STUDY ON THE PERSONAL AIR-CONDITIONING SYSTEM CONSIDERING HUMAN THERMAL ADAPTATION

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Abstract

In this paper, a personal air-conditioning system (PACS) considering the human thermal adaptability is analyzed. Although the conventional personal air-conditioner was proofed to be satisfactory in providing for the thermal comfort, it is being questioned on the term of its energy efficiency. Therefore, it is important and urgent to develop new types of PACS with sustainable control strategy that can ensure energy saving and thermal comfort simultaneously.

In this study, we first examined the problems of the conventional PACS with field interview and laboratory experiment in terms of usage, management and thermal comfort, and proposed the energy-saving PACS considering the human thermal adaptation in succession. Then a laboratory experiment was performed to analyze the characteristics of the human thermal comfort under severe indoor thermal conditions, which were controlled using a new personal air-conditioning unit designed according to the proposal. The results help to illustrate the alleviation effect of the new PACS, and indicate that the thermal alleviation time is useful to maintain the thermal comfort with efficient usage of energy. Finally the recommendations for the sustainable control on the new PACS are summarized by the examination on the results.

1. Introduction

With the rapid development of the office automation in recent years, the non-uniform thermal office environment occurred with the increasing adaptation of the partitioned space. It has become more difficult to ensure the thermal comfort for all the office workers by the present of a mere air-conditioning system that gives a fixed indoor temperature. So in past few years, attention has been paid in Japan to study the PACS, to correspond to the individual thermal sensations in line with the rest of the western world. It is important to make sure that the PACS will not only improve the productivity but also regulate the individual's thermal comfort according to the individual preference. But, unfortunately, the PACS has various problems in both sides of the management and application of the facilities and is not popular in use.

However, the Japanese government recommended a standard minimum of 28℃ to be the setpoint of indoor temperature in Summer as an urgent measure against the global warming at the COP3 Conference held in Kyoto Meeting in December 1997. This is a big thermal stress for most present air-conditioning systems and as such, PACS attracts attention again as an appropriate system to save energy and to ensure thermal comfort of individuals.

Based on the above background, our research aims to develop a new PACS that will be more energy efficient and comfortable by considering the human being's thermal adaptation. In this paper, the thermal nature and controlling characteristics of the conventional PACS are examined, and from the problems derived from the examination, a more efficient PACS is proposed.

2. The state of the conventional PACS and the proposal for an efficient PACS

In 1990s, office automation progressed so rapidly and the concept of PACS was introduced to Japan. Due to the various problems faced in the actual application, the PACS did not become popular. Here, we reviewed a series of field interviews and laboratory experiments to examine the problems and hopefully to find a solution to bring popularity to PACS in the design of office environment.

2.1 Investigation by interviews

By interviewing the designers and users of the conventional PACS, the problems of the system can be deduced as below.

(1) Problems in managing the facilities and inflexibility in future layout alteration

i) For it is necessary to equip a system for each user, both the initial and running costs are very high compared to the normal air-conditioning system.

ii) It takes a great deal of time to repair when problem occurs, and the maintenance cost is also expensive.

iii) Since it is difficult to change the layout of the supply ducts, it is hard to coordinate it into the constant changes of today's office space layout.

(2) Problems on the user's side

i) As the local wind velocity can be strong and the diffusion of the temperature is difficult, the user is susceptible to feel the draft. Moreover, if the supply outlet is close enough to be seen or touched, the negative feeling is strong and may have a disapproving effect on the perception of thermal comfort.

ii) Since the controllable items of a PACS are limited compared to the conventional household air-conditioner, it is taken to increase dissatisfaction toward the thermal environment.

2.2 Examination by laboratory experiment

A series of laboratory experiments were performed to explore the controlling characteristics of the conventional PACS and to investigate the problems faced in detail[1,2] (S., Matsumoto et al, 2002). The experiments were set to being performed in the normal summer office environment. The temperature of the ambient air-conditioning system, which generated a upward uniform flow, was set at 28℃ and the relative humidity was set at 50%RH. The amount of clothes was at 0.55 for man, 0.70 for woman, and the results are shown as below:

(1) The thermal comfortable nature of a conventional PACS (Fig.2-4)

Here the 7-point ASHRAE Thermal Sensation Scale (Fig.1) was used to rate the subjects' current feelings of warmth, and a 6-point general comfort scale (Table.1) was used to evaluate the subjects' thermal comfort. The results are shown as follows.

