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EVALUATION OF ROOM THERMAL ENVIRONMENT OF LOW-TEMPERATURE AIR DISTRIBUTION SYSTEM USING ICE STORAGE SYSTEM

Motoi Yamaha, Hisahiro Ito and Nobuo Nakahara
Nagoya University
Nagoya, Japan

Masaya Okumiya
Chubu University
Kasugai, Japan

SUMMARY

The low-temperature air distribution system using chilled water available with ice storage system can achieve energy savings. However, most of air distribution systems applied to ice storage is conventional one, owing to limited number of practical application of low-temperature air distribution system.

This paper reports the experimental results of operative performances and psychological responses of a low-temperature air distribution system using ice storage system. Experiments of low-temperature air distribution and conventional type were carried out. The low-temperature and small flow rate air distribution produced lower humidity psychrometric condition of the room.

No problem could be recognized for human evaluations/feelings of air dryness, air dirtiness and air stagnation. As far as the present experiments are concerned, the cold air distribution system shifted human thermal sensation to "cold" as compared with the conventional system. Higher air temperature for set point is recommended.

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INTRODUCTION

Ice storage system has been widely applied because of its benefits of reduced energy and electric cost. However, most of air distribution system applied to ice storage system is conventional air distribution system of 12°C to 18°C supply temperature in Japan. The low-temperature air distribution system using chilled water available with ice storage system can achieve additional energy savings as well as cost savings.

The reduced supply air flow rate with low-temperature air distribution system results in downsized supply fans, water pumps, and ductwork. Downsized fans and water pumps reduce electric energy consumption as well as their first costs. Smaller ductwork reduces floor-to-floor height with savings in building construction costs.

Although the low-temperature air distribution with ice storage system has many benefits, Designers and engineers of heating, ventilating, and air-conditioning (HVAC) are reluctant adopting this system. Only little information about operating performance of ice storage, thermal environment and contamination are available owing to limited number of practical example. Some experimental studies have been carried out [1,2,3] in Japan. This paper reports experiments of low-temperature air distribution system using ice storage at actual load condition. The operating performance and psychological response of this system was examined.

SYSTEM DESCRIPTION

Test room

Figure 1 shows a plan and a section of the test room. This test room is designed to simulate an intelligent office room with raised floor whose dimension is 7.5m × 7.5m × 2.35m height. Experiments can be carried out under condition where staffs or subjects work as usual. Table 1 shows main contents in the room as heat load.

Table 1: List of contents of the room

	Numbers	Heat load [W]
Personal Computer Set	6	1,247
Printer	2	440
Data Logger	1	150
Fluorescent Lamps	16	1,920

