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STUDY ON THERMAL COMFORT OF LOW-PARTITION AIR-CONDITIONING SYSTEM

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Introduction

In recent years, creation of high quality thermal surroundings is required to office air-conditioning and the development of new control systems of thermal environment based on the thermal sensation of occupants has become very important. For this reason, many studies concerning thermal comfort(1,2,3,4) have been done in addition to the studies of the airflow distributions and temperature distributions in the offices(5,6,7,8). The present paper is a study on thermal environment and thermal comfort created by a new air-conditioning system designed for intelligent offices. For intelligent buildings some new demands such as personal air conditioning, energy saving, man hour saving and the creation of amenity spaces have been added to the conventional requirement of heating and air conditioning. There are two main characteristics of cooling loads in offices of intelligent buildings. The one is that cooling load is about twice as high in the office of intelligent buildings owing to communication devices and office-automation equipments. The other is that heat generation is often concentrated in some locations surrounded by low-partitions. It is difficult to maintain the temperature in such work areas within proper ranges by the conventional air-conditioning systems.

The low-partition air-conditioning system is a new system which has high possibility of actualizing personal air conditioning and creating high quality thermal surroundings in an intelligent office. The surface of the low-partition works as a radiating surface because cooled air is transported through its panels. Cooled air led to the inlets of low-partitions through free access floor is supplied to the room from many small holes on the top of the low-partition panels and slots on the upper surface of the panels. The new system does not need ducts and it is one of merits of the system. The system is also suitable for personal air-conditioning as persons who work in the space surrounded by the low-partitions can easily control the volume of the air supplied to the space. Moreover, energy saving can be expected because air-conditioning confined to the occupied zone is possible by the supply of cooled-air to a lower zone of office(9).

The purpose of this study is to investigate air temperature distributions, air velocity distributions and thermal comfort created by the low-partition air-conditioning system.

Methods of Investigation

In order to achieve the purpose of this study, we first clarified some fundamental characteristics of the system by experiments. The experiments for investigating dew condensation on the panels of the low-partition were carried out in a environmental test room where the humidity and the room temperature could be controlled. The experiments for investigating velocity distributions and temperature distributions were performed using a test module, in the center of which a pair of low-partitions were set. Subsequently, numerical calculations were carried out to predict the temperature distributions and the velocity distributions in the test module. Thermal sensation tests by subjects were carried out in the test module to evaluate the thermal comfort of the low-partition air-conditioning system. For the purpose of comparing the new system with the conventional systems, thermal sensation tests for the anemo-type diffuser system were also performed which was one of the most excellent conventional air-conditioning system.

Test Module

An outline of the test module is shown in Fig.1 and Fig.2. The width, depth and height of the test module are 3000 mm, 4000 mm and 2600 mm. And a pair of low-partition working-areas are placed in symmetry in the center of the test module. The width and depth of the working area are 1500 mm and 938 mm. The height of the low -partitions is 1155 mm. Subjects take the thermal sensation tests at the points C and E of the left drawing in Fig.2.

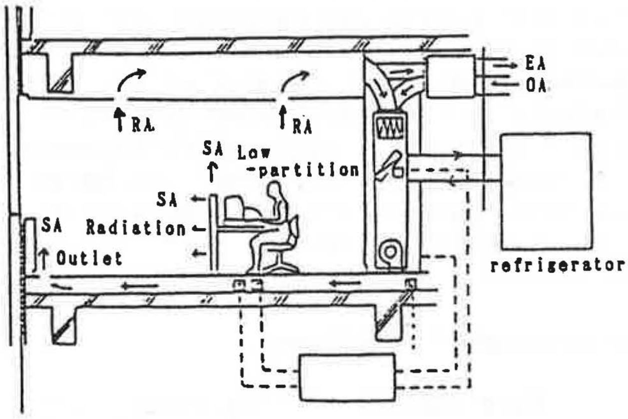


Fig.1 Low-partition air-conditioning system

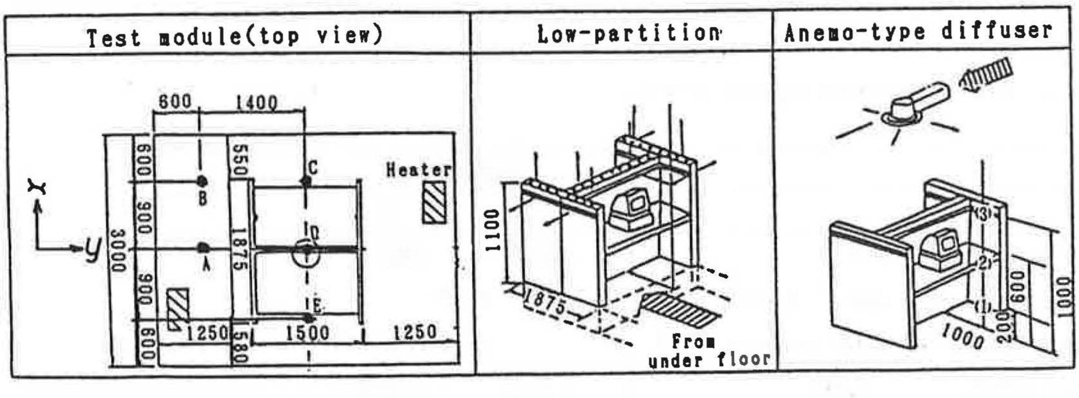


Fig.2 Top view of the test module and low-partition.

Two panel heaters are placed on the floor to control cooling loads of the test module. The locations of the heaters are selected so that the radiation from the heaters does not hit subjects directly. Cooled air is supplied to the room from many holes on the top and slots on the upper surface of each low-partition panel. Surface temperatures of the low-partition panels are lower than set temperature of the room because the cooled air is transported through the panels. Therefore, the low-partition panels work as cool radiation-panels to the human body in the working area surrounded by low-partitions. This means that a higher room temperature is permitted to get the same thermal comfort. The thermal sensation tests were performed under the condition that a personal computer was placed on the desk because personal computers were usually placed on desks of intelligent office. Anemo-type diffuser of a conventional air-conditioning system is set in the center of the ceiling. Two slot-type air-inlets are placed in symmetry on the ceiling.

