Future Direction of Microclimate Evaluation in Clothing

Toshinari NAKAJIMA

Department of Practical Sciences, Graduate School of Practical Sciences, Showa Women's University
1-7-57 Taishi-do, Setagaya-ku, Tokyo 154-0004

ABSTRACT

Non-steady state microclimate change in clothing provides significant information regarding wearing comfort. This paper comprises numerical analysis of clothing microclimate next to skin, development of a new type of sweat capsule and frequency analysis of perspiration, and damp and stuffy sensation and wet sensation through our studies on clothing microclimate in the non-steady state.

Key words : clothing microclimate, perspiration, wet sensation

1. INTRODUCTION

It is said that engineering focusing on humans will develop in the 21st century. Of course, it is likely that material science and engineering will show great advances in the next century. At the same time, scientists who deal with the relationship between humans and materials will play an increasingly important role. In this sense, clothing scientists are expected to make a great contribution in the next century.

When we attempt to make a computerized numerical analysis of the features of clothing users, we face a shortage of reliable data. Concerning heat and moisture transfer, there is a shortage of data : (1) the relationship between the kind of cloth and heat or moisture transfer, (2) the relationship between the shape of clothing and heat or moisture transfer, (3) the relationship between the method of wearing clothes and the transfer of heat and moisture, (4) points which need attention when studying humans as subject, and (5) the relationship between physical stimuli and perception. To state it more concretely, data is insufficient concerning : (1) the heat transfer coefficient and the mass transfer coefficient of the interface between the clothing wearer and the environment, (2) the amount of heat and moisture transferring from parts of clothes such as the collar, sleeves, skirts, the lower part of pants, etc., (3) adaptation and other response of the body (a source of heat and moisture) to the outer environment, and (4) non-steady state coefficients of the transfer of heat and mass.

Through our studies on clothing microclimate in the non-steady state, numerical analyses of clothing microclimate next to skin, development of a new type of sweat capsule and frequency analysis of perspiration, and damp and stuffy sensation and wet sensation, my opinion about research on clothing science should be introduced with a new tide of "kansei engineering" which is a new term in Japan.

2. CLARIFICATION OF THE PHENOMENA OF HEAT AND MOISTURE TRANSFER FROM THE BODY THE TO THE OUTER WORLD

Comparison of clothing materials seems simple, but it is actually very difficult. It is not reasonable to say that the moisture permeability of cotton is higher than that of polyester, just on the grounds that it is higher in clothes made from cotton than in clothes made from polyester. The observed differences between different items of clothing do not necessarily reflect differences in the nature of their raw materials. For example, when the strength of two wires is to be compared, the shape and area of the cross-section must be identical in the two wires. Otherwise, a comparison between the raw materials of which the two wires are made is not possible. The same can be said of textiles. In the case of natural fibers such as wool, cotton and silk which are used as the raw materials of clothing, it is not possible to compare these materials using specimens with the same cross-sectional shape and area. When polyester fibers of the same weight are compared, finer fibers in diameter can block air more effectively and have much greater surface areas than do fibers with a larger size of the same weight. As a result, air friction increases, and air convection is less likely to occur. Thus, the heat-insulating property of ultra-fine fibers is higher. Furthermore, as the size in diameter of fibers decreases, capillary phenomena begin to exert greater influences. In this way, fabrics with ultra-fine fibers feel comfortable and have high heat-insulating properties. The water-absorbing capacity of the fabrics becomes either extremely high or extremely low as fibers decrease in size. Ultra-fine fibers have a disadvantage in that they are likely to become flat when exposed to water. Even identical fibers undergo such marked changes in their properties depending on their size in diameter ; it is difficult to attribute a given difference in the properties of two items of clothing made of different materials to differneces in raw materials or shapes of the clothing. According to current knowledge, the heat-insulating properties of clothing are closely related to the shape of the fiber and are not related to the chemical structure of the raw materials. However, the properties of clothing when exposed to water are determined largely by the chemical structure of their raw materials.

In our studies comparing different raw materials used in clothing, the subjects wore one item of clothing over another, or clothes composed of two layers. I also designed a special artificial climate room, in which wind blows up from the entire floor and exits from the entire ceiling. When the time course of skin temperature of a thermoregulative functional model of a man (a life-sized copper dummy) was measured in this room, there was no time course difference between the right and left sides. In addition, we designed a laboratory with double walls, considering the possible influence of radiated heat. Indoor air was circulated in the space between the two walls of this room to keep the wall temperature the same as the room temperature. I believe that reliable data cannot be obtained without paying such special attention to the experimental environment.