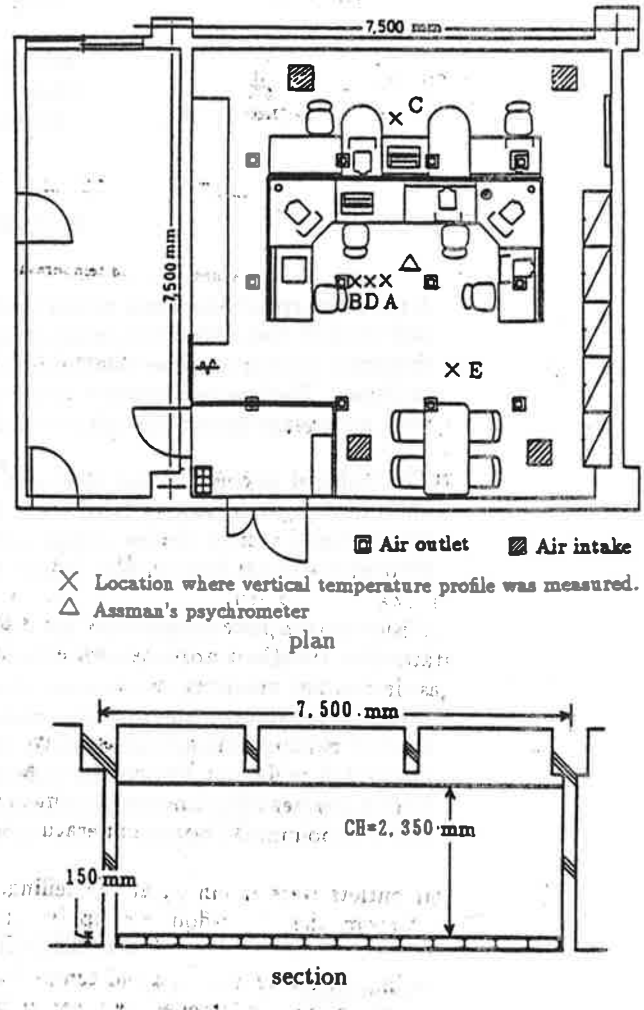


Figure 1: Test room

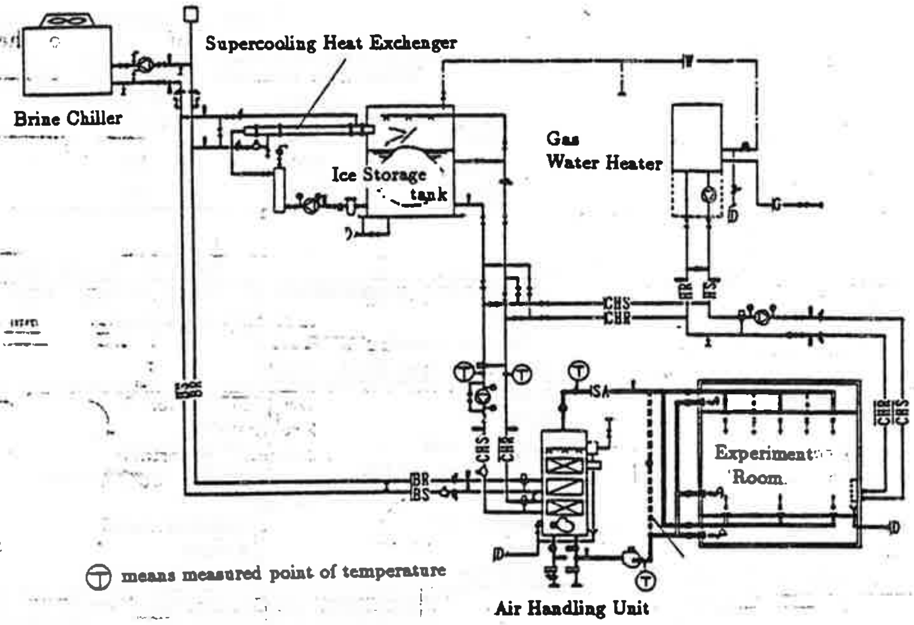


Figure 2: Schematic diagram of HVAC system

HVAC system

Figure 2 shows a schematic diagram of HVAC system. A dynamic type ice storage system utilizing subcooling phenomenon of water is installed as a cooling heat source. Water is pumped from the storage tank to the subcooling heat exchanger that is a kind of shell-and-tube type. When the water temperature is almost freezing point, the water is cooled to a subcooling sate of −3°C at subcooling heat exchanger. Collision with a plate, when the water is projected to the tank, breaks the subcooling state. About 4 % of projected water becomes slurry ice. As heating heat source, a gas fired water heater is installed.

A proptional plus integral plus derivative (PID) controller is installed to control flow rate of chilled water by 3 way valve. A pan humidifier is installed to control humidity for heating. There are no means to control the humidity in the experiment room for cooling. A room temperature sensor is set in center of the room.

Air outlets were mounted at the ceiling. Because the raised floor is applied to the test room, the under-floor air supply is possible. Air intakes are able to be mounted at the ceiling, the floor, or the walls. The supply air fan is mounted windward of cooling / heating coil to avoid temperature raise by fan heat. The supply air flow rate is manually controlled by inverter motor.

