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Modification of sweating model in 2-Node Model and it's application to thermal safety for hot environments

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Abstract

Recently, due to global warming and the heat-island effect, more and more people are exposed to the dangers of heat disorders. A hot thermal environment can be evaluated using various indices, such as new Standard Effective Temperature (SET*) using the 2-Node Model (2NM), Wet Bulb Globe Temperature (WBGT), Predicted Heat Strain (PHS) model, and so on. The authors aim to develop a safety evaluation approach for hot environments. Subject experiments are performed in a laboratory to comprehend the physiological response of the human body. The results are compared with the computed values from the 2NM and PHS models, and improved the sweating model in 2NM in order to take into account the relationship with metabolic rate. A demonstration is provided of using the new sweating model for evaluating thermal safety in a hot environment.

Keywords

Hot environment, Thermal evaluation, 2-Node Model, PHS model, ISO 7933

1. Introduction

In addition to heat waves and abnormal weather on a global scale, the temperature rises in urban areas due to the heat-island phenomenon. Maximum temperatures will continue to rise in all parts of the world, and the number of high temperature days is expected to increase. Such temperature rises have a large influence not only on the environment but also on people’s health, and thus the risk of summer heat problems is one of the main issues. Recently, the number of patients suffering from heat disorders (heat-related problems) has been increasing in Japan. The number of fatalities ascribed to heat disorders totaled some 5,079 cases (male: 3,184 and female: 1,895) during the period from 1968 to 2004 (37 years). Due to the increased prevalence of hot environments, the heat disorders are expected to increase in the super-aging society in Japan (Ministry of Environment, 2006).

At present, the Wet Bulb Globe Temperature (WBGT) is generally used for forecast aimed at preventing heat disorders. The WBGT is a temperature index obtained from the weighted mean of the wet-bulb, globe and dry-bulb temperatures. It was proposed to show the limits for military training in hot conditions, and it is still recognized as a standard under International Organization for Standardization (ISO) 7243 (1989), and the Japanese Industrial Standards (JIS). It is reported that the WBGT represents an efficient index to evaluate risks in hot environments. However, the WBGT is a physical environmental index, and does not adequately reflect heat stress on the human body because the thermal environmental condition of the human body (clothing and metabolic rate), the body’s shape and thermoregulatory responses are not considered. Therefore, in terms of preventing heat disorders, it is only a rough indicator which recommends avoiding physical exercise under hot environments with a certain WBGT.

For outdoor environments, the Physiological Equivalent Temperature (PET) by Höppe (1993, 1999) has been proposed as new thermal index. In this model, the calculation of the heat loss by evaporation of sweat is distinguished by above or below 100% of skin wittedness Höppe (1993). It is thought that all sweat is evaporated when the skin wettedness is below 100%. However, part of the sweat drips off in this condition, and thus the PET is insensitive to the evaporation. The accuracy of this model should be examined from the viewpoint of human thermal physiology for hot outdoor environments.

In ISO 7933 (2004), the Predicted Heat Strain (PHS) model is adopted as a method of evaluating safe thermal environments for workers. This model predicts the thermal physiological response of the human body from the amount of virtual sweating necessary and the heat balance of the human body, and thus this evaluation method reflects the heat stress of the human body. However, this evaluation method is proposed for working environments in which the metabolic rate is comparatively high, and it is not certain whether it is applicable to the overall living environment.

On the other hand, the new Standard Effective Temperature (SET*) has been used as a thermal environment evaluation index in buildings. Recently, it is often used for thermal environment evaluations of the urban heat-island phenomenon. The SET* is an index that reflects the heat stress of the human body because it is calculated using the 2-Node Model (2NM), which is an abbreviated model of the thermal physiological response of the human body (Gagge *et al.*, 1986). However, the above-mentioned two models of the thermal physiology of the human body were based on subject experiments in Europe and America, and may not be suitable for Japanese individuals, being of a different race and having different living conditions. For example, it has been reported that the number of active sweat glands is significantly affected by the growth environment up to the age of two (Kuno, 1956). Therefore, it is thought that physiological responses probably differ by race and living conditions.

In this paper, we investigated the application of a simplified thermal physiological response of the human body under the two existing above-mentioned models for hot summer conditions and their modification method using subject experiments in a hot environment. In addition, we propose the evaluation of thermal safety in hot environments that reflect heat stress and dehydration potential.

2. Subject experiments in hot environments

2.1 Description of experiments

In order to clarify the physiological response of the human body in hot environments, subject experiments were conducted in a climate chamber. Tables 1 and 2 present an overview and the experimental cases. Figs. 1 and 2 show the experimental setup and schedule. The experiments were conducted three times: twice in summer (Experiments A and C) and once in winter (Experiment B). The subjects are 39 healthy male and female university students. After changing into special attire for the experiment, the subjects rest for 60 minutes in an anteroom (in front of the experiment room) which was maintained at about 27°C. Then, they moved into the experiment room and stayed for 60 or 45 minutes. During this period, their skin temperature, core temperature and water loss were measured. Based on ISO 9886 (2004), the skin temperature is measured every minute at eight points (forehead, right back, left upper chest, right upper arm, left lower arm, left hand, right anterior thigh and left calf) using a portable temperature logger and probe (Gram Corporation: LT-8). The core temperature was measured as the tympanic temperature every five minutes using an infrared radiation sensor (Morishita Jintan Company: S-30). The amount of sweating and bodily water lost, including the amount of evaporation due to breathing, and the weight decrease were measured every five minutes using a precise scale (Sartorius: IS150IGG-H, Readability=1g).

Case 1 represents the standard case, and a metabolic rate of 1.0 was achieved by sitting in a chair in a resting condition. Cases 2 and 3 were set to determine the effect of activity, and Cases 4 and 5 were set to determine the effect of high relative humidity and high air temperature respectively. All the experiments were conducted in the still air condition (0.1 m/s). In Cases 2 and 3, the subjects walk on a treadmill at speeds of 0.9 m/s and 1.4 m/s. For the safety of the subjects, the experimental span for Cases 2 and 3 was shortened to 45 minutes. Cases 1, 2, 4 and 5 were investigated in Experiment A. All cases were investigated in Experiment B. Cases 1, 2 and 3 were investigated in Experiment C. Each subject wore a standard set of clothes (0.3 clo) in all cases, namely a white T-shirt and white short pants.

