Verification of Thermal Comfort of Combined Convection-Radiation Air Conditioning System using Building Structure

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ABSTRACT

Combined Convection-Radiation Air Conditioning System using Building Structure combines the advantages of TABS and convection air conditioning. In ordinary TABS, pipes are buried in the frame, but here pipes are laid on the lower (ceiling) surface of the floor slab. Also, jets from a Convection-enhancing Spot fan are sprayed toward the ceiling surface, promoting convection on the frame surface. This airflow promotes timely heat dissipation stored in the frame, and a micro-airflow environment can be formed in the living area. This paper aimed to verify thermal comfort and proper operation. Subjects were given simulated work of low to high metabolic rate, and were asked to report the thermal sensation and comfort in a micro-airflow environment. It was confirmed that comfort could be maintained even at a temperature higher than the general air-conditioning temperature, and an appropriate operating method according to the metabolic rate was elucidated.

INTRODUCTION

In order to create a sustainable society, energy-saving is being promoted in buildings by adopting various technologies such as improvement of building envelopes performance, introduction of high-efficiency equipment, and use of renewable energy. In recent years, building evaluation systems that focus on human health and comfort, such as those with the WELL Building Standard certification, have also been attracting attention, and there is a growing demand for a comfortable and healthy indoor environment.

Against this background, TABS (Thermo-Active Building Systems) is drawing attention as an air conditioning system that achieves both energy savings and comfort. TABS has the advantages of being able to use low-valued energy (low-exergy approach), maintain a stable indoor thermal environment, and contribute to load leveling through proper operation. On the other hand, there are problems that response to the temporal fluctuation of heat load and uneven distribution of space is low, and that the frame weight is expected to increase as the frame thickness must be increased to bury the pipe.

The authors have developed a Combined Convection-Radiation Air Conditioning System using Building Structure (C-R System) that incorporates the TABS mechanism. In addition to the merits of TABS, this system aims also to achieve responsiveness, which is the advantage of convection air conditioning.

In this paper, subject experiment was conducted with the aim of verifying the appropriate operating method of this air conditioning system according and thermal comfort to the metabolic rate of residents.

OUTLINE OF THE AIR CONDITIONING SYSTEM

Figure 1 shows an outline of the air conditioning system, and Figure 2 shows the contact-type radiation fins. Since summer in Japan is hot and humid, it is necessary to consider an appropriate humidity treatment method in order to adopt a radiant air conditioning system. The system configuration was a latent heat-sensible heat separation air conditioning system that adopted radiant air conditioning using floor slabs, and a latent heat treatment air conditioner.

A corrugated aluminum fin (Contact-type Radiation fin, hereinafter referred to as Radiation fin) is installed

