The air-conditioning control technique based on predicted room air distribution

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ABSTRACT

Conventional air-conditioning control in a room assumes perfect diffusion of temperature in the room, and relies on a temperature sensor installed on the wall or ceiling of the room, or in the return duct. Air-conditioning is controlled so that the sensor temperature becomes equal to the sensor-set temperature ("set temperature"). In reality, however, since thermal stratification occurs in a room, the set temperature is often not attained in an occupied zone that should be properly air-conditioned. This may result in excessive cooling. To simultaneously achieve occupant comfort and energy conservation by air-conditioning only the necessary zone to a necessary level, it is essential to base air-conditioning control on the predicted airflow and temperature distributions in the room. The objective of the present study is therefore to develop an air-conditioning control technique that considers such predicted distributions in the room. In this report, computational fluid dynamics (CFD) analysis is used to study the energy-saving effect of controlling the occupied-zone temperature in a standard office-room model to the set temperature, using various air-conditioning systems.

1. INTRODUCTION

The temperature and airflow distributions in a room are not uniform but vary with season, time and various other factors. However, conventional air-conditioning control assumes perfect diffusion of temperature and airflow in the room, relying on the temperature sensor installed on the wall or ceiling of the room, or in the return duct. That is, air-conditioning is controlled so that sensor temperature becomes equal to set temperature. In reality, however, since thermal stratification occurs in a room and the temperature sensor is not installed in the occupied zone, the set temperature may not be attained in the occupied zone. With the conventional air-conditioning control technique, therefore, when the room is cooled the sensor temperature is often higher than the actual temperature of the occupied zone, resulting in excessive cooling. That is, the optimal temperature at which the occupants feel comfortable cannot be obtained; air-conditioning control thus can waste energy without providing comfort to the occupants. If the set temperature is attained in the occupied zone, occupant comfort and energy conservation can be achieved simultaneously. However, it is difficult to control air-conditioning while measuring the temperature of the occupied zone, since the temperature sensor installed in the occupied zone may have to be removed due to floor-layout change, or can be damaged if an occupant collided against it. To maintain the set temperature in the occupied zone and realize occupant comfort and energy conservation simultaneously, air-conditioning control must be based on predicted airflow and temperature distributions in the room. The present study is aimed at developing an air-conditioning control technique that considers such predicted distributions in the room. Using various air-conditioning systems, we used CFD analysis to study the energy-saving effect of maintaining the occupied-zone temperature at the set temperature in a standard office-room model.

2. OVERVIEW OF THE STUDY

2.1 Subject of Analysis (Figure 1)

The following three different types of air-conditioning systems were used for the analysis: packaged ceiling-cassette air-conditioning system ("ceiling-cassette system"), ceiling-outlet/ceiling-intake central air-conditioning system (“ceiling-outlet system”), and floor-outlet/ceiling-intake central air-conditioning system (“floor-outlet system”). The analytical environment was a standard office-room model having a window on the south wall and measuring 10.8 m in length. The 1.8 m wide zone (half the span width of 3.6 m) of the room was subjected to analysis. The space above the ceiling was also considered in analyzing the ceiling-outlet and floor-outlet systems.

2.2 Outline of Analysis (Table 1)

The assumed air-conditioning load generated at noon (12:00) in summer was used. Internal heat loads generated by human bodies, personal computers (PC) and lighting in the room were set based on the coefficient of energy consumption (CEC). As the solar radiation load, standard solar heat gain was applied uniformly over the entire floor surface. For external loads, external-wall temperature and window temperature were used. The external-wall temperature was calculated - with the heat transmission coefficient of external wall set at 0.9 $W/m^2 \cdot K$ - from the equivalent temperature difference based on the maximum design heat load. The window temperature was obtained from the design outside air temperature.