Measurements of the Thermal Environmental Factors

Temperatures were measured with 60 Cu-Co thermo-couples and two multi-points pen-recorders. The room temperatures were measured at five different heights of 200, 300, 600, 1000, 1700 mm at points A, B, C, D and E in Fig.2. However, two heights of 900 and 1100 mm were added to the above heights at the positions of subjects, C and E. The temperatures of wall surfaces, ceiling surface and low-partition panels were also measured. Humidity in the test module was measured with a ventilated psychrometer near a subject's position. Air velocities were observed by a visualization method using metha-aldehyde as a tracer of the airflow and were also measured at the same heights as the measurement heights of temperatures using an anemometer with non-directional response performance. Mean radiant temperatures were calculated from the heat exchange measured with a stereo-radiometer. Surface temperature distributions of subjects and walls were measured with thermography equipment.

Experimental Conditions

Experimental conditions for investigating some fundamental characteristics of the low-partition air-conditioning system are shown in Table 1. Experiments were performed under two cooling conditions. Only cooling load and air volume are different between two experimental conditions, Run 1 and Run 2.

Table 1. Experimental conditions.

	Cooling	
Run	1	2
Air volume [m^3/h]	275.0	669.0
Room air temperature [℃]	26.0	
Temperature of supplied air [℃]	16.8	
Heat load [kW]	1.042	2.079
Personal computer	0.213	1.560
Lighting	0.400	
Human body	0.119	
Panel heater on the floor	0.310	-

Numerical Method

Many researchers (for example, 6,7) have been tried to predict the airflow and temperature distributions of air-conditioned or ventilated room by numerical calculations. In recent years, numerical simulation has become one of very useful methods to predict the airflow and temperature distributions in rooms. In this study we also performed numerical simulations to predict the airflow and the temperature distributions in the test module where a pair of low-partitions are placed. We adopted the Semi-Implicit Pressure Linked Equation algorithm (SIMPLE) by Patankar and Spalding (10) because the calculation algorithm is very simple. We adopted uniform viscosity model as a turbulent model in consideration of CPU time necessary for computation and stability of numerical calculation. As shown in Fig.1 and Fig.2, the domain of calculation includes obstacles with complex shapes. Therefore, we adopted the harmonic-mean method by Patankar(11) which is very useful when the domain of calculation includes obstacles with complex shapes. Computations were carried out using the main frame computer, NEC ACOS 2000, of Osaka University.

Unequal grid was used for numerical analysis. Intervals of the grid have very small values near the slot on the upper surface and the holes on the top of the low-partition panel because the slot thickness and the diameter of the holes are very small (7mm and 8mm, respectively). Concerning the solids such as low-partitions, desks and personal computers, the intervals of the grid are decided so that external shapes of the solids coincide with the grid lines as far as possible. However, the subjects are not taken into consideration as an obstacle.

Boundary conditions of temperature are as follows:

(1) temperature gradient is zero (adiabatic condition) on the wall, symmetric planes of the room and the air inlet.

(2) temperature has a given constant value at the outlets.

Boundary conditions of velocity are as follows:

(1) free slip on the wall and the symmetric planes of the room,

(2) velocity has given constant values at the outlets,

(3) velocity gradient is zero at the air inlets.

Cooling loads such as heat generation from office-automation equipments, lighting equipments, human bodies and auxiliary heating panels are supposed to occur in the control volumes corresponding to the location of each thermal load. However, the heat generation from the human bodies is supposed to be included in the office-automation equipments because the human bodies are not taken into consideration as obstacles and the human bodies locate near the office-automation equipments.

Characteristics of the Low-Partition Air-Conditioning System

Dew-Condensation Experiment

It is very important to confirm that dew condensation does not occur on the panel surface under usual cooling conditions because surface temperatures become lower than the room temperature due to cooled air passing through the panels. Dew-condensation experiments were performed under the condition that room temperature was about 26°C, air volume from the outlets was 296 m^3/h and temperature of supplied air was about 17.1°C. The relative humidity at which dew condensation started on the panel was determined by macroscopic observation. The experiments were carried out increasing gradually the relative humidity. As a result of the observation it was found that dew condensation started at the relative humidity, 74 %, and it was opt to occur at the lower surface of the panel. It is reasonable that dew condensation is apt to occur at the lower surface because the surface temperature is lowest there. However, on the actual cooling, as the relative humidity is usually held between 50%-60%, we may conclude that dew condensation does not occur on the panel surface under the usual cooling conditions.

Throw of Jets Discharged from Slot

It is very important to design so that worker surrounded by low-partitions does not feel cold draft. The air velocity must be below 0.25 m/s at the worker's position in order to avoid the cold draft. Therefore, we performed experiments in order to investigate the relation between the throw and the air volume, Q m^3/h, supplied from the slots to a work area surrounded by low-partitions. As a result, it was found that the throw was about 30 cm at Q = 400 m^3/h. The air volume supplied to a work area from the slots does not exceed 400 m^3/h under usual cooling conditions and usual locations of workers are apart from each low-partition more than 30 cm. Therefore, we may conclude that cold-draft problem caused by the jet discharged from the slots does not occur in the work area surrounded by low-partitions.

Temperature Distributions and Velocity Distributions

<u>**Temperature distributions.**</u> Fig.3 shows the vertical temperature distributions at points A, B, C and E in Fig.2. From the figure, it is found that the temperature distributions are quite different between the low-partition and a conventional anemo-type diffuser: uniform temperature distribution is formed from the floor level to the ceiling level in the case of anemo-type diffuser, on the other hand thermal stratification is obviously formed in the case of low-partition. This means that air-conditioning confined to the occupied zone is possible in the case of low-partition air-conditioning system. However, it is probable for office workers to feel thermal discomfort if the thermal stratification is formed in the occupied zone. Therefore, it is important to investigate the relation between the height where the thermal stratification is formed and the ratio of the air volume supplied upwards from the small many holes to the air volume supplied horizontally from the slot. The problem will be discussed later based on the results of numerical calculations.