Table 1 Outline of the experiment.

Period	Experiment A: 1 ~ 15 Aug. 2005 Experiment B: 9 ~ 23 Jan. 2006 Experiment C: 14 Sept. ~ 5 Oct. 2006
Place	Ultimate environment climate chamber, Institute of Industrial Science, The University of Tokyo
Subject	39 healthy male and female university-age students Experiment A: Male: 6, Female: 7 (Total 13) Experiment B: Male: 6, Female: 6 (Total 12) Experiment C: Male: 7, Female: 7 (Total 14)
Content	Measurement of physiological factors

Table 2 Experimental conditions.

<table>
<tr><th rowspan="2">Case</th><th colspan="4">Environmental conditions</th><th colspan="2">Human body conditions</th><th colspan="2">Number of subjects</th></tr>
<tr><th>Air temperature (°C)</th><th>MRT (°C)</th><th>Relative humidity (%)</th><th>Air movement (m/s)</th><th>Metabolic rate (met)</th><th>Clothing (clo)</th><th>Male</th><th>Female</th></tr>
<tr><td>1</td><td rowspan="4">35</td><td rowspan="4">35</td><td rowspan="3">50</td><td rowspan="5">0.1</td><td>1.0</td><td rowspan="5">0.3</td><td>19</td><td>20</td></tr>
<tr><td>2</td><td>2.0</td><td>19</td><td>20</td></tr>
<tr><td>3</td><td>3.0</td><td>13</td><td>13</td></tr>
<tr><td>4</td><td>70</td><td rowspan="2">1.0</td><td>12</td><td>13</td></tr>
<tr><td>5</td><td>40</td><td>40</td><td>50</td><td>12</td><td>13</td></tr>
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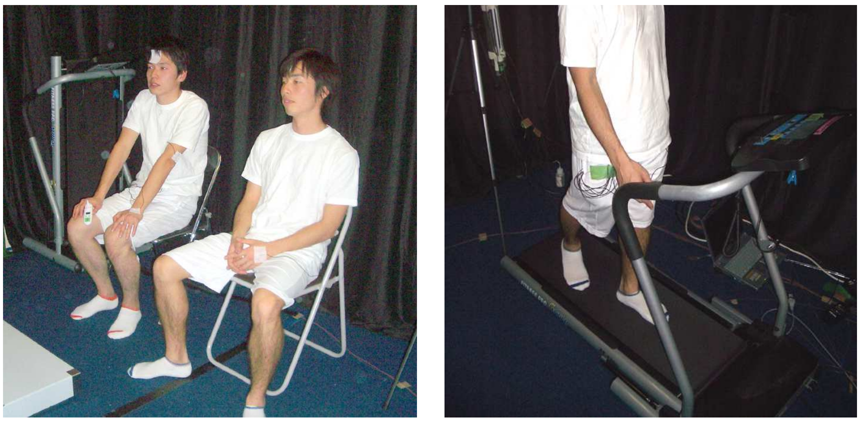


Fig. 1. Photos of the experimental conditions

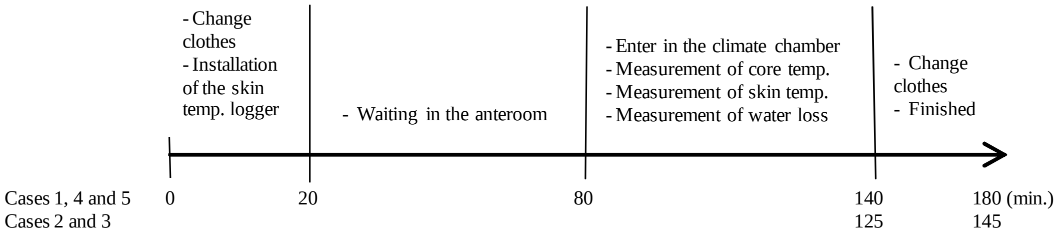


Fig. 2. Schedule of the experiments

2.2 Results and discussion of experiments

Fig. 3 shows a comparison of the water loss rate in summer and winter. Fig. 4 shows the experimental values for the core temperature, skin temperature and the cumulative water loss for each case and a comparison with the results calculated using the 2NM and PHS model. The vertical bars show the standard deviation of the experimental values in Figs. 3 and 4. When each case was compared, it was found that the cumulative water loss tends to increase in Cases 2 and 3, in which a high metabolic rate is apparent (Figs. 4 b & c). It is expected that an increased amount of metabolic thermogenesis is dissipated, and it is thought that this is the result of body temperature regulation by increasing the amount of evaporative heat loss. The skin temperature in Case 5 was higher than other cases (Fig. 4 e). It is thought that the skin temperature is influenced by the high environmental temperature (air temperature and the Mean Radiant Temperature (MRT, 40°C)). Moreover, when we compared the experiments by season (Fig. 3), the water loss rate is smaller in winter (Experiment B, Table 1), yet with the progress of time during the experiment, the final value was almost the same as summer (Experiment A and C, Table 1). It takes 45 minutes longer in winter for the subjects' sweating apparatus to activate. This might be the influence of the definite seasonal adaptation.