Measurements

The room air temperature and the water temperature are measured using thermocouple. The humidity of the room is measured by Assman's psychrometer. The

Table 1: Experimental condition

	Supply air flow rate [m^3/h]	Heat load [W/m^2]	Supply air temp. [°C]	Occupants
Exp.1	400	47	10	4
Exp.2	400	72	7	3
Exp.3	2000	72	17	5

Table 2: Voting scales

· Total thermal sensation(cold / hot) · Thermal sensation at head, neck, chest, arm, hand, or leg	· Total thermal sensation (cool / warm)	· Thermal comfort (comfortable / uncomfortable)
1.very cold 2.cold 3.slightly cold 4.either cold nor hot 5.slightly hot 6.hot 7.very hot	1.very cool 2.cool 3.slightly cool 4.either cool nor warm 5.slightly warm 6.warm 7.very warm	1.very comfortable 2.comfortable 3.slightly comfortable 4.either comfortable nor uncomfortable 5.slightly uncomfortable 6.uncomfortable 7.very uncomfortable

· Evaluation of air quality (dirtiness, stagnation, dryness)	· Existence of drought · Discomfort due to drought
1.feel strongly 2.feel 3.feel slightly 4.not feel	1.not feel 2.feel slightly 3.feel 4.feel strongly

flow rate of chilled water is measured by a paddle type water flow detector. These value are collected and stored by a personal computer. The supply air flow rate is measured by differential pressure gauge. Figure 1 also shows measured points of temperature. Temperature profile of 9 points are measured at "A" to "E". Figure 2 also shows measured points of HVAC system.

EXPERIMENTAL CONDITIONS

HVAC performance test

The tests were carried out to demonstrate how cold supply air temperature can be available in this HVAC system, and the psychrometric condition of the room under various air flow rates. The experiments are carried out during summer vacation (9 / July to 20 / July). It is not restricted that persons entering or leaving the room. The temperature condition of the room is set to 26 °C. The humidity was not controlled because the system didn't have defumidify controller. The 12 supply air outlets were mounted at ceiling, and one air inlet was mounted at the wall. The supply air flow rates conditions were 740 m^3/h (6 air changes par hour) as minimum design value, 1,400 m^3/h (12 air changes per hour), and 2,000 m^3/h (17 air changes per hour). Outdoor air intake volume was set to 200m^3/h for 6 persons.

Psychological responses

Room thermal/air environments were investigated based on human psychological responses under their diurnal working conditions. In the present experiments, occupants (i.e., subjects) had engaged in desk-working and/or VDT-working. In addition, they were free for walking around the room and leaving/entering the room. Every subject got in the room at 9:00 and worked from 9:30 to 17:00, being allowed to put on own preferable casual clothing. Thus, actual office working environment was realized, and psychological evaluations of subjects were audited in every experiment. Vote was conducted every 20 minutes. Voting scales are shown in Table 2. The items of cool/warm proposed by Kuno [4] were included. It should be remarked first that the set-point air temperatures in a series of experiments were 22 °C, which was considered to be standard setting in the winter season in Japan (i.e., the end of November).

OPERATING PERFORMANCE OF HVAC SYSTEM

Figure 3 shows temperature and humidity plots for chilled water flow rates of 0.9 m^3/h and 1.44 m^3/h when the 3 way valve was manually opened. The supply air flow rate was 740 m^3/h. The supply air temperature dropped to 6 °C. Output temperature from the storage tank kept 2 to 3 °C.

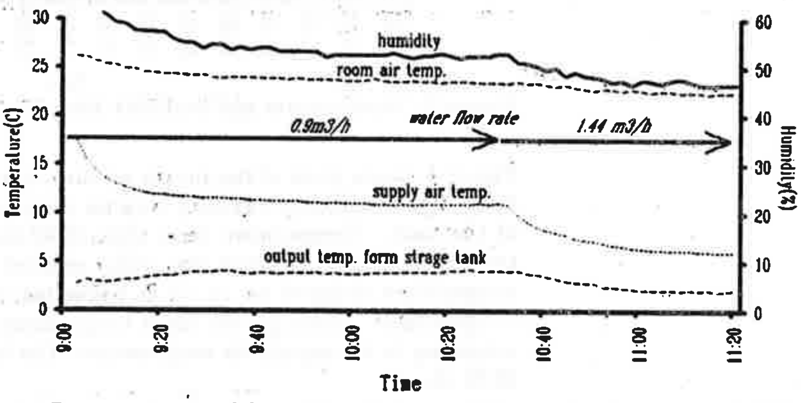


Figure 3: Temperature and humidity plots for chilled water flow rates of 0.9 m^3/h and 1.44 m^3/h when the 3 way valve was manually opened

The room air temperature and humidity dropped as the supply air temperature dropped. In this case, heat load of the room was lower than heat extraction of supply air of 6 °C and 740 m^3/h. Consequently the room air temperature dropped under the set point of 26°C. To adjust the room air temperature to set point, the supply air flow rate should be set to lower value than 740 m^3/h.

