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STUDY ON THERMAL COMFORT OF TASK-AMBIENT AIR CONDITIONING SYSTEM

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ABSTRACT

Task-ambient air conditioning system is one of the systems developed to achieve quality indoor thermal environment and energy conservation simultaneously. The purpose of this study is to find the optimum supply air conditions of floor air outlet required to make thermally comfortable environment in the task area without cold draft. To achieve the purpose were carried out the experiments with subjects, who were allowed to control the supply air volume and the direction of inclined jet according to their tastes. The main results are as follows: the suitable combination of the room air temperature and the supply air temperature is 28°C-20°C under which thermally comfortable environment is created in the task area without cold draft. And the subjects have a tendency to use positively the cooling effect of the air flow by leading the jet to their bodies no matter whether the jet hits them directly or indirectly.

KEYWORDS

Thermal comfort, Air conditioning, Office building, Floor air outlet

INTRODUCTION

Several new air conditioning systems including underfloor air conditioning system (Hirayama et al. 1995), low partition air conditioning system (Naito et al. 1988) and task-ambient air conditioning system (Mizuno et al. 1994,1995) have been proposed to satisfy the requirements for improvement of indoor thermal comfort and energy conservation. Among them, task-ambient air conditioning system seems to have high possibility of achieving the requirements. In the task-ambient air conditioning system, the ambient area is air-conditioned by the supply air from the conventional ceiling air outlets and to achieve energy conservation the air temperature in the ambient area is usually controlled at slightly higher temperature than the task area where occupants work sitting at the desks. Each occupant can control his thermal environment in the task area according to his taste controlling the direction of inclined jet and supply air volume from the floor air outlet which is assigned to individual occupant and is able to be usually controlled remotely. The task-ambient air conditioning system was already applied to a real office in Japan and the authors investigated the thermal comfort in the office through measurements of physical factors, such as air temperature, air velocity, mean radiant temperature etc., and questionnaire to the occupants in the office(Nakamura et al. 1996; Kohyama et al. 1996). However, we have not yet got enough data to determine the most suitable supply air conditions of the floor air outlet. The purpose of this study is to investigate the most suitable supply air conditions of the floor air outlet under which the sedentary occupants in the task area feel thermally comfortable without feeling cold draft and energy conservation is also expected at the same time. We carried out the experiments with subjects to achieve the purpose.

METHODS

Experimental apparatus

Experiments were carried out with an underfloor air supplying chamber which was set up in an environmental test room shown in Figure 1. A floor air outlet of the diameter 60mm is equipped just behind a subject to control the thermal environment in the task area. The angle of elevation of the inclined jet flowing out of the floor air outlet can be controlled in the range of 0° to 90° by changing the direction of the opening face of the motor-driven floor air outlet. The change of the kinds of jet between nonswirl jet and swirl jet is done by setting the angle of inclination of eight adjustable guide vanes in the floor air outlet to appropriate angles. The

Table 1 Measured variables and points of measurement.

measured variables		points of measurement	measuring instruments
temperature	air temperature around subject	100, 200, 300, 450, 600, 800, 1000, 1200 and 1700mm heights above the floor	thermo-couples and data logger
	skin temperature	left and right calves, left and right arms, chest, back, neck, forehead	
	supply air temperature	floor air outlet	
	room air temperature	100, 200, 300, 600, 1000 and 1700mm heights above the floor at the four positions in the environmental test room	
	surface temperature of the body of subject	from 45 degree behind	thermo-camera
	plane radiant temperature	upper, lower, left, right, before and behind directions	thermal environment measuring equipment and radiant temperature asymmetry transducer
air velocity	air velocity behind subject	200, 400, 600, 800, 1000 and 1200mm heights above the floor	multipoint anemometer
humidity		one point in the environmental test room	Assman psychrometer
air volume	supply air volume from floor air outlet		digital manometer
angle of elevation	angle of elevation of inclined jet		potentiometer

Table 2 Category scales of each variable.

