EFFECT OF SWEAT ACCUMULATION IN CLOTHING ON TRANSIENT THERMOPHYSIOLOGICAL RESPONSE OF HUMAN BODY TO THE ENVIRONMENT

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ABSTRACT

The experiments involving clothed subjects are conducted to reproduce the situation in which people enter an air-conditioned room just after sweating, and analyzed using a combined model, which consists of two-node model for thermophysiological response of human body and simultaneous heat and moisture transfer model for thermal and hygric behavior of clothing. The experimental and calculated results of the skin temperatures, the clothing temperatures and the weight are compared. By tuning the parameters related to the moisture transfer in and around the clothing, a quantitative grasp of the characteristics of the moisture behavior during the process is tried in the analysis.

INTRODUCTION

In an environment where body temperature cannot be regulated without a lot of sweating, we often try to get rid of heat from our body by turning on the air conditioning systems or moving into a conditioned room. Just after the change of the environment, we will feel 'cool' or 'comfortable'. But the sweat accumulated in clothing evaporates gradually, until the heat loss from our body can be more than needed and at last we might feel 'cold' or 'uncomfortable'. Is this situation proper for our health? Isn't there any better way of controlling the environment? In order to clarify this problem, it is necessary to investigate, first of all, the thermophysiological response of human body to an environment taking into account moisture accumulation in clothing. In other words this problem should be treated as a non-steady state problem.

A lot of studies have been made on human thermal sensation and thermal comfort, but most of them discuss only steady state and treat clothing just as a resistance to heat and moisture transport (ASHRAE, 1997). Very few studies consider the moisture capacity of clothing. Experiments in which subjects are exposed to thermal transient conditions have been conducted (Hardy et al., 1966; Takemori et al., 1995). The sweat rates and evaporation rates under heat stress have been measured (Kakitsuba et al., 1997). These studies are for unclothed subjects and there are few measurements for clothed subjects or for the temperature of clothing itself. Heat and moisture transfer between the skin and the clothing has been investigated from various viewpoints (Mochida et al., 1977; Farnworth, 1986; Lotens et al., 1995). The relation between the physiological response of human being and the non-steady characteristics of the clothing has not been fully clarified in their studies. Jones et al. (1992) have studied the non-steady state characteristics of the heat and moisture transfer between the human body and the ambient. However, in that study, the moisture transfer in and around clothing is not investigated enough in a real situation.

In this study, so as to clarify the effect that moisture accumulation in clothing has on the physiological response of human body in the transient state, we conducted experiments involving clothed subjects to reproduce the situation in which people enter an air-conditioned room just after sweating, and at the same time, analyzed the experimental results by making use of a combined model, which consists of two-node model for thermophysiological response of human body (Gagge et al., 1971; Jones et al., 1992) and simultaneous heat and moisture transfer model (Matsumoto, 1984) for thermal and hygric behavior of clothing. A quantitative grasp of the effects the sweat accumulation has on the human body is tried in as real a situation as possible.

EXPERIMENT

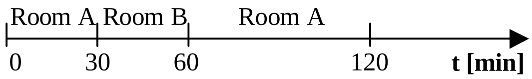
Procedures

Table 1 Physical Data on Subjects

No.	Date	Subject	Age	Weight [kg]	Height [cm]
1	Sep. 2	M	22	58	178
2	Sep. 3	N	22	65.5	179.5
3	Sep. 4	H	23	65.8	174.3
4	Sep. 8	M	22	58	178

The subjects were three university students in good health. A series of experiments from No.1 to No.4 were carried out in the laboratory of Kyoto

University in September, 1998. The physical data on the subjects are listed in Table 1, and the schedule of a single experiment is shown in Figure 1.



25	35	25	**Air temp. [°C]**
50%	90%	50%	**Relative humidity[-]**
0.1-0.3	<0.1	0.1- 0.3	**Wind velocity [m/s]**
seated	seated	seated	**Activity**

Figure 1 Schedule of an experiment along with the ambient conditions

Table 2 Measured items

Clothed skin temperature (Shoulder, chest, back)
Clothing temperature (Shoulder, chest, back)
Unclothed skin temperature (Forearm, thigh)
Armpit temperature
Tympanic temperature
Weight of a clothed man
Room air temperature and relative humidity
Room air wind velocity
Room globe temperature
Weight of the T-shirt (measured only at t=0, 120)