Table 1. General comfort scale

6	very comfortable
5	moderately comfortable
4	slightly comfortable
3	slightly uncomfortable
2	moderately uncomfortable
1	very uncomfortable

i) It was possible for the user to maintain his/her thermal.

ii) There was perceivable difference in the thermal sensation and comfort between men and women.

(2) The physiological and psychological problems on using a conventional PACS (Fig.5)

i) When exposed to an airflow blown directly at the face, the user felt uncomfortable with the air-draft and the effect of dry eyes as a result of it.

ii) The controlling system of the PACS was considered troublesome and the energy wastage was a worrisome factor.

(3) The controlling characteristics of a conventional PACS (Fig.6)

i) Most of the users preferred straight blowing wind. However, women tended to avoid wind blowing directly at the face.

ii) Men preferred the airflow at about 2.0m/s while women tended to be very sensitive to coldness and draft and inclined to turn off the system.

2.3 The proposal for energy-saving PACS

Based on the examination of the conventional PACS mentioned above, some outlines for an improved PACS is suggested, which is more energy efficient while ensuring the preferred thermal comfort, as followed:

(1) Introduction of the concept of human's thermal adaptability into the controlling theory

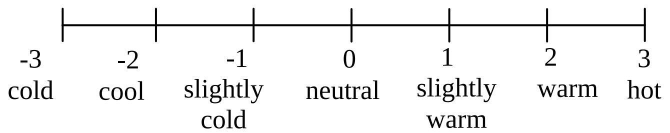

Fig 1. Thermal sensation scale

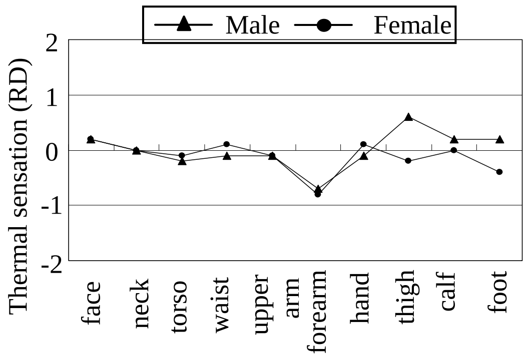

Fig 2. Mean local thermal sensation

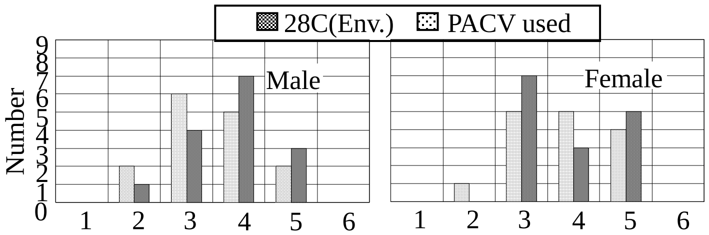

Fig 3. Thermal comfort of whole body