Vertical temperature profile of minimum supply air temperature was shown in Figure 4. The space temperatures are approximately uniform in the occupied area. Temperature fluctuation of ankle level was not observed.

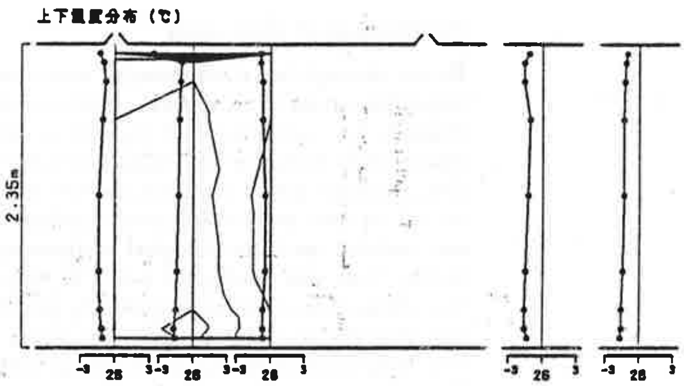


Figure 4: Temperature profile

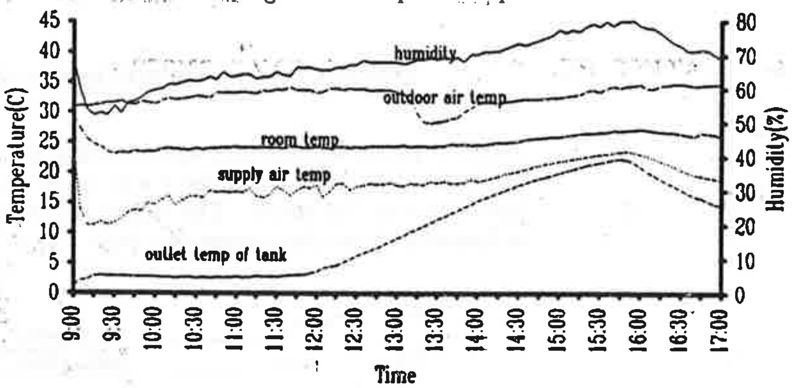


Figure 5: Temperature and humidity plots of the supply air flow rate of 2000 m^3/h

Figure 5 shows plots of the supply air flow rate of 2000 m^3/h. The ice storage tank doesn't have sufficient capacity because there isn't enough space for the installation of the tank. Temperature raise after 12:00 indicated that ice was melted during the experiment. At 16:00 the chiller started for additional cooling. Supply air temperature dropped to 12 °C at beginning of the experiment, and raised to 15 °C gradually. Although the room temperature kept constant, the humidity raised according to the supply air temperature. The humidity of the room raised to about 80 % rh.

Figure 6 shows plots of supply air flow rate of 740 m^3/h. The output temperature of the tank also raised. Because the heat load was smaller than that of Figure 5 in this case, the maximum temperature was lower than that of Figure 5. At this supply air flow rate, supply air volume dropped to 7°C, and the humidity of the room lower than that of Figure 5.

Figure 7 shows the room air psychrometric conditions at the supply air flow rate of 740 m^3/h, 1,400 m^3/h, and 2,000 m^3/h. The deviations of the room air temperature were within ±1°C. The values ranged around 24 °C that was lower than set point of 26°C, because the sensor of controller was heated by a computer set. The location of sensor should be considered. There is no humidity control in cooling, so that