2.3 Cases for Analysis (Table 2)

We analyzed a total of six cases with different air-conditioning systems and different sensor positions. Ceiling-cassette, ceiling-outlet and floor-outlet air-conditioning systems were used. For all air-conditioning systems, airflow volume was set at 10 m^3/min (constant). The temperature sensor was installed in either the air intake or the occupied zone. For air-conditioning control the constant-air-volume (CAV) system was used, which controls the air outlet temperature so that the mean sensor temperature becomes 26°C.

2.4 Analysis Results (Figure 2)

2.4.1 Case 1 (Ceiling-cassette)

In Case 1-1, no clear temperature stratification was observed in the room. The air in the room was well stirred and the room temperature was mostly uniform, at 26°C. Similar results were

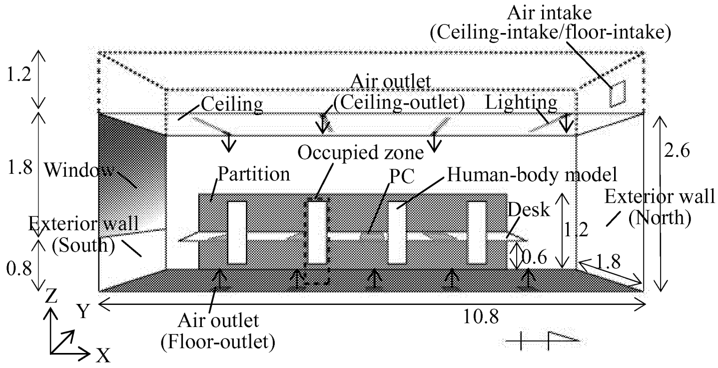


Figure 1. Subject of Analysis

Table 1. Air-Conditioning Load

Internal loads			
Human body (4bodies)	Lighting (4units)	PC (4units)	Solar radiation
240W	400W	200W	583W

External loads		
Window	Exterior wall (South)	Exterior wall (North)
33.1°C	26.6°C	26.6°C

Table 2. Cases for Analysis

Case	Air-conditioning system	Sensor position	Control system*
1-1	Ceiling-cassette	Air intake*	CAV
1-2		Occupied zone **	
2-1	Ceiling-outlet	Air intake	
2-2		Occupied zone	
3-1	Floor-outlet	Air intake	
3-2		Occupied zone	

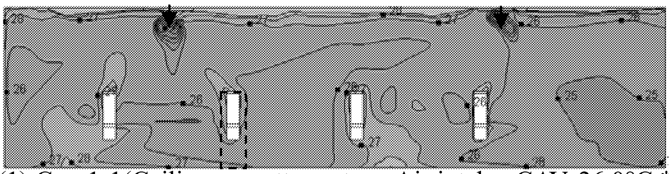
* For the ceiling-cassette system, one air intake was installed per air-conditioner unit (two units in the zone analyzed), with air-conditioning by each unit controlled independently so that the air temperature in each air intake became 26°C. For the ceiling-output and floor-output systems, air-conditioning was controlled so that the mean air-intake temperature became 26°C, on the assumption that temperature sensors were installed in the return ducts.

** The occupied zone is a 400 mm × 900 mm × 1,250 mm area surrounding a human-body model (Fig. 1). The temperature value indicated in Fig. 2 is the mean temperature in this area.

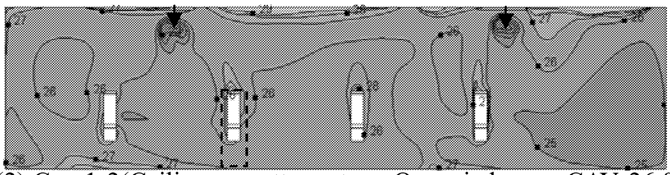
observed in Case 1-2. That is, temperature distribution was hardly influenced by sensor position.