variables	category scales
thermal comfort	1. comfortable, 2. slightly comfortable, 3. neutral, 4. slightly uncomfortable, 5.uncomfortable
thermal sensation	4. very hot, 3. hot, 2. warm, 1. slightly warm, 0. neutral, -1. slightly cool, -2. cool, -3 cold, -4.very cold
feeling of air flow	1. very feel, 2. feel, 3. slightly feel, 4. not feel
comfort for air flow	1. comfortable, 2. slightly comfortable, 3. neutral, 4. slightly uncomfortable, 5. uncomfortable
request on the room air	1. much lower temperature is better, 2. slightly lower temperature is better, 3. suitable, 4. slightly higher temperature is better, 5. much higher temperature is better
request on the supply ai	1. much lower temperature is better, 2. slightly lower temperature is better, 3. suitable, 4. slightly higher temperature is better, 5.much higher temperature is better

room air temperature is controlled by an air conditioner of the environmental test room and the temperature of the supply air from the floor air outlet is controlled by a spot cooler. The physical measuring variables and their measurement points are shown in Table 1 with the measuring instruments.

Experiments with subjects

Thermal comfort in the task area is evaluated based on the votes of five young male and five young female subjects per one experimental condition. The subjects are clothed in uniform office

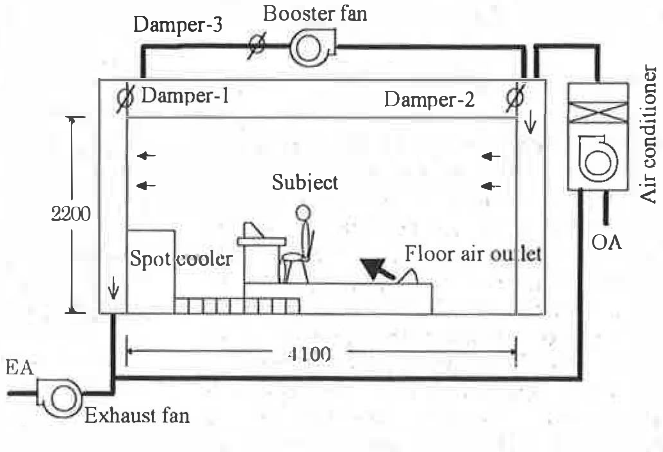


Figure 1 Experimental apparatus in environmental test room.

wear in the summer, that is, a male wears a shirt with half-length sleeves, thin trousers, a tie and underwear and a female wears a blouse with half-length sleeves, a skirt, panty hose and underwear. The subject seated on a chair with a back does ordinary office work during one experimental term of one hour and votes at intervals of ten minutes on the variables shown in Table 2, such as thermal comfort, thermal sensation etc. The category scales of each variable are shown in Table 2, too. Each subject is allowed to control the supply air volume from the floor air outlet and the angle of elevation of inclined jet using a remote controller on the desk to satisfy one's thermal comfort in the task area according to one's taste.

Table 3 Main experimental factors.

Experimental factor	Conditions
kinds of jet	nonswirl jet, swirl jet
relative location of floor air outlet to subject	just behind , 45 degree behind
control range of air volume supplied from floor air outlet	0 - 250m3/h, 0 - 130m3/h
control range of angle of elevation of jet axis	0 - 90 degree
room air temperature	27 - 29 degree
supply air temperature	19 - 21 degree

Table 4 Experimental conditions to investigate diffusion characteristics of cool jet flowing out of floor air outlet.

	Run 1	Run 2	Run 3	Run 4
supply air temperature(°C)	21.5	20.8	20.4	21.5
room air temperature(°C)	28.5	28.4	28.3	28.5
air volume of supply air (m^3/h)	224	228	26	236
air velocity (m/s)	22.0	22.4	2.6	23.2
angle of elevation of inclined jet	60	30	60	60
kind of jet	nonswirl	nonswirl	nonswirl	swirl 45°
Archimedes number, Ar	0.00030	0.00031	0.02515	0.00037

$Ar=gD(\rho_s - \rho_r)/(U^2 \rho_s)$

g : gravity acceleration(m/s^2),

D : diameter of the floor air outlet(m),

U : average wind velocity at the floor air outlet(m/s),

ρ_s, ρ_r : density of the air at the supply air temperature Ts and the room air temperature Tr