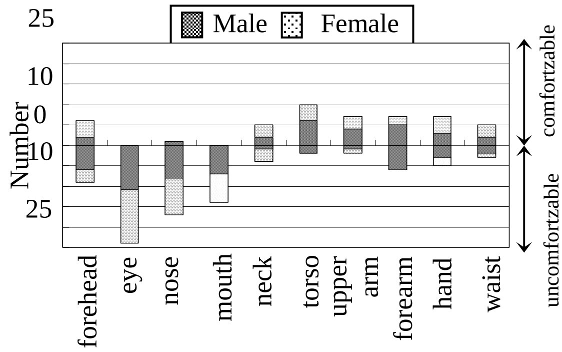

Fig 5. Mean local thermal comfort

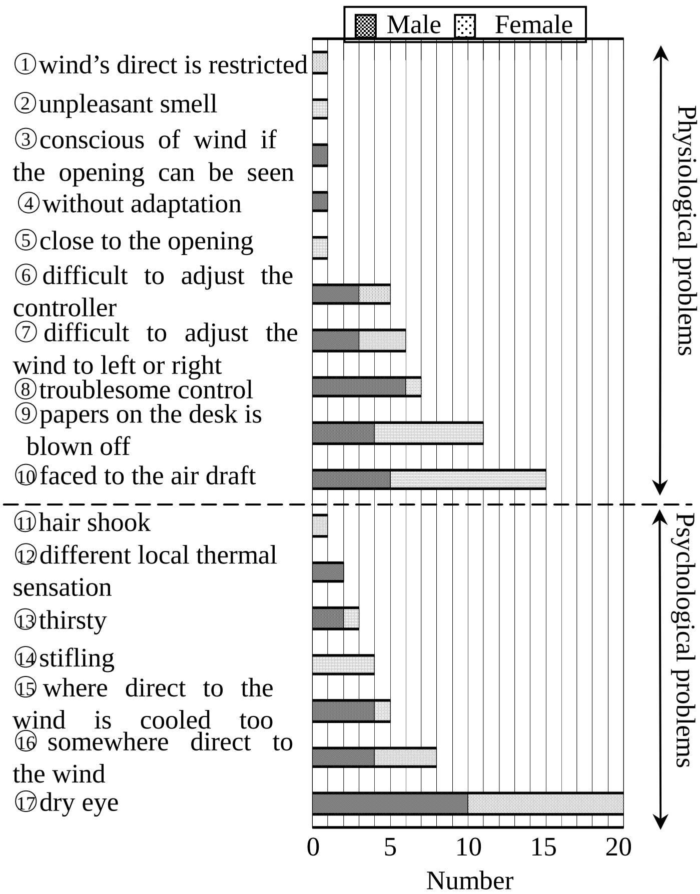

Fig 6. Problems in using the PACS

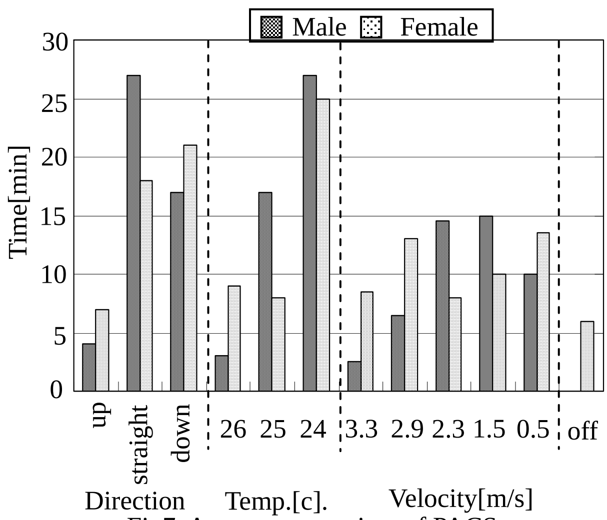

Fig7. Average usage time of PACS

i) By introducing the human's adaptability with the change in the thermal environment, the temperature at the ambient zone can be controlled to change with the outdoor climate thereby reducing the cooling/heating load of the air-conditioner.

ii) Since the thermal stimulus of a person within the air-conditioned zone will be alleviated together with the length of his stay, the air-conditioning control should be reduced accordingly. To the conventional PACS, the wastage of the energy is worrisome if the system is completely controlled by individual user.

(2) Introduction of the local thermal sensitivity into the system

PACS is the system that is used to reduce the local thermal stimulus. It is therefore possible to design a more energy efficient and comfortable air-conditioning system if we can incorporate the variable local thermal sensitivity of human body concept into the system.

(3) Development of the simple personal air-conditioning unit

Conventional PACS does not allow changes in the layout and it is expensive. It is desirable to make the system simple by reducing duct-works for instance, to reduce cost.

3. Proposal of the new PACS based on human's thermal adaptability

As an innovation to design for an energy-saving PACS, in this study, a new control logic of PACS incorporating human's unsteady thermal adaptability is analyzed.