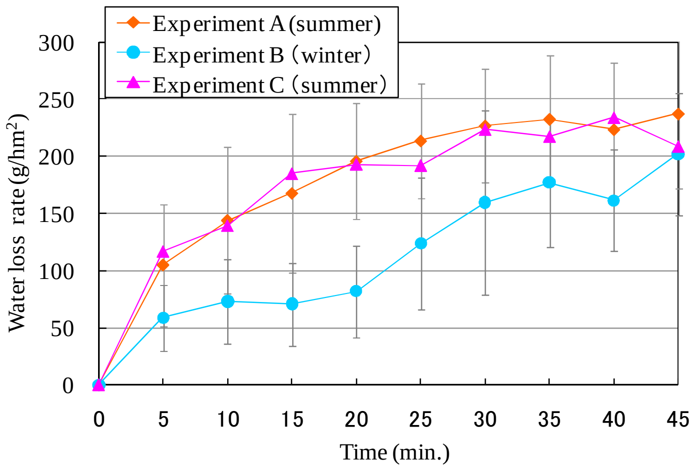
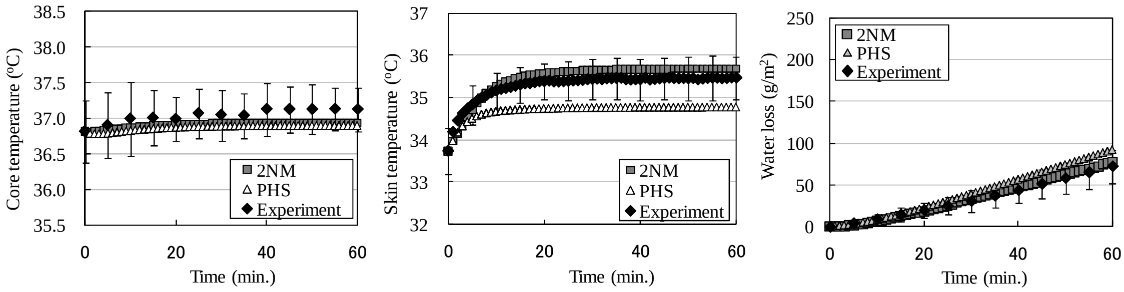
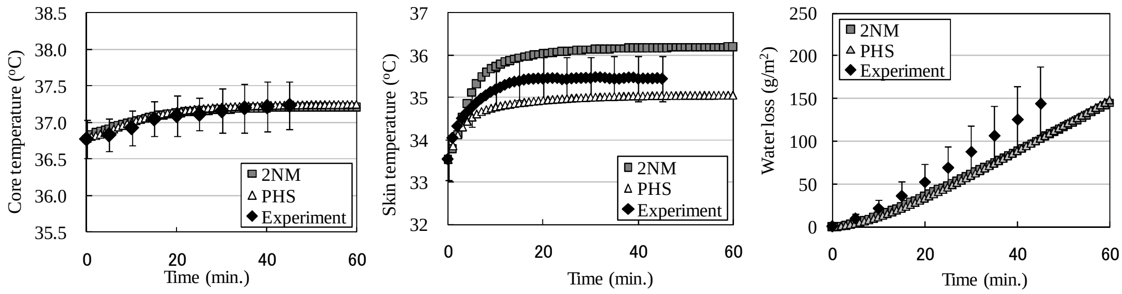


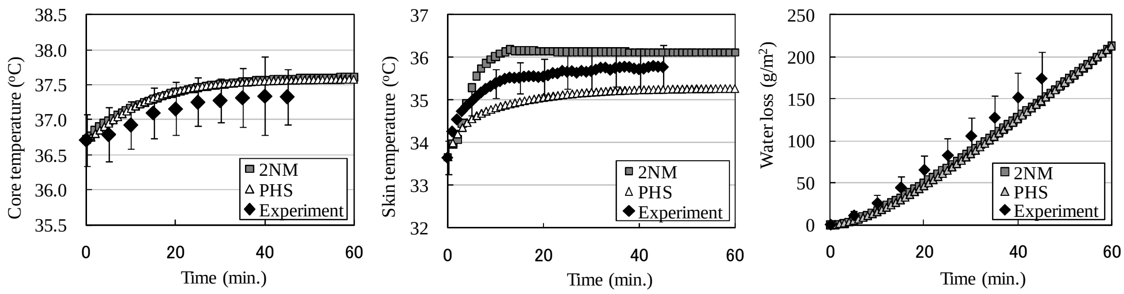
Fig. 3. The water loss rate in each experiment (Case 2: Air temperature and MRT: 35°C, Relative humidity: 50% and metabolic rate: 2 met)



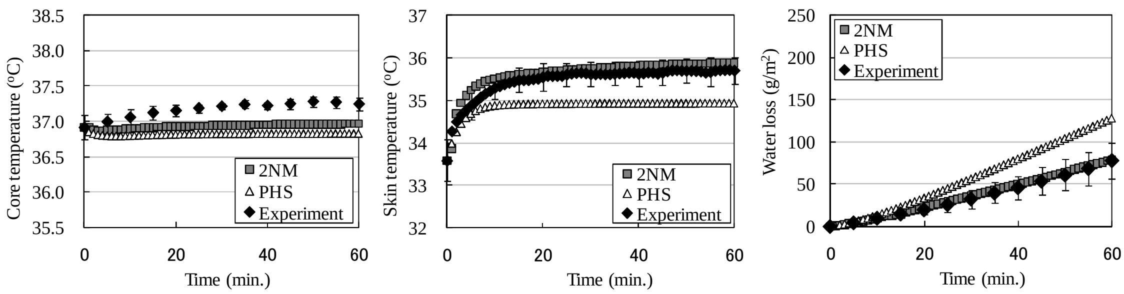
(a) Case 1 (Air temperature and MRT: 35°C, Relative humidity: 50% and metabolic rate: 1 met)



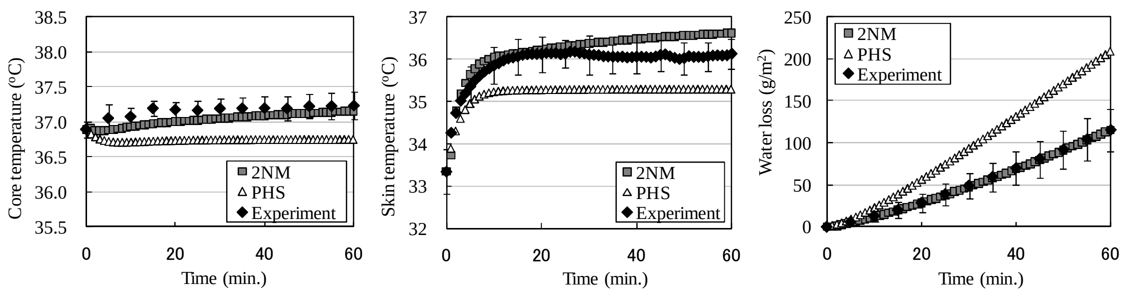
(b) Case 2 (Air temperature and MRT: 35°C, Relative humidity: 50% and metabolic rate: 2 met)



(c) Case 3 (Air temperature and MRT: 35°C, Relative humidity: 50% and metabolic rate: 3 met)



(d) Case 4 (Air temperature and MRT: 35°C, Relative humidity: 70% and metabolic rate: 1 met)



(e) Case 5 (Air temperature and MRT: 40°C, Relative humidity: 50% and metabolic rate: 1 met)

Fig. 4. Comparison between experimental and values predicted using 2NM and PHS model.