Two climate chambers (called 'Room A' and 'Room B') were used. At t=0[min], a subject enters Room A, controlled to 25°C and RH 50%, and wears a T-shirt for the experiment. The attachment of sensors is finished in 15 minutes and the measurement is started at t=15. After 30 minutes the subject moves into Room B, controlled to 35°C and RH 90%. After 30 minutes stay in this room, he returns to Room A and stays there for 60 minutes. During the experiment, the items listed in Table 2 are measured and recorded every minute from t=15 to 120. The subject wears a half-sleeved T-shirt and trunks. The T-shirt (material: cotton 100%, color: white, weight: 104 to 118 g) is prepared by the experimenter, which has been laid in Room A more than 30 minutes before the experiment so that the moisture content of the T-shirt equilibrates with the condition of the air in Room A. Just before the experiment starts, it is weighed. The weight is compared with that at t=120 in order to check the accumulation of moisture in the clothing. In measuring the skin and the clothing temperatures, T-typed thermocouples (0.2mm in diameter) are used and attached with tape. As for the armpit temperature, in addition to attachment with tape, the subject is asked to push his upper arm against the torso and never to release it during the experiment. The tympanic temperature is measured by making a sensor of a thermocouple probe covered with a soft cotton ball (Mon-a-therm) touch the tympanic membrane. The clothed skin temperatures are measured just under the measuring point of the clothing temperature. The clothing temperature is measured at the outer surface of the clothing. In experiments Nos. 2 to 4, the thermocouples are sewn to the T-shirt and also attached with tape. In Room A, the subject is seated on the chair on an electronic scale (Mettler Toledo KCC 150). The data on weight are obtained only in Room A. The room air temperature and relative humidity are measured with thermo-hygrometer (T&D TR-72) .

Experimental results

A part of the experimental results of Experiments Nos.1 to 4 are shown in Figure 2. The skin and the clothing temperatures at the shoulder and the unclothed skin temperatures at the forearm and thigh are shown for each experiment.

1. Sweating process in Room B (t=30 to 60)

The air-conditioning system of Room B could not be controlled accurately, so the conditions of the room air fluctuated around 35°C and RH 90%. A sharp decrease in temperature and humidity ratio is seen just after t=30 due to an exchange of air caused by the entrance of the subject and the experimenters.

In most cases, the clothing temperatures rise sharply just after entering Room B, show sharp rises again 8 to 12 minutes after the entrance, and then decrease gradually in the latter 15 minutes towards the skin temperatures at the same points. The peak temperature of each sharp rise ranges from 35 to 38 °C, which is higher than both the ambient air and the skin temperature in most cases. This shows these sharp rises are due to adsorption of moisture from the ambient air or the skin in the clothing. The first sharp rise is caused by the movement into Room B. The second sharp rise can be explained by assuming an increase in the vapor adsorption from the skin to the clothing caused by an increase in sweat rate; Many dew-drops of sweat were observed on the skin surface around t=40. If the increase in vapor adsorption from the skin causes this sharp rise, an air layer should exist between the skin and the clothing and little sweat moves to the clothing as a liquid drop. Owing to the increase in sweat rate, the sweat begins to remain on the skin surface as liquid drops, and it brings the skin in contact with the clothing. This contact is usually observed often after t=45. Once they contact each other, their temperatures become closer, since the thermal conductance between them becomes larger.

2. Evaporation process in Room A (t=60 to 120)

In all cases, the unclothed skin temperatures show a sharp decrease during t=60 to 67. In most cases, a temperature increase of 1 to 2 °C follows this sharp decrease and, after that, the temperature remains almost constant at 30 to 34 °C after t=80 at latest.

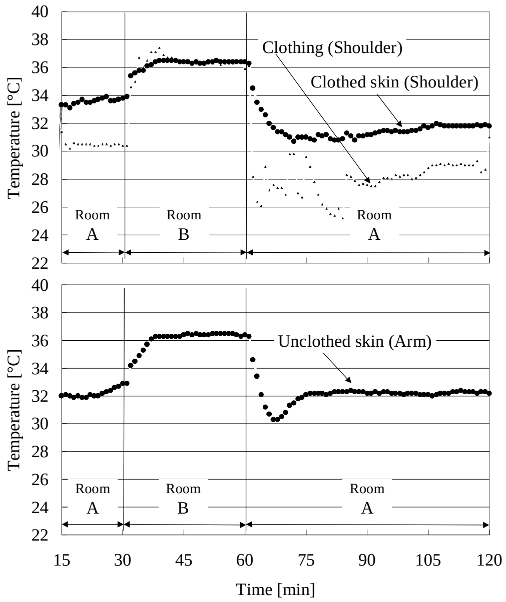


Figure 2-1 Experimental Data (Exp. No.1)

