THERMAL MODEL OF HUMAN BODY TEMPERATURE REGULATION CONSIDERING INDIVIDUAL DIFFERENCE

Satoru Takada[1], Hiroaki Kobayashi[2], and Takayuki Matsushita[1]

[1]Department of Architecture, Graduate School of Engineering, Kobe University, Rokko, Nada, Kobe 657-8501, Japan

[2]Department of Architecture and Civil Engineering, Graduate School of Science and Technology, Kobe University

Rokko, Nada, Kobe 657-8501, Japan

ABSTRACT

This paper proposes the methodology to quantify the individual difference in temperature regulation of human body for transient simulation of body temperature.

Experiments of transient thermal exposure were conducted for four subjects and the characteristics of individual difference in themoregulatory response were observed quantitatively. As the result, the differences in core temperature and heart rate were significant.

For each subject, the physiological coefficients used in the two-node model were adjusted in order to minimize the difference between experimental and calculated values in a series of a representative transient state in core and skin temperature. With the combination of the coefficients determined, the skin and core temperatures calculated with the two-node model agreed well with the experimental results for all the subjects involved in the experiments. This shows that the individual difference in the regulation of body temperature is well described with the combination of the coefficients determined by the optimization.

KEYWORDS

Temperature regulation model, Two-node model, Individual difference, Subject experiment, Optimization

INTRODUCTION

Thermal model of human body plays important role in the design of comfortable architectural environment. The two-node model is widely used in a lot of situations such as calculation of SET*, and there are a lot of models proposed and simulated results shown (Gagge et al. 1986, ASHRAE 2005). Recently, not only for steady state but also for transient state, the results of simulations are presented, but the validity of the model in transient state is not clarified enough so far. In order to show the validity, the calculated results should be compared with the experimental results in transient state. However, the difference in body temperature regulation between real subjects makes it difficult; Even for one environmental condition, more than one kinds of experimental results are obtained from several subjects, while a model gives one result for one condition. In other words, the problem of individual difference cannot be avoided for the validation of thermal model of human body.

Havenith (2001) proposes to express individual differences in the human thermoregulation model by giving several individual characteristics such as body surface area, mass and body fat into the model. In that work, the simulated results with consideration of individual difference are compared with those without consideration, but the improvement by the consideration is not so clear. Zhang et al. (2001) uses ‘body builder model’ that expresses the individual difference by inputting similar elements as Havenith. However the simulated results are shown only for a steady state and not checked from the viewpoint of transient state.

Individual difference in thermoregulation in human body is often mentioned, but the element that causes the difference is not clarified and the several elements would be related to each other. Moreover, not only static but also dynamic response of human body is related to the data. From that viewpoint, this paper presents a methodology of expressing the individual difference in dynamic thermoregulation of human body using human thermal model (two-node model). In the first part of the paper, the individual difference in thermoregulation of human body is shown quantitatively by experiments involving four subjects (naked, sedentary). In the latter part, based on the experimental data of core and skin temperatures, the physiological constants (set point temperature of core and skin, coefficients in the dynamic model of regulatory sweating and skin blood flow) included in two-node model (Gagge et al. 1971) are optimized so that the difference between the experimental and the calculated values should become smallest as a whole transient process. It is shown that by using the determined coefficients, a subject experiment under another kind of thermal transients can be predicted and that the combination of the coefficients describes the characteristics of the individual difference.

SUBJECT EXPERIMENT

Method

Four healthy students seated back-to-back are exposed to a thermal transient, which starts with thermally neutral condition followed by a low air temperature, the second neutral condition, a high air temperature, and at last the third neutral condition (Figure 1). All the subjects wear trunks only and keep sedentary one hour before the experiment starts in the thermally neutral condition (29 deg. C, 50%rh). During experiments, core temperatures and skin temperatures, heart rate and the environmental conditions (air temperature, humidity, globe temperature, wind velocity) are measured continuously with the interval of 10 seconds. For skin temperature, Hardy and DuBois seven points are measured. The measured items are shown in detail in Table 2.