Table 3 Comparison of the predicted and experimental values of each model.

Metabolic rate (met)	Case	2NM			PHS model		
		T_{cr}	T_{sk}	m_{sw}	T_{cr}	T_{sk}	m_{sw}
low	1	O (0.47)	O (0.46)	O (0.22)	O (0.59)	× (1.37)	Δ (0.86)
	4	× (3.74)	O (0.51)	O (0.19)	× (5.43)	× (2.38)	× (2.35)
	5	Δ (0.86)	Δ (1.01)	O (0.05)	× (2.89)	× (2.10)	× (3.22)
high	2	O (0.10)	× (1.29)	Δ (0.88)	O (0.15)	Δ (0.93)	Δ (0.90)
	3	O (0.55)	Δ (1.03)	Δ (0.80)	O (0.56)	× (1.21)	Δ (0.91)

O: Well matched (C<0.8)
Δ: Matched within the standard deviation (0.8≤C≤1.2)
×: Not matched (C>1.2)
The evaluation criterion of the statistic C is defined as follows.

$$C = \sqrt{\frac{\sum_i (Y_i - \bar{y}_i)^2}{\sum_i \sigma_i^2}}$$

Y_i : Predicted value at time i

$\bar{y}_i$: Mean experimental value at time i

σ_i : Standard deviation of experimental value at time i (However, to exclude the influence of an initial value, time i is assumed to be $i \geq 15$ minutes.)

That is to say, when $C = 0$, the predicted value completely matches the mean experimental value, when $C = 1$, the error of the predicted and experimental values almost matches the standard deviation of the experimental value. The value shown in parentheses is C.

3. Comparison of calculated results using human thermal models and experiments

The temporal variation in physiological values obtained from the above-mentioned subject experiment was compared with the values predicted from the 2NM and PHS model, and the applicability of both models to hot environments was examined. Hence, from the objective of the hot environment evaluation, the experimental values were compared using the summer data (Experiments A and C).

3.1 Calculation conditions

In the 2NM and PHS model calculations, the program was created with reference to existing research (ISO 7933, 2004, Gagge *et al.*, 1986). For the initial values of each physiological amount and the environmental conditions, the experimental values were used.

3.2 Comparisons and discussions

Table 3 presents the correspondence between the experimental and predicted values from the 2NM and PHS model. With regard to 2NM, the correspondence differs in terms of sitting in a chair in a resting state and physical exercise, and it agreed comparatively well to the experimental value in the case of low metabolism. In Cases 2 and 3, which have high metabolic rates, the skin and core temperatures were higher than the experimental values, and the reason could be that the evaluation of the evaporative heat loss against the increased metabolic thermogenesis due to physical exercise was underestimated. On the whole, correspondence between the PHS model and the experiment was not very good. The reason could be that it was constructed to predict water loss and core temperature in a working environment assuming a high metabolism. Moreover, calculation of skin temperature was not part of the objective, and in the process of calculation, numerical values are set based on multiple regression analysis, and thus the correspondence with skin temperature is worse in all cases. From the above-mentioned results, the 2NM is adopted as the human thermal physiological model which best agrees with the objectives of this study, and thus the accuracy of the model was further improved.

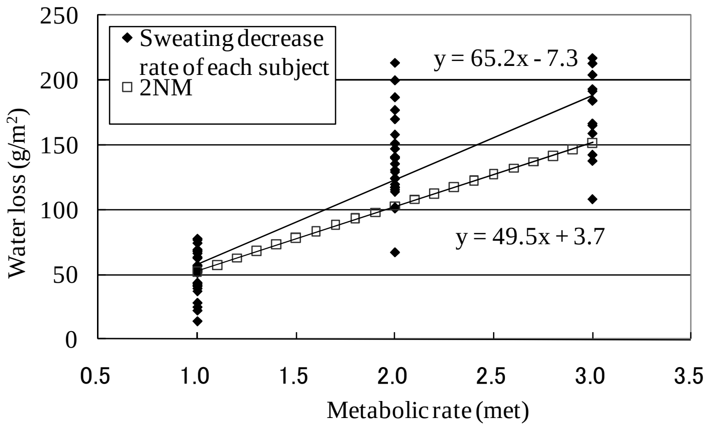


Fig. 5. Relationship between the metabolic rate and water loss (up to 3.0 met)

4. Improvement of the sweating model in 2NM [i)]

4.1 Proposal for improved sweating model

Figure 5 shows the relationship between the metabolic rate and the cumulative water loss. The cumulative water loss is an integrated value for 45 minutes. When the prediction values for the 2NM are compared with the experimental values, in terms of the increase in cumulative water loss caused by the increased metabolic rate, the experimental values were higher, and thus the sensitivity for the metabolic rate of the 2NM is poor in regard to the cumulative water loss. For that reason, the equation for the sweating model of the 2NM is shown below and discussed.

$$m_{sw} = \left\{ 170 \cdot \left(T_b - 36.49 \right) \cdot \exp\left(\frac{T_{sk} - 33.7}{10.7} \right) \right\} \quad (1)$$

where m_{sw} is the sweating rate, T_b is the average body temperature, and T_{sk} is the skin temperature. In addition, when T_b increases by 1.0°C, m_{sw} increases by 170 g/hm^2 on average. Equation (1) is only a function of the core and skin temperatures. Although an increase in metabolism causes an increase in the sweating rate through raised core and skin temperatures, the effect of such metabolism is not directly included in Eq. (1). The average temperature of the human body T_b can be predicted by the weighted average of the skin and core temperatures:

$$T_b = \alpha T_{sk} + (1-\alpha) T_{cr} \tag{2}$$

The value of the weighting coefficient α depends on the rate of blood flow to the skin:

$$\alpha = 0.0418 + 0.745 / (3600\dot{m}_{bl} + 0.585) \tag{3}$$

where, $\dot{m}_{bl}$ is the blood circulation between core and skin.