3. NON-STEADY STATE CLIMATE IN CLOTHING

During repeated experiments on clothing, I paid attention to non-steady state climate in clothing. A sensor was placed within the clothing, and the humidity measured when a female suject wearing the clothing did desk work. Fig. 1 shows that the subject perspired intermittently (Shigaki 1993). Following this study, we prepared a microclimate simulator capable of meauring the temperature on the cloth surface facing the human skin, as shown in Fig. 2. Using this instrument, we studied microclimate in clothing during light work, by measuring the temperature on the skin-facing surface of cotton, polyester and polyethylene film specimens, with an infrared radiation thermometer. If the subject wore an item of clothing made from cotton over another item made from polyester, as shown in Fig. 3-2, it was possible to measure the temperature of the polyester surface. If the subject wore an item made from polyester over another item made from cotton, the temperature of cotton surface could be measured as shown in Fig. 3-1., without changing the heat-insulating effect compared to the case shown in Fig.3. When the humidity was changed slowly, the cotton surface temperature differed little from the polyester surface temperature, as shown in Fig. 4. However, when the humidity was changed rapidly, a marked difference was noted between cotton and polyester surface temperatures. Fig. 5-1 and 5-2 show that the change in cotton surface temperature was greater than the change in polyester surface temperature. Fig. 6 is a graphic representation of this difference. In this figure, the cloth temperature increase rate was plotted against the hmidity change rate. Open circles indicate cotton, and closed circles indicate polyester. The rise in temperature was greater for cotton than for polyester. Hensel reported that the subject felt neither warm nor cold when a small cutaneous area (e. g. 20 cm^2) was

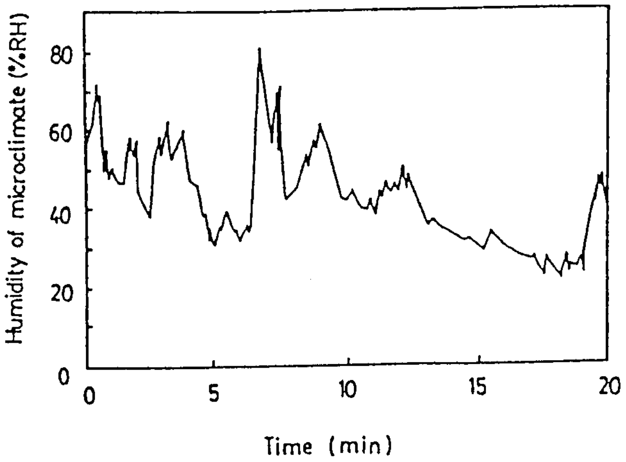


Fig. 1 Humidity fluctuation of microclimate of a female subject

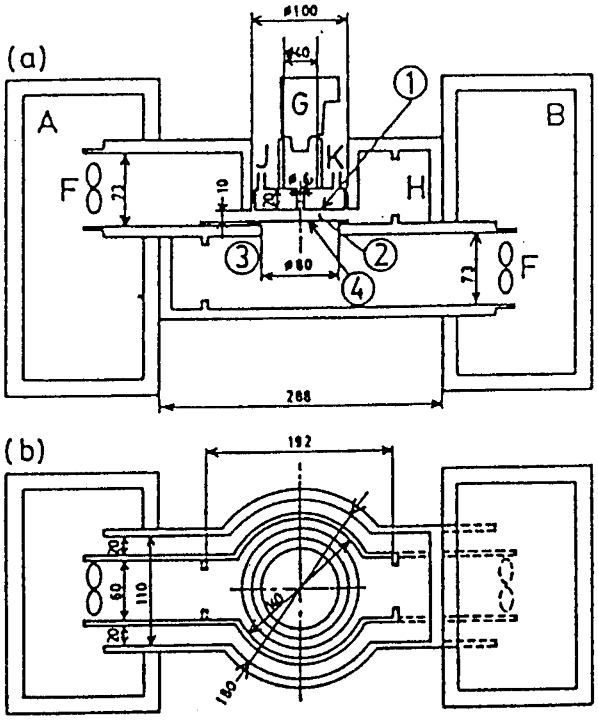


Fig. 2 Sectional and top views of the simulator : (a) sectional view, (b) top view, ① model skin, ② microclimate next to skin, ③ ambient environment, ④ sample fabric, A, B) climate chambers, F) fans, G) radiation thermometer, H) temperature and humidity sensors, J) water inlet, K) water outlet

