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A '*heart rate*'-based model (PHS_{HR}) for predicting personal heat stress in dynamic working environments

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Abstract

The parameter of human body metabolic rates has been popularly used for the prediction of human heat stress in hot environments. However, most modules use the fixed and estimated metabolic heat production. The aim of this study is to develop the prediction of personal heat stress in dynamic working environments. Based on the framework of the predicted heat stress (PHS) model in ISO 7933, a heart-rate based PHS_{HR} model has been developed using the time-based heart rate index, which is suitable for prediction in situations where metabolic rates are dynamic and there are inter-individual variations. The infinitesimal time unit Δt_i, has been introduced into the new PHS_{HR} model and all the terms used in the PHS model related to metabolic rates are thus redefined as the function of real-time heart rates. The PHS_{HR} has been validated under 8 experimental combined temperature-humidity conditions in a well-controlled climate chamber. The feature of the PHS_{HR} model is being able to calculate dynamic changes in body metabolism with exposure time. It will be useful to the identification of potential risks of individual workers so to establish an occupational working environment health and safety protection mechanism by means of simultaneous monitoring of workers' heart rates at the personal levels, using advanced sensor technology.

Keywords: Heat stress, PHS model, Metabolic rate, Heart rate, Infinitesimal time

Nomenclature

A	body surface area (m^2)
A_D	DuBois body surface area (m^2)
Ar	effective radiation area of body(m^2)
Ag	Age (yr)
pa	water vapor partial pressure (Pa)
H	height of human body (cm)
W	weight of human body (kg)
I_{cl}	total thermal insulation of clothing (clo)
f_{cl}	clothing area factor
h_r	radiant heat transfer coefficient (W/m^2)
h_c	convective heat transfer coefficient ($W/m^2 \bullet {}^oC$)
C	convective heat losses (W/m^2)
R	radiative heat losses (W/m^2)
C_{sp}	specific heat of the body (J/kg^oC)
RES	respiratory heat (W/m^2)
C_{res}	respiratory convective heat flow per body surface area (W/m^2)
E_{max}	maximum evaporative heat flow at the skin surface (W/m^2)
E_{res}	evaporative heat loss from respiration per body surface area (W/m^2)
dS_{eq}	body heat storage rate for increase of core temperature (W/m^2)
E_{req}	required evaporative heat flow (W/m^2)
PHS	predicted heat stress model
PHS_{HR}	Heart-rate-based PHS model
HR	Heart rate during activity (bpm)
HR_0	resting heart rate, normally defined as 65bpm when unknown (bpm)
HR_i	heart rate at the time point of "i", (bpm)
HR_{max}	the maximum heart rate based on age (bpm)
M	total metabolic rate (W/m^2)
M_0	resting metabolic rate, normally defined as 55 W/m^2 when unknown (W/m^2)
M_i	metabolic rate at the time point of "i" (W/m^2)

M_{max}	the maximum metabolic rate (W/m^2)
T_{cr}	core temperature (^{o}C)
T_{cl}	mean temperature of the outer surface of the clothed body (^{o}C)
$T_{cr,eq}$	core temperature as a function of the metabolic rate (^{o}C)
$T_{cr,i}$	core temperature at time point “i”(^{o}C)
T_{sk}	skin temperature (^{o}C)
T_{re}	rectal temperature (^{o}C)
$T_{sk,0}$	the initial skin temperature of the subject at resting status(^{o}C)
$T_{sk,i}$	the skin temperature at the time point "i"(^{o}C)
$T_{sk,eq}$	skin temperature as a function of the metabolic rate (^{o}C)
$T_{sk,eq,x}$	the ideally stable skin temperature at the time point “x”(^{o}C)
MST	mean skin temperature (^{o}C)
t_a	mean air temperature (^{o}C)
RH	relative humidity (%)
t_r	mean radiant temperature (^{o}C)
v_a	mean air velocity (m/s)
t_i	time point after $i*\Delta t$ (s)
Δt	time infinitesimal
x	intermediate variables, $1< x< i$
i, i-1	time point
α	proportion of core part in body weight, normally at 0.22
εsk	average emissivity of skin
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant (W/ (m^2•K^4))
$\sigma*\varepsilon sk*Ar/AD$	constant value, normally taken as $4.234923*10^{-8}$
Mean	mean value of the data
SD	standard deviation

1. Introduction

According to the “Fourth Assessment Report” from IPCC, climate change has led to an increase in ambient temperatures around the world[1] and a warming of 0.2 ^{o}C per decade is projected for the next two decades. The consequent extremely hot environments have created a great threat to people’s health and work performance [2], and increased heat-related morbidity and mortality[3]. It is estimated that there are two out of every 1,000 people exposed to high overheating risks[2]. In 2003, for example, heatwaves led to extra mortality and morbidity in the population during the summer in Europe[4] and North America[5-7]. As the risk of heat-related illness and injuries is expected to rise[8,9] due to the globally frequent hot days and heatwaves[10], preventing occupational heat stress presents a great challenge requiring a concerted and multi-disciplinary effort from employers, health authorities, engineers, and researchers[11]. Although workers on construction sites, military operations, sports training, factory workshops, etc., would have a higher health and safety risk in such situations, the extent and consequences of heat exposure in different occupational settings, countries, and cultural contexts are not well studied[11]. As such, it is of importance to evaluate accurately the heat stress of workers in such high- temperature working environments[12, 13], which is helpful in producing legislation and making instant managerial decisions to mitigate overheating risks.

The high-temperature working environment is defined as one in which the dry bulb temperature is over 35 ^{o}C with the combined effect of radiation, high humidity and other thermal factors[14], and that would cause significant heat storage in the human body[15,16]. The initial studies have mainly concentrated on the physiological responses of the human body to heat stimuli and health protection[17-20], and the indices to evaluate heat stress (e.g. the thermal work limit (TWL)[21,22], the equivalent temperature (ET)[22], and the air enthalpy[23]). According to these studies, upper limits for some human physiological indices have been recommended. For example, a rectal temperature of 38 ^{o}C-38.2 ^{o}C is suggested to be the upper limit for light work while a value of 39.2 ^{o}C is the upper limit for heavy work[24]. In addition, it is suggested in ISO 9886 that the maximum heart rate should be under 180bpm during work [25]. Moreover, studies on the effect of heat acclimatization showed that the overheating risk would be increased by over 50%[2] for people without heat acclimatization, while acclimatization to extreme hot environments would modify the human physiological responses: reducing heart rates[26], decreasing core temperatures[27], lowering the sweating threshold[27, 28], and increasing exposure time to fatigue[29, 30]. Therefore, ISO 7933-1989[31] suggests a maximum sweat rate of 780g/h-1040g/h for acclimatized individuals while the acceptable value is just half that for people without heat acclimatization.

With the in-depth studies on heat stress, some evaluation indices[32-36] are proposed, aiming to predict the human thermoregulation and give guidance for specific populations from the view of health, safety, and work performance. More than 100 heat stress indices and models have been developed during this time, with varying complexity and easiness to use [37]. Havenith and Fiala reviewed[38] the most commonly used indices and models, looking at how these were deployed in the different contexts of industrial, military and son on. In general, these indices have been categorized into three types[2]: 1) the rational indices (e.g. Heat Stress Index(HSI), Required Sweat Rate(SW_{req}), Predicted Heat Stress(PHS)) based on the heat balance equation for the human body; 2) the empirical indices (e.g. Effective Temperature(ET), Predicted Four Hour Sweat Rate(P4SR)) based on the experience indicators in hot environments and their physiological response; 3) the direct indices (e.g. Wet Bulb Globe Temperature(WBGT), Oxford Index(WD)) based on environmental parameters. Parsons[39] summarized the different assessment methods in the ISO series of standards on heat stress and discussed the improvements for different indices. Among these indices, the rational indices are recognized as the most complex but the most accurate ones. Based on the 672 experiments in 8 European thermal physiology laboratories and 237 field experiments, Malchaire[40] improved the typical SW_{req} in ISO 7933[31] and proposed the modified index - the Predicted Heat Strain model (PHS) - in 2001, which laid the foundation for the PHS model for heat stress prediction. During the next few years, the accuracy of the PHS model was widely examined and compared to the other indices. Kampmann[41], comparing the PHS and SW_{req} indices, showed the results from the PHS model were much better. Further comparison by Malchaire and Piette[40] between the PHS model and the WBGT index similarly manifested the advantages of the PHS model in heat stress prediction. Ingvar[42] analyzed WBGT and PHS under similar climate conditions and the results indicated that WBGT provided a more conservative assessment that allowed much shorter working times than did the PHS model. Besides, the PHS model provides a method to predict the maximum allowable exposure time through calculating the limitations of rectal temperature and the water loss[43-45]. Malchaire[46] found that the PHS ensured a high degree of accuracy for the sweat rate and rectal temperature between the predicted values and the measured values via experiments and on-site surveys. A number of powerful verifications contribute to the results so that the PHS model has been adopted in the ISO 7933-2004[47] and remains widely used today.