On the other hand, besides the body temperature information, some reports suggest that exercise itself stimulates sweating independently. Yanagimoto *et al.* (2003) conducted subject experiments using a bicycle exercise at 60 rpm at random for 60 seconds based on the exercise strength for three cases in a climate chamber whose air was maintained at 35°C with 50% relative humidity and minimum air movement. They found that the sweating response increased from hairy skin (chest, forearms and thighs) as the exercise strength increased during such exercising before the body temperature changed (Yanagimoto *et al.*, 2003). According to Kondo (2005), if dynamic exercise is conducted in sweaty conditions, the sweating increased within a few seconds without the core and skin temperatures changing. On the other hand, the skin blood flow briefly decreases at the beginning of dynamic exercise. It was pointed out that these responses depend on the exercise strength (Kondo, 2005). In order to ensure blood flow in muscles during dynamic exercise, the blood flow distribution to the skin is controlled. As a result, the amount of thermal diffusion decreases. To offset this decrease, it is thought that a non-thermal factor causes an increase in sweating (Kondo, 2005). It is necessary to reconsider the model in terms of the influence on sweating of exercise strength, which increases the metabolic rate.

Table 4 shows the ratio of the calculated value by substituting the experimented value of the skin and core temperatures in the sweating model of the 2NM and the experimental value according to the metabolic rate. Based on this ratio, the influence of the metabolic rate was included in the sweating model as expressed in Eq. (4). Moreover, the sensitivity analysis was conducted using the experimental values of Hayakawa *et al.* (1988) in a hot environment, and it was applied up to 6.0 met [ii)].

$$m_{sw} = \left\{170 \cdot (T_b - 36.49) \cdot \exp\left(\frac{T_{sk} - 33.7}{10.7}\right)\right\} \times \left[\left\{1 + 3 \cdot \exp\left(-0.5(M-1)\right)\right\} \cdot \left\{1 - \exp\left(-(M-1)\right)\right\}^2\right] \tag{4}$$

where M is the metabolic rate (met). Furthermore, in the 2NM, the maximum skin wettedness was set by the function of the wind velocity, and the evaporative efficiency of sweating was assumed to be 1.0 up to the point at which maximum skin wettedness was exceeded. However, the evaporative efficiency of sweating of Eq. (5) (Alber-Wallerström and Holmér, 1985, Candas *et al.*, 1979, Peters, 1995) was introduced in the improved model, and now approaches the actual evaporative thermal diffusion phenomenon.

When $w < 1.0$,

$$\eta = 1 - \frac{w^2}{2} \tag{5}$$

$$E_{rsw} = \eta \cdot 0.68 \cdot m_{sw} \tag{6}$$

Table 5 summarizes the improvements to the sweating model. Figure 6 shows the experimental value of water loss for 15 minutes in existing research up to 6.0 met (Hayakawa *et al.*, 1988) and the numerical results of the 2NM (Kondo, 2005),and the numerical results of the improved sweating model (2NMnew) which incorporates 2NM. The experiment was conducted in an environment with air temperature of 35°C, MRT of 35°C, relative humidity of 50%, and wind velocity of less than 0.2 m/s. Clothing insulation was rated at 0.5 clo. Subjects exercised for 15-minute stages on an Ergometer at four metabolic rates: 0.91 met, 2.66 met, 4.37 met and 6.20 met. The subjects were five healthy females.

Table 4 Variation in water loss as the metabolic rate changes in 2NM.

	Metabolic rate (met)	2.0	3.0
Average water loss (g/hm^2)	Experimental value	192.1	235.6
	Calculated value using experimental values of the skin and core temperatures	112.4	135.9
	Ratio (-)	1.71	1.73

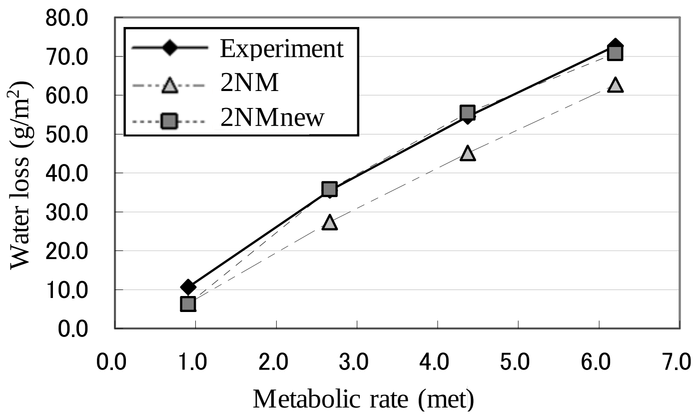


Fig. 6. Relationship between the metabolic rate and the water loss (up to 6.0 met). Experiment was conducted by Hayakawa *et al.* (1988) (Air temperature: 35°C, Relative humidity: 50%).