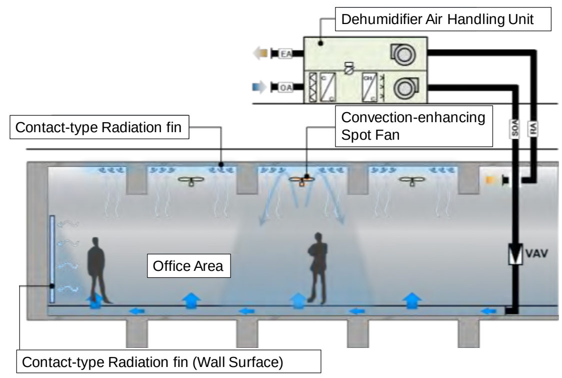


Figure 1. Outline of air conditioning system

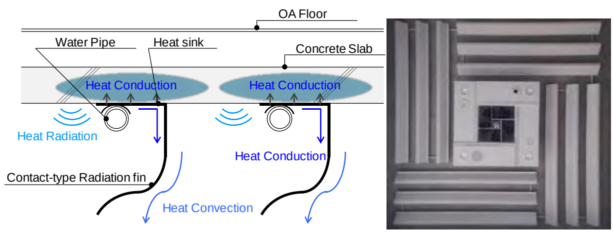


Figure 2. Contact-type radiation fins

so as to contact under the slab to store heat in the slab and dissipate heat to the living room. Since the slab surface is also cooled when water is supplied, the area where the amount of building materials used for the Radiation fin at least contributes to radiant air conditioning can be increased. Furthermore, under the slab, a convection-enhancing spot fan (hereinafter referred to as a Spot fan) that creates an air flow on the ceiling surface was built in. The jet from the Spot fan blows toward the ceiling, and after reaching the side of the flow beam through the Radiation fin and the ceiling surface, it descends to the living area. The Spot fan promotes convection on the ceiling surface to improve responsiveness to heat load fluctuations. In addition, by not embedding the pipes in the slab, the amount of concrete in the pipe burial part was reduced and the frame weight load was also reduced. By adjusting the rotation speed of the Spot fan so that the airflow in the living area does not become excessively fast, and operating it at the timing according to the resident's needs, the system can generate the airflow only in the required area.

METHOD

Facilities for experiments

Figure 3 shows an overview of the facility to be tested, and Figure 4 shows the outline of verification target area. This facility is a training facility for practical training in building equipment management work. The new C-R System is installed in the training room. In the training room, training with practical skills is conducted in addition to classroom lectures, and the amount of metabolism of building users varies depending on the training content. Therefore, in the subject experiment, the authors decided to verify the operating method that can maintain comfort while the amount of metabolism changes. The subject experiment was conducted using a specific area in the building.

Figure 3. Overview of the facility to be tested

The space for the subject experiment has a ceiling height of 3.65 m, and the ceiling is finished with concrete slabs and beams. As shown in Figure 2, an aluminum Radiation fin is placed on the ceiling surface, and air conditioning is performed by supplying cold or hot water to it. An air outlet was also provided in the center of the floor of the verification target area to supply temperature-controlled outside air so that good air quality could be maintained.

Thermal environment measurement

Figure 4 also shows thermal environment measurement points. Various measurement points were set in order to grasp the temperature distribution and airflow environment in the space around the subject in detail. The measurement points were 96 air temperature points, 4 airflow velocity points, 13 ceiling / beam surface temperature points, 13 floor surface temperature points, 1 relative humidity point, and 1 PMV point. The measurement points at each location were arranged so as not to restrict the behavior of the subject during the subject experiment.

Subject experiment procedure

Figure 5 shows the measurement location of the subject, Figure 6 shows the measurement scene, Table 1 shows psychological and physiological measurement items, and Figure 7 shows the physiological data measurement position. Four seats were set up in the verification target area, and a maximum of three subjects were allowed to stay at the same time. A thermal manikin was seated in the remaining seat, and the equivalent whole body temperature, sensible heat loss, and skin surface temperature were measured in parallel with the measurements of the subjects. The subjects were 12 healthy men and women in their twenties, and the amount of clothing was standardized to about 0.5 clo (0.511 clo, 0.554 clo in 2 clo value measurements).