However, the PHS model is too complicated due to the difficulty in measuring all these parameters accurately and the limitations of cheap and compact computing power, which thwarts its application more widely[38, 39]. More importantly, it fails to reflect some non-environmental or physiological factors affecting human heat stress (e.g. changing work intensity, individual differences, etc.), leading to some deviations in application[44]. In fact, the workers’ activity levels change from time to time at work but the metabolic rate input in the traditional PHS model is mainly based on the estimated values, thus failing to reflect the real-time and continuous changes of metabolic rates. To close these gaps, it is necessary to modify the PHS model to simulate responses of individuals rather than population-based /group-based responses. As a result, the aim of this research is to develop an improved PHS model through adopting the easily-obtained physiological index - the heart rate - to provide dynamic metabolic rate estimations and reflect the inter-individual variations. In addition, the infinitesimal time Δt_i is introduced into the framework of the PHS model, in order to simplify the calculation and application. The developed model is expected to predict heat stress at the level of individuals in a dynamic process due to allowing the real-time inputs of personal heart rates and predicting the personal heat stress in responding to changing environmental parameters through opening the time-iterative program in the PHS model.

2. Modification of the PHS model

2.1 Basic theory of the PHS model in ISO 7933

The PHS model in the current edition of ISO 7933 was prepared by Technical Committee ISO/TC159, Ergonomics, Subcommittee SC5 and Ergonomics of the Physical Environment[47]. The basic human heat balance equation in the PHS model is described in Eq. (1).

$$E_{req}=M-C_{res}-E_{res}-C-R-dS_{eq} \tag{1}$$

Where

E_{req}: required evaporative heat flow, W/m^2;

M: metabolic heat generation, W/m^2;

C_{res}: convection heat exchange of respiration, W/m^2;

E_{res}: evaporation heat exchange of respiration, W/m^2;

C+R: convective and radiant heat exchange between body surface and surroundings, W/m^2;

dS_{eq}: body heat storage under heat stress, W/m^2;

The different terms of Eq.(1), like RES, C&R and dS_{eq}, and the involved variables during calculation in the PHS model are shown in Table 1.

Table 1: The terms used in the PHS model

Terms	Equations	Involved Variables
RES	$C_{res}=0.00152M(28.56-0.885t_a+0.641P_a)$	M, t_a, P_a
	$E_{res}=0.00127M(59.34+0.53t_a-11.63P_a)$	M, t_a, P_a
C&R	$C=h_{cdyn}\times f_{cl}\times(T_{cl}-t_a)$	T_{sk}, T_{cl}, t_a, v_a, M, I_{cl}
	$R=h_r\times f_{cl}\times(T_{cl}-t_r)$	T_{sk}, T_{cl}, tr, I_{cl}
dS_{eq}	$dSeq=C_{sp}\times\left(T_{cr,eq,i}-T_{cr,eq,i-1}\right)(1-\alpha)$	$T_{cr,i}$

From Table 1, the PHS model includes a wide range of direct and intermediate variables. However, some of them are difficult to obtain in the practical working process, such as the rectal temperatures and the varying metabolic rates. Besides, the closed calculation program through time iteration in the PHS model fails to provide the intermediate results during a dynamic working process.

2.2. Modification of the PHS model

As discussed above, the PHS in ISO 7933[47] has some shortcomings in its application; thus, in this study we focus on modifying the PHS model considering the following principles:

a) to replace estimated metabolism in the PHS model with more convenient and real-time measurable parameters;

b) to limit system deviations caused by intermediate variables and simplify the computation process making it suitable for real world practice.

2.1.1 Metabolic rate (M)

As seen in Table 1, the variable M is a required parameter for the PHS model. However, in most cases, M is estimated by the different job classification and empirical estimation based on ISO 8996[48]; whereas it will change with time and thermal environments. Under such a case, the value of M would significantly affect the prediction accuracy of the PHS model.

From the concept of physiology, heart rate and oxygen consumption are the two main parameters to estimate metabolic rates accurately. Measuring the rate of oxygen consumption requires an analysis of the person’s expired air, which needs to be collected over the period of interest using a “Douglas bag”. The problem is not to interfere with the task being measured and avoid problems with leaks, experimental variability, and calibration, which is almost unachievable in the workplace[49]. In contrast, studies have shown that the human heart rate changes significantly with different working status and is a typical physiological index to reflect the metabolic rate[2, 50]. Thanks to advanced sensor technology, wearable heart rate sensors are available on the market which could be used to monitor workers’ simultaneous heart rates during a working process. Therefore, in this study the idea emerged to use the ‘heart rate’ as an input parameter to estimate the ‘metabolic rate’ in the original PHS model.

Based on the ISO 8996[48], the prediction of metabolic rate based on heart rate can be defined using Eq. (2).

$$M_i=M_0+\frac{HR_i-HR_0}{180-0.65Ag-HR_0}\left[(41.7-0.22Ag)\times W^{0.666}-M_0\right] \qquad (2)$$

Where:

M_i: metabolic rate at t=i, W/m^2;

M_0: initial metabolic rate at t=0, W/m^2;

HR_i: heart rate at t= i, bpm;

HR_0: heart rate at t= 0, bpm;

Ag: age of subject, yr;

W: weight of subject, kg.

2.1.2 Convective, and evaporative heat exchange of respiration

In Table 1, the convection and evaporation heat transfer of respiration, RES can be defined as the function of M, t_a and P_a, as shown in Eq. (3).

$$RES=M_i(0.118773-0.00067t_a-0.01379578P_a) \tag{3}$$

Where

M_i: the metabolic rate at t=i;

t_a: the air temperature, ^oC;

P_a: the atmospheric pressure, kPa.

2.1.3 Convective and radiative heat exchange from the body surface

The calculation of C&R in the PHS model introduces the intermediate variable of clothing temperature "T_{cl}". However, it is difficult to determine the size, style, and material of the clothing and other garments such as gloves and helmets of the workers in practical working situations. So in this study, the clothing temperature "T_{cl}" has been simplistically considered in the modification of C&R, which is expressed in Eqs. (4) (5).

$$C=h_cf_{cl}(T_{sk,i}-t_a) \tag{4}$$

$$R=h_rf_{cl}(T_{sk,i}-t_r) \tag{5}$$

Where:

h_c: convective heat transfer coefficient (W/m^2•^{o}C);

h_r: radiative heat transfer coefficient (W/m^2•^{o}C);

f_{cl}: clothing area factor;

$T_{sk,i}$: mean skin temperature at t=i, ^oC;

t_a: air temperature, ^oC;

t_r: radiant temperature, ^oC.

In Eqs.(4)(5), the key point is to determine the values of h_c and h_r. Referring to the ISO 7933[47], the convective heat transfer coefficient $h_{c,}$ which considers dynamic characteristics of convective heat exchange between body and environments, is dependent on the highest value according to the calculating results from Table 2.

Table 2: The value of h_c under different air velocities during working

Ventilation status	h_c
natural ventilation	$2.38\left\|T_{sk,i}-t_a\right\|^{0.25}$
$v_{ar} \leqslant 1m/s$	$3.5+5.2v_{ar}$
$v_{ar}>1m/s$	$8.7{v_{ar}}^{0.6}$

To note, the v_{ar} in Table 2 represents the relative air velocity during the period of working process, rather than the absolute air velocity. As the v_{ar} would affect the total clothing insulation, this study referred to the ISO 7933[47] definition:

1) when the environmental air velocity is more than 3m/s, the value of 3m/s is adopted;
2) when the walking speed is more than 1.5m/s, the value of 1.5m/s is adopted.
3) when the walking speeding is undefined or the person is static, the value can be calculated as: $v_{ar}=0.0052(M_i-58)$.