Experimental conditions

Main experimental factors and conditions are shown in Table 3. Generally speaking, swirl jet has the merit that it hardly causes the problem of cold draft because it is excellent in diffusion performance of jet. On the contrary, due to its low diffusion performance nonswirl jet has the merit that it can make cooler thermal environment in the task area than swirl jet. So the experiments with subjects were carried out under these two kinds of jet to make clear which kind of jet was better. Concerning relative location of floor air outlet to subject, two conditions of jet from just behind and 45° behind were taken up. The former corresponds to the condition that the jet envelops the subject after hitting the back of the chair and the latter corresponds to the condition that the jet hits the subject directly. The reason why the supply air volume is limited below 250m^3/h is that the rated air volume of floor air outlet used often in Japan is limited below 250m^3/h. The experiments limiting the supply air volume below 130m^3/h are carried out to investigate the possibility of energy conservation. The room air temperatures and the supply air temperatures are taken slightly higher than the conventional air conditioning system to achieve energy conservation and to protect occupants from cold draft. Before the subject tests, the experiments to investigate basic diffusion characteristics of nonisothermal swirl and nonswirl jets were carried out under the conditions given in Table 4.

RESULTS

Temperature and velocity distributions

Vertical distributions of the air temperature and velocity are shown in Figure 2 and Figure 3, respectively. The run numbers in the figures correspond to those in Table 4. The dimensionless temperature T* is defined by the equation(1).

$$T^* = \frac{T - T_s}{T_r - T_s} \qquad (1)$$

where T = air temperature(°C)

T_s = supply air temperature(°C)

T_r = room air temperature(°C)

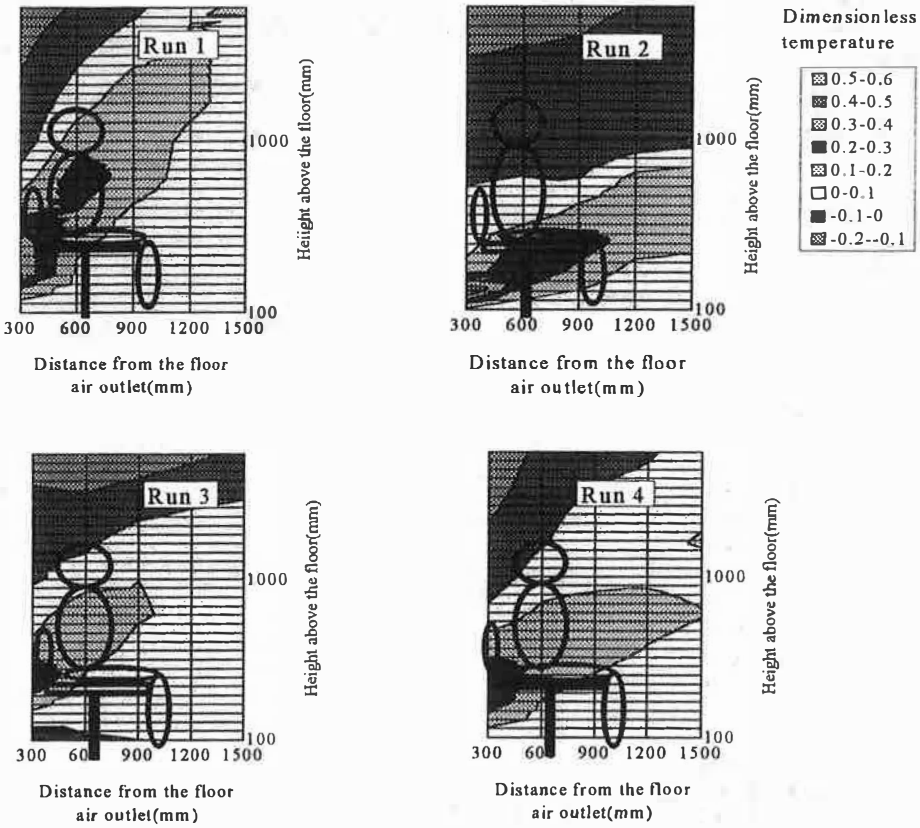


Figure 2 Comparison of dimensionless temperature distribution.