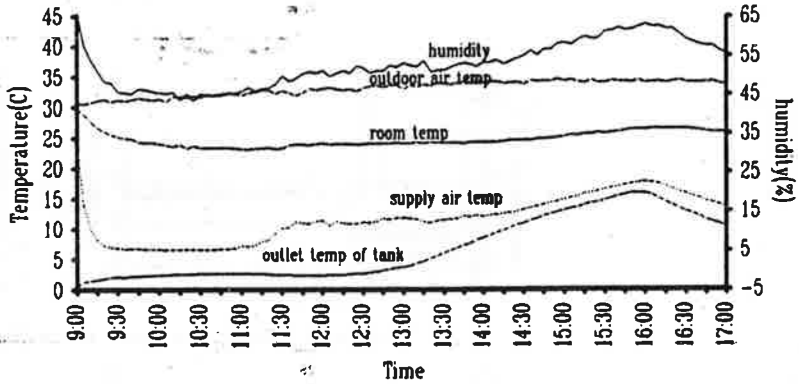


Figure 6: Temperature and humidtiy plots of supply air flow rate of 740 m^3/h

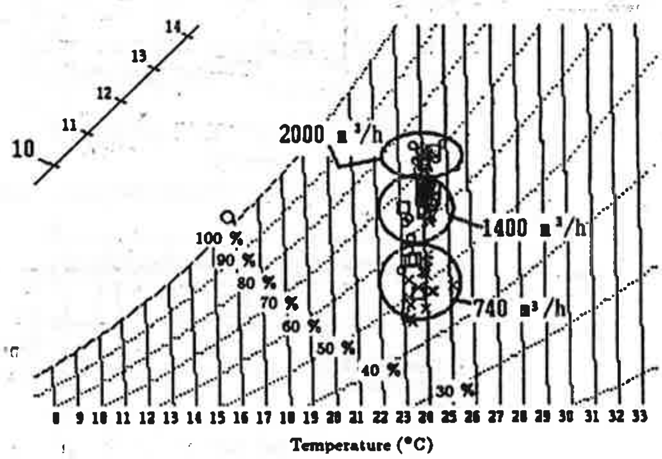
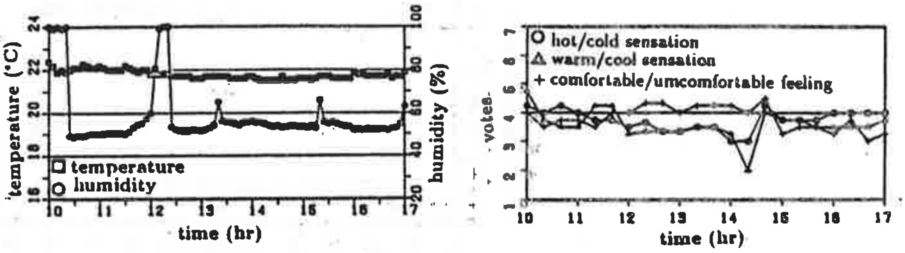


Figure 7: The psychrometric condition of the room

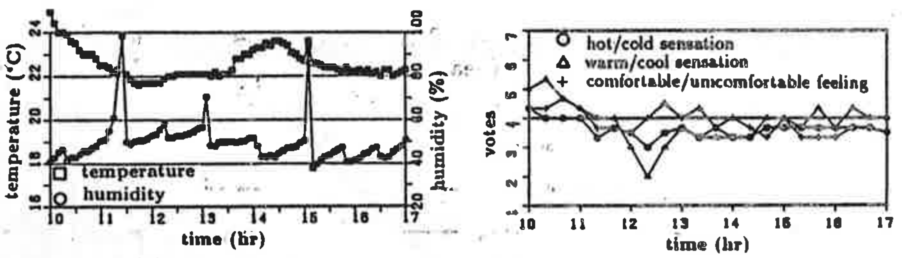
humidity varies according to the supply air flow rate. The humidities were 70 % rh at 2,000m^3/h, 65 % rh at 1,400 m^3/h, and 50 % rh at 740 m^3/h. The large quantity of supply air flow rate is not able to dehumidify the room air enough. Small quantity of supply air flow rate is recommended to keep the room condition dry.