Table 1 Information on subjects

	AGE	HT	WT	SEX	BSA
	[year]	[cm]	[kg]	[-]	[m^2]
A	25	169	55.6	Male	1.64
B	24	167	66.0	Male	1.73
C	24	163	54.8	Male	1.59
D	24	174	76.8	Male	1.89

HT: Height, WT: Weight, BSA: Body surface area calculated from height and weight (Kurazumi 1994)

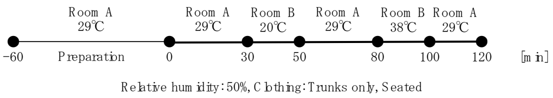

Figure 1 Schedule of experiment

Table 2 Measured items and methods

ITEM	METHOD (INSTRUMENT)
Core temperature (tympanic, rectal)	Thermocouple (T type, 0.2 mm in diameter)
Skin temperature (head, forearm, back of hand, instep, calf, thigh, abdomen)	Thermocouple (T type, 0.2 mm in diameter)
Heart rate	Photoelectric pulse wave method (Cat Eye)
Body weight	Electric balance (Mettler Toledo KCC 150)
Air and globe temperatures	Thermocouple (T type, 0.2mm in diameter)
Relative humidity	Electric resistance method (T and D, TR-72S)
Wind velocity	Hot wire method (Kanomax, 6543),

Result

As shown in Figure 2, the difference in rectal temperature between subjects reaches 1 [K] at maximum. This is a significant difference from the viewpoint of numerical model of thermoregulation of human body, because 1 [K] difference in core temperature brings a significant difference in thermoregulatory responses such as skin blood flow rate and sweat rate. As for the tendency in change, difference between subjects is significant. For example, during the process in the low temperature room (condition of 20 deg. C in air temperature), the rectal temperature of Subject D rises while that of Subject B decreases. The time when the rectal temperature reaches a maximum or minimum and the range of variation are different from subject to subject.

As shown in Figure 3, the individual difference is seen similarly for the tympanic temperature.

In Figure 4, the averaged skin temperature (Hardy and DuBois seven points) is shown. The difference between subjects reaches 1 [K]. By nature the range of variation is wider than core temperature. Therefore it can be said that the individual difference in skin temperature is smaller than that in core temperature.

The heart rate is shown in Figure 5. The difference is significant and this suggests the individual difference in the characteristics in the regulation of the blood flow.

Table 3 shows the body weight loss during experiment. The loss of subject B and D is more than the others and this suggests the difference in quantity of sweat perspired during the experiment and also the difference in regulatory sweating response.

As shown in Table 4, the room air temperature and humidity were controlled slightly different from the setting shown in Figure 1, and the movement of subjects between rooms was started at the scheduled time and it was necessary to take c.a. 1 minute to go out the former room.

Table 3 Weight loss (difference between before and after experiment)

	WEIGHT LOSS	
	[g/h]	[g/(h·m^2)] (per body surface area)
A	61.4	37.0
B	89.9	52.9
C	53.8	33.6
D	94.5	52.0

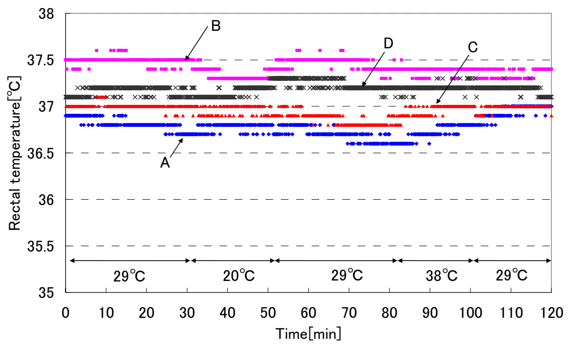

Figure 2 Rectal temperature (Experiment)

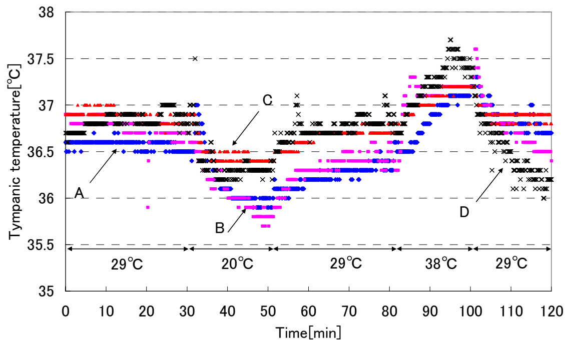

Figure 3 Tympanic temperature (Experiment)