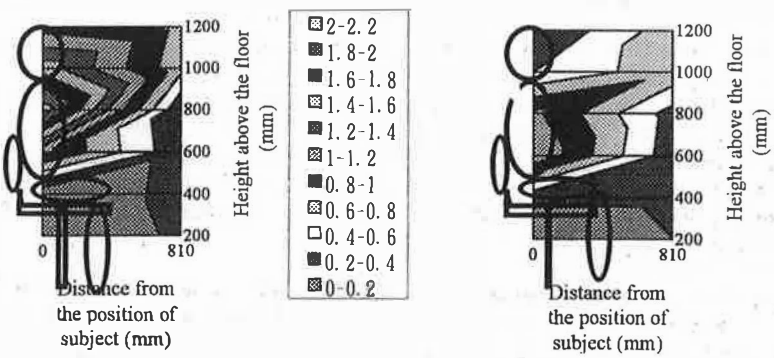


Figure 3 Comparison of velocity distribution.

As seen from the comparison of Run 1 and Run 2 in Figure 2, a spot where the jet hits the subject is easily controlled by changing the angle of elevation of inclined jet. From the comparison of Run 1 and Run 3, it is found that the air temperatures in the surroundings of the subject take similar values, though the supply air volume from the floor air outlet is about eight times larger in Run 1 than in Run 3. It means that the temperature in the surroundings of the subject is not affected very much by the quantity of the supply air volume. On the other hand, the air velocity is extremely affected by the supply air volume but the figure is not shown here. In case of swirl jet, the trajectory of jet axis takes slightly lower position than nonswirl jet (see Run 1 and Run 4) and the wind velocity is reduced faster as is obvious from Figure 3. It means that if the problem of cold draft does not occur, nonswirl jet is superior to swirl jet in the sense of having the ability to make thermal environment in the task area cooler. Another important result is also found from Figure 2; that is, the temperature around the subject is reduced by about 1.5°C at the highest, even though the supply air temperature difference T_r - T_s is 8°C.

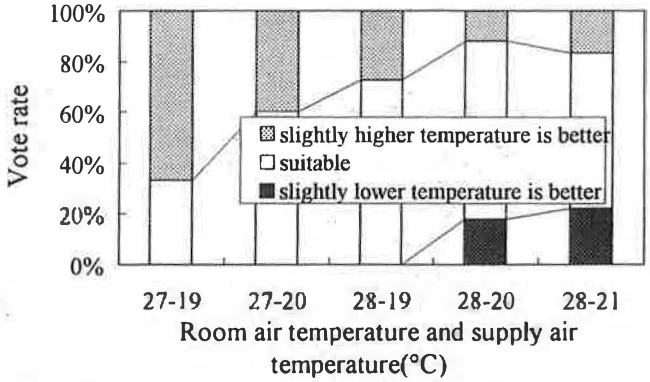
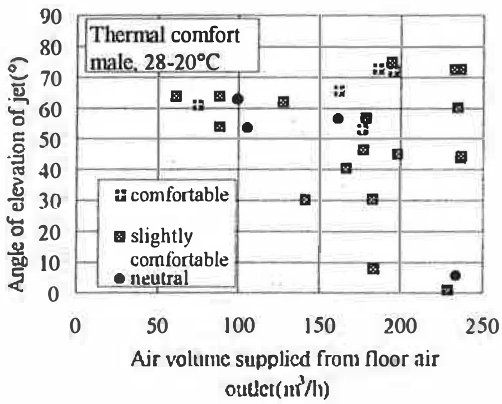


Figure 4 Requests on supply air temperature (nonswirl jet from just behind).



Requests on the supply air temperature

Figure 4 shows requests of the subjects on the supply air temperature. The subjects feeling "slightly higher temperature is better" reach about 65% when the combination of the room air temperature and the supply air temperature is 27°C-19°C and about 40% when 27°C-20°C. On the other hand, in the case of the room air temperature 28°C the rate of the subjects requiring warmer thermal environment reduces and the combination of 28°C -20°C is chosen as neutral. The result shows that the combination of 28°C-20°C is suitable to reduce the claim for cold draft and hot environment at the same time.

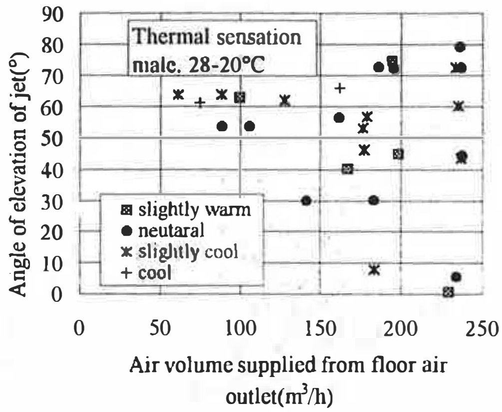


Figure 5 Votes on thermal comfort and thermal sensation (nonswirl jet from just behind).