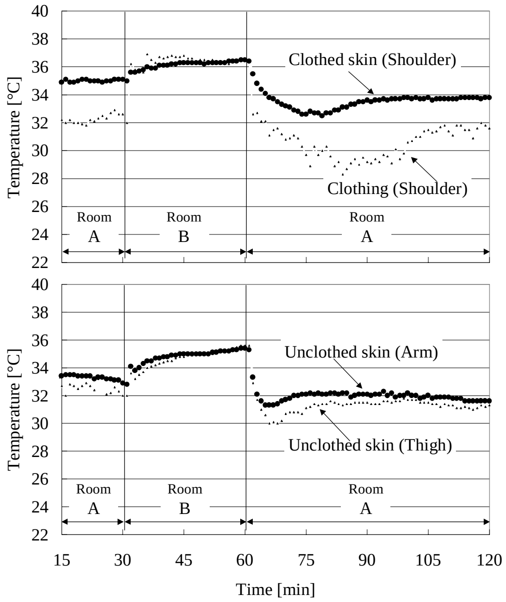


Figure 2-2 Experimental Data (Exp. No.2)

In most cases, the clothing temperatures first decrease to 25 to 29 °C and then increase to 28 to 32°C again. The time when they assume the minimum value is different from experiment to experiment and also from place to place on the body. Among the three measurement points, the clothing temperature at the shoulder tends to take the minimum value quickly. This is mainly because the moisture accumulation in the clothing or the skin at the shoulder is less than that at other parts of the body. From the visual observation, little wetting in the clothing are found at the shoulder, while a lot of wetting is detected at the chest. In addition, in experiment No.4, where the total amount of sweat was much less than any other experiment because of the lower temperature control in Room B, the clothing temperature at every part assumes the minimum value sooner compared with the other experiments.

The temperature difference between the skin and the clothing at the same point on the body is smallest at the shoulder, except in experiment No.3, in which it is smallest on the back. It may be explained by assuming that the more widely the clothing contacts the skin, the larger the heat conductance between the skin and the clothing is and the smaller the temperature difference is.

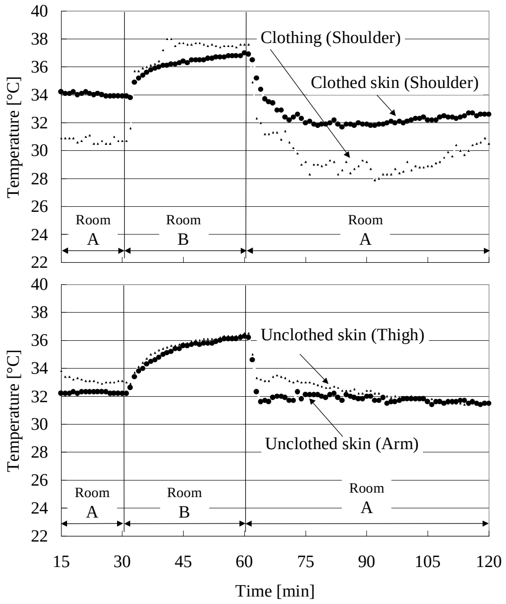


Figure 2-3 Experimental Data (Exp. No.3)

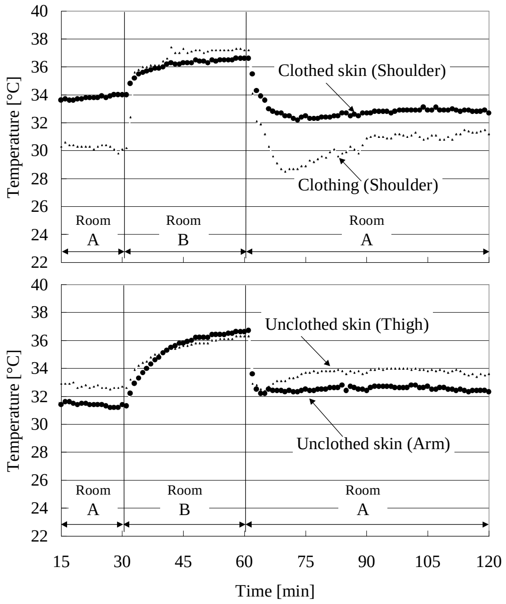


Figure 2-4 Experimental Data (Exp. No.4)