Table 5 Improvements to the 2NM sweating model

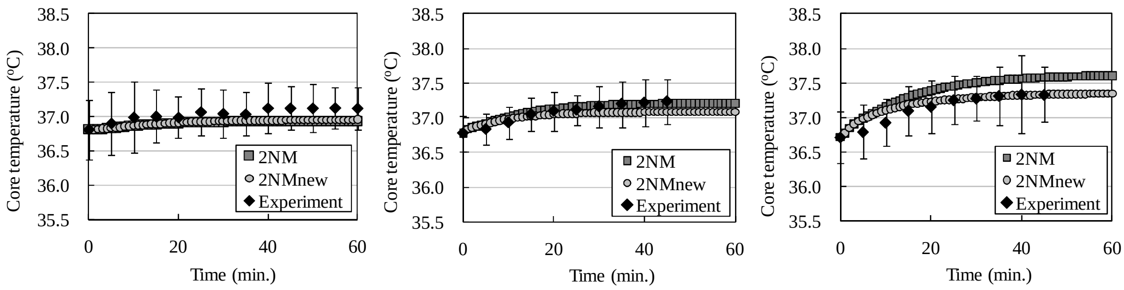
Description	Existing 2NM	Improved 2NM
Integration of the influence of the metabolic rate on the sweating rate	$m_{sw}=\left\{170\cdot\left(T_b-36.49\right)\cdot\exp\left(\frac{T_{sk}-33.7}{10.7}\right)\right\}$	$m_{sw}=\left\{170\cdot\left(T_b-36.49\right)\cdot\exp\left(\frac{T_{sk}-33.7}{10.7}\right)\right\}$ $\times\left[\left\{1+3\cdot\exp\left(-0.5(M-1)\right)\right\}\cdot\left\{1-\exp\left(-(M-1)\right)\right\}^2\right]$
Integration of the evaporative efficiency of sweating	$E_{max}\geq 0$ $E_{rsw}=0.68\cdot m_{sw}$ $w_{rsw}=E_{rsw}/E_{max}$ $w=0.06+0.94\cdot w_{rsw}$ $E_{sk}=w\cdot E_{max}$ $w_{dif}=0.06(1-w_{rsw})$ $E_{dif}=w_{dif}\cdot E_{max}$ Maximum skin wettedness w_{max} set by wind velocity. when, clo=0 $w_{max}=0.38\cdot V^{(-0.29)}$ when, clo >0 $w_{max}=0.59\cdot V^{(-0.08)}$ Greater than skin wettedness: when $w\geq w_{max}$ All sweating is evaporative sweating below the maximum skin wettedness, and the sweat trickles away when maximum skin wettedness is exceeded. $w=w_{max}$ $w_{rsw}=(w-0.06)/0.94$ $E_{rsw}=w_{rsw}\cdot E_{max}$ $w_{dif}=(1.0-w_{rsw})\cdot 0.06$ $E_{dif}=w_{dif}\cdot E_{max}$ $E_{sk}=E_{rsw}+E_{dif}$ $m_{drip}=(m_{sw}\cdot 0.68-E_{rsw})/0.68$	$E_{max}\geq 0$ The initial value of skin wettedness is arbitrary (Default is 0.06 of insensible perspiration assuming no sweating.) Maximum skin wettedness of 1.0 Evaporative efficiency of sweating at time *i*, $\eta_i=1-\frac{w_{i-1}^2}{2}$ when, $w_{i-1}<1.0$ $E_{rsw}=\eta\cdot 0.68\cdot m_{sw}$ $w_{rsw}=E_{rsw}/E_{max}$ $w_{dif}=(1.0-w_{rsw})\cdot 0.06$ $E_{dif}=w_{dif}\cdot E_{max}$ $w=w_{rsw}+w_{dif}$ $E_{sk}=w\cdot E_{max}$ Greater than maximum skin wettedness: when $w_{i-1}=1.0$ $w=1.0$ $w_{rsw}=1.0$ $E_{rsw}=E_{max}$ $w_{dif}=0$ $E_{sk}=w\cdot E_{max}$ $m_{drip}=(m_{sw}\cdot 0.68-E_{rsw})/0.68$

4.2 Verification of 2NM using improved sweating model

The experimental values were compared with the calculated values using the existing sweating model (2NM) and the newly developed sweating model (2NMnew), and the accuracy of the 2NMnew was verified.

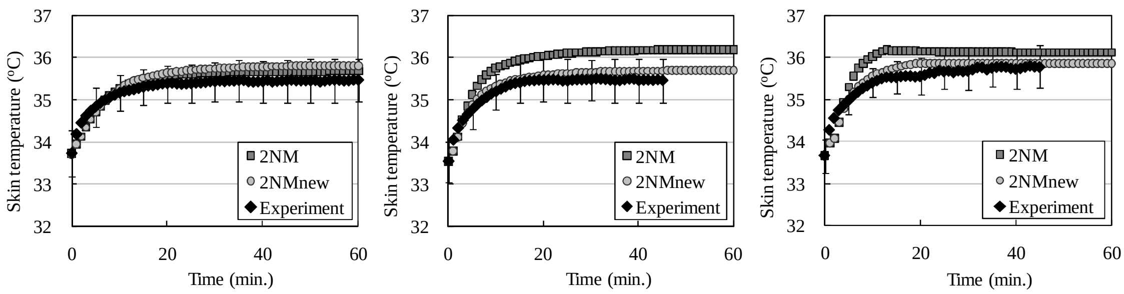
Fig. 7 shows the results for the core temperature. There was almost no change in the low metabolic rate, and both the 2NM and 2NMnew were close to the experimental value. In the case of a high metabolic rate (2.0 met), it was 0.17°C lower than the experimental value, which is within the standard deviation. It was very close to the experimental value in the case of 3.0 met. Figure 8 shows the results for skin temperature. In the case of the low metabolic rate, the 2NMnew was 0.35°C higher than the 2NM, which is within the standard deviation. In the case of the high metabolic rates (2.0 met and 3.0 met), both were close to the experimental values. Fig. 9 shows cumulative water loss. As a result of the skin temperature, there was almost no change in the low metabolic rate, and both the 2NM and 2NMnew values were close to the experimental values. In the case of the high metabolic rates (2.0 met and 3.0 met), both were close to the experimental values.

Due to the increased heat loss by evaporation, the core and skin temperatures decreased, and the values were close to the experimental values. On the whole, it can be said that 2NMnew is more accurate than 2NM.



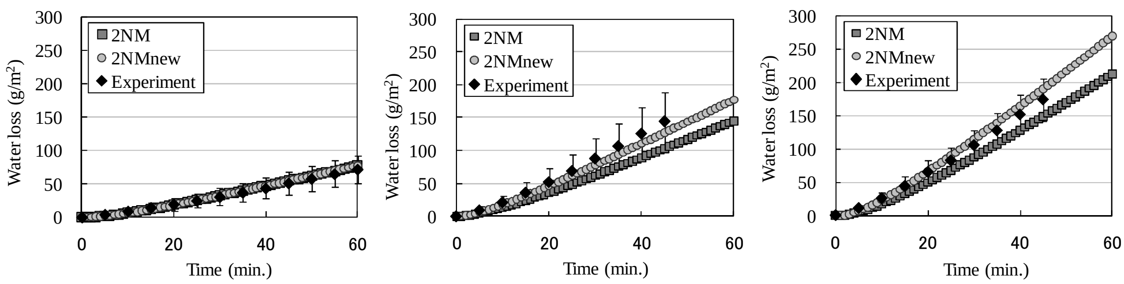
(a) Case 1 (b) Case 2 (c) Case 3

Fig. 7. Result for core temperature from the 2NM using the improved sweating model



(a) Case 1 (b) Case 2 (c) Case 3

Fig. 8. Results for skin temperature from the 2NM using the improved sweating model



(a) Case 1 (b) Case 2 (c) Case 3

Fig. 9. Results for cumulative water loss from the 2NM using the improved sweating model

5. Evaluation of thermal safety in hot environments

In ISO 7933 (2004), a core temperature exceeding 38.0°C is defined as dangerous. Furthermore, water loss is deemed dangerous if it is greater than 3% by body weight if drinking water is not available, and 7.5% of weight for 50% of people, or 5% for 95% of people when drinking water is available. By predicting the physiological element of the unsteady state using the human thermal physiological model, the possible exposure time in a hot environment can be calculated, from the value of threshold limits to hot environment exposure for each physiological amount (ISO 7933, 2004).