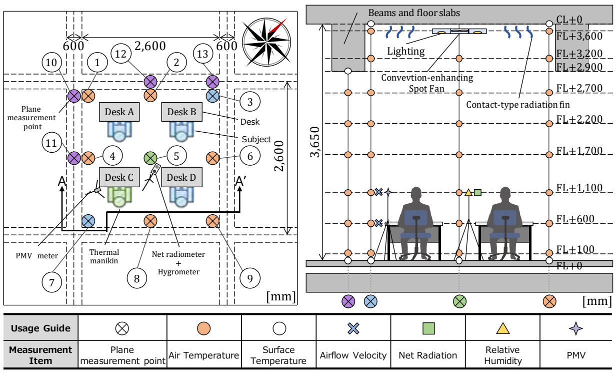


Figure 4. Outline of verification target area

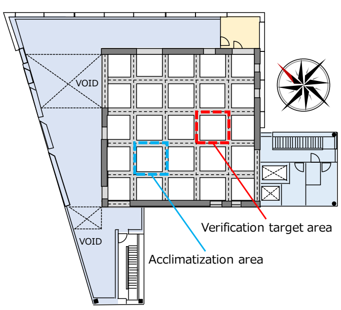


Figure 5. Measurement location of the subject

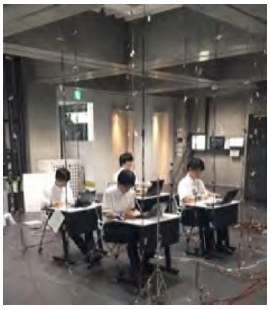


Figure 6. Measurement scene

Table 1. Psychological / Physiological measurement items

Psychological measurement items	Personal attributes, Life background, Health, Thermal sensation, Comfort sensation, Acceptance of thermal environment
Physiological measurement items	Skin surface temperature, Sweat rate, Heart rate, Pulse rate, Activity intensity, LF/HF

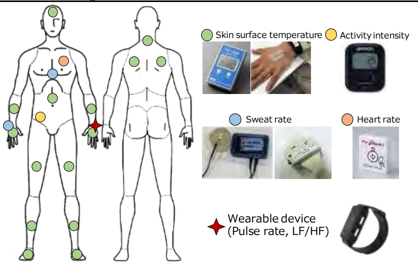


Figure 7. Physiological data measurement position

Table 2 shows the experimental cases, and Figure 8 shows the experimental schedule. The experimental cases consisted of a steady case in which the subject continued the same simulated work, and an unsteady case in which the simulated work was changed during the experiment. Before the start of the experiment, a time for acclimatization to the thermal environment was provided, and the subjects were allowed to stay at rest for 30 minutes in the acclimatization area. Then they were moved to the verification area, and the simulated work set in each case was carried out. In the simulated work, typing (equivalent to 1.1 met) and step exercise on a stepladder (equivalent to 2.1 met) were imposed for 60 minutes in the steady case, and typing, standing file organization (equivalent to 1.4 met), and step exercise on a stepladder (equivalent to 1.7 met) were imposed for 90 minutes in the unsteady case. The metabolic rate of step exercise on the stepladder in the steady and unsteady cases was adjusted by determining the number of ascents / descents (times / minute) from the relational expression between ascent / descent and energy metabolism proposed by Hirakawa.

As thermal environment conditions, the air conditioning temperature was set to 26°C and 27°C, and the air conditioning was controlled so that the relative humidity was 50%. The Spot fan was changed in three stages; stop / weak / strong, depending on the experimental case.

A report regarding thermal sensation and thermal comfort was requested at the following points of time; after 15 minutes of staying in the acclimatization area, immediately after moving to the verification target area, and every 10 minutes after moving.

The air conditioning temperature of 27°C is higher than the general air conditioning design temperature (= 26°C) in Japan. A productivity test was imposed at 27°C excluding Steady case 3 and 4 to confirm that a thermal environment that did not reduce productivity was maintained. (Steady case 3 and 4 were not tested because the simulated work was to ascend and descend the stepladder). In the productivity test, 3-digit addition problems were solved as quickly as possible for five minutes at three or four times, i.e., during the acclimatization period, during the experiment and immediately after the experiment.

Table 2. Experimental cases

Case		Spot fan operation	Simulated work (Estimated metabolic rate)	Environmental Condition
Steady	1	Stop	Typing (1.1[met])	Room temperature :26°C,27°C ±0.5°C
	2	Weak		
	3	Weak	Step exercise on a step ladder (2.1[met])	
	4	Strong		
Unsteady	1	Weak	Typing (1.1met)	Relative humidity :37 - 55%
	2	Strong	File sorting in the standing position (1.4met) Step exercise on a step ladder (1.7met)	

