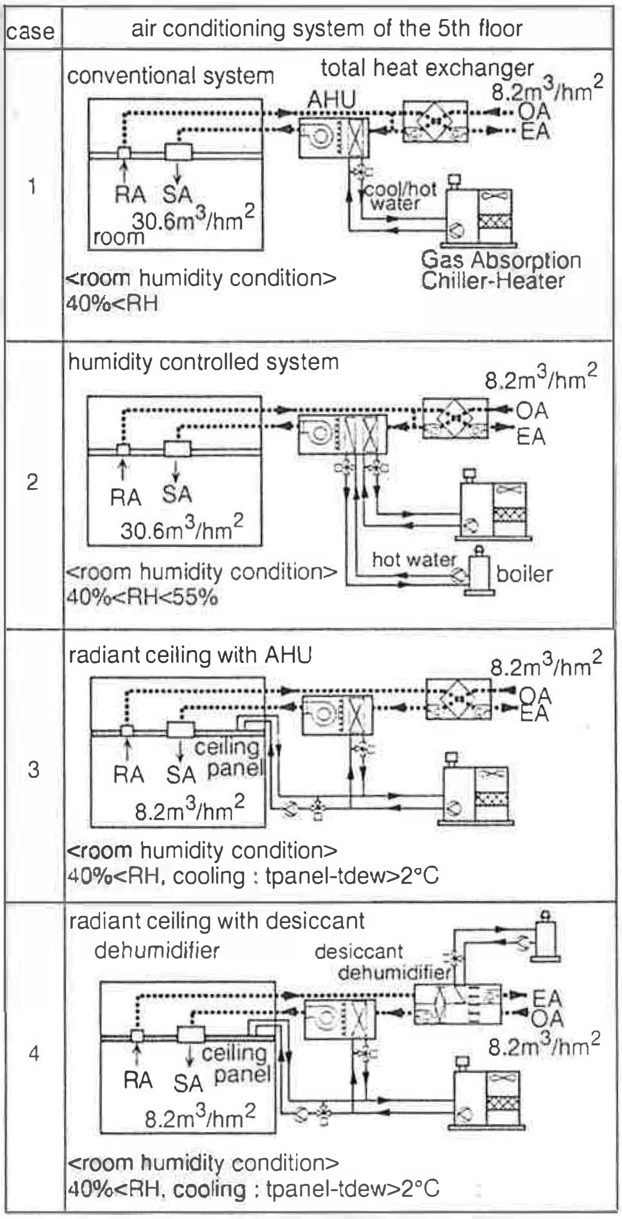


Fig. 8. Result of the work efficiency test.

calculated and necessary appliances were selected. Finally, primary energy consumption and energy cost were obtained by using the predicted annual thermal load. Partial load efficiency of the gas absorption chiller–heater was taken into account [7]. At the same time, total air-conditioning systems were designed and initial costs were estimated. Costs for installation were included in the initial costs.

These cost estimations were based on the standard price, though some sort of discounts are observed in the real market. The price of the radiant ceiling panel, which has not been on the market yet, was assumed, as a possible market price, to be half that of the hand-made experimental sample's price. Note that these cost estimations were based on the standard price of January 1994.

Table 5
Air-conditioning systems simulated the 5th floor



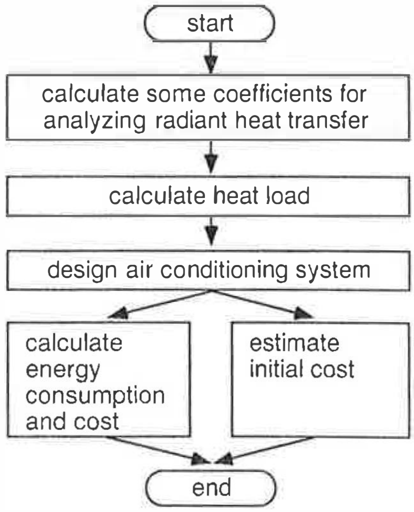


Fig. 9. Flow chart of the calculation procedure.

3.3. Calculation results

In Tokyo, heat generation in office rooms is, in fact, generally so large that cooling is necessary during most of the year. Calculation results show similar trend. Fig. 10 shows monthly variation of room air temperature, mean radiant temperature (t_{mrt}), relative humidity and ceiling panel temperature of the 5th floor. In the figure, results of each month are actually the average of hourly values from 8:00 am to 6:00 pm. During the summer, though PMV in all cases were maintained almost identically, the air temperature created by radiant ceiling (cases 3 and 4) was 1.0 to 1.5°C higher than that of the all-air systems (cases 1 and 2). This appears due to a radiative effect. Compared with the all-air systems, the radiant ceiling systems created a relatively low mean radiant temperature. Concerning the humidity control, systems without a dehumidifier (cases 1 and 3) inevitably allow high humidity, over 60%, during the summer. Particularly in June and October when the cooling load is small, the temperature of the supplied air becomes relatively high, resulting in insufficient dehumidification at the cooling coils. During the winter period, all the systems require humidification in order to maintain relative humidity higher than 40%. As for the ceiling panels, the panel temperature is primarily determined depending on the dew point temperature while cooling. Case 4, that is equipped with a desiccant dehumidifier, created a superior radiant environment because the room dew point can be maintained low enough in the summer.