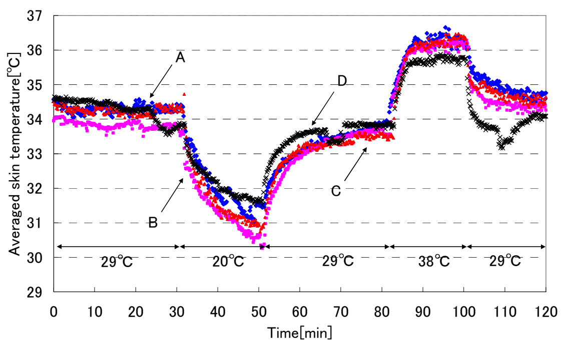

Figure 4 Averaged skin temperature (Experiment)

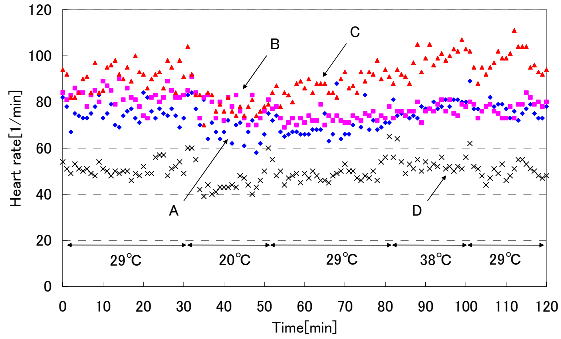

Figure 5 Heart rate (Experiment)

Table 4 Environmental conditions (Measured values averaged for time)

Time[min]	0 to 31	31 to 51	51 to 81	81 to 101	101 to 120
	Room A	Room B	Room A	Room B	Room A
Air temperature[°C]	29.4	20.0	29.4	40.9	29.4
Relative humidity[%]	47.5	55.6	47.6	53.5	47.8
Globe temperature[°C]	29.6	20.2	29.5	40.2	29.6
Wind velocity[m/s]	0.10	0.24	0.10	0.12	0.12

ANALYSIS USING TWO-NODE MODEL

Method

In the two-node model (Gagge 1971), the thermoregulatory responses are expressed as following equations.

For sweating rate,

$$m_{sw} = pr3 \cdot (T_{cr} - pr1)(T_{sk} - pr2) \cdot \frac{1}{3600} \cdot \frac{1}{1000} \quad (1)$$

, if the value of a bracket is minus, the value of the bracket should be displaced as zero.

For skin blood flow rate,

$$v_{bl} = \frac{pr4 + pr5(T_{cr} - pr1)}{1 + pr6(pr2 - T_{sk})} \cdot \frac{1}{3600} \quad (2)$$

, if the value of a bracket is minus, the value of the bracket should be displaced as zero.

In these equations, there are six coefficients included and the values of them are given in the original paper. Some of the coefficients were determined based on thermophysiological experiment, and for the others, the process of determination is not clear. The model would be tuned to measured results of a specific subject. Anyway, the individual difference is not taken into account in the two-node model. Thus in this paper, the six coefficients are adjusted for each subject.

The six coefficients included in the two-node model are determined so that the difference between calculated and experimental core and skin temperatures becomes smallest.

For six coefficients, candidates of the solution are prepared among the assumed domain as shown in

Table 5. The number of the combination is 1,260,000. The objective function is shown in equation (3).

$$J = \sum_{i=1}^{N}\left\{(T_{cr,i} - T_{cr,i}')^2\right\} + \sum_{i=1}^{N}\left\{(T_{sk,i} - T_{sk,i}')^2\right\} \qquad (3)$$

As the experimental data, the mean skin temperature (Hardy and DuBois seven points) and rectal temperature are used for skin and core temperatures respectively. The interval of data acquisition was 10 seconds. Therefore the total number of the time series data is 721 for two hours experiment.