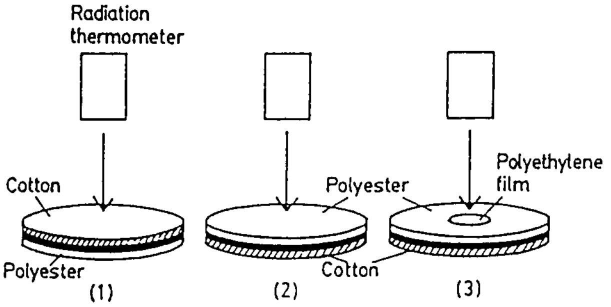


Fig. 3 Measurement of the surface temperature of the sample fabrics

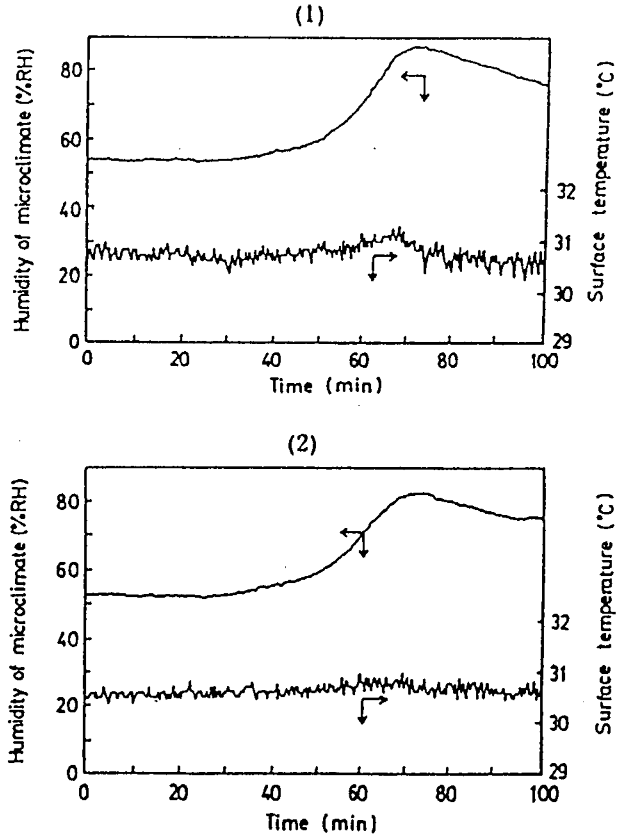


Fig. 4 Temperature change on the surface in the case of moderate humidification and dehumidification of the microclimate :
(1) cotton fabrics, (2) polyester fabrics

adapted to a temperature of 34°C. Linear warming from this point of indifference led to warm sensations, linear cooling to cold sensations. The more the threshold of warm or cold sensations deviated from this point, the slower the temperature had changed. By plotting the rate of change versus the thermal threshold, a hyperbolic function was obtained (Hensel 1952). Similar results have been found by Kenshalo, *et al.*, (1968). These studies revealed that the subject could perceive even a 1°C or smaller change if the change was sudden, but that the subject did not perceive even a 5°C or greater change if the change was slow. This result indicates that the threshold temperature difference for skin temperature perception decreases as the change in temperature becomes more rapid. The observed rapid changes of cotton surface temperature probably affect clothing comfort greatly through their effect on temperature perception.

This kind of phenomenon is unlikely in a steady state. When discussing climate in clothing, we must consider changes in a non-steady state or transitional state. Thus, I measured non-steady state climate in clothing, using two methods.

4. NUMERICAL SIMULATION OF CLIMATE IN CLOTHING

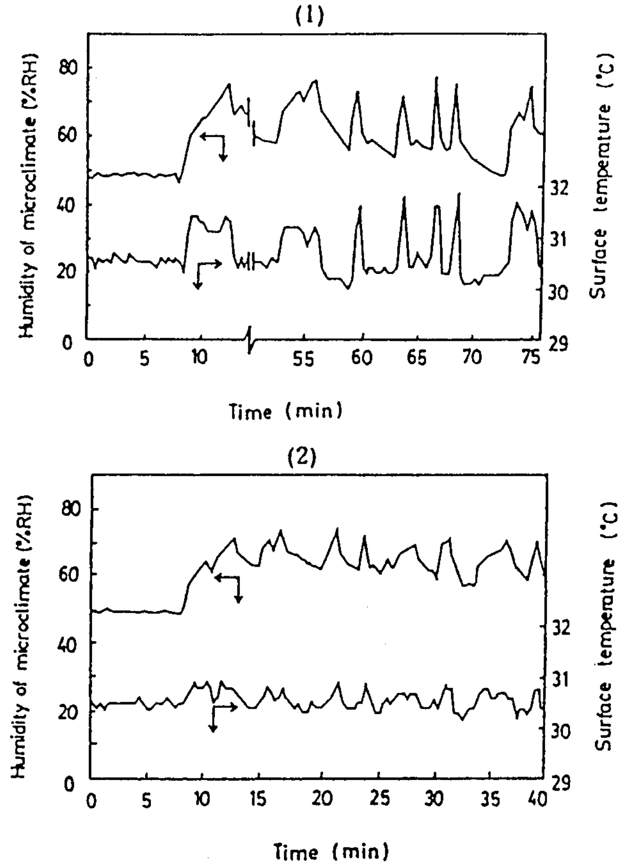


Fig. 5 Temperature change on the surface in the case of rapid humidification and dehumidification of the microclimate :
(1) cotton fabrics, (2) polyester fabrics

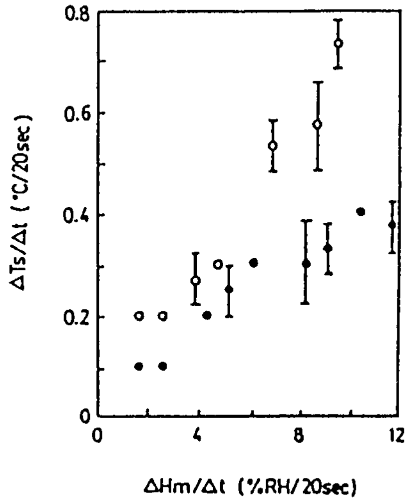


Fig. 6 Increasing rate, ΔTs/Δt, of the surface temperature of the fabrics plotted against increasing rate, ΔHm/Δt, of the microclimate humidity :
(○) cotton, (●) polyester

Now, I should present an experiment reported by Chu Mi-Seaon (Chu 1994). A functional model of man, wearing polyvinyl chloride clothing was used. After the air within the clothing was completely replaced with nitrogen, air was supplied via the sleeve opening. At the same time, a computerized numerical analysis of heat and mass transfer was started, using the continuity equation, the equation of Navier-Stokes, the energy equation and the diffusion equation. Fig. 8 compares the actually measured oxygen level and the calculated oxygen level for each site.