The radiative heat transfer coefficient "h_r" is expressed as Eq. (6).

$$h_r=\sigma\times\varepsilon_{sk}\times\frac{A_r}{A_D}\times\frac{\left[\left(T_{sk,i}+273\right)^4-(t_r+273)^4\right]}{T_{sk}-t_r} \tag{6}$$

The clothing insulation coefficient "f_{cl}"in Eqs. (4)(5) is defined as Eq. (7).

$$f_{cl}=\frac{1}{\left[(h_c+h_r)I_{cl}+\frac{1}{1+0.97I_{cl}}\right]} \tag{7}$$

In Eqs. (6,7), where

M_i: metabolic rate at t=i, W/m^2;

Ar: effective radiation area of body, m^2;

A_D: DuBois body surface area, m^2;

$\sigma\times\varepsilon_{sk}\times A_r/A_D$: constant, 4.234923×10^{-8};

$T_{sk,i}$: mean skin temperature at t=i, ^{o}C;

t_a: air temperature, ^{o}C;

t_r: radiant temperature, ^{o}C;

v_a: air velocity, m/s;

2.1.4 Body heat storage

When the human body is exposed to the hot environment with non-steady working states, the stable inner core temperature $T_{cr,eq,i}$ and the transient $T_{cr,i}$, will change over time. Therefore, introducing Eq.(2), where the M_i changes with the HR_i, the $T_{cr,i}$ in the original PHS model can be expressed as the function of HR_i. As a result, it would inevitably cause some deviations using the stable $T_{cr,eq}$ to predict dS_{eq}. In that case, the transient value of dS_{eq} at t=i is introduced, and the corresponding body heat storage at t= m and t= n (n> m, MIN (m) = 0), which stood for the period after m*Δt and before n*Δt, could be redefined as follows in Eqs. (8-10).

$$T_{cr,tm}=36.8+\sum_{i=1}^{m}0.0036(M_i-55)\times\left[1-\exp(-\frac{\Delta t_i}{10})\right] \quad (8)$$

$$T_{cr,tn}=36.8+\sum_{i=1}^{n}0.0036(M_i-55)\times\left[1-\exp(-\frac{\Delta t_i}{10})\right] \quad (9)$$

$$dS_{eq}=C_{sp}\times\left[36.8+\sum_{i=m}^{n}0.0036(M_i-55)\times\left[1-\exp(-\frac{\Delta t_i}{10})\right]\right]\times(1-\alpha) \quad (10)$$

Eqs (8,9) describe the changes of $T_{cr,t}$ with the real time metabolic rate M_i after a period of m*Δt and n*Δt. This based on the T_{cr} calculation in ISO 7933 but used the function M_i instead of M. Meantime, during the calculation, we transform the time iteration from ti to ti+1 to the cumulative sum of a period of Δt. Based on Eqs.(8,9), the cumulative effect on body heat storage from t=m to t=n can be reflected. Therefore, the original expression describing dS_{eq} in PHS model Table 1 can be transformed as the function of M_i, as shown in Eq (10).

Accordingly, the heat storage of the human body from t=0 to t=i can be defined as Eq. (11).

$$dS_{eq}=C_{sp}\times\left\{36.8+\sum_{x=1}^{\mathbf{i}}\left[0.0036(M_x\text{-}55)\times\left(1\text{-}\exp(\text{-}\frac{x}{10})\right)\right]\right\}\times(1\text{-}\alpha) \quad (11)$$

where

dS_{eq}: total heat storage of the human body, W/m^2;

C_{sp}: specific heat of body, 2890.435(J/kg ^{o}C);

x: calculating variable, $1 \le x \le i$;

α: weight of the core layer of body, 0.22.

In theory, the dS_{eq} would change continuously under some cases, including changing thermal environments, activity levels, locations, etc. In such cases, the introduction of the infinitesimal summation unit Σ in Eq. (11) has advantages in calculating the heat storage of the human body in such situations.

2.1.5 Intermediate variables

The skin temperature (T_{sk}) and core temperature (T_{cr}) are the intermediate variables during the calculation in the developed model, which will affect the accuracy significantly.

① *Core temperature T_{cr}*

The core temperature shows a fluctuation of exponential volatility over time in the PHS model; while in fact it acts as a function of the metabolic rate; hence, the changes of metabolic rate caused by the dynamic working status would significantly affect the prediction of the core temperature. Therefore, in the developed model, the introductions of the infinitesimal time variable Δti and indirect heart rate are considered to calculate the core temperature. The following definitions are proposed:

(a) the mean heart rate is $\overline{HR_i}$ at $t=t_i$;

(b) the mean heart rate variation is described by ΔHR during Δt_i;

(c) the corresponding metabolic rate change is ΔM.

As a result, the changes in body core temperature T_{cr} over time can be redefined as Eq. (12).

$$T_{cr,i}=36.8+\sum_{1}^{i}\left\{0.0036(M_i-55)\times\left[1-\exp(-\frac{i}{10})\right]\right\} \qquad (12)$$

② *Skin temperature T_{sk}*

Human skin temperature plays an important role in determining the heat exchange between the body and the ambient environment[2] so it is a main factor for the model prediction. In the PHS model, T_{sk} is determined through the iterative calculation process based on time. In fact, both the skin temperatures ($T_{sk,eq,i}$) at steady-state and at the transient ($T_{sk,i}$) would change simultaneously over time. With the introduction of Δt, the $T_{sk,eq,i}$ and M_i can be obtained at t=i , and thus the skin temperature $T_{sk,i}$ at the t= i after the period of i*Δt can be determined as in Eq. (13).

$$T_{sk,i}=0.7165^{i}T_{sk,0}+0.2835\sum_{x=1}^{i}T_{sk,eq,x}\times 0.7165^{i-x} \qquad (13)$$

The $T_{sk,eq}$ at steady state can be calculated as Eq. (14).

$$T_{sk,eq,i}=12.17+0.020t_a+0.044t_r-0.253v_a+0.194p_a+0.005346M_i+0.5124T_{cr,i} \qquad (14)$$

Where

$T_{sk,i}$: the mean skin temperature at t=i, °C;

$T_{sk,0}$: the mean skin temperature at t=0, input parameters according to measurement, °C;

x: the calculating variable, $1\leq x\leq i$;

$T_{sk,eq,x}$: the stable mean skin temperature at t=x, °C;

Indeed, at steady state the sensible heat loss from body skin surface to the adjacent clothing is equivalent to the value from clothing to surrounding. Given the $T_{sk,eq}$ would be significantly affected by changing clothing during work, the values thus should be modified by clothing insulation differences, as shown in Eqs. (15-17), according to the empirical formula[2]. Combined with Eqs.(12-14), the temperature of the clothing surface T_{cl} therefore can be calculated based on Eqs. (15-17). Eqs. (15-17) reflects the physiological responses of body skin temperatures to hot environments under different clothing insulation levels, which contribute to the calculation of the convective and radiant heat exchanges between the clothing surface and the environments.

When $I_{cl}\leqslant 0.2$, as Eq. (15):

$$T_{sk,eq,nu}=7.19+0.064t_a+0.061t_r-0.348v_a+0.198P_a+0.616T_{cr,i} \quad (15)$$

When $0.2< I_{cl}<0.6$, as Eq. (16):

$$T_{sk,eq}=T_{sk,eq,nu}+2.5\times\left(T_{sk,eq,cl}-T_{sk,eq,nu}\right)\times(I_{cl}-0.2) \quad (16)$$

When $I_{cl}\geqslant 0.6$, as Eq. (17):

$$T_{sk,eq\ cl}=12.17+0.02t_a+0.044t_r-0.253v_a+0.194P_a+0.005346M_i+0.51274T_{cr,i} \quad (17)$$

Where

$T_{sk,eq}$: the mean skin temperature, ^oC;

$T_{sk,eq,nu}$: the mean skin temperature of a nude body at t=i, ^oC;

$T_{sk,eq,cl}$: the mean skin temperature of a clothed body at t=x, ^oC;

Based on the aforementioned, the newly developed model is renamed the PHS_{HR} model, referring to the outline of the PHS model in ISO 7933[47], and covers the six basic environmental and individual factors in the heat stress prediction[2]; on the other hand, introducing the heart rate index enables the prediction of the dynamic metabolic rates, which can directly reflect the changes of activity levels during work. Based on this, the terms pertaining to the metabolic rates are redefined as the functions of heart rates, successfully reflecting the individual differences in heat stress prediction. More importantly, the model introduces the infinitesimal time Δt, instead of the time iteration calculation in the PHS model, making it possible to predict and output the heat stress-related physiological indices in dynamic conditions like step changes of thermal environments and varying work intensity.