The experimental values are given for the initial condition of skin and core temperature in the calculation. For the boundary condition, the raw data of the room air temperature and humidity are inputted to the calculation program. As the mean radiant temperature, the air temperature was given, because the difference between the globe temperature and the air temperature was small enough as shown in Table 4.

The detailed conditions of calculation are shown in Table 6. The mass and the surface area of the subject are as shown in Table 1. The mass ratio of core and skin was set to 95 :5 (Gagge et al. 1971).

Table 5 Candidates of parameters in the two-node mode in optimization (All the combinations for these six parameters are tried in the calculations.)

pr1	pr2	pr3	pr4	pr5	pr6
37.7	34.7	100	12.6	150	1
37.5	34.5	80	10.08	120	0.8
37.3	34.3	60	7.56	90	0.6
37.1	34.1	40	5.04	60	0.4
36.9	33.9	20	2.52	30	0.2
36.7	33.7	10	1.26	15	0.1
36.5	33.5	5	0.63	7.5	0.05
36.3	33.3		0.315	3.75	0.025
36.1	33.1		0.1575		0.0125
35.9	32.9		0.07875		0.00625
35.7	32.7				
35.5	32.5				
35.3	32.3				
35.1	32.1				
34.9	31.9				

Table 6 Calculation conditions

Air temperature	Measured data
Air humidity	Measured data
MRT	Equal to air temperature
Convective heat transfer coefficient	3.1 [W / (m ^{2}·K)]
Radiative heat transfer coefficient	4.65 [W / (m ^{2}·K)]
Clothing	0.1 [clo]
Metabolic rate	58.2 [W / m ^{2}]
External mechanical efficiency	0

Result

The coefficients determined are shown in Table 7. The experimental results, the calculated results with the determined coefficients and the calculated results with the default coefficients (proposed by Gagge et al., the original authors) are compared in Figures 6 to 9 for both core and skin temperatures, for each subject. For all the subjects, the calculated results with determined coefficients agreed with the experimental results better than those with default coefficients. This means that the parameters were tuned well to describe the experimental values of each subject.

Table 7 Combination of parameters minimizing difference between experimental and calculated skin and core temperatures in two-node model for each subject

Subject	Parameter					
	Pr1	Pr2	Pr3	Pr4	Pr5	Pr6
	$T_{cr,set}$ [℃]	$T_{sk,set}$ [℃]	Perspiration [g/(m ^{2}·h·K ^{2})]	Basal blood flow rate [kg/(m ^{2}·h)]	Vaso dilation [kg/(m ^{2}·h·K)]	Vaso constriction [1/K]
A	36.1	32.7	10	1.26	15	0.00625
B	36.9	32.3	20	0.07875	15	0.00625
C	36.7	32.1	20	2.52	30	0.00625
D	37.1	33.1	100	7.56	7.5	0.00625
default	36.6	34.1	100	6.3	75	0.5

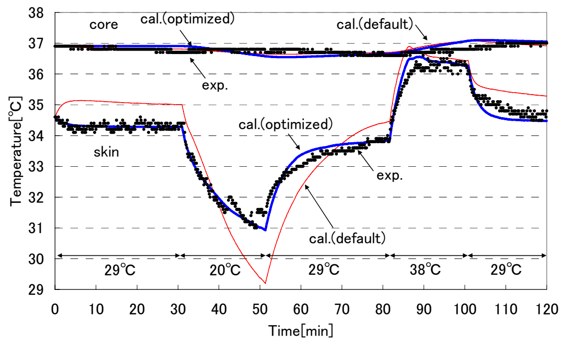

Figure 6 Calculated and measured results for Subject A (Core and skin temperatures)

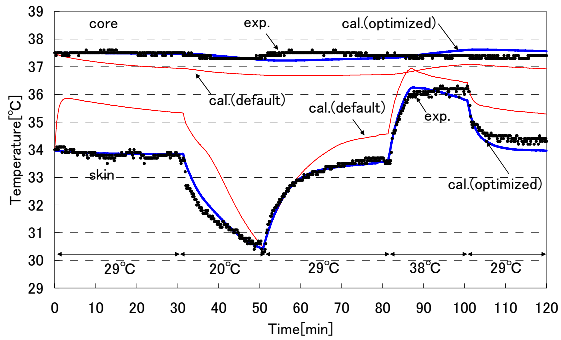

Figure 7 Calculated and measured results for Subject B (Core and skin temperatures)