<u>**Velocity distributions.**</u> Velocity distributions in the test module were observed by visualization method using metha-aldehyde as a tracer on 3 y-z planes and 2 x-z planes which cross the work area surrounded by low-partitions and photographs of the velocity distributions were taken. As a result of the investigation of the air velocities with photographs, it was found that the air velocities was a little slower in the case of the low-partition than the anemo-type diffuser. However, both did not exceed 20 cm/s within the work area, so worker will probably not feel uncomfortable cold draft.

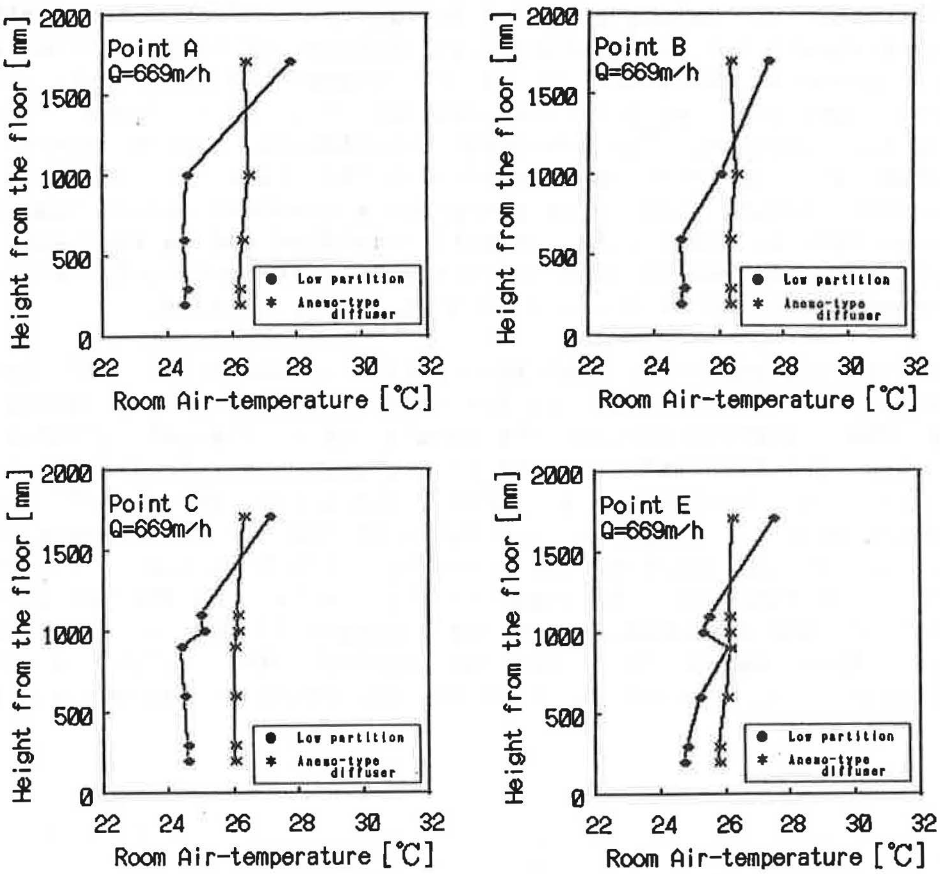


Fig.3 Difference of temperature distributions between low-partition air-conditioning and anemo-type diffuser system.

Results of numerical calculations. First we discuss the accuracy of numerical calculations. Fig.4 shows the vertical temperature distributions at points B and C in Fig.2. Numeral in the parenthesis in the explanatory notes show the ratio of air volume supplied upwards from the many small

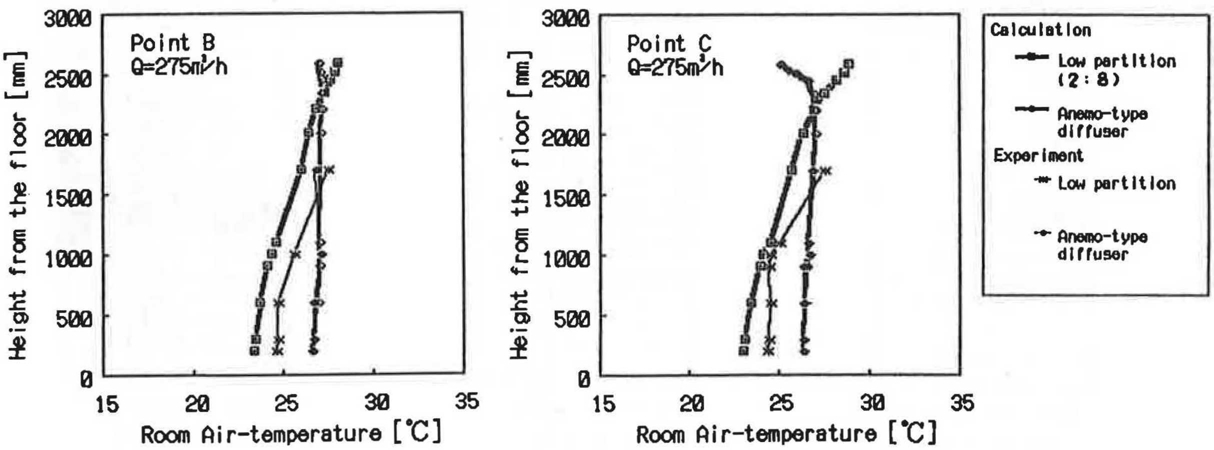


Fig.4 Comparison of numerical calculation results with experimental result.

holes to the air volume supplied horizontally from the slots. Square symbols represent the temperature distributions of low-partition system and circular symbols represent those of anemo-type diffuser; thick lines represent numerical calculation results and thin lines represent the experimental results. The numerical calculation results agree relatively well with the experimental values: in the case of low-partition, the experimental result that large temperature gradient occurs near the height of low-partition, about 1.1m, is well simulated and in the case of anemo-type diffuser, the result that temperature is approximately uniform from the floor level to the ceiling level is also well simulated.