Similar to the clothing temperature, the time when the clothed skin temperature assumes the minimum value is the earliest at the shoulder. However, the clothed skin temperatures assume their minimum values much later than the unclothed skin temperature, and in experiment No.3, the temperatures at the chest and back continue to decrease even at t=120. While the unclothed skin temperatures become almost constant after t=80, the clothed skin temperatures vary for longer time and, in most cases, they continue to vary even after t=120, at the end of the experiment. Not only the thermal and the hygric resistance of the clothing but also the moisture accumulation in the clothing is responsible for this fact.

In experiment No.3, the armpit temperature responds to the room air temperature quickly, while in the other experiments the response of the armpit temperature tends to lag behind the transient in room air temperature. (Cf. Figures 13 and 14) After entering Room B, the armpit temperature remains almost constant or slightly decreases and then starts increasing at t=45 or later. Even after moving to Room A again, it keeps increasing for 10-15 minutes. At t=70 to 75 it assumes the maximum value and decreases. At t=120, the value of the armpit temperature becomes almost the same as that at t=30. On the other hand, in all experiments, the tympanic temperatures respond quickly to the change in room air temperature and are slightly lower at t=120 than those at t=30. They increase monotonically in the sweating process and decreases in the evaporation process.

Table 3 Weight variation [g]

	Exp. No.1	Exp. No.2	Exp. No.3	Exp. No.4
$B_{t=120}$-$B_{t=30}$	129	121	112	85
$C_{t=120}$-$C_{t=0}$	5.2	2.0	2.2	1.1

-B: Weight of a clothed man
-C: Weight of a T-shirt

As shown in Table 3, the difference in the weight loss between the experiments is mainly caused by the difference in the amount of sweat. Even though there might exist a difference between individuals, the difference in weight loss can be explained based on the difference in ambient air conditions in Room B. The difference in the weight of T-shirt before and after the experiment is shown in Table 3.

ANALYSIS

Procedures

As a model for physiological response of human body, the two-node model (Gagge et al., 1971) is used. The skin is split into the clothed and the unclothed segments as Jones et al. (1992) have done. For the heat and moisture balance in the clothing, following equations are used and the schematics of the whole model are shown in Figure 3.

$$c\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left[\lambda \frac{\partial T}{\partial x}\right] + H \frac{\partial}{\partial x}\left[\lambda' \frac{\partial X}{\partial x}\right] \qquad (1)$$

$$\rho \frac{\partial w}{\partial t} = \frac{\partial}{\partial x}\left[\lambda' \frac{\partial X}{\partial x}\right] \qquad (2)$$

$$w = f_1(RH,T) = f_2(X,T) \qquad (3)$$

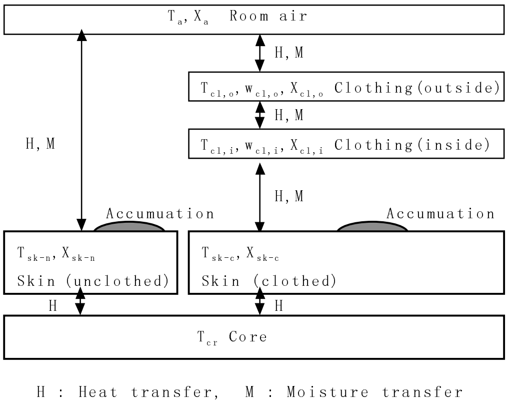


Figure 3 Schematics of model

Conditions of calculation

The ratio of the area of the clothed skin segment to that of the unclothed is 2 : 3 for all the calculations. The experimental results at t=30 are used as the initial conditions of the temperatures. The water content of the clothing and the humidity ratio of the skin surface at t=30 are decided by the preparatory calculation associated with t=0 to 30; At t=0, the core, the skin, the clothing temperatures and the water content of the clothing are set at 36.6, 34.1, 32.2 °C and 0.03 m^3/m^3 respectively. The measured room air temperature and relative humidity are inputted as boudary conditions. In solving the moisture balance equation, the humidity ratio on the skin surface is decided by solving the moisture balance on the skin surface. It considers the moisture production by sweating, the moisture flux from the outer node (air or clothing) and the flux from the node under the horny layer of the epidermis, where the temperature is assumed to be the same as that of the skin node and is vapor saturated. The transfer coefficients between the nodes are listed in Table 4. The name of the nodes are the same as the suffix in Figure 3. The moisture transfer coefficients are decided from the convective heat transfer coefficient using Lewis relation.