3.1 Outline of the new PACS

It is hopeful to achieve a great motivation on future design of the control system of an air-conditioner to ensure the desired thermal comfort on one hand while achieving the goal of energy saving. It is necessary to clarify the relationship between the physiological phenomena and the indoor thermal environment. The personal air-conditioning unit mentioned here, which is conscious of human's thermal adaptability and has been tested in a subject building, is made simple together with its control methods. The new simple unit regards the personal individuality as an important feature. As shown in Fig.8, the new personal air-conditioning unit comprises the following four parts: ① a supply opening at task zone; ② an MD switch device which can be operated with time adjustment; ③ supply/exhaust installations; ④ the controller. The supply opening at the task zone is fixed at the middle of the desk, directly opposite the user. Similar to the conventional system, the direction of airflow can be adjusted manually by individual user. But the airflow's velocity and temperature aer decided by the caretaker. The most distinctive feature of the new PACS is that an MD switch device is used to enable time adjustment on the quantity of the airflow. Using this device, one can shut down the airflow within 3 seconds or apply an opposite operation in 30s~5min (with time adjustment enabled). The device is designed for speed cooling/heating for users coming in from outside whom require instant conditioning, without disrupting the energy saving feature of the total air-conditioning system.

3.2 Measurement of the alleviation time

A laboratory experiment was performed to determine the human's unsteady thermal adaptability and this was

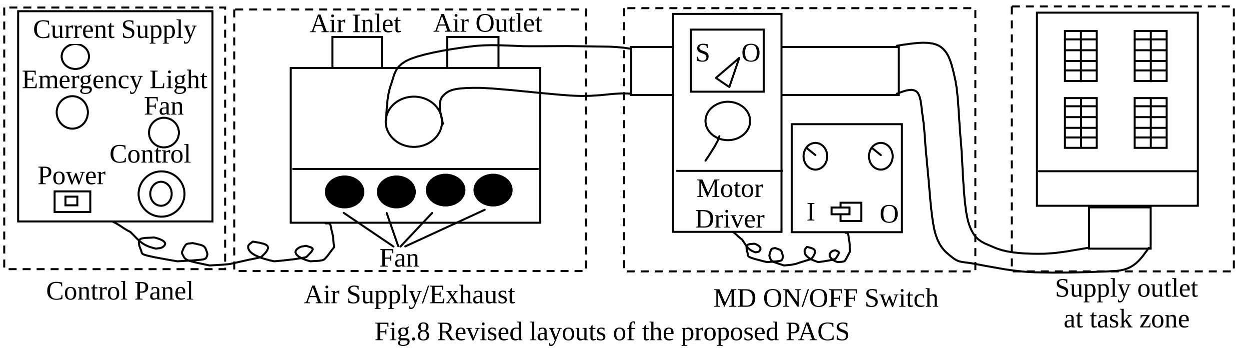

Fig.8 Revised layouts of the proposed PACS

examined in detail with respect to the controlling of the new PACS.

3.2.1 Definition of the alleviation time

As shown in Fig.9, the alleviation time is defined as the time taken to eliminate the thermal stimulus, which has been induced by the unsteady change of the experienced environment, until the thermal comfort was reached with neutrality through the use of PACS.

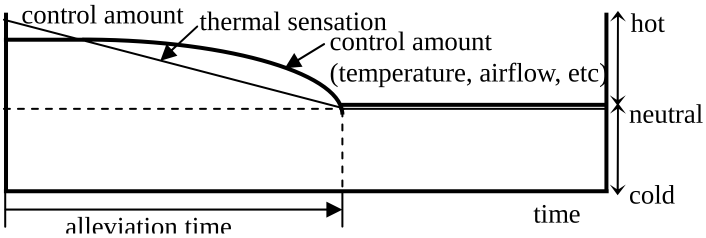

Fig.9 Definition of alleviation time

3.2.2 Outline of the laboratory experiment[3] (Fig.10)

Selected ten young healthy subjects (5 men and 5 women in their 20s) were tested in the experiment. The amount of clothing for men and women were at 0.7clo and 0.55clo, respectively.