As it was confirmed that the results of numerical calculations were relatively accurate, based on the results of numerical calculations we discuss the relation between the height where thermal stratification is formed and the flow ratio of the air volume supplied upwards to the air volume supplied horizontally. Fig.5 shows the change of the vertical temperature distributions with the ratio of the air volume supplied upwards to the air volume supplied horizontally. Fig.5 is the result at Q = 669 m^3/h (Run.2 in Table 1). As shown in the figure, the thermal stratification is weakened and disappears with the increase of the air volume supplied upwards. This means that we can control the height where thermal stratification is formed by changing the ratio of the air volume supplied

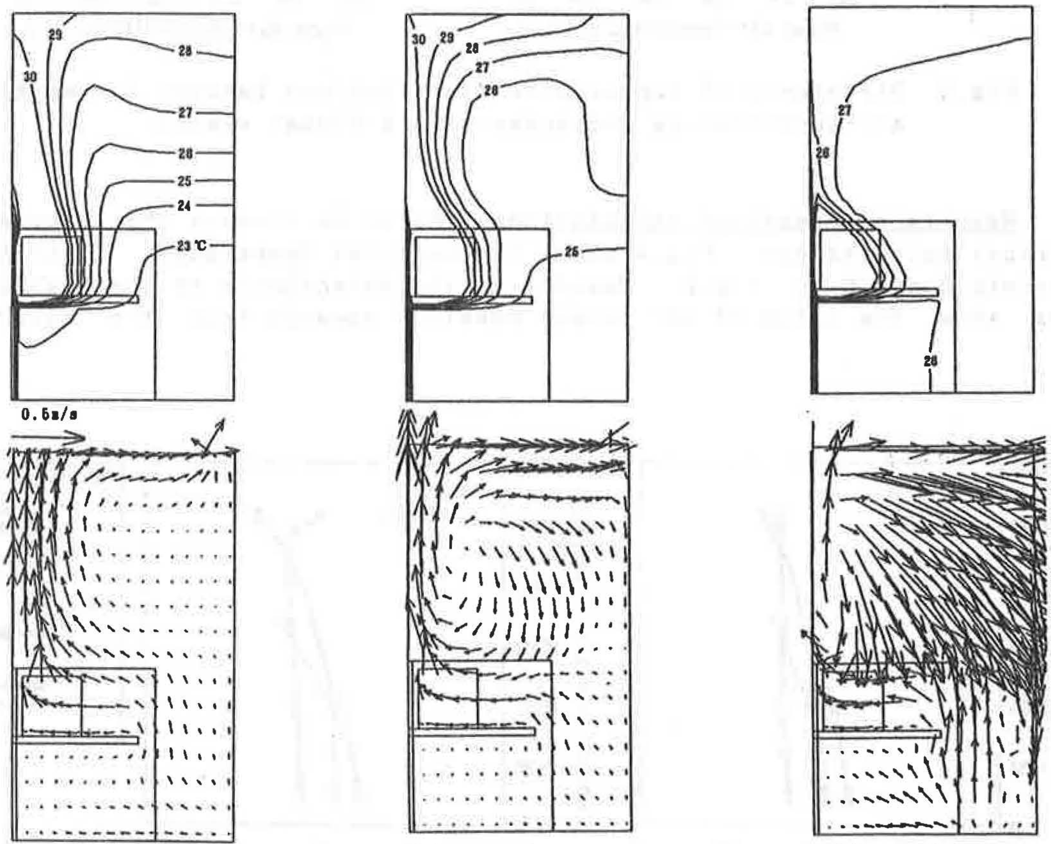


Fig.5 Temperature distributions and flow fields obtained by numerical calculations.

upwards: we can create by the low-partition air-conditioning system not only thermal environment where only the occupied zone is held cool, but also uniform temperature distributions from the floor level to the ceiling level.

Thermal Comfort of the Low-Partition Air-Conditioning System

There are several indexes such as Effective Temperature (ET), New Effective Temperature (ET^*) and Predicted Mean Vote (PMV) as warmth index. Recently ET^* and PMV are often used for predicting thermal comfort because the physical backgrounds for the derivation of the indexes are clear and the values of the indexes are easily calculated if the variables necessary for calculation are known. These warmth indexes are useful for the evaluation of the thermal comfort to some extent. However, the thermal environment in the actual room is generally affected by many factors and very complicated; especially it is true in the case of low-partition air-conditioning system investigated here. In such a case, it is desirable to evaluate the thermal comfort through thermal sensation tests by subjects in addition to the evaluation by the above warmth indexes. For this reason we carried out the thermal sensation tests by subjects in order to evaluate the degree of the thermal comfort of the new low-partition air-conditioning system. Thermal sensation tests were also performed for the conventional air-conditioning system of anemo-type diffuser in order to compare the thermal comfort of the new system with the conventional systems. The air-conditioning system of anemo-type diffuser is one of the most excellent systems which can create a desirable thermal environment of the room. We used PMV as warmth index.

Procedure of Thermal Sensation Tests

The conditions of the thermal sensation tests is shown in Table 2. The tests were performed in the test module shown in Fig.2 under three different room temperatures, 24, 26 and 28°C. Subjects consist of five healthy males and five healthy females. Their ages range from 20 to 23 years old. Two subjects took the thermal sensation test simultaneously at the positions C and E in Fig.2. The all subjects were asked to sit on chairs and do usual desk works, so the activity level of the subjects is approximately 0.058 WK/m^2 (1 met). Clothing insulation value (clo-value) of the male subjects

Table 2. Conditions of thermal sensation tests.