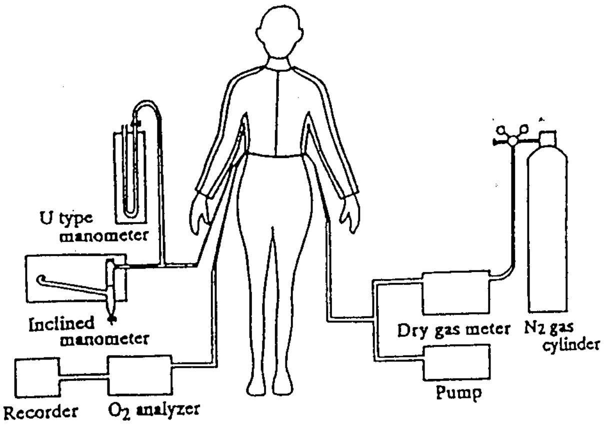


Fig. 7 Schematic illustration of the apparatus for measuring the clothing microclimate

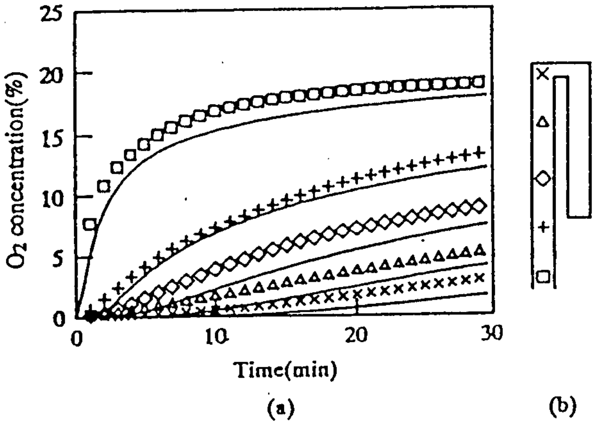


Fig. 8 Change in O_2 concentration within the microenvironment when the cuffs were opened ; experimental (□ : wrist, + : forearm, ◇ : elbow, △ : upper arm, × : shoulder, calculated (—))

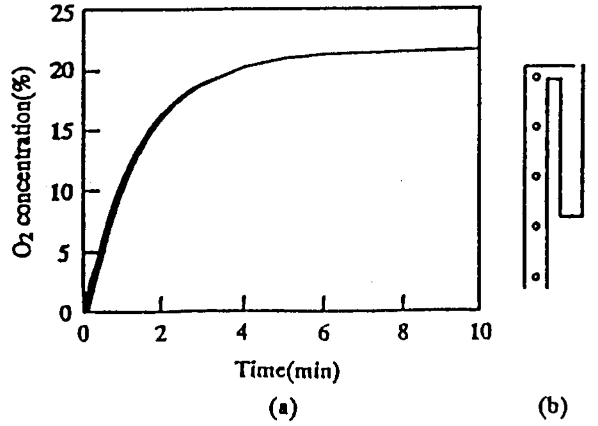


Fig. 9 Change in O_2 concentration within ghe microenvironment at different positions of the upper limb

This simulation was easy. Then, Ms. Chu opened both the sleeve and the collar. This resulted in a smaller difference in oxygen level among different sites, identical to the experimental results. She also studied how the features of convection would change as the space between skin and clothing was progressively reduced from 5cm to 0.5cm. As shown in Fig. 10, little convection occurred when the space was 5 mm. Furthermore, she prepared an apparatus as shown in Fig. 11 for visualization of clothing microclimate using holographic interferometry. Fig. 12 shows a picture in which changes in water density represent changes in temperature. Stripes are visible in this figure. Numerical calculation of the data yielded similar results as shown in Fig. 13. In her study, the calculation was performed by the system of vorticity and stream function. Fig. 14 shows an example in which another calculation method called MAC was used. This shows the distribution of temperature. When convection in clothing climate was calculated at intervals of one-ten thousandth of a second, beginning immediately after the collar and sleeve were opened, a steady state was seen 240 seconds later. Fig. 15 shows the distribu-

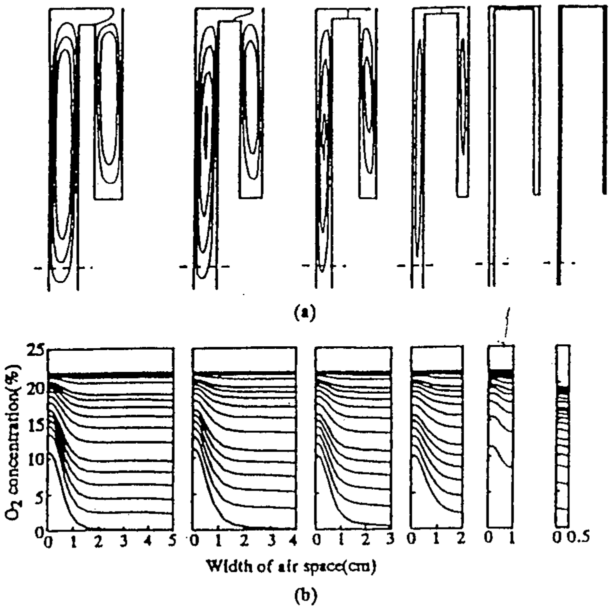


Fig. 10 Differences among the flow patterns and among the changes in O_2 concentration due to the variation in the air space thickness