2.4.2 Case 2 (Ceiling-outlet)

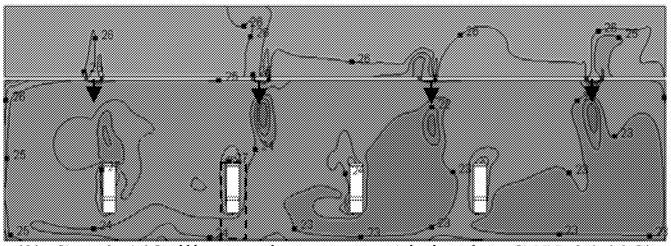
In Case 2-1, a vertical temperature difference of approximately 2°C was observed in the room; despite the set temperature of 26°C, the



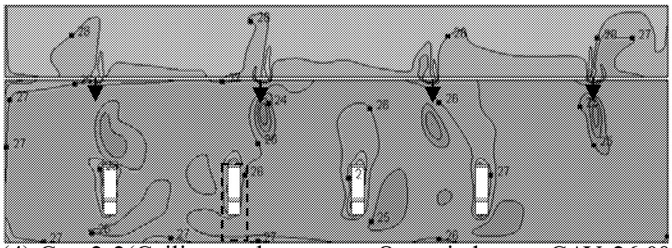
(1) Case1-1(Ceiling-cassette system, Air intake, CAV, 26.0°C *)



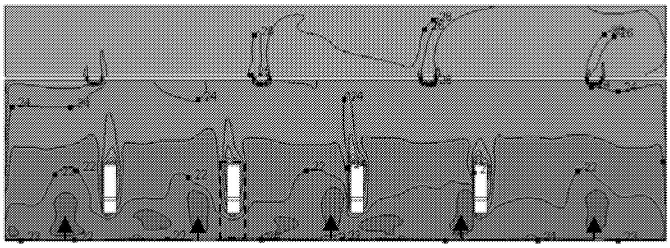
(2) Case1-2(Ceiling-cassette system, Occupied zone, CAV, 26.0°C)



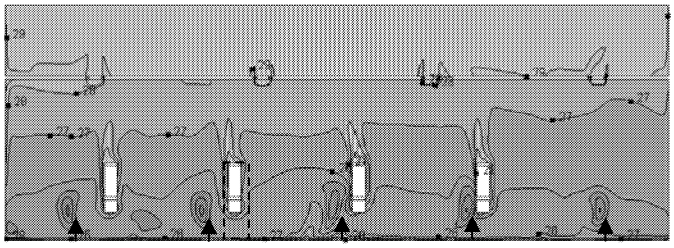
(3) Case2-1(Ceiling-outlet system, Air intake, CAV, 24.0°C)



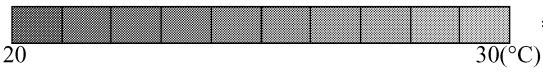
(4) Case2-2(Ceiling-outlet system, Occupied zone, CAV, 26.0°C)



(5) Case3-1(Floor-outlet system, Air intake, CAV, 22.0°C)



(6) Case3-2(Floor-outlet system, Occupied zone, CAV, 26.0°C)



* Mean temperature of occupied zone [ ] Occupied zone ▲ Air outlet position

Figure 2. Temperature Contours (Vertical Section through Center of Human Body)

temperature in the occupied zone was approximately 24°C (slightly too cool). The temperature in the perimeter zone was also slightly lower than the set temperature. In Case 2-2, a high temperature of approximately 28°C occurred in the above-ceiling space while the set temperature was maintained in the occupied zone.

2.4.3 Case 3 (Floor-outlet type)

In Case 3-1, a vertical temperature difference of approximately 3°C was observed in the room; despite the set temperature of 26°C, the temperature in the occupied zone was 22°C (too cool). Excessive cooling can occur with the conventional air-conditioning control system. In Case 3-2, distinct vertical stratification of temperature occurred in the room while the set temperature was maintained in the occupied zone. This indicates that only the occupied zone was effectively air-conditioned, while hot air was allowed in the upper non-occupied zone, which did not require air-conditioning.