Thermal comfort and thermal sensation

Figure 5 shows the thermal comfort and thermal sensation voted under the experimental condition of 28°C-20°C, nonswirl jet from just behind and male. The subjects are allowed to control freely the supply air volume within maximum 250m^3/h and the angle of elevation of inclined jet in the range of 0° to 90°. As is obvious from the figure, the subjects control the angle of elevation of the inclined jet and the supply air volume to create thermally comfortable environment in their task area and the majority of them succeed in creating thermally comfortable environment more than "neutral". Most of votes on thermal sensation range over from "slightly cool" to "slightly warm". The angle of the elevation of the inclined jet is controlled in the range of about 40° to 80° which corresponds to the situation that the cool jet envelops the body of the subject after having hit the back of the chair. The supply air volume is controlled over the significantly wide range of about 60 m^3/h to 230m^3/h. In regard to how the subjects feel about the air flow, most of them feel "comfortable", "slightly comfortable" or "neutral" as shown in Figure 6. The category numbers in the figure corresponds to those in Table 2. As there exist a few subjects feeling "uncomfortable" or "slightly uncomfortable", however, the floor air outlet must be equipped with control function to the supply air volume.

Figure 7 shows the experimental results when the supply air temperature is 21°C. Most of the subjects choose large amount of the supply air volume around 200m^3/h to compensate the rise of supply air temperature and the quality for thermal comfort reduces slightly than the case of the supply air temperature 20°C as seen comparing with Figure 5. Judging from the results, the combination of the room air temperature 28°C and the supply air temperature 20°C is suitable for task ambient air conditioning system from the standpoint of thermal comfort, too. From the viewpoint of energy conservation, however, it is desirable to be able to create thermally comfortable environment by as small amount of the supply air volume as possible. So the subject tests were carried out under the same conditions as the case of Figure 5 except limiting the supply air volume below 130m^3/h. The vote rate of "neutral" on thermal comfort increases and the vote rates of "comfortable" and "slightly comfortable" decrease in comparison with the case of upper limit 250m^3/h(see Figure 8 and Figure 5). It shows that the upper limit 130m^3/h to the supply air volume is rather low and needs to be raised to create more comfortable thermal environment but the upper limit 130m^3/h is acceptable if high priority is given to the energy conservation.

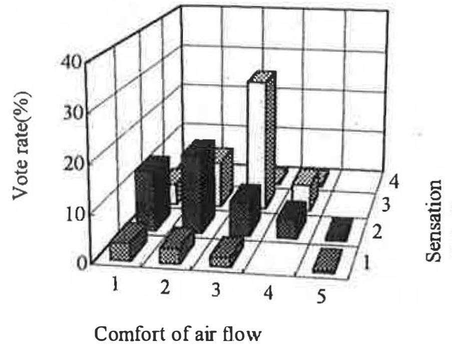


Figure 6 Comfort of air flow (nonswirl jet from just behind).

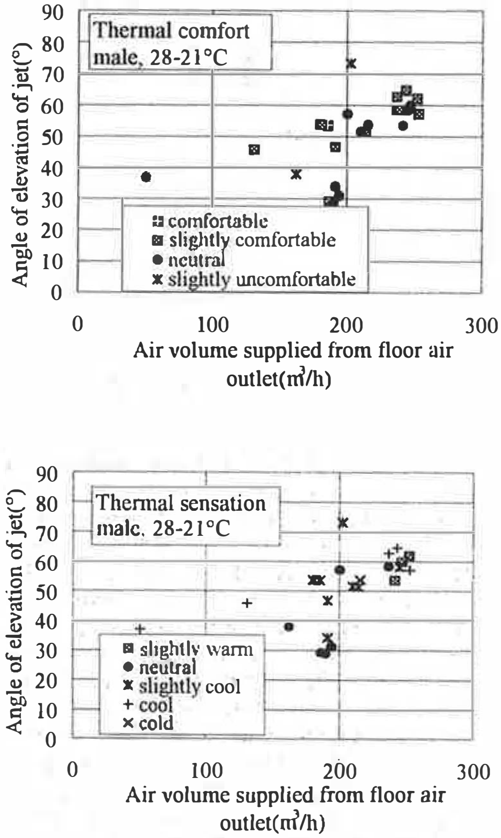


Figure 7 Votes on thermal comfort and thermal sensation (nonswirl jet from just behind).