	Cooling		
Run	1	2	3
Air volume [m^3/h]		275.0	
Room air temperature [℃]	24.0	26.0	28.0
Temperature of supplied air [℃]	14.8	16.8	18.8
Heat load [kW]		0.731~0.964	
Personal computer		0.213	
Lighting		0.400	
Human body		0.119	
Panel heater on the floor		0.0~0.233	

is about 0.109 Km^2/W (0.7 clo) and that of the female subjects is about 0.129 Km^2/W (0.83 clo) which are calculated consulting the literatures of Rohles et al.(12,13,14). Thermal sensation tests were performed only under cooling conditions because cooling is necessary almost over a year at usual intelligent offices in Japan. Thermal sensation tests were carried out fundamentally according to "Method of investigation of thermal sensation tests" by The Society of Heating, Air-Conditioning and Sanitary Engineers of Japan(15). Each thermal sensation test was continued for two hours with reference to a experimental result of Fanger(16). He showed that the votes of thermal sensation continued to change for half and one hours after entrance into a test room. The subjects are asked to vote their thermal sensations and thermal comforts at 30-minutes intervals including just after entrance into the test module.

Thermal Environments during the Thermal Sensation Tests

<u>**Temperature distributions.**</u> Vertical temperature distributions at points A, B, C and E are shown in Fig.6 (Run 2 in Table 2). Points C and E correspond to the positions of subjects. Uniform vertical temperature distribution is formed at the condition of anemo-type diffuser. On the other hand, at the low-partition air-conditioning system low temperatures

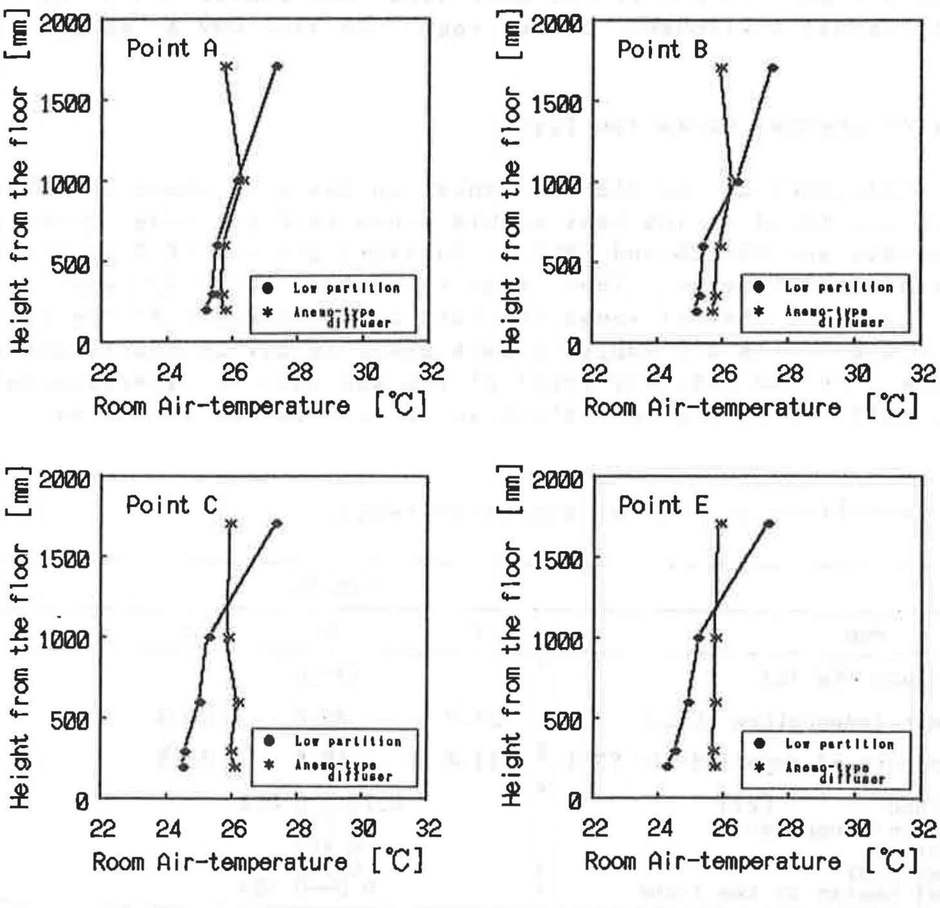


Fig.6 Vertical temperature distributions on thermal sensation tests.

appear in the lower zone than the height of about 800-1000 mm and the temperature in the upper zone increases with the height. The same tendency as Run 2 is obtained in Run1 and Run3, too. The room temperature was steady and nearly constant during a test and the fluctuation of the room temperature was negligible.

Velocity distributions at the position of subject. Fig.7 shows the velocity distributions at the points C and E. The air velocity was measured with a micro-anemometer which can measure down to about 5 cm/s. Under both conditions of anemo-type diffuser and low-partition, all the measurement values of the air velocities were below 20 cm/s. At almost all the height, however, the air velocity takes slightly faster values at the anemo-type diffuser. This result coincides with the prediction by numerical calculations mentioned above.

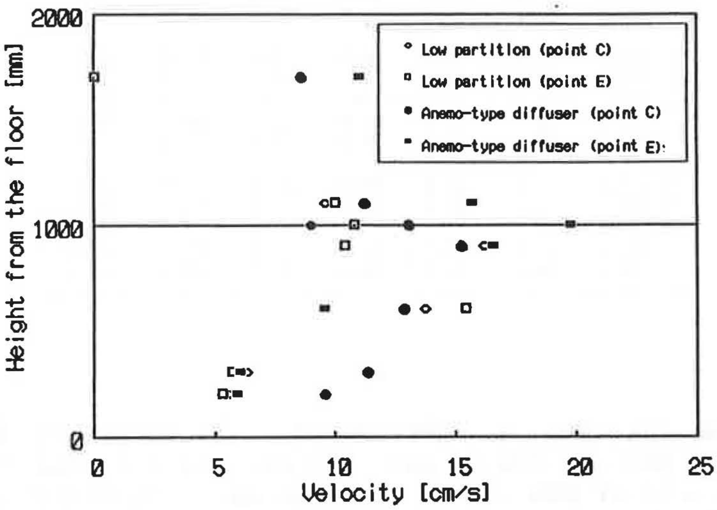


Fig.7 Velocity distributions at the position of subjects.