Moreover, water supply is very important to prevent heat-related problems. Otani *et al.* (2003) found that when working or exercising in a hot environment, a water supply equivalent to the amount sweated is most effective to control the rise in core temperature and to maintain body fluid homeostasis. That is to say, water replacement is the most effective way to prevent heat-related problems and a decline in exercising ability. By precisely calculating bodily water loss using the human thermal physiological model, the necessary amount of water replenishment can be calculated, and thus it is possible to positively prevent heat-related problems.

Furthermore, SET* shows the relationship between sensation and the physiological response (Nakayama, 1981). By using this, it is also possible to evaluate the thermal safety of an environment roughly similar to the WBGT.

5.1 Example application: walking outdoors

The possible exposure time walking in a hot environment in shaded and non-shaded areas around a single building, the SET* and the amount of water supply necessary were calculated using the 2NM and 2NMnew. For the environmental conditions, the results for convection and radiation calculations of a single building model at 13:00 hrs on 23 July in Tokyo were used. Figure 10 shows the simulation model. The analysis domain is 110 m (x) × 110 m (y) × 60 m (z), the size of the building model is 10 m × 10 m × 10 m, and the building and ground surface are all assumed to be concrete. The Monte Carlo method is used for the radiation calculation, and the standard k-ε model is used for the convection calculation. The calculation method can be found in Chen *et al.* (2004). The albedo, long wavelength emissivity and the convection heat transfer coefficient of the building and ground were assumed to be 0.2, 0.95, and 11.6 W/m^2 respectively. The wind velocity was assumed to have a one-quarter power profile of 2.0 m/s at the 10-m building height. An air temperature of 31°C and an initial value of 2.8 Pa (relative humidity of 61.6%) for the water vapor pressure of the atmosphere were applied to all analytical areas. The possible exposure time in the hot environment, the SET* and the amount of water supply necessary were calculated at Point A (un-shaded) and Point B (shaded) in Fig. 10. The calculation method for the MRT of the human body is given in the footnote [iii)]. The body surface area was calculated using the DuBois formula based on the average Japanese height and weight (161.9 cm and 59.0 kg). The shortwave absorption rate of the human body, long wavelength emissivity, and clothing insulation were 0.5, 0.95 and 0.5 clo respectively. Assuming an outdoor walking condition, the metabolic rate was set to 2.0 met. In addition, the heat transfer coefficient of the human body surface was calculated using the equation of Seppanen *et al.* (1972) (ASHRAE, 2009). Table 6 shows the environmental conditions of Points A and B, and the human body conditions.

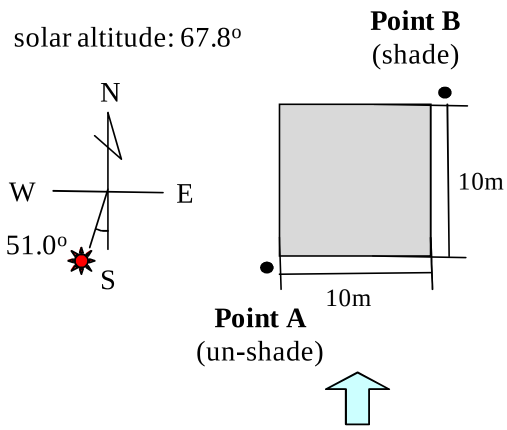


Fig. 10. Simulation model for convection and radiation calculations.

Table 6 Calculation conditions for 2NM and 2NMnew

Descriptions	Air temperature (°C)	MRT (°C)	Relative humidity (%)	Wind velocity (m/s)	Clothing insulation (clo)	Metabolic rate (met)
Point A (un-shaded)	31.2	53.3	61.7	1.98	0.5	2.0
Point B (shaded)	31.2	43.8	61.5	2.01		

5.2 Results and discussions

Table 7 shows the calculated results of the possible exposure time in the hot environment, the SET* and the amount of necessary water supply. When we compare the 2NMnew and 2NM, both SET* were 34°C in the un-shaded area and 32.2°C in the shaded area, and thus no difference was discerned by the model. However, the possible exposure time in the hot environment of the 2NMnew was 26 minutes less compared with the 2NM both for the shaded and non-shaded areas. The amount of water supply necessary after 1 hour in the 2NMnew was 49.5 g more in un-shaded areas and 37.3 g more in shaded areas. When we compare the shaded and un-shaded areas, the possible exposure time in a hot un-shaded environment was 36 minutes less for both 2NMnew and 2NM, and the amount of water supply necessary after 1 hour was 47.8 g more in 2NMnew and 36.5 g more in 2NM. The revised sweat predictions in 2NM have a significant effect on water supply and thus the revisions are very important for safety applications [iv)].

Table 7 Possible exposure time in hot environments, SET*, and the amount of water supply necessary

Descriptions	Point A (un-shaded)		Point B (shaded)	
	2NM	2NMnew	2NM	2NMnew
Possible exposure time in a hot environment (min.)	214	188	250	224
SET* (°C)	34.0	34.0	32.2	32.2
The amount of water supply necessary after 1 hour (g)	263.4	312.9	227.8	265.1

6. Conclusions

This study aimed to improve the evaluation of thermal safety of hot outdoor environments by improving an index of heat stress on the body, and to quantify positive countermeasures to heat-related problems.

(1) In order to clarify the thermal physiological response of the human body in hot environments, subject experiments were conducted in Japan. Seasonal adaptation was found to influence the experimental results.

(2) Using the summer data, the results for the core temperature, skin temperature and amount of sweating were compared with the 2NM and PHS models. The results showed the 2NM was accurate in low metabolic cases.

(3) A new sweating model (2NMnew) was proposed by integrating metabolic influences into the 2NM sweating model. The prediction accuracy of 2NMnew was improved, especially in the high metabolic rate region.

(4) The possible exposure time in hot environments in shaded and non-shaded areas around a single building, the SET*, and the amount of water supply necessary (equivalent to the amount of water lost) were calculated using the 2NM and 2NMnew, and estimates of the thermal safety of that environment and of necessary countermeasures can be more accurately determined.