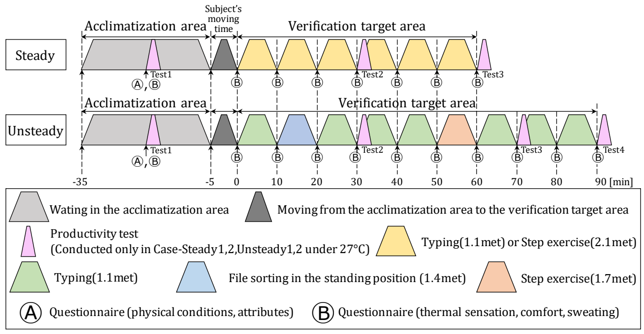


Figure 8. Experimental Schedule

RESULTS

Thermal environment

Figure 9 shows the airflow measurement results, and Table 3 shows the average airflow velocity in the living area. When the fan was stopped, the average airflow velocity in the living area was 0.02-0.03 m/s, which was a quiet environment. As the operating conditions were changed from weak to strong, the average wind speed increased and the variation increased. The average wind speed was 0.16 m/s in weak operation and 0.26 m/s in strong operation, and a micro-airflow environment of 0.5 m/s or less, which is the indoor environment recommended by “Act of Maintenance of Sanitation in Buildings (Japanese law)”, could be created.

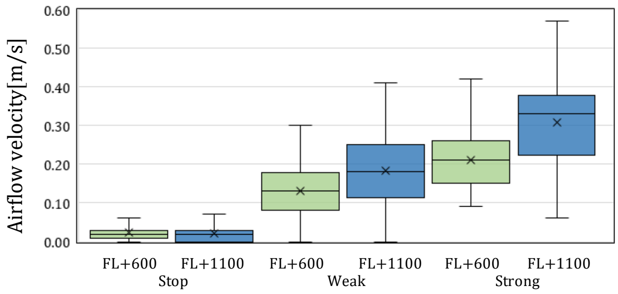


Figure 9. Airflow velocity during subject experiments

Table 3. Average air flow velocity in the living area

Spot fan operation	Stop	Weak	Strong
Average air velocity	0.02 m/s	0.16m/s	0.26m/s

Figure 10 shows the results of vertical temperature distribution measurement. The temperature of the measurement points directly above the floor outlet tended to be low in the range of FL+100-600, but the temperature of the other measurement points was within the range of the air conditioning set temperature of ±0.5°C. A similar trend in the temperature distribution was confirmed under the condition of 27° C. The ceiling surface temperature was cooled by the Radiation fin by maintaining water supply for a certain period of time, and when it was stable, it was around 24°C.

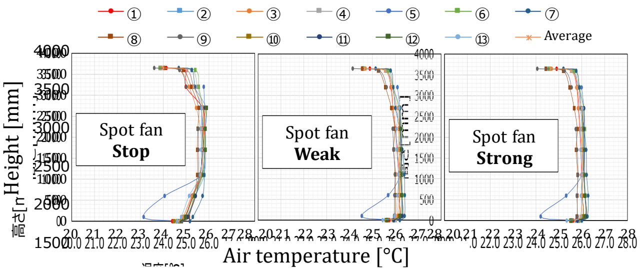


Figure 10. Vertical temperature distribution under 26°C conditions

Total equivalent temperature / equivalent temperature for each body segment

Figures 11 and 12 show the results of measuring the total equivalent temperature and that for each body segment using the thermal manikin. The average air temperature of FL+1100 and PMV is also shown. When the fan was operating, it was confirmed that the total equivalent temperature measured with the thermal manikin tended to be lower than the air temperature. The PMV was on the warm side, except for Steady case 2 and Unsteady case 2 under 26°C conditions. As for the equivalent temperature for each body segment, especially the upper body tended to be low.