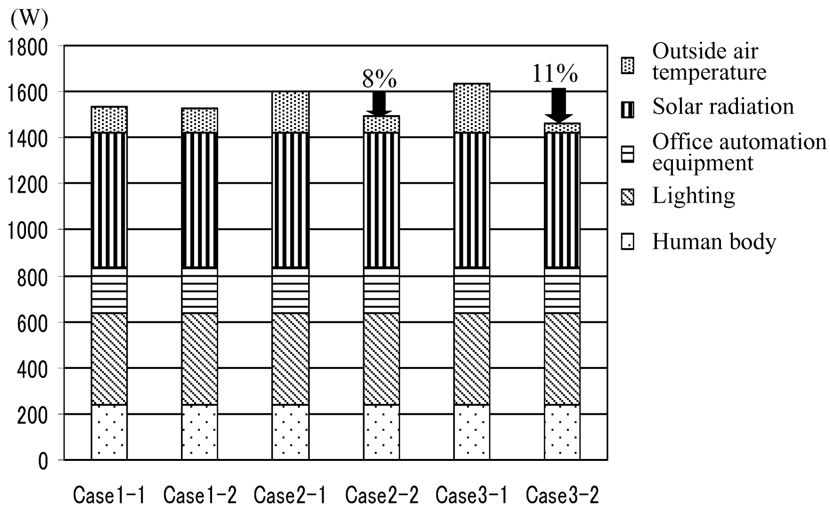


Figure 3. Heat Input Result

2.5 Result of Heat Input to Air-conditioning System (Figure 3)

With the ceiling-cassette system (Case 1), the room temperature was relatively uniform, and temperature distribution did not vary with sensor position. Therefore, change in the sensor position did not lead to any significant difference in heat input to the air-conditioning system. With the ceiling-outlet system (Case

2-2), overall heat input was reduced by approximately 8% when the occupied-zone temperature was controlled to the set temperature. This is because the heat load from the outside air temperature was suppressed as a result of vertical stratification of temperature in the room. With the floor-outlet system (Case 3-2), overall heat input was reduced by approximately 11% when the occupied-zone temperature was controlled to the set temperature. The heat load from the outside air temperature was reduced by approximately 83%. This is presumably because the heat load from the outside air temperature was substantially suppressed due to distinct vertical stratification of temperature in the room.

3. STUDY FOR IMPROVING OCCUPANT COMFORT AND ENERGY EFFICIENCY BY ADOPTING PERSONAL AIR-CONDITIONING CONCEPT

The results revealed that air-conditioning control in the occupied zone has a higher energy-saving effect than does the conventional control in the air intake, and that the floor-outlet air-conditioning system can be the most energy efficient. On the basis of these findings, we studied a new air-conditioning system that can improve energy-saving performance and occupant comfort. For that study, we used the personal air-conditioning concept (Figure 4), which provides a particular individual with higher comfort via thermal and airflow sensations. In addition, a mechanical ventilation unit was installed in the upper part of the room; this mechanical ventilation unit and ambient air-conditioning system removes internal heat load generated in the room, thereby reducing the amount of heat to be processed by the ambient air-conditioning system. We conducted CFD analysis to study the energy-saving performance and occupant comfort that can be achieved by installing personal air-conditioner and mechanical ventilation units in a standard office-room model.

4. OVERVIEW OF THE STUDY

4.1 Subject of Analysis (Figure 5)

Figure 5 shows the office-room area subjected to analysis. We assumed an office room measuring 3.8 m from floor level to ceiling (above-ceiling space height: 1.2 m) and 10.8 m in length. The 1.8 m wide zone (half the span width of 3.6 m) of this room was analyzed. The air intake for the ambient air-conditioning system and the exhaust port for the mechanical ventilation unit were installed in the above-ceiling space. The floor was provided with five air outlets, one of which was used for the personal air-conditioner.