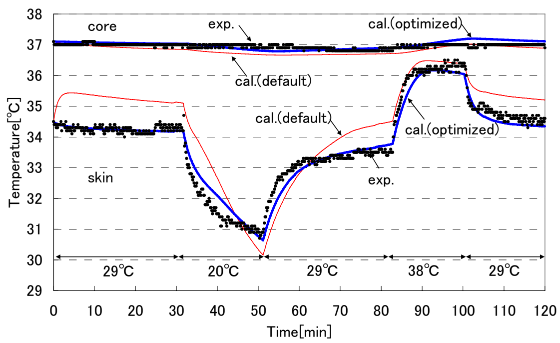

Figure 8 Calculated and measured results for Subject C (Core and skin temperatures)

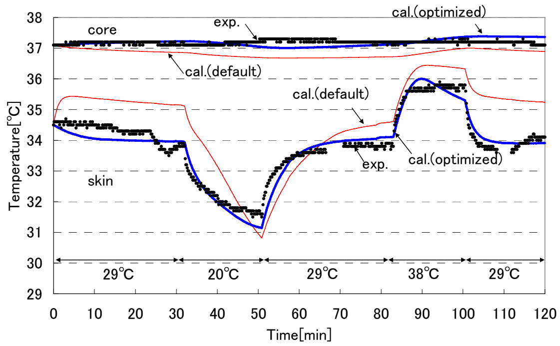

Figure 9 Calculated and measured results for Subject D (Core and skin temperatures)

DISCUSSION

It was shown that by selecting properly the six coefficients related to body temperature regulation in the two-node model, the solution of two-node model agrees well with the experimental results.

In order to ensure that the determined coefficients describe the characteristics of the body temperature regulation of each subject well, a test is done in this section. The problem is whether the calculated results by the two-node model with the determined coefficients agree with experimental results under another series of thermal transients or not.

Another type of experiment was conducted at the same time, at the same week as the first experiment, for the same four subjects, and in the same manner. Only the room air temperature condition is different as shown in Figure 10.

The environmental conditions measured in the experiment are shown in Table 8 as averaged values for each process. Like as the first experiment, they are slightly different from the setting and the measured values are inputted to the calculations.

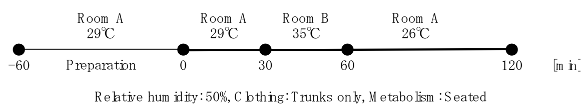

Figure 10 Schedule of experiment for verification

Table 8 Environmental conditions (Measured values averaged for time)

Time[min]	0 to 32	32 to 61	61 to 120
	Room A	Room B	Room A
Air temperature[℃]	29.4	35.2	26.3
Relative humidity[%]	47.1	47.3	46.0
Globe temperature[℃]	29.6	35.0	27.0
Wind velocity[m/s]	0.10	0.11	0.12

The results are shown in Figures 11 to 14. For all the subjects, the calculated results agree well with the experimental results. By using the combination of coefficients optimized from a series of thermal transients experiment, the experimental results of another series of thermal transients were explained well. This indicates that the determined coefficients in the two-node model describe well the body temperature regulation system of the each subject.

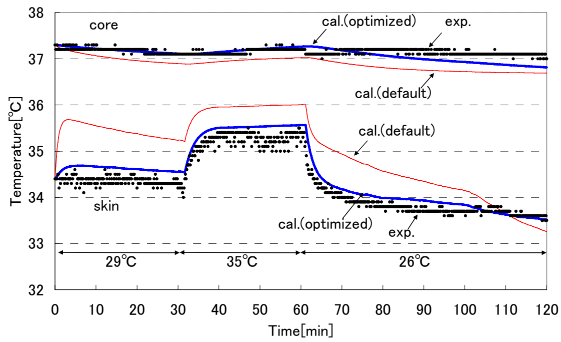

Figure 11 Calculated and measured results for Subject A (Core and skin temperatures)