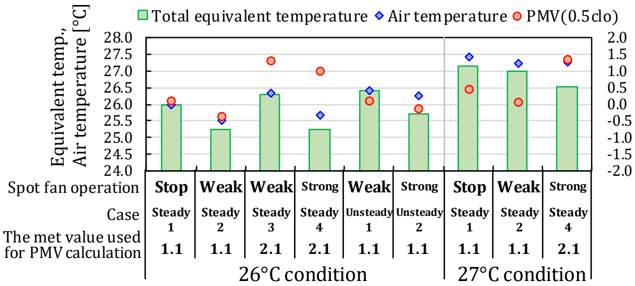


Figure 11. Total equivalent temperature by thermal manikin

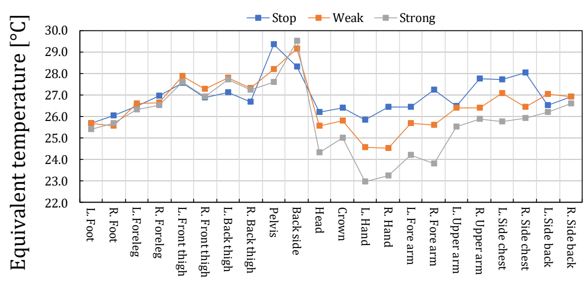


Figure 12. Equivalent temperature on each body segment under 27°C conditions

Thermal sensation votes / thermal comfort votes

Figure 13 shows the votes of thermal sensation and thermal comfort under 26°C conditions. Under the steady condition for the same metabolic rate, the number of votes on the cool side increased when the fan was stronger. In Steady case 2, the number of votes on the cool side was more than 50%, and the feeling of comfort was slightly lower than in Steady case 1. In Steady case 4, votes on the cool side were about 65%, and those on the comfortable side increased from 28.6% in Steady case 3 to 80.9%. Comparing Steady case 2 and Steady case 3 in which the fan operates in the same condition, votes on the warm side increased from 11.9% to 33.3%, and those on the comfortable side decreased from 54.8% to 4.8% in Steady case 3 with a high metabolic rate. Regarding the unsteady

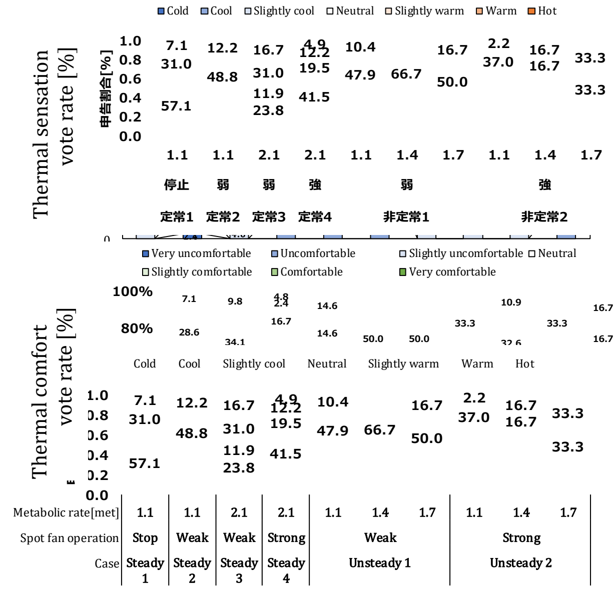


Figure 13. Votes of thermal sensation and thermal comfort under 26°C conditions

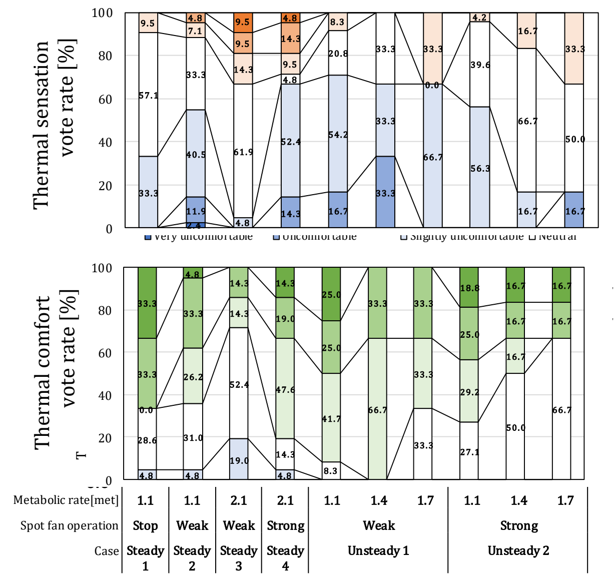


Figure 14. Votes of thermal sensation and thermal comfort under 27°C conditions

condition, the number of votes on the comfortable side was maintained, but those on the comfortable side tended to decrease as the metabolic rate increased.