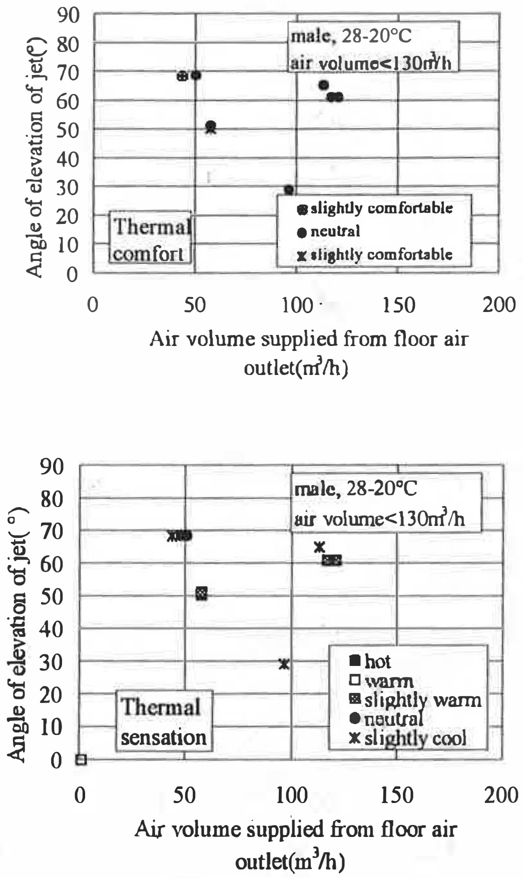


Figure 8 Vote on thermal comfort and thermal sensation (nonswirl jet from just behind).

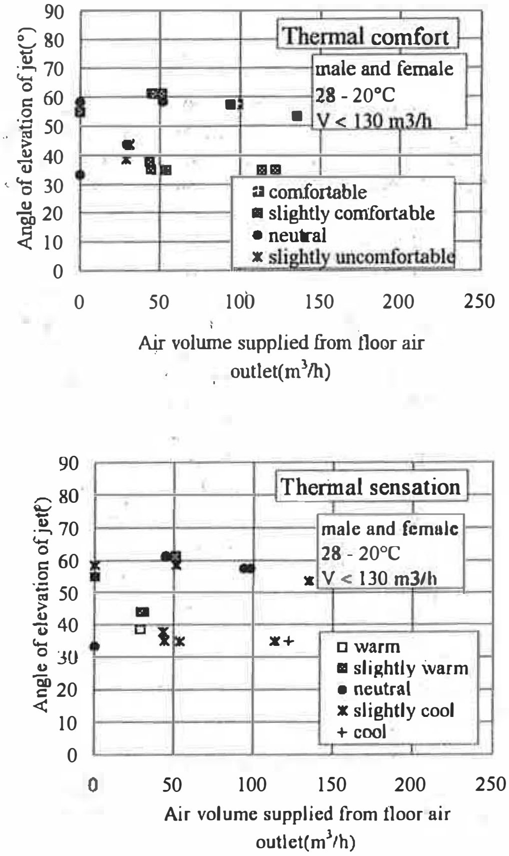


Figure 9 Votes on thermal comfort and thermal sensation (nonswirl jet from 45° behind).

So far, it has been considered that the cool supply air should not hit the body of person directly to protect him from cold draft. In the present study, however, we were able to obtain the result that severe problem concerning cold draft did not occur, though the subjects were exposed to cool jet hitting them directly. As shown in Figure 9, most of the subjects feel thermally comfortable at the level more than "neutral". Two votes of "slightly uncomfortable" appear but they are not caused by cold draft ; they are caused by feeling "warm" or "hot". As seen from Figure 10, the majority of the subjects feel "comfortable", "slightly comfortable" and "neutral" about the jet hitting them directly. As a few subjects feel "slightly uncomfortable" and "uncomfortable" about the jet, however, it is important for the floor