The transfer coefficients between the clothed skin and the clothing vary depending on their contact condition and thus are non-uniform over the body surface. They have a significant influence on the clothing and the clothed skin temperatures in the sweat evaporation process (Umeno et al., 1998). The contact of clothing with the skin due to the profuse sweating observed in the experiment is expressed as a large value of transfer coefficient during t=60 to 120 in the calculation.

As for the weight loss, the respiration and the evaporation of moisture from the unclothed skin and the clothing are taken into account.

Table 4 Transfer coefficients between the nodes
Heat: [W/m^{2}K], Moisture: [kg/m^{2}s(kg/kg')]

Nodes between	Time [min]	Heat (con-vective)	Heat (radi-ative)	Moisture
air&cl,o air&sk-n	0-30	4	4.65	4×10^{-3}
	30-60	2	4.65	2×10^{-3}
	60-120	4	4.65	4×10^{-3}
cl,i & sk-c	0-30	4	4.65	4×10^{-3}
	30-60	4	4.65	4×10^{-3}
	60-120	40	4.65	40×10^{-3}

Table 5 Thermal and hygric properties of clothing used in calculation

Moisture conductivity	0.048 [kg/ms(kg/kg')]
Equilibrium moisture content curve	RH=1 (w>0.25) RH= $(w/0.25)^{1/2}$ (0<w<0.25)
Thermal conductivity	0.0556 [W/mK]
Specific heat	1380 [J/kgK]
Density	329 [kg/m^3]

Thickness of clothing: 0.5 [mm]

Comparison of calculated with experimental results

The calculated results are compared with the experimental results. In this section, only the result for Experiment No.3 is shown.

1. Sweating process in Room B (t=30 to 60)

As shown in Figure 4, the two rises and the following decreases in clothing temperature seen in the experiment also appear in the calculated result. The decrease starts at t=42, when the relative humidity of the skin surface reaches 100% (Figure 5). This makes the rise in humidity ratio at the skin small, and the sensible heat loss becomes larger than the adsorption heat gain since the clothing temperature is higher than those of the room air and the clothed skin.

The first sharp rise in the calculated clothing temperature seen in Figure 4 is caused mainly by the measured data inputted to the calculation (both temperature and relative humidity). The true temperature and relative humidity of the air which the subject is exposed to could not be measured during the movement from Room A to Room B. The way of measuring the air around the subject should be improved. By modifying the input data to probable ones, the sharp rise disappears and the results (not shown) becomes closer to the experimental results during t=30 to 35.