3. Method of validation

The validation of the new PHS_{HR} model has been tested by comparing the data from the model with the experimental data from human subjects obtained in the laboratory.

3.1 Climate chamber

The experiments were conducted in a climate chamber in Chongqing University, with the dimensions of 4m(L)×3m(W) ×3m(H). The chamber was enclosed with

100mm thick double color steel plate with polyurethane filling in the middle. This ensured that the indoor thermal environment was less affected by external environments and solar radiation. The controlled range of temperatures in the chamber was from 10 °C to 40 °C within an accuracy of ±0.3 °C and from -5 °C to + 10 °C within an accuracy of ±0.5 °C. In addition, the RH was controlled from 10% to 90%, with an accuracy of ±5%. The air supply was from a ceiling perforated plate, designed to ensure a uniform air distribution during the experiments. A room, adjacent to the chamber, was maintained at 26 ^{o}C, and used by testers and subjects to do preparation work.

3.2 Subjects

A priori power analysis in G*Power 3[51] was used before the experiments to determine the sample size. According to the analysis(in this study, $f=0.5$, $1\text{-}\beta=0.05$, $\alpha=0.05$), the calculated sample size for each group of males and females was 8. At first, twenty-five subjects were recruited randomly in school to minimize the effect of individual differences such as age, body constitution, cultural background etc. After the pre-experiments, 11 males and 9 females were identified to participate in all the formal experimental conditions. The subjects were all healthy college students between 20 and 30 years of age, and were paid to participate in the experiments. The experiments were approved by the Institutional Review Board(IRB), Ethics Review Committee for Life Science Study of Central China Normal University (the partner in the program). The Project Ethics Ratification ID was CCNU-IRB-2009-003. Written informed consent was obtained from the participants and no privacy-related personal information was involved in the experiments. Basic information of the 20 subjects is shown in Table 3.

Table 3: Basic information of the 20 subjects

Physiological Indicators	Mean ± SD	Range
Age (yr)	24.4±2.8	22-27
Height (cm)	171.2±3.1	161-182
Weight (kg)	55.7±3.6	46.5-81.6

Resting Heart Rate (bpm)	74±7	55-79
Clothing insulation (clo)	0.4	/

3.3 Experimental conditions

To create the hot environments, the air temperature was referred to the standards of hot environments by WMO and three air temperature levels (33 ^{o}C/36 ^{o}C/39 ^{o}C) were selected in experiments. Considering a combination of elevated relative humidity and air temperatures would create significant stress on the human body under hot conditions[23,30,52], three different relative humidity levels (30%/60%/90%) were selected to make comparisons. The preliminary experiment was conducted to check all the 9 conditions but the majority of the subjects were not accepted for the extreme condition of 39 ^{o}C/90%RH during the test. Since such a condition seldom takes place and workers in real situations would be protected from working, the condition of 39 ^{o}C/90%RH was excluded in the formal study. Thus, 8 experimental conditions were used during the tests.

Table 4 presents the experimental conditions and the measured physical parameters during the test. It is seen that the thermal environments were well controlled during the experiments to meet the design requirement. Besides, due to the inner enclosure structure of the chamber, the globe temperatures were close to the air temperatures. The air velocity was controlled around 0.1m/s during the experiments.

Table 4: The designed and measured environmental parameters (mean±SD)

Cases	Designed conditions	Experimental conditions			
	T_{air}/RH	T_{air}(^{o}C)	T_{glob}(^{o}C)	RH(%)	V(m/s)
1	33 ^{o}C/30%	33.1±0.2	32.5±0.2	31.9±3.1	0.09
2	33 ^{o}C/60%	32.8±0.3	32.6±0.3	58.9±2.2	0.09
3	33 ^{o}C/90%	33.0±0.2	32.4±0.2	86.9±3.6	0.09
4	36 ^{o}C/30%	35.7±0.1	35.5±0.2	26.9±2.7	0.08
5	36 ^{o}C/60%	35.8±0.2	35.4±0.3	59.1±1.7	0.13
6	36 ^{o}C/90%	36.3±0.1	35.6±0.2	88.6±1.3	0.09
7	39 ^{o}C/30%	38.9±0.1	39.1±0.3	32.4±2.4	0.11
8	39 ^{o}C/60%	39.1±0.1	39.3±0.2	57.9±2.9	0.11

3.4 Experimental design

Considering that in real situations the activity levels and work intensity of workers change over time, the experimental procedure referred to the related heat stress studies[53, 54]. For each condition, two activity levels (i.e. walking and resting) were conducted for subjects. The set-up of time interval of walking and resting for hot environments were referred to studies of Lv[55] and Chan *et al.*[54].

Before the experiment, subjects were asked to change into uniform clothes including T-shirts, thin pants, and shoes, with an estimated insulation value of 0.4clo [56] in the preparation room. The temperature sensors (TMC6-HD, accuracy: ±0.2 ^{o}C) were attached using medical adhesive tapes to four left body parts of subjects (arm, chest, thigh and calf) and data were recorded by a HOBO U12-006 Data Logger (Onset, US). The mean skin temperatures of subjects were calculated using the following Eq.(18) [57]. Besides, subjects were asked to put the heart rate sensor on their chest with skin contact (Polar RS800, Finland, accuracy: ±1bpm). After that, subjects were sedentary in the preparation room for 30min and clearly informed of the experiment schemes and potential risks and that they were allowed to quit at any time. Experiment termination conditions were set based on the World Health Organization (WHO)[58].

$$MST=0.3\times T_{chest}+0.3\times T_{upperarm}+0.2\times T_{thigh}+0.2\times T_{calf} \quad (18)$$

The whole test was set for 150 minutes for formal experiments, as shown in Fig. 1. Subjects were asked to be sedentary in the neutral thermal environment (t_a=26^{o}C, RH=60%) for 30min before they entered the chamber. Then they were exposed to different hot environments in the chamber for 50min and were asked to do light office work. After that, they were required to walk at the treadmill (1.2m/s, 2.6met, 150W/m^2 [56]) for 20min to increase their metabolic rates, as seen in Fig. 1. After finishing the heat exposure, subjects returned to the preparation room to be sedentary for 50 min recovering from heat strain. During the whole heat exposures, the instantaneous heart rates and skin temperatures of subjects were measured at a time interval of 10s. To point out, during the analysis, the data in the first 10 minutes were not used because the subjects' initial thermal conditions were not yet stable[53].