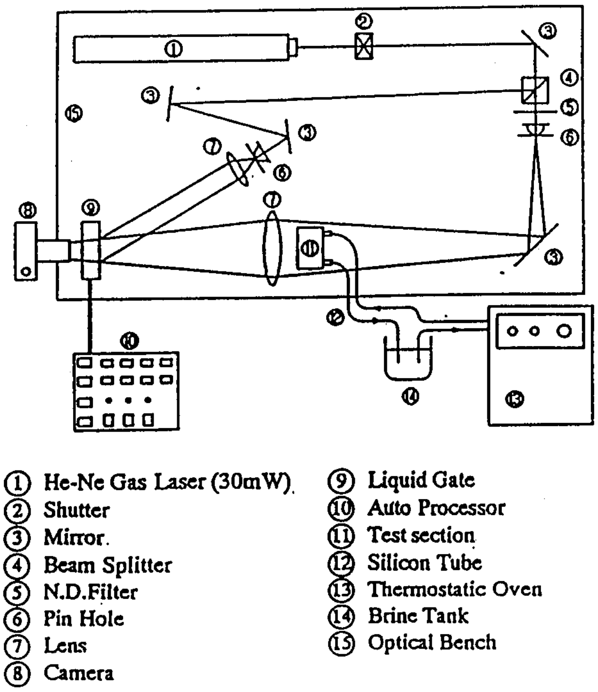
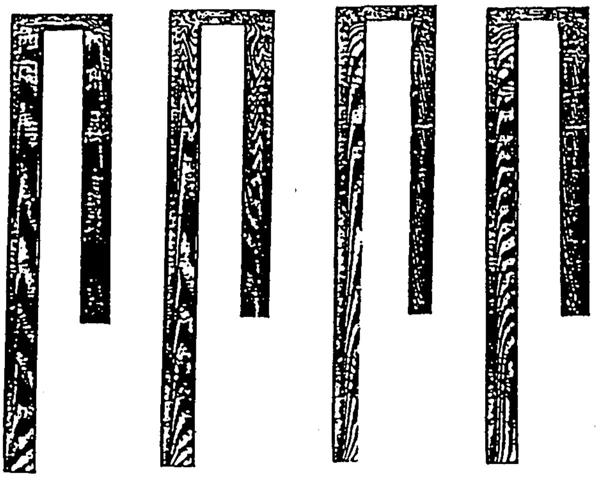


Fig. 11 Schematic diagram of real time holography inter.



(a) 10sec (b) 30sec (c) 100sec (d) 1800sec

Fig. 12 Holography interferogram (temperature field) ; temperature difference = 5°C

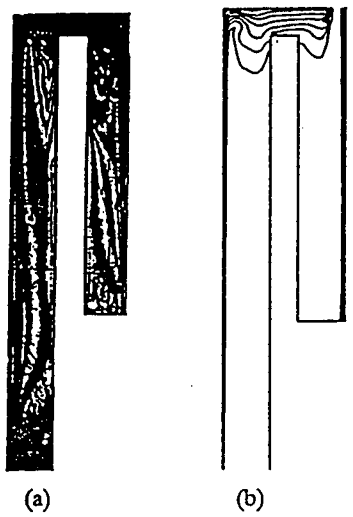
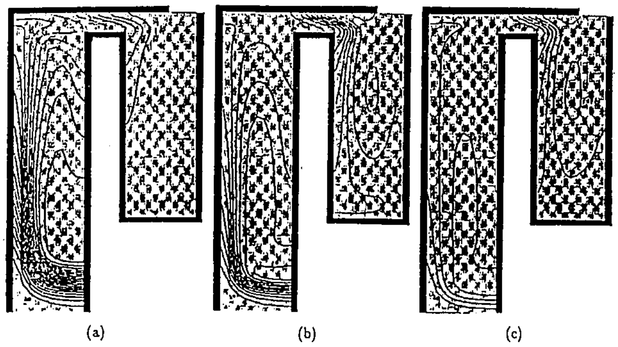
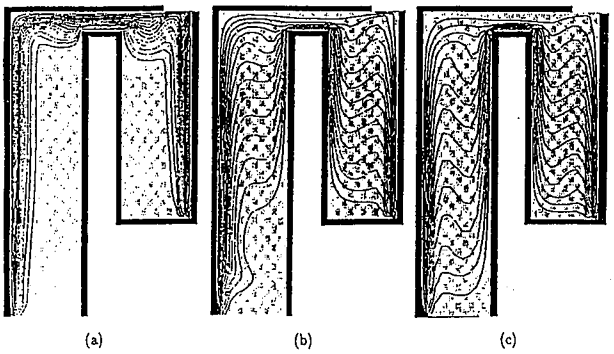


Fig. 13 Comparison of the experiment result with the calculation one



酸素濃度分布：(a)10*sec* (b)30*sec* (c)60*sec* ($\Delta C^* = 1\%$)