(1) Test chamber - The experiment was performed in a thermostatic chamber (3.5m×3.0m×2.5m) located at the Institute of Industrial Science, Tokyo University. The experiment was assumed to being performed under a typical summer condition with the chamber being ventilated by the floor-supply displacement ventilation, and the ambient

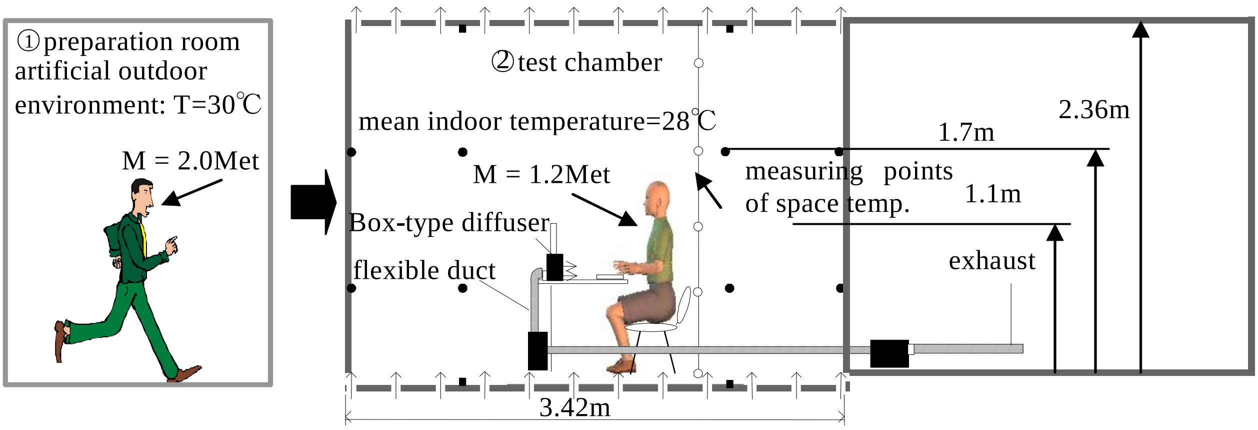

Fig.10 Concept diagram of the experiment

Table 2. Experiment Cases

Place	Preparation	Outdoor	Indoor (Experiment Chamber)		Adjustment
Time	30 min.	20 min.	20 min.	40 min.	10 min.
Task	Cloth Change, Put on Copper wire、Questionnaire (Personal recording)	Walking (up/down steps)	Doing works at Desk-top	Doing works at Desk-top	Cloth Change, Remove Copper wire
Reporting		Thermal Sensation (10 min. after)	Thermal Sensation (every 5 min.)	Thermal Sensation (every 10 min.)	
Measurement	Weight	Skin Temperature (Every 10 sec.)			Body Weight

Table 3. Methodology and contents of experiment

	Indoor Environment	Works	Clothing Level	PACS Settings
Case1	Room Temp.:28℃ Humidity : 60%RH	Content : Typing Metabolism : 1.2Met	Male : Short-sleeves Shirt with Tie Female : Short-sleeves Shirt, Skirt and Stockings	OFF
Case2				Supply Air :28℃、2.0m/s
Case3				Supply Air: 26℃、2.0m/s

temperature was being kept constant at 28℃ with its relative humidity at 60%RH.

(2) Cases examined (Table.2) - Three separate cases were being examined here. i) to investigate the subject's thermal characteristic in a summer indoor environment of 28℃, Case 1 was performed without the PACS. ii) In Case 2, the supply airflow's temperature at the PACS's outlet was also set at 28℃ to examine the alleviation effect of the thermal sensation caused by the airflow. iii) In Case3, the supply airflow's temperature was set as 26℃. In every case, the airflow was blowing horizontally at 2.0m/s, not directly onto the face of the subjects.

(3) Experiment procedure - The procedure and the contents in each period are shown in Table.3. In order to eliminate the season-acclimating effect at the time of the experiment, subjects were conditioned in the preparation room (30℃) for 30 minutes before the experiment began. They were asked to walk for 20 minutes in the preparation room first and then entered the test chamber immediately. The subjects were instructed to do manual deskwork for 60 minutes. The subjects were asked to mark down their thermal sensation level after 10th minute in the preparation room, then once every 5 minutes for the first 20 minutes and once every 10 minutes in the next 40 minutes intervals, after entering the test chamber. The 7-point ASHRAE Thermal Sensation Scale (Fig.1) was used in marking the thermal sensation in the experiment. In additional to that, the temperatures of head (T_1), upper arm (T_2), hand (T_3), leg (T_4), lower thigh