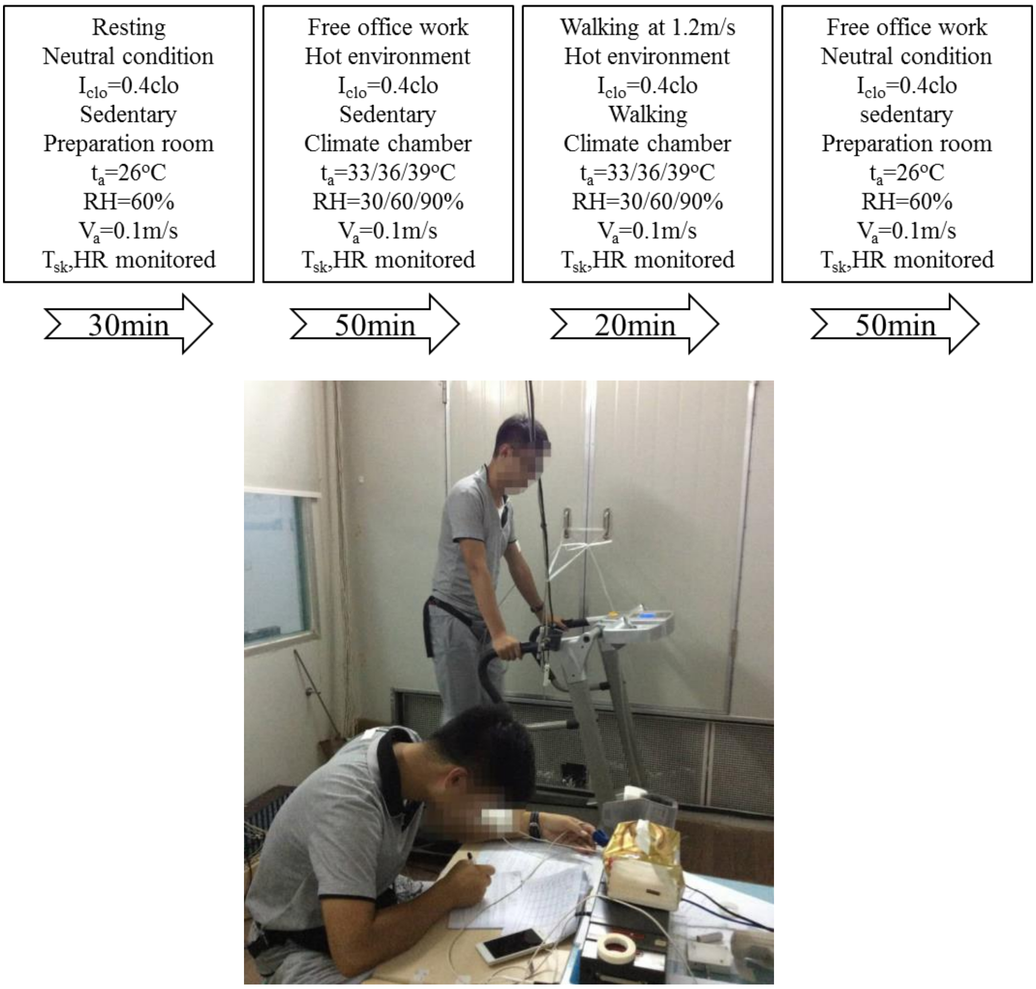

Fig. 1: Experimental procedure and on-site test in the chamber

4. Validation of the developed PHS_{HR} model

4.1 Changes in the subjects' mean skin temperatures (MST) and heart rates (HR)

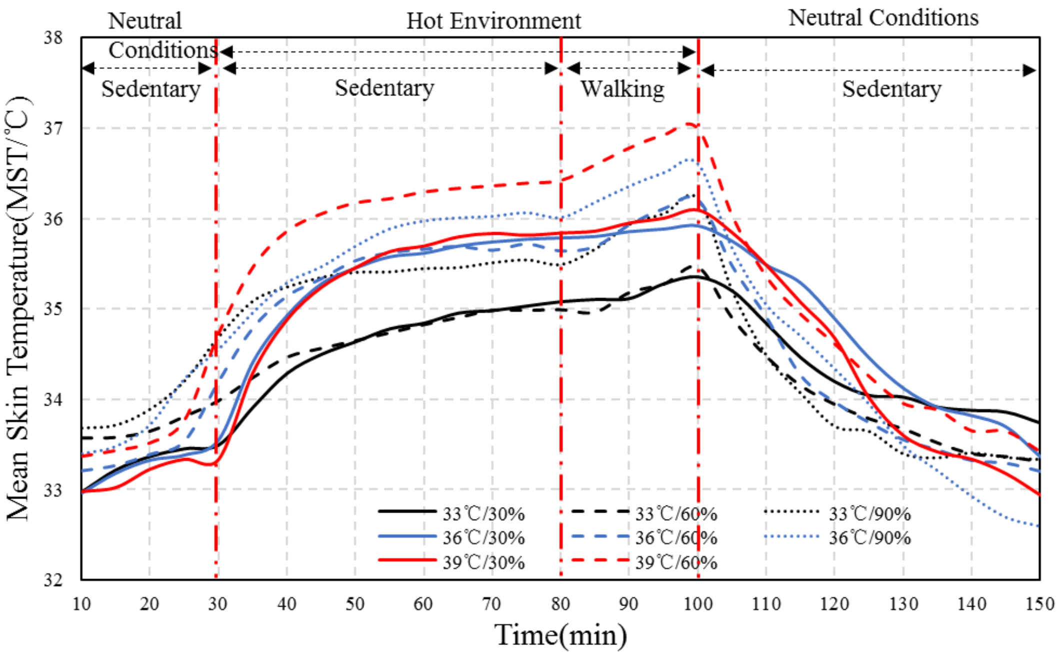

Fig. 2: The skin temperature changes of subjects in different conditions

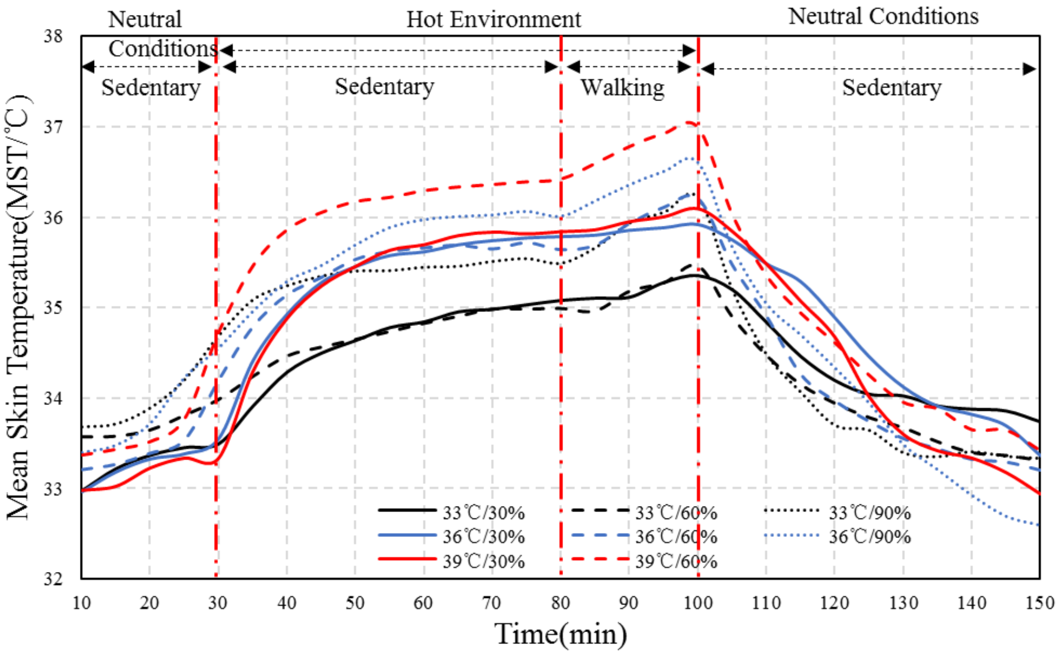

Fig. 2 shows the changes of the subjects' mean skin temperatures (MST) over time from t=10min to t=150min under 8 experimental conditions. From the figure, it is clearly seen that the MST of subjects increased significantly when they were exposed to hot environments, and increased with increasing air temperatures and relative humidity, suggesting the human body increased heat dissipation through the skin surface in hot environments. There were obvious increases in the MST when the subjects were walking from t=80min to t=100min. The MST reached its peak value at t=100min in each condition, the value of which was even up to 37 ^{o}C at 39 ^{o}C/60%RH. However, after they returned to the neutral thermal environment in the preparation room, remarkable decreases of MST for subjects were found, suggesting subjects' recovery from heat strain was quick once they left the hot environments. Besides, it is interestingly found that the change of subjects' MST differed with increasing relative humidity under different air temperature conditions. When the temperatures were 33 ^{o}C and 36 ^{o}C, there were slight differences of subjects' MST under 30%RH and 60%RH, while the MST increased significantly when the RH increased to 90%, manifesting the negative effect of relative humidity on human heat stress. Moreover, the effect was enhanced at higher air temperature of 39 ^{o}C, where the significant differences were found between 30%RH and 60%RH.