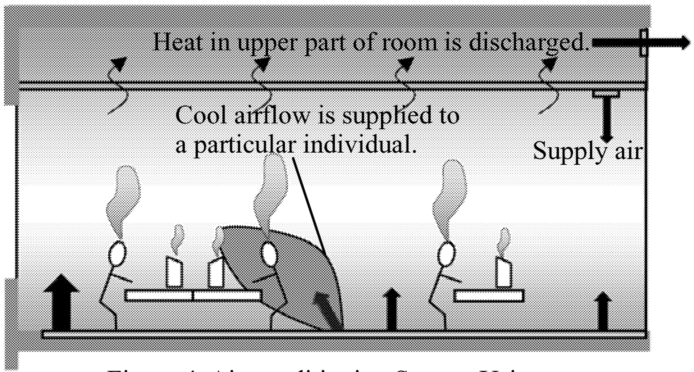


Figure 4. Air-conditioning System Using Personal Air-Conditioning Concept

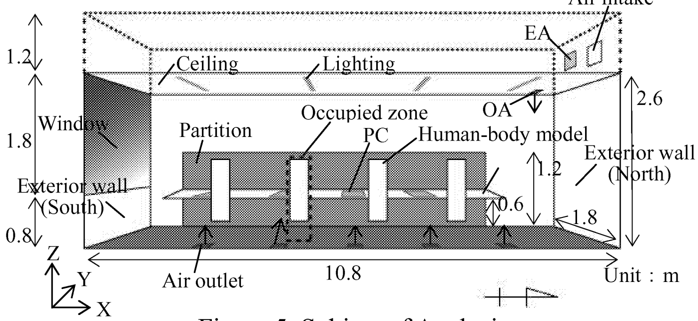


Figure 5. Subject of Analysis

Table 3. Air-Conditioning Load

Internal loads			
Human body (4bodies)	Lighting (4units)	PC (4units)	Solar radiation
240W	400W	200W	583W

External loads		
Window	Exterior wall (South)	Exterior wall (North)
28.0°C	26.6°C	26.6°C

4.2 Outline of Analysis (Table 3)

The same internal loads as specified in Section 2.2 were assumed. As for external loads, the outside air temperature was set at 28°C, since mechanical ventilation was used. The external-wall temperature was set at the same value as in Section 2.2, on the assumption that the wall was properly heat-insulated. The volume of outdoor air supplied by the mechanical ventilation was set at 303 m^3/h, assuming 6 ventilation cycles per hour. The supply-air temperature was also set at 28°C (same as the outside air temperature). We carried out CFD analysis while changing the air outlet angle of the personal air-conditioner at intervals of 5 degrees, to provide a particular individual with comfort of airflow and thermal sensations.

Table 4. Cases for Analysis

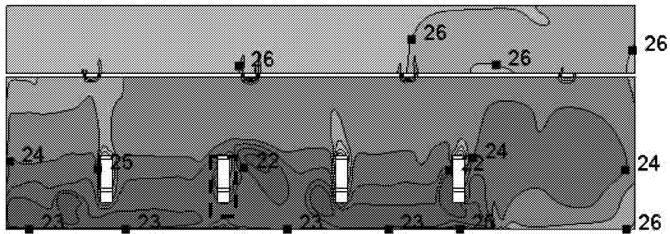
Case	Air-conditioning system	Sensor position	Personal air-conditioner(PA)	Mechanical ventilation (MV)	control system
4-1	Floor-outlet	Air intake	With	With	CAV
4-2		Occupied zone			
5-1		Occupied zone	Without	Without	

4.3 Cases for Analysis (Table 4)

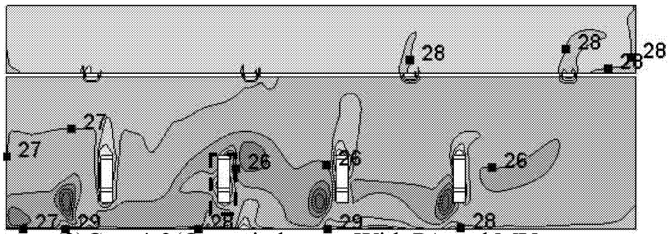
To study the occupant comfort and energy conservation achieved by installing a personal air-conditioner and mechanical ventilation, analysis was conducted for each of the three cases shown in Table 4. For Cases 4-1 and 4-2, personal air-conditioner and mechanical ventilation were installed. A temperature sensor was installed in the air intake for Case 4-1 and in the occupied zone for Case 4-2. For Case 5-1, neither personal air-conditioner nor mechanical ventilation was installed, and a temperature sensor was installed in the occupied zone (case corresponding to Case 3-2 of Table 2).