Fig. 11 shows energy consumption for handling peak cooling load. Note that the word 'energy consumption' used in the figure are equivalent for the peak thermal load, so energy consumption for air transport and energy for heat source, etc., are not included. In the graph, negative

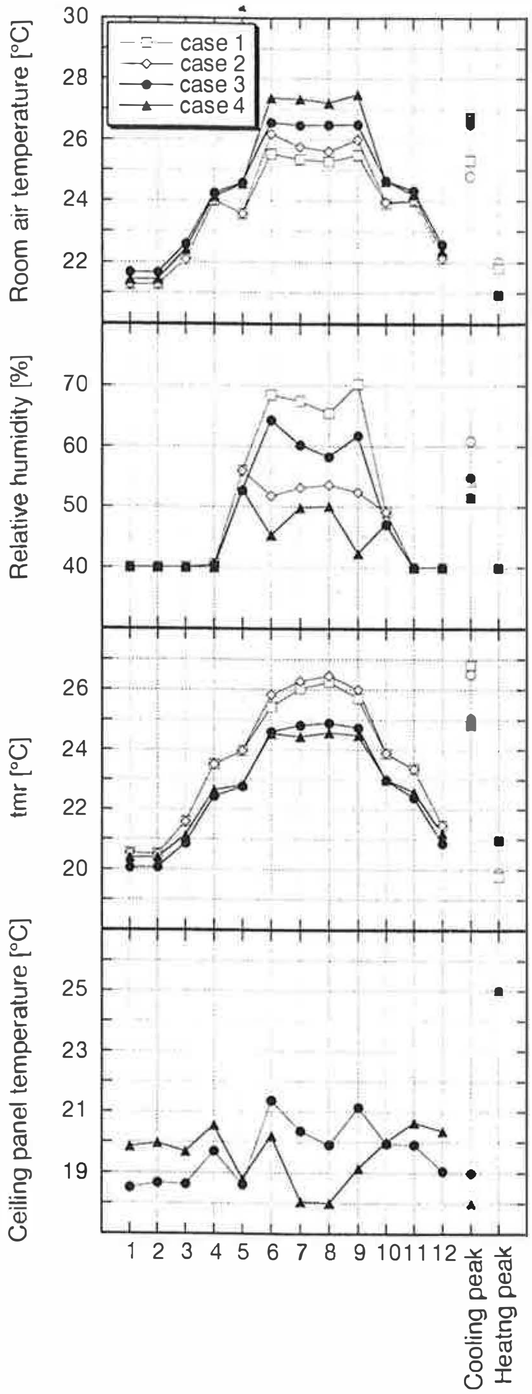


Fig. 10. Calculated room conditions of the 5th floor.

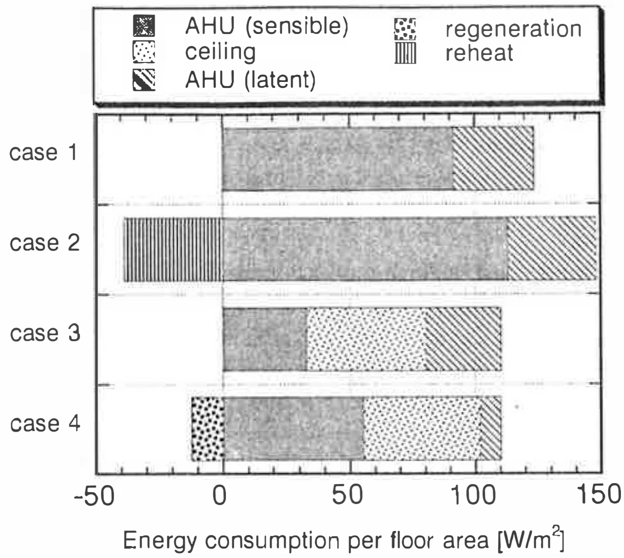


Fig. 11. Energy consumption of the 5th floor at the peak cooling load.

values mean energy consumption with hot water. Cases 2 and 4 required hot water during the summer in order to reheat the overcooled air or to regenerate the adsorption wheel of the desiccant dehumidifier. Care should be taken such that room thermal environments created by these systems are not identical. Though the room air temperature of case 3 was higher than case 1, marginal reduction of the energy consumption for sensible thermal load (AHU + ceiling) was identified. This appears to be due to a relatively larger amount of radiative heat exchanged between the cooled ceiling and the walls and floor. Radiant ceiling panel systems appear to allow relatively large energy loss by heat conduction through the walls and floor.