Evaluation of Thermal Environment

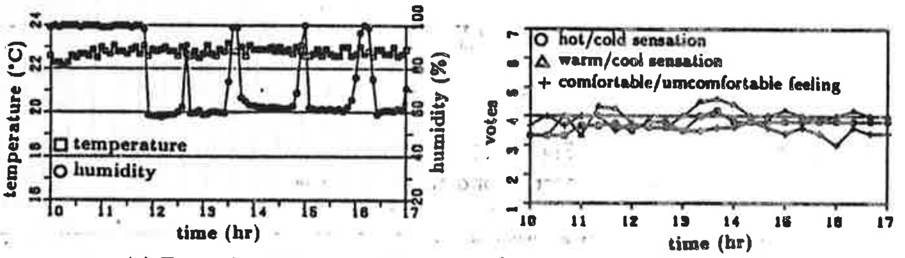
Figure 8 shows transient responses of hot/cold sensation, warm/cool sensation, and comfortable/uncomfortable feeling, as compared with those of room temperature/humidity, for each experiment. They are expressed by the mean votes of all subjects (three to five persons) employed in each experiment. Figure 9 shows transient responses of the hot/cold sensations of individual subjects in two typical experiments. Figure 10 also shows transient responses of the hot/cold sensations at four typical body elements (head, chest, hand, and ankle) in two typical experiments. They are expressed by the mean votes of all subjects employed in each experiment.



(a) Exp.1 (supply flow rate : 400 m^3/h outlet temperature 10°C)

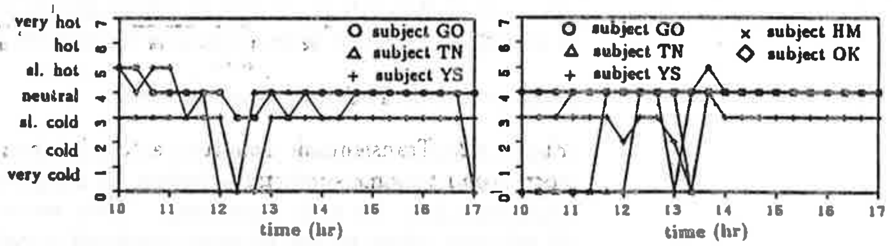


(b) Exp.2 (supply flow rate : 400 m^3/h outlet temperature 7°C)



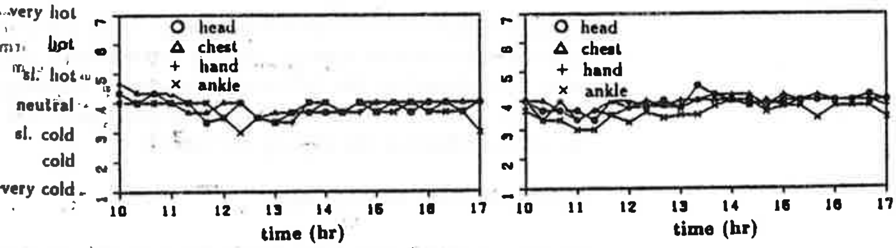
(c) Exp.3 (supply flow rate : 2000 m^3/h outlet temperature 17°C)

Figure 8: Transient responses of hot/cold sensation, warm/cool sensation, the comfortable/uncomfortable feeling. They are expressed by the mean votes of all subjects



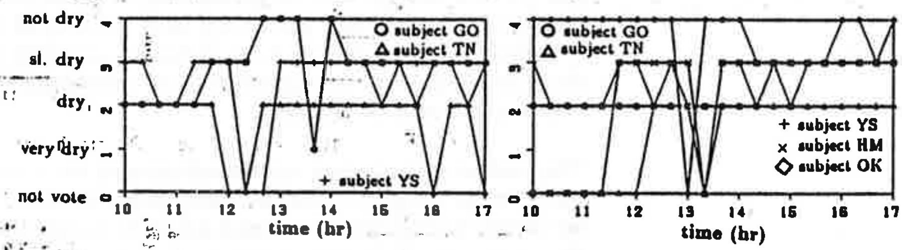
(a) Exp.2 (b) Exp.3

Figure 9: Transient responses of the hot/cold sensations of individual subjects. Same symbols correspond to same subjects.