Figure 14 shows the votes of thermal sensation and thermal comfort under 27°C conditions. Similar to 26°C, the number of votes on the cool side increased as the fan became stronger. In Steady case 1 and 2 with a low metabolic rate, votes on the comfortable side were 50% or more, but in Steady case 3 and 4 with high metabolic rates, votes on the comfortable side were less than 30%, while those on the dissatisfied side were over 30%. Under unsteady conditions, the comfort side was maintained at more than 50%, and good comfort was obtained despite the 27°C temperature.

Productivity

Figure 15 shows the rate of change in the correct answer rate of the productivity test. It was confirmed that the average correct answer rate of all subjects could be maintained without decreasing over time in Steady case 1 and 2, Unsteady case 1 and 2.

Figure 16 shows a comparison of a correct answer rate depending on airflow. It was found that many subjects had higher correct answer rates when there was stronger airflow.

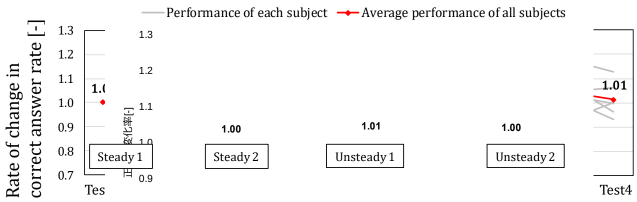


Figure 15. Rate of change in the correct answer rate of productivity test

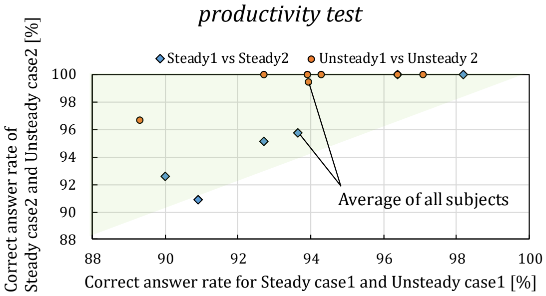


Figure 16. Comparison of a correct answer rate depending on airflow

Physiological data

Figure 17 shows the results of skin surface temperature and sweat rate. As an example of a typical physiological response, the measurement results of one male subject at 26°C are shown. In Steady case 1-4, in which steady simulation work was performed, the skin surface temperature was lower and sweat rate was greater at higher metabolic rates (Steady case 3 and 4). In a comparison between Steady case 2 and Steady case 3, the difference in sweating in the chest area was small, but sweating in the right wrist was about three times greater in Steady case 3. On the other hand, under unsteady conditions, sweating was less and the skin surface temperature tended to be slightly lower during strong fan operation than during weak operation.

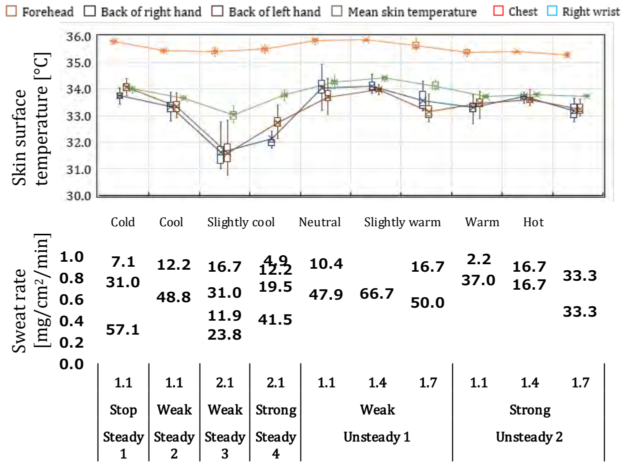
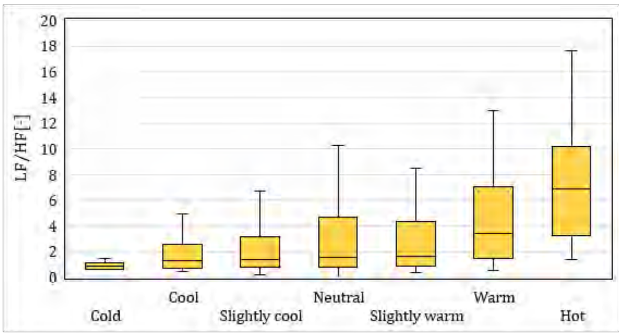