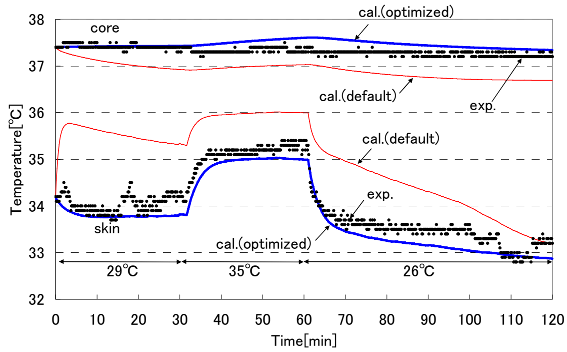

Figure 12 Calculated and measured results for Subject B (Core and skin temperatures)

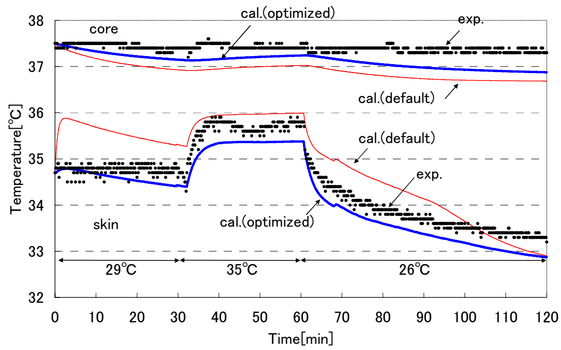

Figure 13 Calculated and measured results for Subject C (Core and skin temperatures)

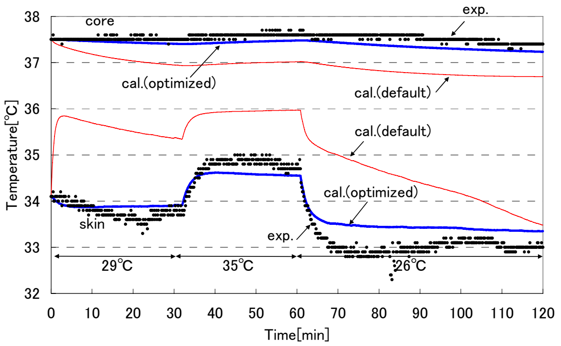

Figure 14 Calculated and measured results for Subject D (Core and skin temperatures)

In the two-node model (Gagge et al. 1971) used in this study, the model of shivering is not included. From 30 min to 50 min in the first experiment shown in Figure 1, the air temperature is 20 deg. C and shivering was observed for a part of subjects. In the newer version of two-node model (Gagge et al. 1986), a shivering model is included. By adding the shivering model to this calculation, the determined coefficients did not change significantly.

In this paper, as the definition of the objective function, the rectal and the mean skin temperatures are summed up with an equal weight, 1:1 as shown in equation (3). However another way of weighting is possible, and there are other methods using other data like blood flow rate, sweating rate, or a skin temperature measured at some part of the body (not averaged) as an element of the objective function to optimize the parameters.

CONCLUSION

Experiments of transient thermal exposure were conducted for four subjects and the characteristics of individual difference in themoregulatory response were observed quantitatively. As the result, the differences in core temperature and heart rate were significant.

At the same time, a methodology of quantitative description of individual difference in thermoregulatory responses of human body was proposed considering transient state. The thermoregulatory parameters included in the two-node model were tuned in order to minimize the difference between experimental and calculated results during a transient condition including stepwise air temperature change of coming and going to lower and higher temperature condition from thermally neutral condition. With the use of the determined combination of parameters, the calculated results agreed well with the experimental results both for skin and core temperatures for all four subjects. In order to verify the determined parameters, another transient case of subject experiments for the same member of subjects were simulated, and the calculated results, again showed good agreement with the experimental results. Therefore it was shown that the combination of the parameters determined in this paper describe the characteristics in dynamic thermoregulatory responses of each subject.

ACKNOWLEDGEMENTS

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NOMENCLATURE

m_{sw}: Regulatory sweating rate [kg/(m^2・s)]

v_{bl}: Skin blood flow rate [kg/(m^2・s)]

*pr*1: set point of core temperature [deg. C]

*pr*2: set point of skin temperature [deg. C]

*pr*3: Coefficient of sweating rate model [g/(m^2・h・K^2)]

*pr*4: Skin blood flow rate in thermally neutral condition [kg/(m^2・ h)]

pr5: Coeffcients of vasodilation [kg/(m^2・ h・ K)]

pr6: Coefficients of vasoconstriction [1/K].