4.4 Analysis Results (Figure 6)

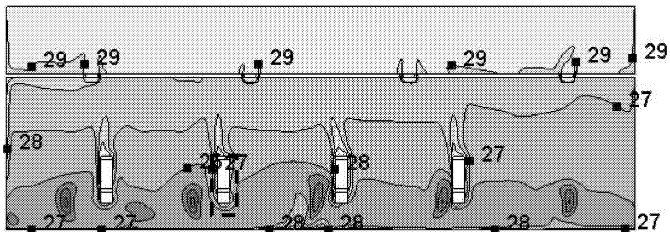
In Cases 4-1 and 4-2, the temperature distribution was uniform, without stratification, owing to the effect of the mechanical ventilation unit installed on the north wall of the room. In both cases, the temperature stratified in the occupied zone, and cool airflow was supplied directly from the air outlet to a particular individual. While the predicted mean vote PMV[(1)] in Case 5-1 (in which occupied-zone temperature was controlled to constancy without using PA and MV) was 0.5, those in Cases 4-1 and 4-2 were -0.5 and -0.2, respectively, which indicates improved occupant comfort due to the effect of PA. The heat input to the ambient air-conditioning system in Case 4-2 (with PA and MV, and a sensor in the occupied zone) was approximately 5% less than in Case 5-1 (without PA and MV). This result verifies the energy-saving effect of installing PA and MV.



(1)Case4-1(Air intake, With PA and MV, Occupied-zone temperature: 22.8°C)

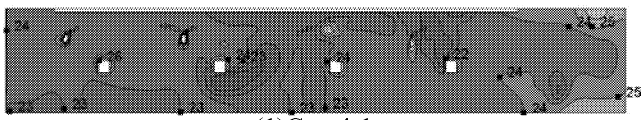


(2)Case4-2(Occupied zone, With PA and MV, Occupied-zone temperature: 26.0°C)

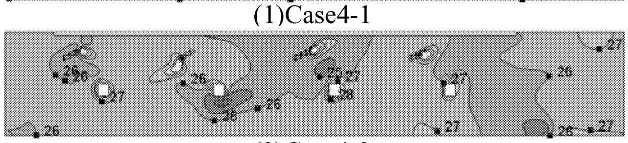


(3)Case5-1(Occupied zone, Without PA and MV, Occupied-zone temperature: 26.0°C)

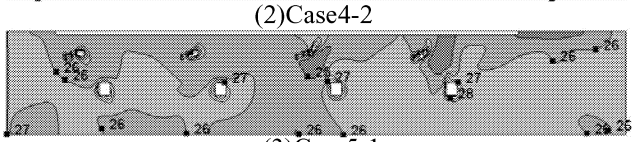
Figure 6. Temperature Contours
(Vertical Section through Center of Human Body)



(1)Case4-1



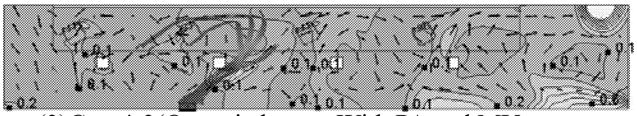
(2)Case4-2



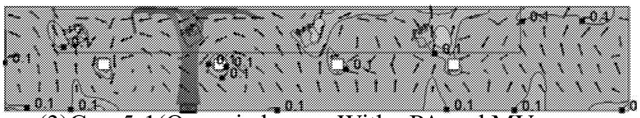
(3)Case5-1

Figure 7. Temperature Contours
(Horizontal Section at 1.0m above Floor)

(1)Case4-1(Air intake, With PA and MV, Occupied-zone temperature: 22.8°C)