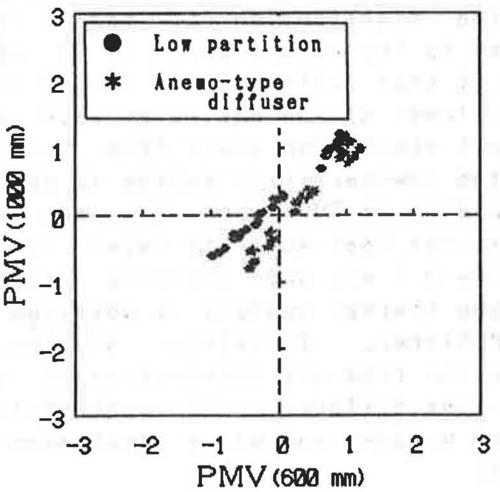
Radiation characteristics The surface temperatures of the low-partitions are about 5K lower than the room temperature in the lower portion and about 3K lower in the upper portion. In the case of anemo-type diffuser the surface temperatures of the low-partitions are approximately equal to the room temperature because cooled air does not pass through the panels of the low-partitions. Table 3 shows the distribution of mean radiant temperatures in the work area surrounded by low-partitions. It is obvious that the low-partitions have the effect of cool radiation. At almost all the points the mean radiant temperatures are lower at low-partition than anemo-type diffuser. At the position of subject about 80cm apart from the front panel, the mean radiant temperature of the low-partition system is about 0-2K lower than anemo-type diffuser. According to PMV, when the mean radiant temperature is 1K lower under the conditions that activity level is 0.058 WK/m^2 (1 met), relative velocity is below 0.1 m/s and clothing insulation value is 0.117 Km^2/W (0.75 clo), the same thermal comfort is obtained even though the room air temperature is 1K higher. Therefore, at the low-partition system it is possible to raise the room air temperature to obtain the same thermal comfort as the anemo-type diffuser. It contributes to energy saving because the heat loss from windows and walls decreases with the increase of the room air temperature.

Table 3. Mean radiant temperature.

upper row: Anemo-type diffuser
lower row: Low-partition [℃]

Set tempera -ture [℃]	Height from the floor [mm]	Distance from the front panel [mm]						
		200	400	600	800	1000	1200	1400
24	200	23.1 20.4	23.2 20.4	23.2 20.8	23.2 21.3	23.4 21.8	23.4 22.2	23.4 22.2
	600	23.5 21.0	23.3 21.1	23.6 21.2	23.2 21.7	23.4 22.1	23.4 22.3	23.5 22.3
	1000	23.3 22.4	23.3 22.8	23.5 22.9	23.5 22.9	23.2 23.1	23.2 23.1	23.2 23.1
26	200	26.0 22.2	26.0 22.6	26.0 23.0	26.1 23.2	26.1 23.5	26.1 24.0	26.1 24.2
	600	25.8 23.1	25.8 23.2	25.9 23.3	25.9 23.8	25.9 24.1	25.9 24.2	25.9 24.3
	1000	25.9 24.3	26.0 24.5	26.0 24.6	26.0 24.7	26.0 24.7	25.9 24.7	25.9 24.7
28	200	26.7 26.0	26.8 26.2	27.0 26.6	27.1 27.0	27.3 27.2	27.3 27.5	27.3 27.5
	600	27.4 27.0	27.5 27.0	27.5 27.2	27.6 27.3	27.8 27.7	27.8 27.9	27.8 27.9
	1000	27.5 28.0	27.6 28.2	27.7 28.3	27.7 28.3	27.8 28.3	27.9 28.5	27.9 28.5

<u>Vertical distributions of PMV-values.</u> The values of PMV at three different heights, 200 mm, 600 mm and 1000 mm, are compared in Fig.8. The remarkable difference of PMV is not found between the height of 200 mm and 600 mm. The data shown in Fig.8 include both data of low-partition and anemo-type diffuser. As seen from the right figure in Fig.8 the difference of PMV values between the low-partition system and the anemo-type diffuser is not found at the heights of 200 mm and 600 mm. Between the heights of 600 mm and 1000 mm, however, PMV values at 1000mm are slightly smaller than 600 mm in the case of low-partition and the reverse holds true in the case of anemo-type diffuser.



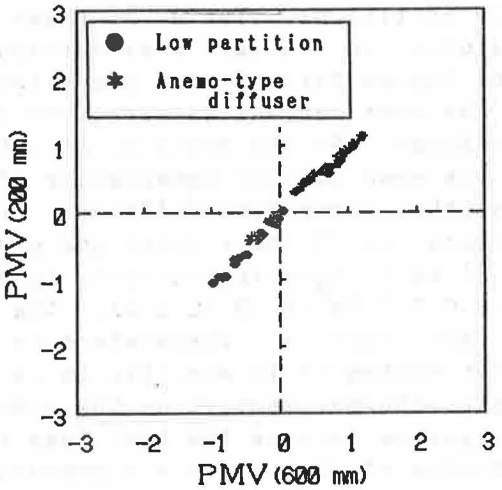


Fig.8 Change of PMV with the height from the floor.

Results of Thermal Sensation Tests

General thermal sensation. The averages of general thermal sensation of 5 males and 5 females are shown in Fig.9. The thermal sensation scales of the axis of ordinate are shown in Table 4.