Fig. 14 Temperature distribution of microenvironment next to skin



温度分布：(a)2*sec* (b)10*sec* (c)240*sec* $T_a = 27.22$ ℃

Fig. 15 Oxygen concentration of microenvironment next to skin

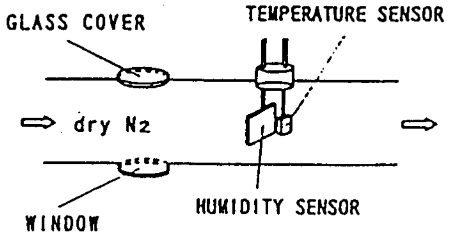


Fig. 16 Temperature and humidity sensors

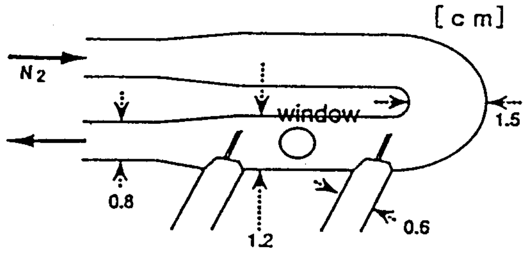


Fig. 17 A sketch of a new type of temperature and humidity indicator

tion of oxygen level. Immediately after the collar and sleeve were opened, air flowed in. It was also found that opening the collar produced a chimney effect, causing a rapid increase in air flow from the sleeve along the skin. Although a one-dimensional numerical calculation has been reported by other research groups, I believe a two-dimensional numerical calculation, as we did, is more useful because it allows visualization of convection in clothing climate. In this way, computerized simulation allows estimation of short-lasting changes which cannot be analyzed in experiments.

5. DEVELOPMENT OF A SWEAT CAPSULE AND FREQUENCY ANALYSIS OF SWEATING

We attempted to clarify clothing climate using another method. A sweat capsule with a amall time constant was prepared for observation of sweating behaviors in a group of subjects different form the previous group. A sweat capsule as shown in Fig. 16 was devised to examine sweating (Nakajima 1993, 1995), because measurement of the temperature within clothing did not yield detailed information. Sweating was recorded on video tape under a microscope. At the same time, the sweating rate was quantified. The capsule has been modified many times. At present, the modified version as shown in Fig. 17 is used. Fig. 18 shows how the capsule is used. An apparatus as shown in Fig. 19 was prepared to check how sensitive-

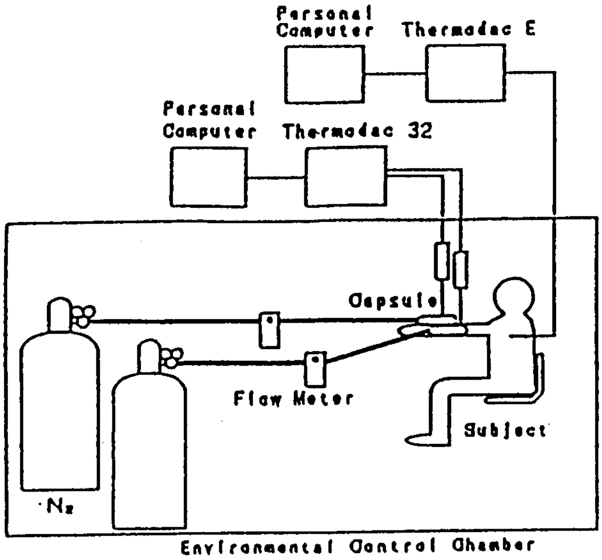


Fig. 18 A sketch of an experiment for the measurement of the local sweat rate

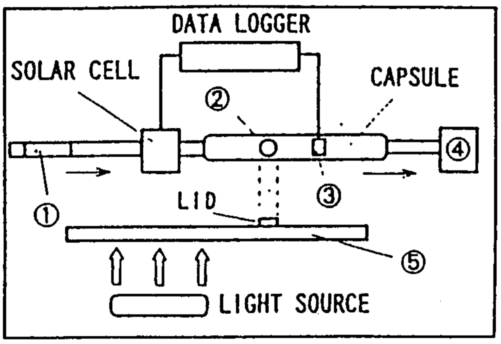


Fig. 19 Measurement of response speed of the humidity sensor
① silica gels, ② window, ③ temperature and humidity sensors, ④ fan, ⑤ shield plate

ly this sensor can measure. The time constant was measured, data was collected at intervals 5 times as long as the time constant, and frequency analysis of sweating was carried out. In this way, we detected fluctuation in the sweating cycle. The Power spectrum was plotted against the frequency on a full-logarithmic scale to yield a graph as shown in Fig. 20. The gradient was-1, indicating 1/f fluctuation.

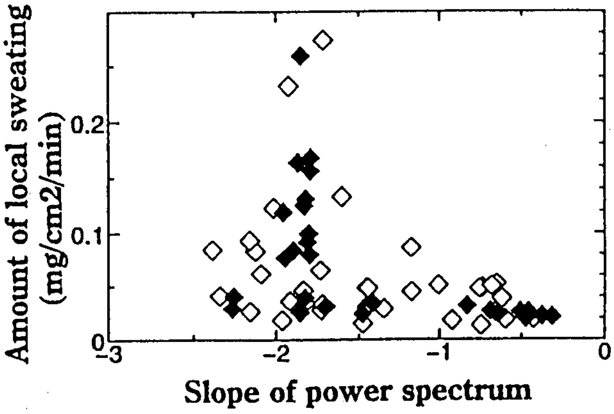


Fig. 21 Sweat rate and fluctuation of sweating cycle
◇ : under thermal stress, ◆ : under exercise

The importance of 1/f fluctuaton has been reported by prof. emeritus Toshimitsu Musha of the Tokyo Institute of Technology. During our first frequency analysis, cotton and silk showed 1/f fluctuation, while polyester did not show it. On the basis of this result, we thought it likely that there are two types of sweating, comfortable and uncomfortable sweating. When we repeated experiments, it was found that polyester also sometimes shows 1/f fluctuation, and that the 1/f fluctuation becomes distorted when sweating does not occur smoothly. Fig. 21 shows the latest data. The amount of sweat was plotted against the gradient I have stated previously. This analysis revealed that the gradient was about -2 when the amount of seeat was large. At present, we are attempting to classify sweating using wavelet analysis.