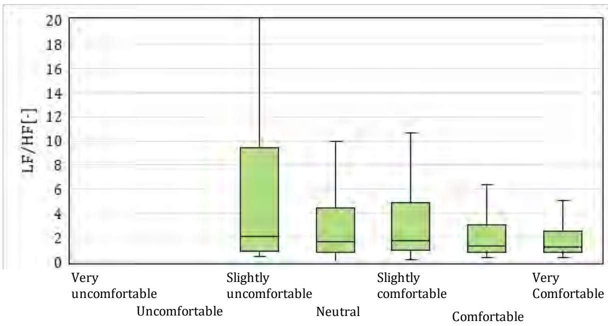
Figure 17. Skin surface temperature and sweat rate

Relationship between physiological data and psychological data

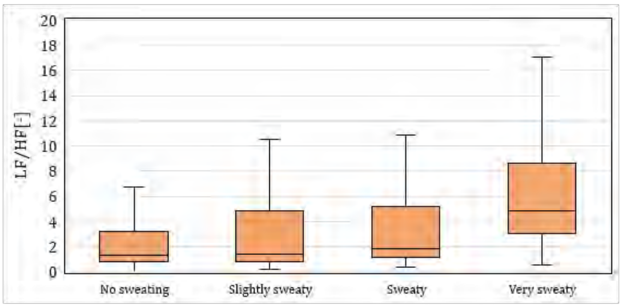
Figure 18 shows the relationship between LF/HF and subjective votes. For physiological data, the focus was on LF/HF, which is used as a stress index, and the



(a) Thermal sensation



(b)Thermal comfort



(c)Sweat rate

Figure 18. Relationship between LF/HF and subjective votes

relationship with psychological data obtained by subjective votes. All results were at a temperature condition of 26°C.

LF/HF was derived by frequency analysis of pulse wave interval (PPI) acquired by a wearable device. For data cleansing, values with a PPI of 450 msec or less and 1,250 msec or more were excluded as outliers. In addition, PPI was replaced with continuous data by spline interpolation, and resampling was performed. The total amount of power spectra in the frequency band of 0.04-0.15 Hz derived by frequency analysis was defined as LF, the total amount of 0.15-0.40 Hz was defined as HF, and their ratios were defined as LF/HF. The frequency analysis was performed every 300 seconds for the calculation interval and every 60 seconds for the analysis cycle, and the output data was shown as a box plot classified according to the report result. It is said that LF reflects both sympathetic and parasympathetic activity, and HF reflects parasympathetic activity. Therefore, it was thought that the larger LF/HF, the more dominant the sympathetic nerve is, indicating the stress state.

The hotter is the feeling of warmth or coolness, and the more sweating is felt, the higher becomes LF/HF. On the other hand, the stronger is the feeling of comfort, the smaller is LF/HF.

DISCUSSION

Thermal environment

The airflow was larger in FL+1100 than in FL+500 because the Spot fan generated a downward flow from the upper part of the space. It was inferred that this air conditioning system generates an environment in which the upper body is more easily cooled by the air flow. The average airflow velocity was as small as 0.3 m/s even at FL+1100 during strong fan operation, but the maximum value was up to 0.57 m/s, so it is thought that the subject could occasionally feel the airflow fluctuation.

Regarding temperature distribution, the temperature was almost the same in the range of FL±0 to FL+1700, which is thought for the living area. When the feeling of warmth/coolness was different for each part of the body, it was presumed that the airflow was the cause.

Total equivalent temperature / equivalent temperature for each body segment

The total equivalent temperature tended to be lower than the air temperature due to operation of the Spot fan. It was expected that the airflow would shift the feeling of thermal sensation to the cooler side. The reason why the equivalent temperature did not decrease uniformly by the fan was thought to be that the airflow velocity was small and was easily affected by the disturbance due to the measurement in the actual building.