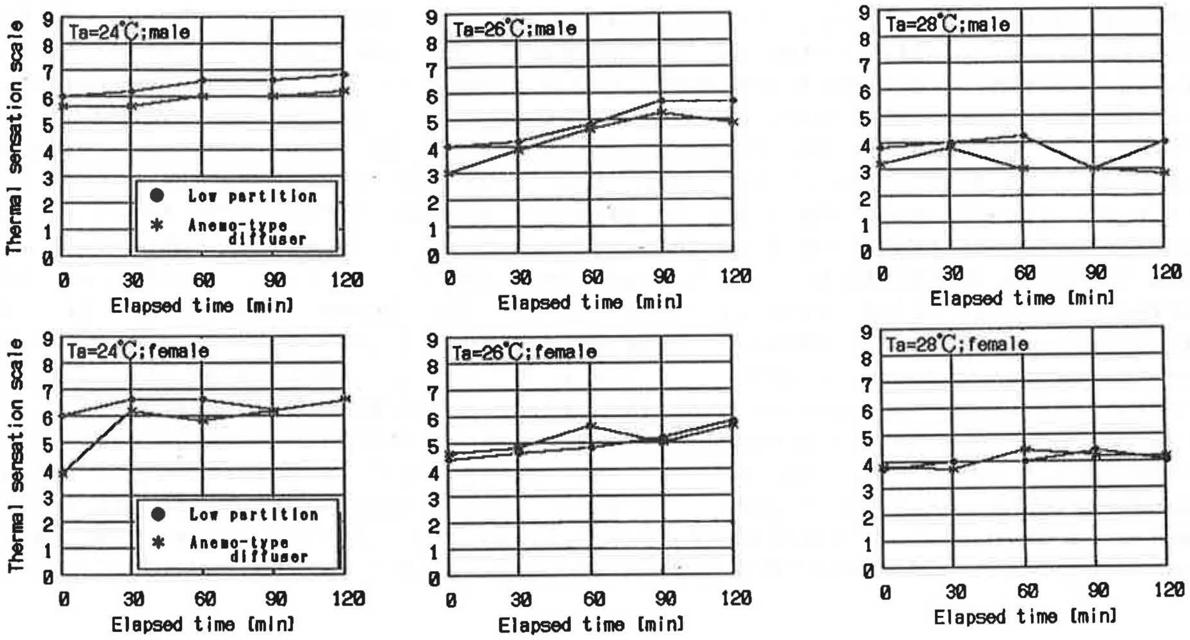


Fig.9 Average general thermal sensation.

Table 4. Scale of thermal sensation

Scale	1	2	3	4	5	6	7	8	9
Thermal sensation	very hot	hot	warm	slightly warm	neutral	slightly cool	cool	cold	very cold

There is a tendency that the votes of subjects change with time for first half and one hours. However, the votes concerning thermal sensation do almost not change after half and one hours. Therefore, each thermal sensation test should be continued at least for more than half and one hours. According to the votes of males, thermal environment created by low-partition is slightly cooler than the anemo-type diffuser when the average room air-temperatures are held at the same temperature. According to the votes of females, however, a remarkable difference of thermal sensation is not found between two air-conditioning systems. A clear correlation is observed between the thermal sensation votes and the room air-temperatures: thermal sensation votes are near neutral at the room air-temperature of 26°C, slightly cool at 24°C and slightly warm at 28°C.

Thermal sensation of each part of the body. Fig.10 shows the thermal sensation of each part of the body under the condition of set air-temperature of 26°C; the average thermal sensations of five subjects are shown according to sex. The scale of thermal sensation of the axis of ordinate is the same as the scale of Table 4. As seen from the figure the subjects have a tendency to feel cooler around the arm and the leg than other parts of the body in the case of low-partition. Especially around the arms females feel cooler than males. It is reasonable to consider that the reason why the females feel cooler than males around the arms arises from the difference of their clothing; that is, the arms of females are directly exposed to the surrounding cool air and cool radiation from the panels of low-partitions because their clothing are dress shirts with short sleeve and sleeveless vests, on the other hand the arms of the males are covered with shirts with long sleeve. The thermal environment surrounding legs of the subjects is a little worse at the low-partition than anemo-type diffuser. Three reasons are considered about why a slightly cool thermal environment is created near the floor at low-partition air-conditioning system. The first is cooling by the floor which is cooled by supplied air passing through the free-access space under the floor. The second is the effect of cold air staying near the floor by negative buoyant force. The third is the effect of cool radiation from the surface of low-partitions. According to the measured temperature distributions near the floor, it is found that the effect of the cooled floor is large because the thermal insulation of the floor was poor on the thermal sensation tests. Therefore, it is expected that the thermal environment near the floor can be improved by the use of tiles and carpet possessing high insulation property. As already seen in Fig.3, air temperature gradually increases with height in the higher zone than about 1000 mm, so we worried about that subjects might feel uncomfortable near their head. However, nobody voted that heads were hot and uncomfortable. Similar tests performed under different two set air-temperatures of 24°C and 28°C showed similar results as the result of 26°C.

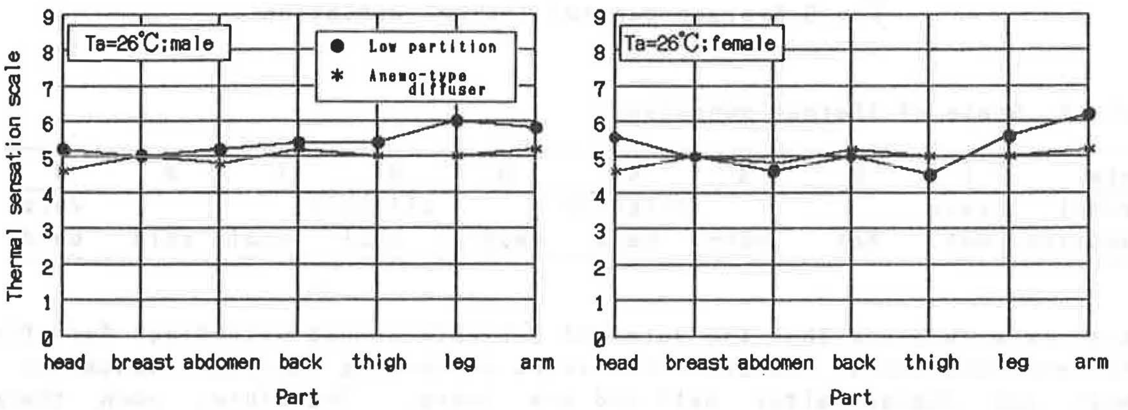


Fig.10 Thermal sensation of each part of the body.