(5) In this research, healthy male and female university students were examined. However, to extent its applicability to the elderly and children who are at greater risk, it is necessary to widen the subject experiment.

Nomenclature

T_{cr}	Core temperature (°C)
T_{sk}	Skin temperature (°C)
T_b	Average body temperature (°C)
M	Metabolic rate (met)
η	Evaporative efficiency of sweating (-)
E_{max}	Maximum possible evaporative heat loss (W/m^2)
E_{sk}	Evaporative heat loss from skin (W/m^2)
E_{rsw}	Evaporative heat loss due to regulatory sweating (W/m^2)
E_{diff}	Evaporative heat loss due to moisture diffusion through skin (W/m^2)
m_{sw}	Sweating rate (g/hm^2)
m_{drip}	Fraction of sweat trickles away (g/hm^2)
w	Skin wettedness (-)
w_{rsw}	Skin wettedness required to evaporate regulatory sweat (-)
w_{diff}	Skin wettedness due to moisture diffusion through skin (-)
clo	Clothing insulation (clo)
v	Wind velocity (m/s)

Footnotes

i) When 2NM is improved, any discrepancies arising from differences in race or environment are expected to be treated as other parameters. As for 2NM parameters which may cause a difference, the following can be considered: the blood flow volume, the thermal capacity and thermal resistance in the core area due to differences in the percentage of fat, the bone quantity, and the muscle quantity ratio. Although not shown in this paper, some sensitive analysis was conducted into these parameters. When the influence of these parameters was examined, hardly any difference was found. That is to say, the results tend to diverge from experimental values. Hence, the influence of these parameters is small, and they were not considered in these improvements to the 2NM.

ii) The derivation of the improved sweating model is given below. Equation (1), which is shown in the main text, is multiplied by the correction term $X(M)$.

$$m_{sw} = \left\{ 170 \cdot \left(T_b - 36.49\right) \cdot \exp\left(\frac{T_{sk} - 33.7}{10.7} \right) \right\} \cdot X\left(M\right) \tag{7}$$

where, $X(M)$ is the function of the metabolic rate (met). At a low metabolic rate ($M = 1$), the accuracy of the sweating prediction of 2NM is high, and thus it is assumed to be $X(1) = 1$. Sweat promoted by exercise is assumed to be caused by signals of muscle stimulation, and in conditions of significantly high metabolic rate, the influence of the stimulation is assumed to be small. That is to say, $X(\infty)=1$ is the constraint condition. Hence, $X(M)$ is determined as follows.

$$X(M) = 1 + X'(M), \quad X'(1) = 0, X'(\infty) = 0 \tag{8}$$

$$X'(M) = X_1(M) \cdot X_2(M), \quad X_1(1) = 0, X_2(\infty) = 0 \tag{9}$$

$X_1(M)$, $X_2(M)$ are formulated as follows.

$$X_2(M) = a(\exp(b(M-1)))^c$$

$$X_1(M) = (1-\exp(d(M-1)))^e \tag{10}$$

where, $a \sim e$ are model constants. In the above-mentioned formulation, the constants $a \sim e$ were decided by agreement with the experiments in this research (Fig. 5) and the experiment by Hayakawa *et al.* (1988) (Fig. 6). The profile of $X(M)$ is shown in the supplement Fig. A1. It is 1 for $M=1$, and the peak is approached at $M=2.5$, with the curve gradually decreasing afterwards.

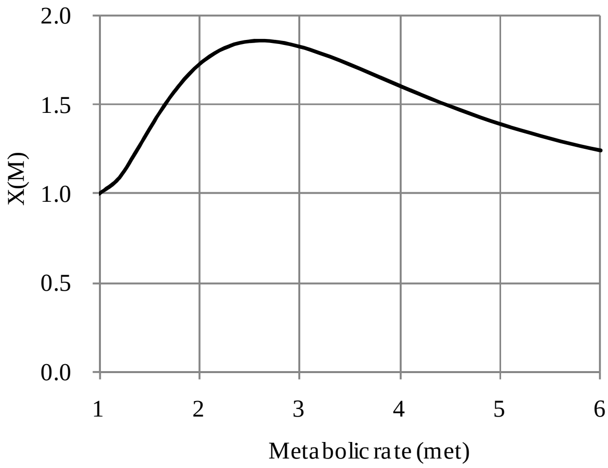


Fig. A1. Profile of the X(M).

iii) The MRT T_{ri} at position *i*, which is considered the total radiation energy including solar radiation, is calculated by Eq. (11).

$$6h^2\sigma T_{ri}{}^4 = 6h^2\sum_{l=-3}^{3} q_l \alpha_h c_l + 6h^2\sum_{l=-3}^{3}\left[\sum_{j=1}^{n} B_{lj}\sigma T_j{}^4 c_l\right] \tag{11}$$

T_{ri} The MRT at position i (K)

L Index to express the direction of the surface, which is composed of a micro-cube (6 surfaces in total)

q_l Solar radiation which reaches the surface l of the micro-cube (direct + diffusion + reflection) (W/m^2)

c_l Weighting coefficient related to absorption of solar radiation by each surface of the micro-cube. A coefficient of 0.024 is used for the top and bottom surfaces of the cube, and 0.238 is used for the sides (Nakamura, 1987).

T_j Temperature of the micro-surface element j (K)

α_h Shortwave radiation (solar radiation) absorptance of body (-) (In this research, α_h = 0.5)

B_{lj} Coefficient of absorption to the *l* surface of the micro-cube from arbitrary element *j* (ND).

h The length of a side of the micro-cube. However, it is not necessary in the calculation.

The first term on the right hand side of Eq. (11) shows the radiation energy due to solar radiation, while the second term shows the long wave radiation energy.

iv) The simulation of Section 5 was conducted by assuming the actual outdoor environmental conditions. However, the experiment for the original sweating equation which is proposed in this study was conducted indoors, and thus environments peculiar to the outdoors, such as strong radiation and wind, were not considered. On the other hand, in this study, if the thermal acquisition is the same, the thermal response of the human body is based on the assumption of the same response even though it has a different form (for example, due to radiation or convection). Of course, if these forms are different even though the thermal acquisition is the same, the human body may exhibit a different thermal response. To resolve this matter, further investigation is required in the future.

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