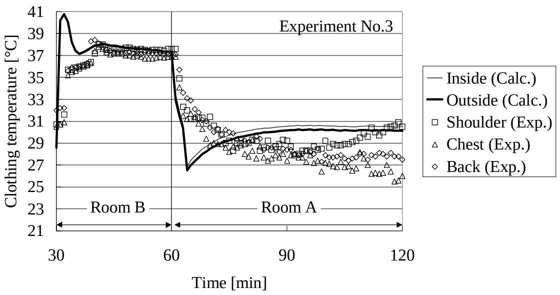


Figure 4 Calculated and experimental clothing temperatures

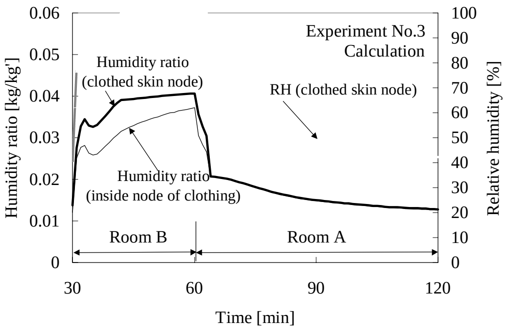


Figure 5 Calculated humidity of clothed skin and clothing

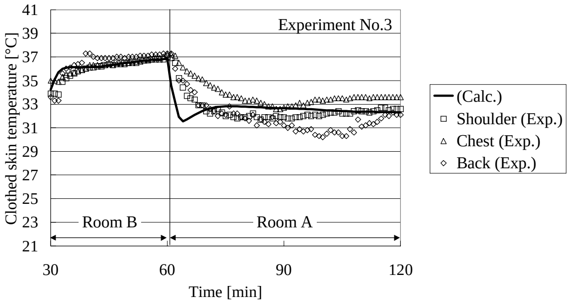


Figure 6 Calculated and experimental clothed skin temperatures

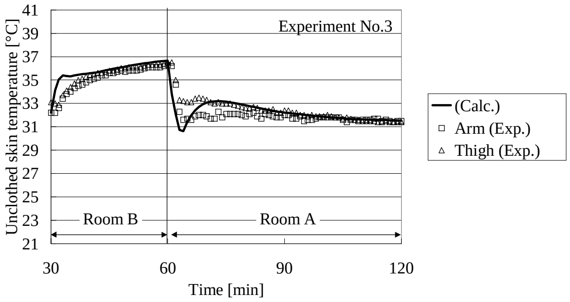


Figure 7 Calculated and experimental unclothed skin temperatures

2. Evaporation process in Room A (t=60 to 120)

The first decrease in calculated temperature seen in Figures 4, 6 and 7 is due to the evaporation of sweat accumulated on the skin surface or in the clothing. If there were not any sweat accumulated, the sensible heat transfer would play a main role in the heat balance and the temperatures might decrease monotonously. Just after t=60, the calculated clothing temperatures show sharper decrease than the experimental results while the clothed and unclothed skin temperatures show better agreement with the experimental results.

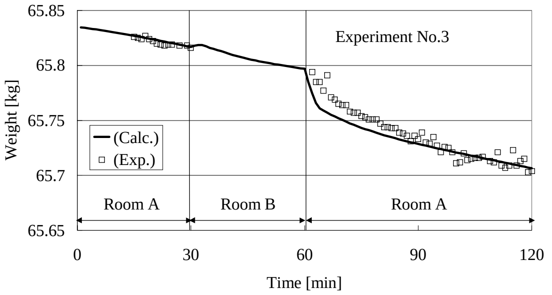


Figure 8 Calculated and experimental weights of whole body

The accmulated moisture on the unclothed skin surface disappears at t=65 in the calculation, which is also observed in the experiment around t=65. In addition, the total weight loss through the experiment (Figure 8) and the decrease in the unclothed skin temperature just after t=60 (Figure 7) are properly predicted. From these facts, the heat and moisture transfer coefficients between the room air and the unclothed skin or the clothing surface seem to be correct. As shown in Figures 6 and 7, the skin temperatures rise again after the decrease just after t=60. This 'rebound' will be described in detail at 'Discussion'.

The calculated rate of the weight loss during t=60 to 70 is faster than the experimental as shown in Figure 8. This is consistent with the faster decrease in the calculated clothing temperature than the experimental just after t=60 (Figure 4).

Sensitivity analysis

The calculation so far is called 'base' hereafter.

1. Convective transfer between clothing and clothed skin during the evaporation process (t=60 to 120)

As decribed at 'Procedures', a precise determination of the transfer coefficient between the clothed skin and the clothing is not easy. Thus in this section, other two values of the transfer coefficient are tried and the results are presented in Figures 9 and 10. The value for 'base x 0.1' is nearly equal to the transfer coefficient in a room with little air flow, while 'base x 2' corresponds to the case where the clothing contacts with the skin over a wider area on the body surface. The moisture transfer coefficients are set to change in relation to the heat transfer coefficient (Lewis relation). The coefficients for t=30 to 60 is the same as shown in Table 4. As shown in Figures 9 and 10, a larger heat transfer coefficient makes the clothing temperature and the clothed skin temperatures close. The difference in the skin temperature between the cases is significant from the view point of prediction of physiological response of the human body. By tuning the value of this coefficient, it is possible to make small the difference between the experimental and calculated values in the clothing and the clothed skin temperatures to some degree. However the sharp decrease in the calculated clothing temperature just after t=60 not seen in the experimental results, does not disappear. The evaporation of the moisture accumulated in the clothing can not be expressed well yet.