Table 4.Results of alleviation Time

	Male	Female
Case2	30 min.	15 min
Case3	10 min.	10 min

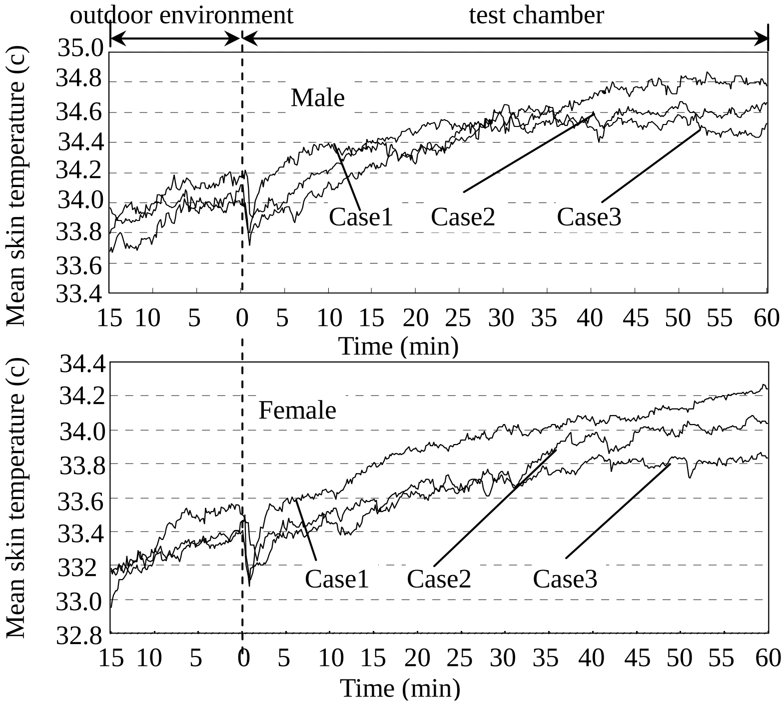

Fig.11 Fluctuation of mean skin temperature over time

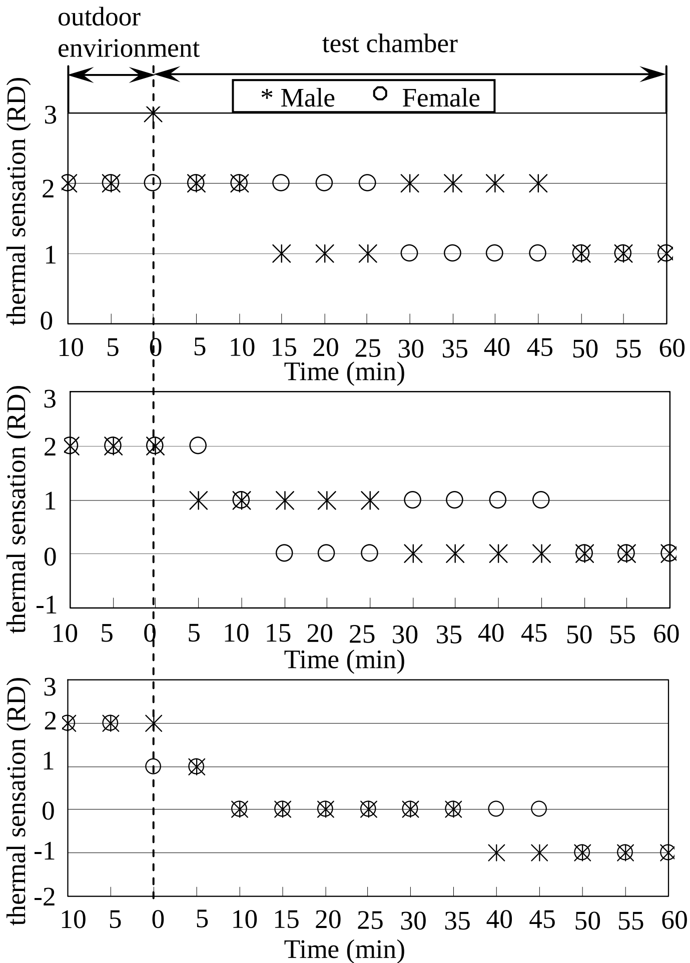

Fig.12 Fluctuation of the thermal sensation over time

(T_5), thigh (T_6) and body (T_7) of the subjects were measured at every 10 seconds intervals. The 7-points method derived from Hardy and Dubois was applied to get the mean skin temperature.