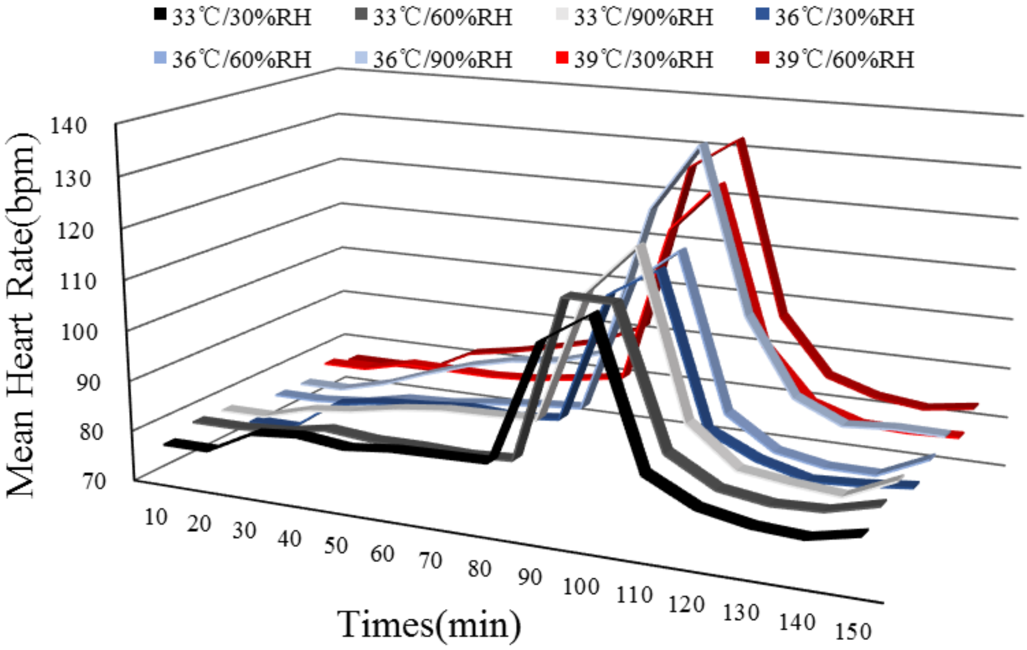

Fig. 3: The heart rate changes of subjects in different conditions

In a similar vein, Fig. 3 shows the changes of real-time mean heart rates of 20 subjects under 8 conditions. From Fig. 3, subjects' heart rates differed in different conditions. The higher the air temperature and relative humidity were, the higher the heart rates of subjects were, especially when subjects walked under hot environments. After subjects returned to the neutral thermal environments, the heart rates reduced quickly to their normal levels. However, being different from the changes of MST in

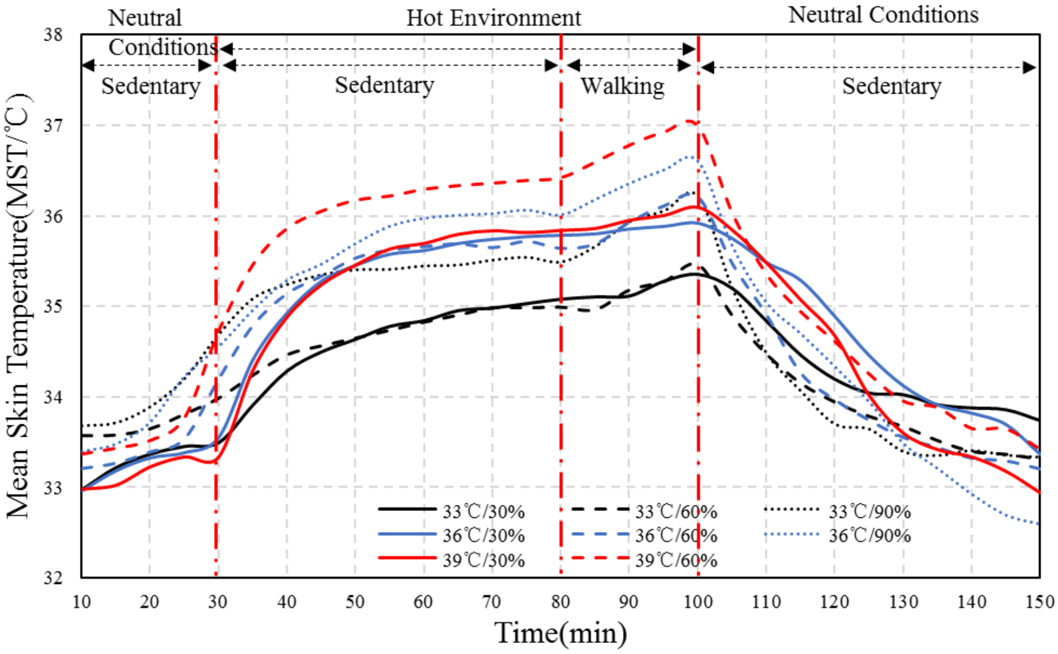

Fig. 2, when subjects entered the chamber at t=30min, there were just slight increases of heart rates, suggesting the subjects' MST were more sensitive to heat stimuli than their heart rates. While subjects' heart rates sharply increased when they began to walk at the treadmill at t=80min, suggesting the activity levels had a significant effect on human heart rates. This indicates that human metabolic rates would change significantly with the coupling effect of thermal environments and activity levels, which should be carefully considered for model estimation and prediction.

4.2 Evaluation of the predicted MST between the PHS and PHS$_{HR}$ models

To test the validity of the developed PHS$_{HR}$ model, which introduced the use of heart rate to predict the changing metabolic rates, we compared the predicted results from two models based on experimental data. Taking the MST as an example, Fig. 4 shows the changes of subjects' predicted MST (MATLAB tool (R2011b)) with time under 8 different temperature-humidity conditions based on the original PHS model using estimated metabolic rate (M) according to ISO 8996[48], and the developed model based on the measured heart rates of subjects in experiments. Besides, to examine the prediction performance of the two models in hot environments, here we also plotted the measured mean skin temperatures of subjects under hot conditions in Fig.4, as shown in black dot lines.