6. CLARIFICATION OF THE HOT, STUFFY FEELING AND THE WET FEELING

No humidity receptors have been identified on human skin. It has been suggested that some animals, such as cockroaches, have such receptors. Does this mean that cockroaches are more advanced than human beings? What receptors perceive stimuli lead-

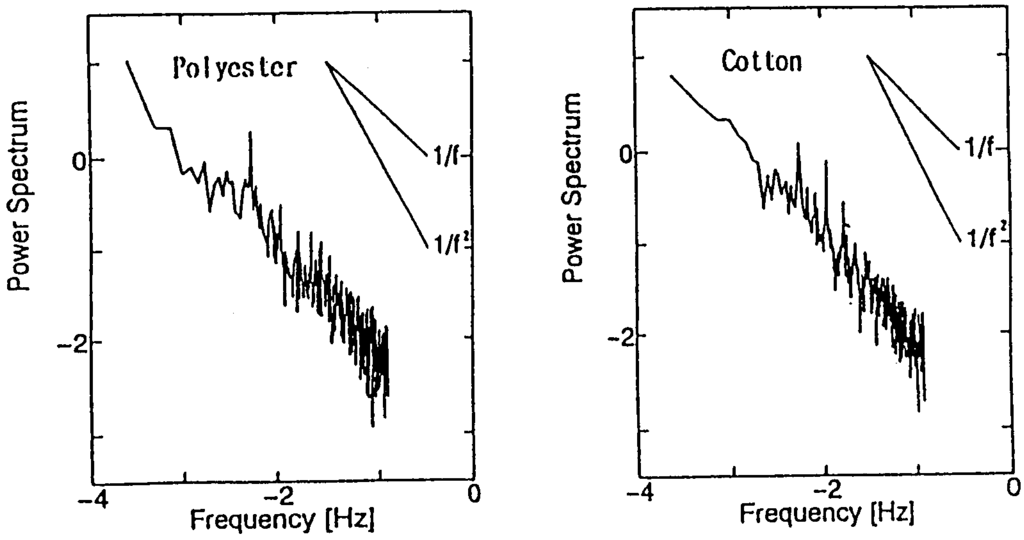


Fig. 20 Power spectrum of local sweat rate at 33°C

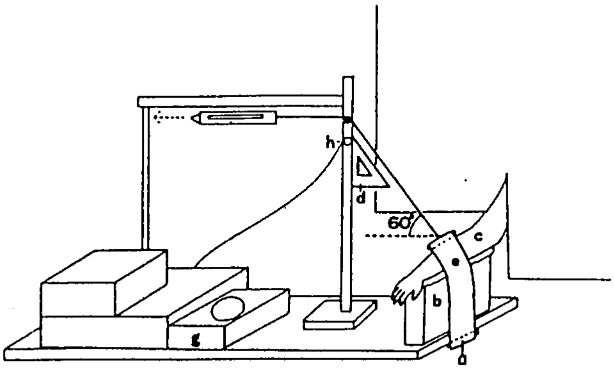


Fig. 22 Experimental apparatus
a : curtain, b : stand, c : right arm of the subject, d : set square, e : sample, f : spring balance, g : electronic balance, h : thermometer and hygrometer

ing to the "hot, stuffy" felling or the "wet" feeling? To examine whether relative humidity or absolute humidity is perceived by human sense, we created two different environments in an artificial climate room. In one environment, the absolute humidity was changed, while the relative humidity was kept constant. In the other environment, the relative humidity was changed, while the absolute humidity was kept constant. In these different environments, we measured the friction coefficient and the wet feeling when the cloths with varying water contents were pulled. At the same time, the friction coefficient of an arm model made from synthetic leather was also measured. The results of this experiment suggest that humans perceive absolute humidity rather than relative humidity. Although no scientific definition of the wet feeling or the hot, stuffy feeling is available, we found that these feelings can be explained well when they are represented three-dimensionally in combination with the feeling of compression and the warm and cold feeling (Ushioda 1995 a).

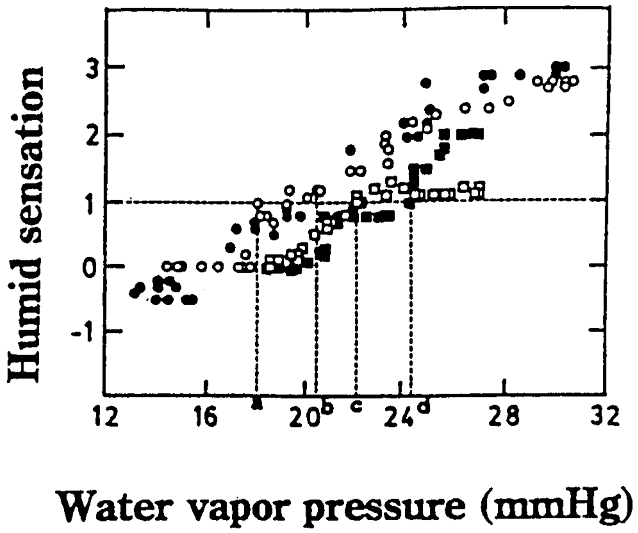


Fig. 23 Relationship between humid sensation and ambient vapor pressure
○ : experiments of rising in temperature
● : experiments of dropping in temperature
□ : experiments of rising in humidity
■ : experiments of dropping in humidity