T_{cr}: Calculated core temperature [deg. C]

T_{sk}: Calculated skin temperature [deg. C]

T_{cr}': Measured rectal temperature [deg. C]

T_{sk}': Measured skin temperature (averaged) [deg. C]

N: Number of data obtained in a series of transient state (In the experiment in this paper, the data were collected for 120 minutes with the interval of 10 seconds, and therefore *N*=721.)

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APPENDIX

Basic equations of the two-node model (Gagge et al. 1971) used in this paper are shown here.

The heat balance equation for core node

$$\frac{c_{cr}W_{cr}}{S}\frac{dT_{cr}}{dt} = (1-\eta)M - q_{res} - (c_{bl}v_{bl} + K_{\min})\cdot(T_{cr} - T_{sk}) \quad \text{(A1)}$$

The heat balance equation for skin node

$$\frac{c_{sk}W_{sk}}{S}\frac{dT_{sk}}{dt} = (T_{cr} - T_{sk})\cdot(K_{\min} + c_{bl}v_{bl}) - (\alpha_c + \alpha_r)\cdot(T_{sk} - T_o)\cdot F_{cl} - (q_{diff} + q_{rsw}) \quad \text{(A2)}$$

The elements appearing in equations (A1) and (A2) are described as follows.

The heat loss by respiration

$$q_{res} = 0.0023\times M\left(44-\phi_a P_a\right) \quad \text{(A3)}$$

The heat loss by sweating

$$q_{rsw} = r\cdot m_{sw}\cdot 2.0^{\frac{T_{sk}-T_{sk,set}}{3.0}} \quad \text{(A4)}$$

The heat loss by skin diffusion

$$q_{diff} = p_{wet}\cdot q_{\max} - q_{rsw} \quad \text{(A5)}$$

where,

$$q_{\max} = r\cdot\alpha'\cdot(P_{sk} - \phi_a\cdot P_a)\cdot F_{pcl} \quad \text{(A6)}$$

$$p_{rsw} = q_{rsw}/q_{\max} \quad \text{(A7)}$$

$$p_{wet} = 0.06 + 0.94\cdot p_{rsw} \quad \text{(A8)}$$

$$F_{cl} = \frac{1}{1+0.155\cdot(\alpha_c+\alpha_r)\cdot clo} \quad \text{(A9)}$$

NOMENCLATURE

c: specific heat [J/(kg·K)]

W: mass[kg]

S: body surface area[m^2]

T: temperature[deg. C]

t: time [s]

η: working efficiency [n.d.]

M: Metabolic rate [W/m^2]

q_{res}: Heat loss by respiration [W/m^2]

K_{min}: Minimum heat conductance by skin tissue [$W/(m^2 \cdot K)$].

α: Heat transfer coefficient [$W/(m^2 \cdot K)$]

F_{cl}: Heat transfer efficiency of clothing [n.d.]

q_{diff}: Heat loss by skin diffusion [W/m^2]

q_{rsw}: Heat loss by regulatory sweating [W/m^2]

ϕ_a: Relative humidity [n.d.]

P_a: Saturated vapor pressure of ambient air [mmHg]

r: evaporative heat of water [J/kg]

q_{max}: Maximum heat loss by evaporation [W/m^2]

P_{sk}: Saturated vapor pressure due to skin temperature [mmHg]

α': Moisture transfer coefficient [$kg/(m^2 \cdot s \cdot mmHg)$]

F_{pcl}: Vapor transfer efficiency of clothing [n.d.]

p_{rsw}: Skin wetness due to regulatory sweating [n.d.]

p_{wet}: Skin wetness [n.d.]

clo: Thermal resistance of clothing [clo]

SUFFIX

cr: core

sk: skin

bl: blood

c: convective

r: radiative

o: ambient

set: set point

The values not defined in this paper are same as those in the original paper (Gagge et al. 1971)