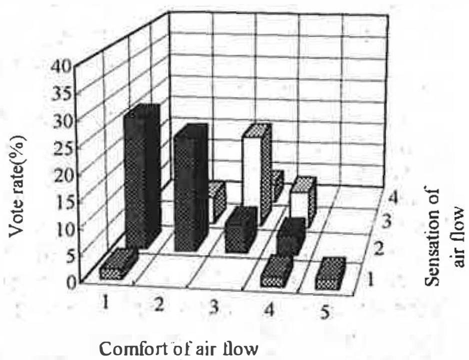


Figure 10 Comfort of air flow (nonswirl jet from 45° behind).

air outlet to be equipped with some control function to the supply air volume when it is applied to task-ambient air conditioning system.

DISCUSSION

Supposing that the temperature difference between the room air temperature and the supply air temperature is 8°C, the temperature reduction in the task area is about 1.5°C at the highest. The effect of cool jet on the temperature reduction in the task area almost never depends on the supply air volume but the coolness in the task area increases with the supply air volume and it is mainly caused by the increase of wind velocity. Therefore, nonswirl jet is superior to swirl jet in the sense that the cool thermal environment can be created in the task area by less supply air volume than swirl jet if the upper limit to the supply air volume is the same.

The suitable combination of the room air temperature and the supply air temperature is 28°C-20°C. Under the condition, most of the subjects are able to create thermally "comfortable", "slightly comfortable" and "neutral" environment in the task area controlling the supply air volume and the angle of elevation of inclined jet and almost all subjects are free from cold draft. However, as there exist a few subjects who do no like to feel the jet, it is important to equip the floor air outlet with function to control the supply air volume. At the beginning of the study, it was feared that subjects might feel cold draft when the cool jet flew out of the floor air outlet 45° behind and hit their bodies directly. Contrary to expectations, however, it became clear that almost all subjects were free from cold draft and they had a tendency to direct positively the cool jet to their bodies to get cooler thermal sensation. There are two main reasons why the subjects are free from cold draft. One is that the temperature of the supply air from the floor air outlet is higher by a few degree Celsius than the conventional air conditioning system using ceiling air outlets; the other is that the subjects can control the supply air volume and the direction of inclined jet freely according to his taste. The method using nonswirl jet from 45° behind has a merit that comfortable thermal environment can be created in the task area by less supply air volume than nonswirl jet from just behind.

ACKNOWLEDGMENTS

The present study could not be achieved without co-operation of Miss Sachie Kitani. We should like to express our appreciation for her contribution concerning experiments.

REFERENCES

Hirayama M., Hisamoto, H. and Souga, H. (1995) Research and development of underfloor air conditioning systems for offices(Part-15). *Proceedings of SHASE technical conference*, 1097-1100, Saijo, Japan

Kohyama, M., Mizuno, M., Nakamura, Y., Sekimoto, Y., Akagi, K., Kunimatu, Y. and Otaka, K. (1996) Field measurements of the indoor environment of an office with a task-ambient air conditioning system. *Proceedings ROOMVENT '96*, 1, 141-148, Yokohama, Japan.

Mizuno, M., Nakamura, Y., Nakanishi, Y., Sekimoto, M., Miura, M., Otaka, K., Kohyama, M., Ueda, K., Ishii, T. and Won, M. (1994) Thermal environment studies on task-ambient air conditioning systems (Part 1-3). *Proceedings of SHASE technical conference*, 1685-1696, Kumamoto, Japan

Mizuno, M., Nakamura, Y., Ohnishi, J., Otaka, K. and Kohyama, M. (1994) Thermal environment studies on task-ambient air conditioning systems (Part 4). *Proceedings of SHASE technical conference*, 69-72, Kumamoto, Japan

Naito, K., Nakamura, Y., Kanno, S., Kayahara, M., Okubo, K., Ueda, K. and Ono, T. (1988) Study on thermal comfort by low-partition air conditioning system applying radiation from panel surface. *Proceedings of SHASE technical conference*, 349-352, Naha, Japan

Nakamura, Y., Mizuno, M., Sekimoto, Y., Akagi, K., Kunimatu, Y., Otaka, K and Kohyama, M. (1996) Study on thermal comfort and energy conservation of task-ambient air conditioning system. *Proceedings ROOMVENT '96*, 1, 91-98, Yokohama, Japan.