Fig. 12 shows the summary of the yearly primary energy consumption of all the cases considered. Compared with the conventional all-air system (case 1), radiant ceiling panel systems (cases 3 and 4) successfully reduced air transport energy by 20%, resulting in total energy consumption 10% less than the conventional system. As a result, energy cost was reduced by 9–10% by using radiant ceiling panel system. From the result mentioned above and subjective experiments, it can be said that radiant ceiling panel system creates a more comfortable environment with less energy consumption.

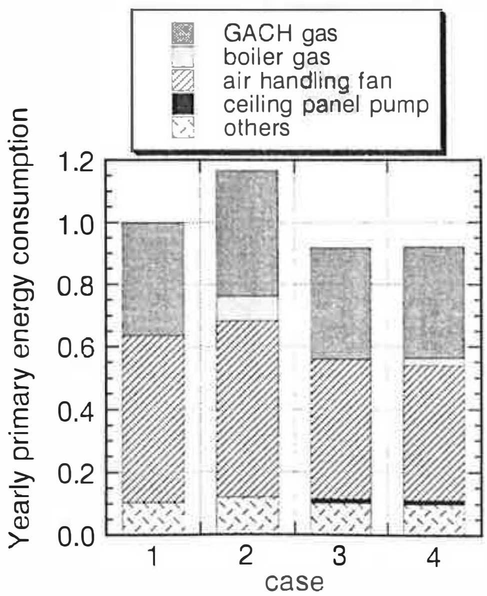


Fig. 12. Yearly primary energy consumption ratio to case 1.

Table 6
Initial cost ratio to case 1

	Heat source appliances	Air handling units	Ducting and piping	Control and electrical equipment	Ceiling panels	Other	Total
Case 1	0.166	0.328	0.334	0.081	–	0.091	1.000
Case 2	0.179	0.375	0.354	0.109	–	0.102	1.117
Case 3	0.167	0.280	0.310	0.098	0.057	0.091	1.003
Case 4	0.178	0.259	0.317	0.104	0.057	0.091	1.006

Table 6 shows initial cost ratio to case 1, which is applying conventional all-air system for all three floors. Applying radiant ceiling panel system, small size of AHUs can be used, leading to less expensive cost for AHUs, ducting and piping. On the other hand, extra cost for ceiling panels was necessary, along with special control equipment. In cases 3 and 4, total costs were slightly increased compare to case 1, but the energy cost could be reduced as mentioned above. Estimated pay back time was around 1 year with an assumption of the market price of the ceiling panel. Considering the worst case, the market price is similar to the hand-made experimental sample's price, the pay back time will be 17 years.

4. Conclusions

The radiant ceiling panel system and conventional air-conditioning systems have been compared both experimentally and numerically in terms of thermal comfort, energy consumption and cost efficiency. The following conclusions have been reached:

1. The radiant ceiling panel system creates a superior radiant environment while cooling.
2. The system is also capable of creating a smaller vertical variation of air temperature, while heating, than a conventional system.
3. The radiant ceiling panel system obtained more votes for comfort from the subjects.
4. Since part of the sensible thermal load is handled by radiant ceiling panels, the volume of supplied air can be reduced. Draughts are eliminated and lower energy consumption for air transport is achieved.
5. Estimated pay back time of using the radiant ceiling panel system in one of the three floors of an office building was 1 to 17 years depending on the market price of the ceiling panel.

In this study, basic characteristics of the radiant ceiling panel system were obtained and practical application to office buildings was simulated. Before being on the market in Japan, following developments would be necessary.

- The effective and less expensive control system of the ceiling panel temperature and room humidity (i.e., quick response to rapid change of the room condition),
- Interior co-ordinated radiant ceiling panel with reasonable price,
- Operational life of the system.

The results obtained in this study are believed to be applied to many areas with similar climates such as Southeast Asia, Middle America, the southern part of the US and Europe.

References

[1] C.K. Wilkins et al., Cool ceiling system: a European air-conditioning alternative, ASHRAE Journal, August 1992, pp. 41–45.

[2] M.F. Brunk, Cooling ceilings—an opportunity to reduce energy costs by way of radiant cooling, ASHRAE Trans. 99 (1993) 479–487, Part 2.

[3] U. Busweiler, Air conditioning with a combination of radiant cooling, displacement ventilation, and desiccant cooling, ASHRAE Trans. 99 (1993) 503–510, Part 2.

[4] International Standard ISO 7730, Moderate Thermal Environments—Determination of PMV and PPD indices and Specification of the Conditions for Thermal Comfort, Ref. No. 7730, 1984(E) (August 1984).

[5] P.O. Fanger et al., Air turbulence and sensation of draft, Energy and Buildings 12 (1988) 21–39.

[6] T. Omori et al., Radiative heat transfer analysis of indoor thermal environment, Proc. 6th Int. Conf. on Numerical Method for Thermal Problems, 1989, pp. 730–740.

[7] N. Nishiyama et al., Modeling and control of a double-effect absorption refrigerating machine (part 1: Model analysis), Proc. 17th Int. Cong. of Refrig. Vol. B, 1987, pp. 571–576.