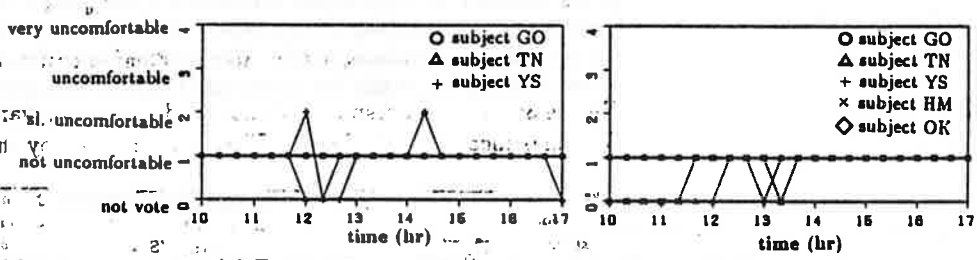
(a) Exp.2 (b) Exp.3

Figure 10: Transient responses of the hot/cold sensations at four typical body elements (head, chest, hand, and ankle). They are expressed by the mean votes of all subjects.



(a) Exp.2 (b) Exp.3

Figure 11: Transient perceptions of the air-dryness in each subject. Same symbols correspond to same subjects.



(a) Exp.2 (b) Exp.3

Figure 12: Transient discomfort due to drought in each subject. Same symbols correspond to same subjects.

The hot/cold sensation votes changed approximately between " slightly hot" and " slightly cold" through all three experiments (Figure 9). The mean votes were intermediate between " slightly cold" and " neutral" in the cold distribution system (Exp. 1 and 2), and almost " neutral" in the conventional system (Exp. 3). The slight difference could be explained by the decreases in both humidities and temperature in the former case. A decrease in the humidity could be reduced to the belongings of the cold air distribution system, while the decrease in the temperature may be reduced to experimental lapse. Therefore, about 24 °C dry bulb in the cold air distribution system may give equal sensation to the present conventional case.

The difference in hot/cold sensations at body parts could be observed between the cold air distribution system and the conventional system (Figure 10). This results may be reduced to the following two causes; uniform air temperature distribution could be formed throughout the occupied region and drought of the cold air could be avoided despite the supply air volume.

Evaluation of Air Quality

Figure 11 shows transient perceptions of the air-dryness in every subject in two typical experiments. Figure 12 also shows transient discomfort due to the drought in every subject.

The low-humidity ambient, which could be achieved by the cold air distribution system, was related to little perceptions of air dryness in subjects. The difference between 40 % rh (Exp.1 and 2) and 60 % rh (Exp.3) may affect on the perceptions. Although the perceptions of air dirtiness and stagnation had difference between the cold air distribution system and the conventional system,no problem for those evaluations could be observed.

The cold air distribution system indubitably decreases the ventilation efficiency of the room as compared with the conventional system. The air qualities affected little on human psychological responses owing to no smoking, suffcient amount of outside air intake, and adoptation of higher-efficient ventilation system (i.e.,ceiling-mounted outlets and floor-mounted intakes).

The discomfort due to drought may be related to the following causes; the intrusion of the primary air with higher-temperature but higher-velocity for the conventional system and the dumping of the primary air with lower-tempeature and lower-velocity for the cold distribution system. The former case (Exp.3) generated no discomfort to whole subjects, while the latter case (Exp.2) also generated little discomfort.

CONCLUSIONS

The experiments on low-temperature air distribution system using ice storage system were carried out. The conclusions are summarized as follows.

1. If 2 to 3 °C cold water from ice storage tank was available, the supply air temperature under 6 °C could be obtained.
2. The water temperature available with ice storage was 2 °C to 3 °C while the ice existed. If the ice in tank was completely melted, the water temperature raised to inadequate for low-temperature air distribution. Therefore sufficient storage capacity or additional chiller operation is required.

3. For the HVAC system without dehumidify controller, the low-temperature air and reduced supply air flow rate resulted in lower space humidity.

4. As far as the present experiments are concerned, the cold air distribution system shifted human thermal sensation to "cold" as compared with the conventional system. The cold air distribution system can make the set-point air temperature higher than the conventional system. This results in energy saving effect due to the reduced cooling load.

5. No problem could be recognized for human evaluations/feelings of air dryness, air dirtiness and air stagnation in the cold air distribution system. Further, the discomfort due to drought could not be generated little.

ACKNOWLEDGMENTS

The authors were indebted to Takasago Thermal Engineering Co., Ltd. for contribution of installation and adjustment of the ice storage system. This work was supported by grants from Chubu Electric Power Co., Ltd.

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