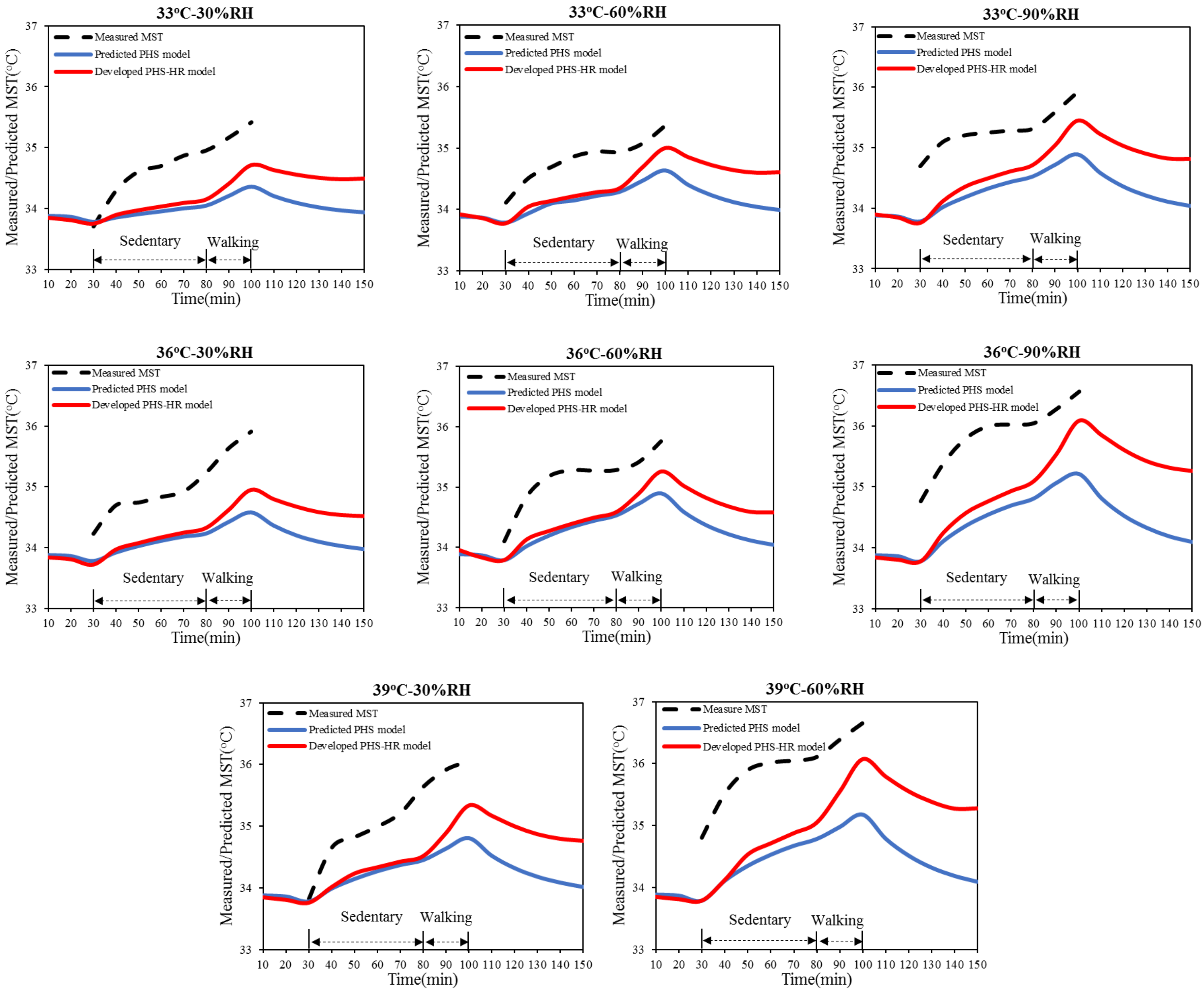

Fig. 4: The measured and predicted MST by the PHS and PHS$_{HR}$ models

When interpreting the developed model in Fig. 4, the similar trends of predicted MST can be found in two models. Before t=30min, the differences of the predicted MST of subjects were much smaller. This may because that subjects were static at 26 ^{o}C and the personal heart rate fluctuated slightly. Thus the advantage using heart rate to estimate the metabolic rates was not significant. When subjects entered the chamber and were exposed to heat stimuli, the predicted MST by the PHS and PHS$_{HR}$ models increased. When the air temperature and relative humidity were moderate, the predicted

MST by two models were close to each other and were slightly higher in $\mathrm{PHS_{HR}}$ model with increasing air temperature and humidity. It is thus speculated that the differences using the two methods to calculate the metabolic rates in PHS and $\mathrm{PHS_{HR}}$ models may be small for light activities (e.g. sedentary). However, both the MST obviously increased when subjects began to walk at t=80min, and under this condition, the differences of MST between two models were enlarged. Since subjects' heart rates changed sensitively with exposure time when they were walking, the developed $\mathrm{PHS_{HR}}$ model adopted the real-time heart rates were more sensitive to the changes of activity levels, thus leading to significant increases of MST. Specifically, when subjects were exposed to high air humidity conditions at 33 ^{o}C/90%RH and 36 ^{o}C/90%RH, the deviations increased gradually with prolonged exposure, so that the predicted MST by the developed $\mathrm{PHS_{HR}}$ model were higher than that by the PHS model. It is inferred that subjects' metabolic rates would increase with increasing temperature and air humidity[59, 60]; while in the PHS model the metabolic rate was assumed as a constant value due to the unchanged activity level of subjects. By contrast, thanks to the real-time heart rate input, the developed $\mathrm{PHS_{HR}}$ model enables to reflect the changes of metabolic rates over time. When subjects returned to the preparation room (26 ^{o}C), the predicted MST by the two models decreased gradually. However, because subjects had accumulated significantly the heat storage in body due to activity and prolonged heat exposure before, the predicted MST of subjects were still higher after a period of recovery time of 50min. It is thus concluded that the activity intensities and exposure time would have significant affected the heat strain of human body and thus the recovery time, which is worthy of consideration in design.

To further examine the prediction performance of the two heat stress models, Fig.4 compares the predicted MST by the two models to the measured MST from experiments. From the whole, subjects' measured MST were visibly higher than the predicted MST from models, especially when subjects entered the climate chamber at t=30min. Since the empirical formula calculating the different terms of body heat exchanges in the PHS an $\mathrm{PHS_{HR}}$ models were based on a large number of labs experiments and semi-theoretical derivations, this would cause some deviations between the real values and the predicted values from models. Especially, the PHS model was developed based on European and American populations [40] and the geographic and individual differences in this experiment would also make influence, which would be further verified and modified for application for Chinese people in our following study. Besides, from Fig.4, in fact, subjects' skins were exposed to hot air directly, contributing to the sharp increases of MST. While the predicted MST by models based on mathematical calculation of heat exchanges and it therefore presented a cumulative effect rather than a step change. One more we noticed was that in hot environments, subjects began to sweat and the increased wetness on skin surface affected the contact between skin surface and thermocouples. As a result, the surrounding hot air possibly increased the values by thermocouples, leading to higher measured MST than the predicted ones. All these may attribute to some deviations in Fig.4, when comparing the experimental results to the predicted outcomes from models.

After all, from Fig. 4, when subjects walked from t=80min to t=100min, the MST using PHS_{HR} model increased sharply while the increase of MST in PHS model was slight without considering the accumulative effect of subjects' metabolic heat generation. The remarkable increases of differences of skin temperatures were found at 36 ^oC/90%RH and 39 ^oC/30%RH, and 39 ^oC/60%RH from t=80min to t=100min. This suggested that the air temperature and humidity, coupled with the exposure time, had significant effect on human heart stress. In this case, the PHS model under-predicted the skin temperature increasing, while the MST predicted by PHS_{HR} model was much closer to the measured MST. As heat stimulus acts as a risk factor, it is expected for people to identify and prevent in advance. In this line of thought, the PHS model may underestimate the risk of physiological strain and thus the required recovery time, which was in agreement with Karin' study [61] that the PHS simulation underestimated the thermal strain in experimental scenario of intermittent work. Given this, the developed PHS_{HR} model can improve the prediction accuracy in dynamic working conditions if the heart rates of workers change significantly, which is superior to the original model. However, even though, it is the fact that both the two models have some deviations predicting MST compared to the experiments, especially for the hot humid environments, which should be further improved in future study of the model.

To sum up, Table 5 further shows the deviation values (D-value) of average MST of 20 subjects during the whole process between the experimental and predicted values from the two models, where AV was the average value of the 8 experimental conditions. The SD represented the standard deviation of the AV fluctuation among the 8 experimental conditions. The SDT represented the total standard deviation. From Table 5, the average D-values of MST during the whole tests between the experiments and the predictions by the developed model fluctuate in the range of 0.3±0.76 ^{o}C, while they are 0.3±0.73 ^{o}C between the experiments and the PHS models, further manifesting that the method used in PHS_{HR} model is reliable.

Table 5: D-value of subjects' MST between the experimental and the PHS and PHS_{HR} models

MST	Difference between experiments and the PHS_{HR} model			Difference between experiments and the PHS model			Difference between the PHS_{HR} model and the PHS model		
index	AV	SD	SDT	AV	SD	SDT	AV	SD	SDT
D-values	0.3	0.76	0.765	0.3	0.73	0.765	0.041	0.1529	0.2584

In fact, considering workers in the practical working sites would change their work intensities from time to time, the traditional PHS model relies on a number of physiological inputs and metabolic rate estimations in ISO7933[47], which would limit the applications and reduce the accuracy, especially in dynamic conditions with frequently-varying activity levels. From Fig. 4, the developed PHS_{HR} have good consistency with the original PHS model in predicting mean skin temperature and have better sensitivity in dynamic working, validating the modification method in this study. In such cases, the developed PHS_{HR} model would win its advantages because it can predict the real-time changes of body metabolic rates according to combining simulation with body worn sensors and using non-invasive sensor information, leading to the real time risk assessment of personal heat strains.

5. Application of the developed $\mathrm{PHS}_{\mathrm{HR}}$ model

5.1 Development of the new PHS_{HR} model

The original idea of this study is to simplify the calculation of the heat stress models, to make them more applicable in work places. As aforementioned, the related six basic indicators in the PHS model (Table 1) in ISO 7933[47] can be re-expressed in the developed $\mathrm{PHS}_{\mathrm{HR}}$ model, which are summarized in Table 6. From Table 6, it is clearly seen that all the terms in the human heat balance Eq.(1), including RES, C&R, dS_{eq}, can be directly calculated using seven variables, i.e., 4 physical parameters (air temperature, radiant temperature, air pressure, and air velocity) and 2 individual parameters (clothing insulation and heart rates), as well as the exposure time. Compare to the original PHS model (Table 1), all the required variables in the $\mathrm{PHR}_{\mathrm{HR}}$ model (Table 6) are accessible without measuring the skin and body temperatures and so on. Instead, the personal heart rates are easily obtained with wearable and portable devices, without disturbing workers in the working place. More importantly, it takes advantages identifying the potential high risk populations exposed to extreme hot environments through monitoring individual heart rates, instead of predicting body heat stress of average people.