The equivalent temperature for each body segment tends to be lower in the upper body than that in the lower body., thus, it was found that the downward flow from the upper body contributes to cooling of the upper body.

Thermal sensation votes / thermal comfort votes

Comparing comfort in Steady case 1 and 2 at 26°C, it was slightly higher when the Spot fan was stopped. In Steady case 2, the number of votes on the cool side increased, suggesting that the environment was slightly cooler than the neutral thermal state, and that comfort could be maintained even at an air conditioning temperature higher than 26°C. On the other hand, even at high metabolic rates, good comfort and a thermal sensation could be maintained by operating the Spot fan strongly. It was found that the Spot fan can create a good thermal environment in response to fluctuations in the metabolic rate.

In Steady case 2 at 27°C, the same comfort as at 26°C could be maintained. It was considered that when the metabolic rate was low, by operating the Spot fan at 27°C, it was possible to operate with energy-saving while still maintaining comfort. In addition, the heat stored in the frame could be dissipated by the airflow generated on the ceiling surface during the time when people were staying in the area, which could contribute to load leveling. On the other hand, when the metabolic rate was high, good comfort could not be maintained even if the fan was operated. When work with a high metabolic rate is expected, it was considered desirable to operate at 26°C.

Productivity

An air conditioner temperature of 27°C is higher than the general cooling temperature set in Japan. Therefore, even if the thermal sensation and comfort can be properly maintained, there was a concern that thermal stress could occur without subjects knowing, and productivity would decline. However, productivity test results showed that it was possible to maintain a certain level without loss of productivity. In addition, the number of subjects whose correct answer rate was high due to the airflow, increased. This suggested that maintaining an appropriate thermal environment with a Spot fan may have a positive effect on productivity.

Physiological data

It was considered that the skin surface temperature decreased due to increase of sweating, and the increase of transpiration on the skin surface at high metabolic rates. Under unsteady conditions, sweating under the strong fan operating condition was less than that under the weak fan operating condition. Hence, sweating was evidently suppressed by the cooling effect of the air flow.

Relationship between physiological data and psychological data

LF/HF is an index to confirm which of the autonomic nerves, the sympathetic nerve or the parasympathetic nerve, is dominant. The fact that LF/HF was larger when subjects reported “hotter” in the thermal sensation vote, was considered to indicate that the sympathetic nerve was dominant due to heat stress. On the other hand, it is said that the sweat glands become more active when the sympathetic nerve becomes dominant, and the same trend was confirmed in this measurement.

Regarding relationship with thermal comfort vote, it was found that the more comfortable the vote, the smaller the LF/HF value and the parasympathetic nerve tended to dominate. Since LF/HF is physiological data that can be easily acquired with a wearable device, this suggested that it may be a useful index for evaluating the thermal sensation and thermal comfort.

In this verification, only cooling conditions were examined, so the behavior of LF/HF when thermal stress occurred on the cool side during heating could not be confirmed. In addition, it is generally recognized that LF/HF is not a highly reliable metrics, and the relationship between physical stress such as physical activity and mental stress is unclear. In the future, the authors would like to examine whether LF/HF can be used as an evaluation index of thermal stress by evaluating the relationship with psychological data under heating conditions. It was also considered necessary to verify the effects of physical stress and reliability.

CONCLUTIONS

In this paper, a subject experiment was conducted for the purpose of verifying the thermal comfort and appropriate operating method of the C-R System introduced in a training facility.

It was found that the C-R system can create a good thermal environment according to the metabolic rate by controlling the rotation speed of the Spot fan. At the air-conditioning temperature of 26°C, good comfort could be maintained over a wide metabolic range of 1.1 to 2.1 met. On the other hand, at low metabolic rates, comfort can be maintained well even at 27°C, and it is thought that both energy-saving and comfort can be achieved.

The authors believe that the results of this paper can provide useful data for designing air conditioning control methods that match changes in metabolic rate.

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