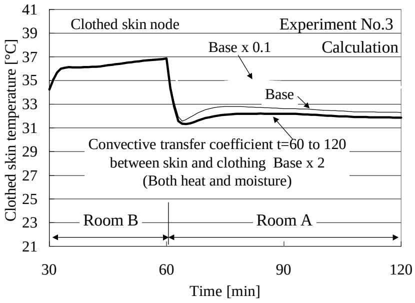


Figure 9 Calculated clothed skin temperatures corresponding to different transfer coefficients between clothing and clothed skin

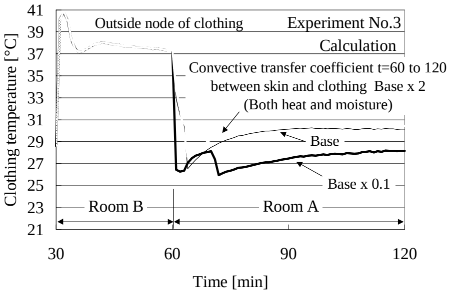


Figure 10 Calculated clothing temperatures

2. Moisture conductivity of clothing

In the calculation in this paper, the clothing is divided into two nodes. The moisture transfer between the nodes is expressed as the product of a constant moisture conductivity and the gradient in humidity ratio which is decided by the equilibrium moisture content. The equation (2) is basically for the moisture transfer in vapor phase. In expressing the moisture in liquid phase using equation (2), much larger moisture transfer coefficient should be used. The value of the coefficient used in 'base' is comparatively large as can be seen from the fact that the calculated moisture contents of the inside and outside nodes are almost the same. Therefore a smaller value of the conductivity is tried here. The result is shown in Figures 11 and 12. When the moisture conductivity becomes 1/30, the moisture contents at the two nodes differs further. The secreted sweat is accumulated in the inside node for longer time and it takes more time for the moisture to evaporate from the clothing. In addition, the adsorption of moisture from the clothed skin surface to the clothing helps to lessen the temperature decrease just after t=60. As a result, the history in the clothing temperature just after t=60 seen in the experimental result is expressed better (Figure 11).

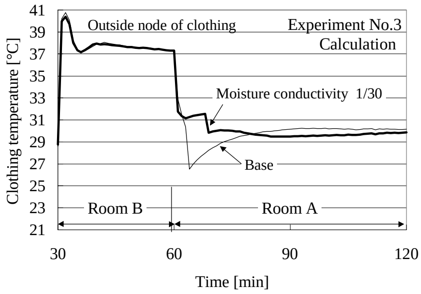


Figure 11 Calculated clothing temperature corresponding to two types of moisture conductivity

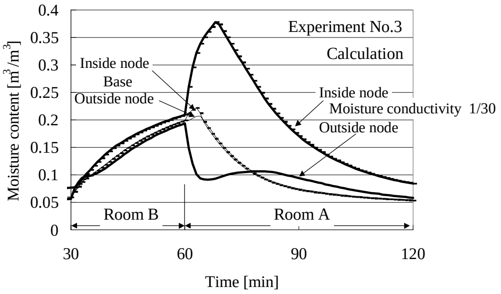


Figure 12 Calculated moisture content

DISCUSSIONS

The quantity of the moisture accumulated in the clothing or on the skin surface during the sweating process is closely related to how much the temperatures decrease in the evaporation process. In other words, the sweat rate in Room B has a significant influence on the resulting temperatures. In the case of Experiment No.3, the total amount of sweat seems to be predicted correctly, since the calculated weight at the end of the experiment agrees with the measured value (Figure 8). However, they do not show such a good agreement in the case of other experiments (not shown). The value of the core temperature seems to be closely related to this, for the sweat rate as well as blood flow rate is decided by the deviation from the setpoint temperature of the core (36.6°C) and the skin (34.1°C) in the model. They are set at constant irrespective of the difference between subjects. In that sense, the agreement for Experiment No.3 could be just a coincidence. In the calculation in this paper, the average of the measured values of the armpit and the tympanic temperatures at t=30 is used as the initial conditions. The effect of the initial conditions is significant for the calculated core temperature, which is closely related to the sweat rate. In addition, as shown in Figures 13 and 14, the calculated core temperatures are not in good agreement with the armpit or tympanic temperatures. Further investigation on the measurement of the core temperature and on the validity of the thermophysiological model is necessary.