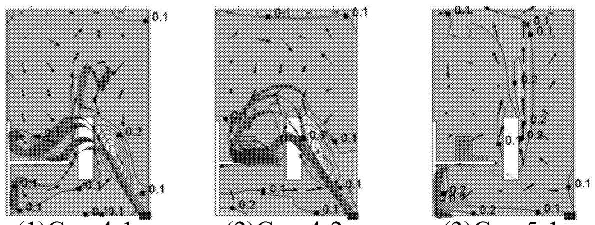


(2)Case4-2(Occupied zone, With PA and MV, Occupied-zone temperature: 26.0°C)



(3)Case5-1(Occupied zone, Witho PA and MV, Occupied-zone temperature: 26.0°C)

Figure 8. Wind Velocity Contours & Airflow Vectors
(Airflow Streamlines from Air Outlets)
(Horizontal Section at 1.0m above Floor)



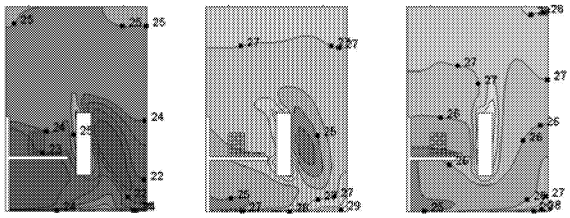
(1)Case4-1 PMV: -0.5 (2)Case4-2 PMV: -0.2 (3)Case5-1 PMV: 0.5

0 1.0(m/s)

Figure 9. Wind Velocity Contours & Airflow Vectors
(Airflow Streamlines from Air Outlets)
(Vertical Section through Center of Human Body)

5. CONCLUSION

In a standard office-room model, we studied the energy-saving effect of controlling the occupied-zone temperature to the set temperature by using various air-conditioning systems. The result shows that although the heat load in the room is the same in all cases, the heat input to the air-conditioning system differs from case to case, owing to difference in temperature distribution. It was also shown that the greatest energy-saving effect can be expected from a floor-output air-conditioning system that generates distinct vertical stratification of temperature in the room. The occupant comfort and energy-saving performance of the floor-output air-conditioning system was also studied, with the occupied-zone temperature controlled to the set temperature and personal air-conditioner and mechanical



(1)Case4-1 (2)Case4-2 (3)Case5-1

20 30(°C)

Figure 10. Temperature Contours
(Vertical Section through Center of Human Body)

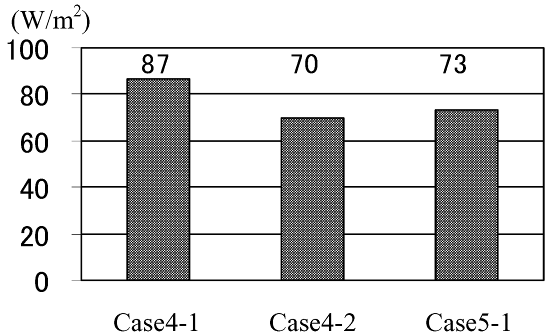


Figure 11. Temperature Contours
(Vertical Section through Center of Human Body)

ventilation installed in the room. The results indicate that remarkable energy-saving can be attained by generating a high temperature zone in the room and removing the heat by mechanical ventilation. That is, the installation of personal air-conditioner and mechanical ventilation is effective in improving energy-saving performance and occupant comfort. For the present analytical study, hot outdoor air at 28°C was supplied to the room. Even greater energy-saving effect can certainly be expected during the intermediate seasons (spring and fall).

(Note 1) PMV was calculated from the temperature and airflow velocity around the human-body model at neck level (1 m above the floor), as obtained by CFD analysis. For PMV calculation, mean radiation temperature was set at 26°C, relative humidity at 50%, clothing at 0.6 clo, and metabolic rate at 1.2 Met.

Part of the present study was conducted under a grant-in-aid for basic scientific research (B) (General) "Development of Environmental and Energy Performance Analysis Technique for Each Room and Load Factor in an Architectural Space" (Representative researcher: Tomoyuki Chikamoto), funded by the Ministry of Education, Culture, Science, Sports and Technology of Japan.