Draft. Draft was almost not felt as shown in Fig.11. This result well coincides with the measured velocity distribution (Fig.7) and the observed velocity distributions by visualization of flow field mentioned in the preceding paragraph.

Thermal comfort. Fig.12 shows the average thermal-comforts of five subjects according to sex. Remarkable difference of thermal comfort was not found between the low-partition air-conditioning system and the anemo-type diffuser air-conditioning system. Both air-conditioning system can create a good thermal environment where almost all workers feel thermally comfortable.

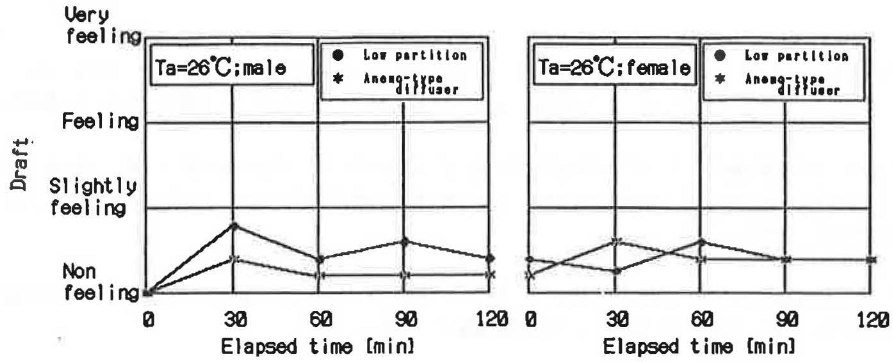


Fig.11 Cold draft.

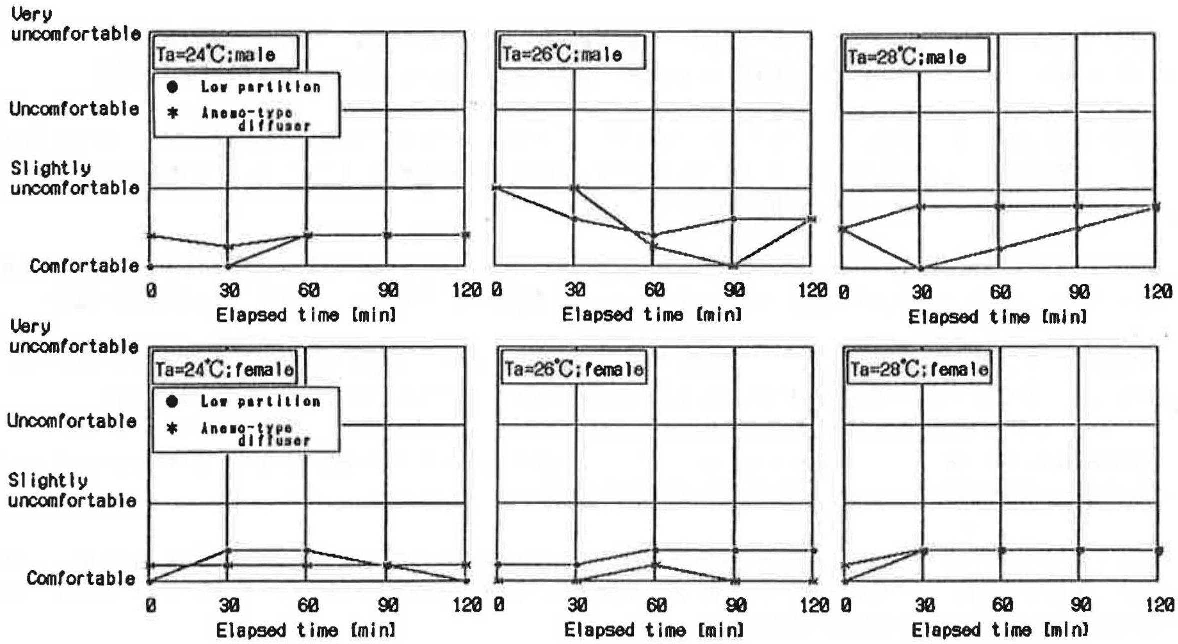


Fig.12 Votes of thermal comfort.

Conclusion

We investigated the temperature distributions, velocity distributions and the thermal comfort of the low-partition air-conditioning system which is a new air-conditioning system having high possibility of actualizing personal air conditioning and creating high quality thermal surroundings in an intelligent office where a lot of cooling load is generated locally. As a result of thermal sensation tests by subjects, it was found that the new low-partition air-conditioning system could create a thermally satisfied comfortable work area without raising cold draft. Moreover, according to the results of measurements and numerical calculations of temperature distributions, confined air-conditioning to the occupied zone is possible by controlling the air volumes supplied upwards and horizontally from the low-partition panels. Considering that the low-partition air-conditioning system is also suitable for personal air-conditioning and useful for saving energy through a confined cooling to the lower occupied zone, that is a hopeful air-conditioning system for the intelligent offices.

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SUMMARY

Low-partition air-conditioning system is a new system which has high possibility of actualizing personal air conditioning and creating high quality thermal surroundings in an intelligent office. The purpose of this study is to investigate air temperature distributions, air velocity distributions and thermal comfort created by the low-partition air-conditioning system. As a result of thermal sensation tests by subjects, it was found that the new low-partition air-conditioning system could create a thermally satisfied comfortable work area without feeling uncomfortable cold draft. Moreover, according to the results of measurements and numerical calculations of temperature distributions, air-conditioning confined to the occupied zone is possible by controlling the flow ratio of the air volumes supplied upwards and horizontally. Considering that this system is suitable for personal air-conditioning and useful for saving energy through a confined cooling to the lower occupied zone, this is a hopeful air-conditioning system for future intelligent offices.