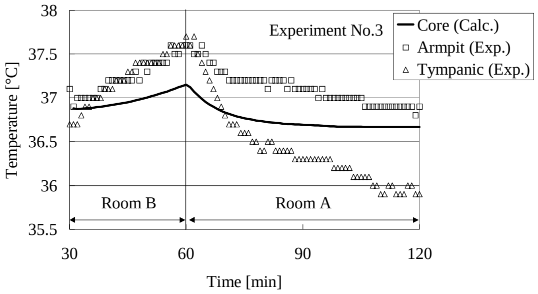


Figure 13 Calculated and experimental core temperatures

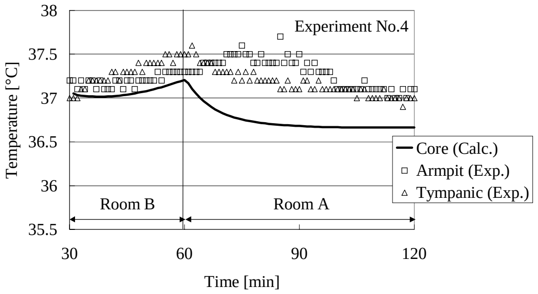


Figure 14 Calculated and experimental core temperatures

The rise on the rebound of the decrease in the skin temperatures is seen just after t=60 (Figures 6 and 7). This rebound is due to the sensible heat transfer from the core node to the skin node and caused by the sudden decrease in the evaporation of the sweat from the skin surface. This does not necessarily appear when the decrease in temperature due to the heat loss by evaporation is smaller (Umeno et al., 1998). Furthermore, the blood flow regulation, which decides the thermal conductance between the core and the skin is related to the magnitude of the rebound. Since in two-node model, the blood flow rate is decided by the deviations of the skin and the core temperatures from their setpoints, the higher the skin temperature becomes, the more the heat flux from the core becomes. This helps to make the rebound bigger. A more remarkable rebound can be seen in the unclothed skin than the clothed skin where the change in temperature is softened by the clothing. The rebound can also be seen in the experimental results, although the magnitude is not so big as the calculated results.

As shown in 'Sensitivity analyasis', more detailed studies on the moisture accumulation and movement in the clothing seem necessary for the quantitative understanding of the characteristics in the moisture evaporation from the clothing. For example, the non-uniformity in the moisture content distribution on the surface of the clothing can be caused by the absorption of sweat into the clothing at some points by random and partial attachment of clothing to the skin or by the random gathering of sweat on the skin surface. Furthermore the in-plane diffusion of the absorbed moisture can also be related to the distribution (Takada et al., 1998). In other words, the moisture movement in the clothing should be considered three-dimensionally along with the distribution of sweat secretion on the skin surface. How the sweat secreted as a liquid moisture at the skin surface move into the clothing should be grasped quantitatively in a more precise way.

CONCLUSIONS

In order to clarify the effect moisture accumulation in clothing has on the physiological response of human body in the transient state, we conducted experiments involving clothed subjects to reproduce the situation in which people enter an air-conditioned room just after sweating. At the same time, the experimental results were analyzed by making use of a combined model, which consists of two-node model for thermophysiological response of human body and simultaneous heat and moisture transfer model for thermal and hygric behavior of the clothing. The obtained conclusions are as follows.

1. In the sweating process, the clothing temperatures show sharp rise due to the adsorption of the vapor from the ambient air or the skin. In the experiment, the peak clothing temperature ranges from 35 to 38 °C, which is higher than both the ambient air and the skin temperature.

2. After the sweating, the decrease in the clothing temperature starts as soon as the relative humidity of skin reaches 100%.

3. In the experimental results in the evaporation process, the unclothed skin temperatures become almost constant 20 minutes after the beginning of the evaporation process, while the clothed skin temperatures vary for longer time. Not only the thermal and the hygric resistance of the clothing but also the moisture accumulation in the clothing is responsible for this fact.

4. By tuning the parameters related to the moisture transfer in and around the clothing, a quantitative grasp of the characteristics of the moisture behavior during the process is tried in the analysis.

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NOMENCLATURE

c : specific heat [J/kgK], ρ : density [kg/m^3], T : temperature [K], λ : thermal conductivity [W/mK], H : latent heat [J/kg], λ' : moisture conductivity [kg/ms(kg/kg')], X : humidity ratio [kg/kg'], w : volumetric moisture content [m^3/m^3], f : equilibrium moisture content [m^3/m^3], RH : relative humidity [-], t : time [s], x : coordinate [m]