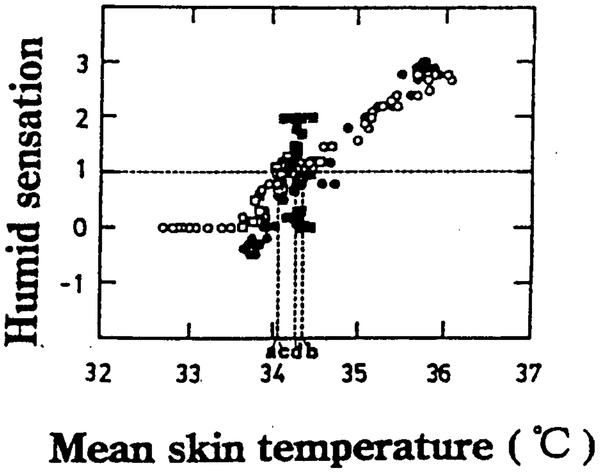


Fig. 24 Relationship between humid sensation and mean skin temperature
○ : experiments of rising in temperature
● : experiments of dropping in temperature
□ : experiments of rising in humidity
■ : experiments of dropping in humidity

Concerning the hot, stuffy feeling, we found that this feeling began to be perceived when the average skin temperature rose to about 34°C. This feeling seems to appear immediately before sweating begins. The temperature at which this feeling began to be noted remained constant in experiments at varying conditions. As shown in Fig. 23, the hot, stuffy feeling appeared at lower steam pressure levels when the humidity was elevated rapidly than when it was elevated slowly (Ushioda 1995 b). This means that, like the case concering temperature reported by Hensel (1952), changes in humidity can be perceived more sensitively when humidity changes rapidly.

On the basis of these experimental results, we may explain the wet feeling as follows. If the skin is exposed to water and the droplets move on the skin, the friction coefficient of the cloth increases, and the sweat evaporates, stimulating the mechanical receptors (Pacinian corpüscle and Merkel's tactile disk) to produce the wet feeling. The hot, stuffy feeling probably represents a condition where although the body temperature has risen, sweating cannot occur because of the high humidity around the skin, resulting in further increase in body temperature. This feeling therefore seems to involves heat receptors.

7. CONCLUSION

If fluctuation is pleasant to people, this can be provided by varying the fineness of fibers, surface irregularities of woven cloths, color changes, and designs. Although these features were previously the province of art, they deserve to be reviewed from the viewpoint of engineering. I would like to call this field Kansei Engineering, the study of the individual as a consumer, using the methods of natural sciences such as engineering.

If wearing clothing is a behavior motivated by a desire for comfort, the 1/f fluctuation will contribute to the optimal selection of clothing.

REFERENCES

Chu, M. S., T. Kato, Y. Kamata, & T. Nakajima (1994), Experimental and Numerical Analyses of Clothing Microclimate (1) Thickness Effect of the Air Layer on the Microclimate within the Space between a Human Body and the Clothes, *J. Fiber Science & Technology*, Japan, Vol. 50, (No. 7) 298-305.

Hensel, H. (1952). Physiologie der Thermoreception, *Ergebn. Physiol.* 47, 166-368.

Kenshalo, D. R. (1968). Behavioral and electrophysiological responses of cats to thermal stimuli. In "The Skin Senses" (D. R. Kenshalo, Ed.), pp400-422. Thomas, Springfield, Ill.

Nakajima, T., N. Susuki, H. Yamano, & Y. Kamata (1993), A New Apparatus for the Measurement of Local Sweat Rate, *J. Fiber Science & Technology*, Japan, Vol. 49, (No. 10) 556-558 (1993)

Nakajima, T., N. Susuki, N. Tsuchiya, J. Hoshi, H. Yamano & Y. Kamata, (1995b), A New Apparatus for the Measurement of Local Sweat Rate, Bulletin of the Doctoral Research Course in Human Culture, Ochanomizu University, Vol. 19, 244-253 (1995)

Shigaki, M., Y. Niki, K. Nishizawa, H. Ushioda, T. Nakanishi & T. Nakajima (1993), Effect of Hygroscopic Fabrics on Wear Comfort in the Fluctuating Microclimate of Clothing. *J. therm. Biol.*, Vol. 18, (No. 5/6), 429～434.

Ushioda, H., T. Nakajima, (1995a), Sensory Evaluation of Soaking Sense by Using Natural Fiber Fabrics, *J. Japan Research Association for Textile End-Uses*, Vol. 36, (No. 1) 44-52.

Ushioda, H., A. Aoki, & T. Nakajima, (1995b), Evaluation Factors of Damp and Stuffy Sensation, *J. Japan Research Association for Textile End-Uses*, Vol. 36, (No. 1) 162-164.

(Received May 8 1998, Accepted June 25 1998)