$$T_{skin} = T_1\times0.07+T_2\times0.14+T_3\times0.05+T_4\times0.07+T_5\times0.13+T_6\times0.19+T_7\times0.35 \qquad (1)$$

3.2.3 Experiment results

(1) Fluctuation of the mean skin temperature - Fig.11 shows the fluctuation of the mean skin temperature from the 5th minute after the subject entered the artificial outdoor environment. Having been subject to walking (about 2.0Mets) for 20 minutes at that thermal environment of 30℃, the subjects were perspiring when entering the test chamber, and this being the natural cooling mechanism of human body, the mean skin temperatures dropped 0.3℃ rapidly in the first 2-3 minutes. Then the mean skin temperatures rose slowly before coming to a halt at a constant temperature. Mean skin temperature was shown to be lower with the improvement of the ventilating conditions. However, the mean skin temperature of women was shown to be about 0.6℃ lower than that of men.

(2) Fluctuation in the thermal sensation - Fig.9 shows the fluctuation in the thermal sensation of the subjects in each case. For being perspiring, the subjects felt “warm” or “slightly warm” upon entering the test chamber. In contrast to the rising mean skin temperature after the subjects stopped sweating, the level of the thermal sensation became lower and it seems to be difficult for the subjects to reach thermal neutrality without the use of PACS. Together with the ventilation conditioning of PACS improved, lower thermal sensation level could be reached more quickly. In Case 3, both the female subjects and the male subjects felt “slightly cool” in the end which can be attributed to the alleviation effect of PACS.

(3) Alleviation time - The alleviation times measured in Case 2 and 3 are summarized in Table.4. The alleviation time becomes shorter along with the improvement of the ventilation conditions. In Case 2, which was with strict ventilation conditions, the alleviation time was longer, and the female subjects were able to attain the thermal neutrality first as they wore little compared to the male subjects in the experiment. In Case 3, the difference between the male and the female subjects disappeared and both the male and female subjects attained thermal neutrality in the 10th minute.

3.3 Discussion on the controlling methods for the new PACS

The sustainable controlling methods of the new PACS are being discussed here based on the results of the experiment shown above.

From the result of case 2, it indicates that the PACS can in fact helps people attain thermal neutrality in a warm ambient thermal environment of 28℃ even when it acts just as a ventilating device. But it will take longer time and the thermal sensation is unstable, especially for women whose thermal sensation always tends to be “slightly warm”, the setup in Case 2 is therefore not a preferred setting to attain thermal comfort in the office environment. Moreover, the PACS in this setting needs to be run continuously, it is not energy efficient even though the system may be set at higher temperature.

The setting in case 3, with the temperature at 2℃ lower, is considered more ideal compared to case 2 because the subjects attained the thermal neutrality in less time. But the thermal sensation of some users slowly reversed to a uncomfortably cool level and therefore a controlling method incorporating the alleviation time will help to improve the setting. In order to ensure the thermal comfort of the users, it is necessary to be able to turn on and off the PACS according to individuality to allow the body to attain thermal neutrality when necessary. Since the air-conditioning will be shut off at intervals, this can also be considered as a way to achieve energy efficiency for the PACS.

To ensure a more reliable controlling method to be used in the future development of PACS, further studies are necessary to observe the relationship between the thermal sensation of human being with respect to PACS volume control under various conditions to formulate a design database for the sustainable development of more comfortable and energy efficient PACS.

4. Conclusions

(1) In this research, the problems of the conventional PACS were examined by the results of the interviews and laboratory experiment and the outline for the designing of the energy-saving PACS was proposed.

(2) A new personal air-conditioning unit designed according to the above proposal was introduced.

(3) Three cases of laboratory experiments were performed to verify the thermal alleviation effect of the new PACS. It indicates that the new PACS can help the users to attain the thermal neutrality merely through ventilation. Moreover, in Case 3, both male and female subjects can attain their thermal neutrality within 10 minutes.

(4) The sustainable controlling method for the new PACS was discussed. Being able to switch on/off the new PACS at individual level can be considered a good method to ensure thermal comfort while achieving energy saving.

(5) Further researches to study the responses of human body's thermal sensation in various air-conditioning conditions are necessary to come out with a database to be used as the design guideline for a more sustainable and efficient controlling protocol of the new PACS.

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