Table 6: The six basic terms of the developed $\mathrm{PHS}_{\mathrm{HR}}$ model

Terms	Definitions	Input Variables
RES	$Mi(0.118773-0.00067t_a-0.01379578P_a$	t_a, P_a, HR, t_i
C&R	$C=h_c f_{cl}(T_{sk,i}-t_a)$ $R=h_r f_{cl}(T_{sk,i}-t_r)$	t_a, t_r, v_a, I_{cl}, P_a, t_i
dS_{eq}	$dS_{eq}=C_{sp}[36.8+\sum_{i=m}^{n} 0.0036(Mi-55)\times[1-\exp(-\frac{\Delta ti}{10})]](1-\alpha)$	HR, t_i
M_i	$M_i=M_0+\frac{HR_i-HR_0}{180-0.65Ag-HR_0}[(41.7-0.22Ag)\times W^{0.666}-M_0]$	HR, t_i
T_{cr}	$T_{cr}=36.8+\sum_1^i [0.0036(M_i-55)\times\left[1-\exp\left(-\frac{i}{10}\right)\right]]$	HR, t_i

T_{sk}	$T_{sk}=0.7165^{i}T_{sk,0}+0.2835\sum_{x=1}^{i}T_{sk,eq,x}\times0.7165^{i-x}$	t_a, t_r, v_a, P_a, t_i

According to ISO 7933, the required evaporative heat flow E_{req} is regarded as a key object function to predict and evaluate human heat stress and its degree of severity. As analyzed in Eq.(1), the E_{req} is the function of M, C_{res}, E_{res}, C&R and dS_{eq}. However, from Table 6, since all the terms, M, C_{res}, E_{res}, C&R and dS_{eq}. can be calculated by the seven variables, the E_{req} is therefore indirectly dependent upon the seven factors, as marked in Eq.(19).

$$E_{req}=f(t_a, t_r, P_a, v_a, HR_i, I_{cl}, t_i) \quad (19)$$

As a result, through introducing the real time M_i to re-express the different terms in Eq.(1), the object function E_{req} can be easily calculated based on four physical parameters(t_a, t_r, v_a, P_a), two individual factors(I_{cl} and real time HR_i), and the time variable t_i. In practice, the environmental parameters and clothing insulation are usually available and measurable. The input parameter of heart rates can be monitored with the real-time devices. One more advantage is that the results during the calculating process of the PHS_{HR} model are able to be output at any time, which is different from the closed routine in the PHS model. In such cases, based on the Eqs. (1,19) and Table 6, the human physiological responses under the single and coupled effect of the seven factors can be predicted, which would be guided for on-site environmental design.

5.2 Application of the new model

As discussed before, to depict the applications of the developed PHS_{HR} model, the following sections explored how the body's physiological indices correlated to human heat stress change when the input parameters change. Here we referred to our previous on-site survey[62] and took the measured data of a typical working scenario in the field survey as the initial input parameters (see Table 7) to discuss the single and coupled effect of some factors in Eq. (19) on human heat stress.

Table 7: Basic inputs for the application of the model

Parameters	Value	Unit
Age	30	yr
Weight	75	kg
Original skin temperature	34.16	ºC
Heart rate	94	bpm
Air temperature	34.8	ºC
Radiation temperature	35.5	ºC
Air velocity	1.5	m/s
Water vapor pressure	2.5541	Kpa
Clothing insulation	0.4	clo
Time	80	min

5.2.1 Effect of the single factor-exposure time

As mentioned in Eq. (19), the exposure time t_i is a key variable determining body heat stress. According to the given inputs from Table 6, we examined the changes of body temperatures with increasing exposure time, as well as the body heat generations and dissipations involved, using the developed PHS_{HR} model, as shown in Fig. 5.

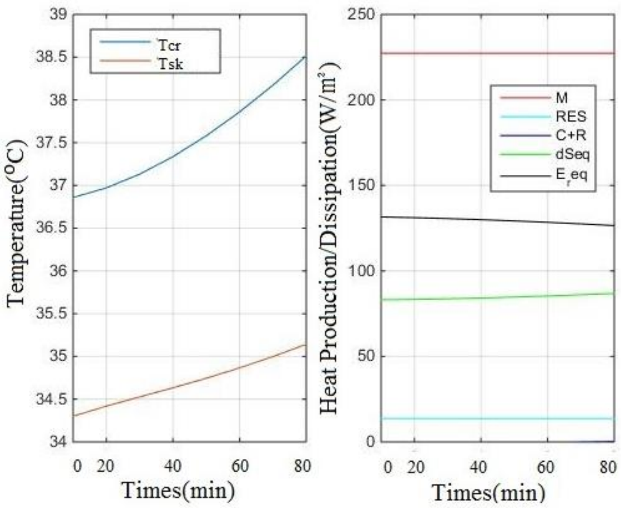

Fig. 5: The fluctuation of T_{sk} and T_{cr} and the corresponding heat generation and dissipation of

the human body over time

From Fig. 5, with the time increasing, the T_{sk} and T_{cr} gradually increase. By contrast, the T_{sk} has a linear increase to exposure time due to the direct contact with hot environments, in order to enhance the heat dissipation; while due to the cumulative heat storage in the body, the T_{cr} increases slowly at the initial stage but increases significantly as time goes on. This shows that the exposure time has a significant effect on human heat stress, i.e. extending exposure time under hot environments would lead to body heat storage, which would increase the potential risk for people's health and safety.

Fig. 5 also presents the changes of heat generation and dissipation of the human body. Under the design conditions, M is the main source of body heat generation, which is up to 230W/m^2. Although both evaporative and convective heat exchange take place through respiration, the value is much smaller compared to the heat generation by metabolism. So is the C&R heat dissipation. By contrast, as the direct indicator of heat stress prediction, the heat storage (dS_{eq}) and the required evaporative heat flow (E_{req}) are maintained at around 80W/m^2 and 130 W/m^2 respectively.

5.2.2 Coupled effect of environmental and non-environmental factors

In fact, workers exposed to hot environments are not only threatened by single factors but also by multiple factors, like air temperature & radiation, air temperature & air velocity, air temperature & work intensity, & exposure time, etc. Therefore, it is necessary to identify and quantify the coupling effect of these factors on human heat stress in order to provide references for working protection in hot environments.

① *air temperature VS air velocity*

The air temperature and air velocity are the two main physical factors that affect human heat stress. Fig. shows the predicted E_{req} changes with the coupled impact of t_a and v_a according to the developed PHS_{HR} model.

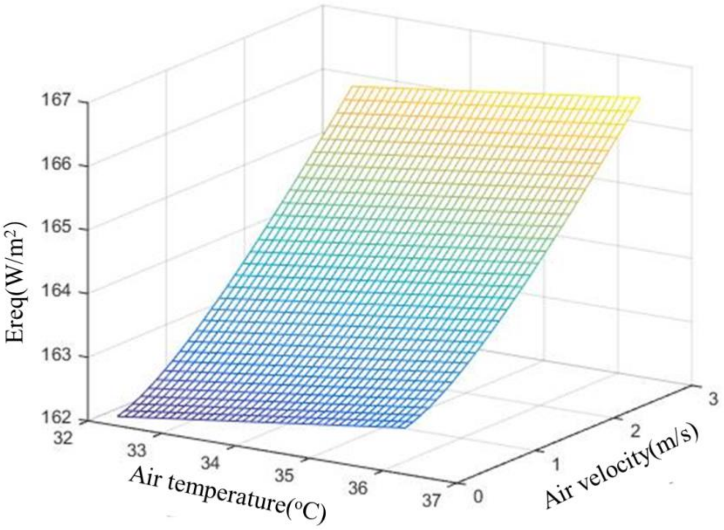

Fig. 6: The E_{req} variation with coupling impact of t_a and v_a based on the developed model

In Fig. , E_{req} changes significantly with increasing t_a and v_a: the values increase when v_a and t_a increase but the increase of v_a has a greater effect on E_{req}. The E_{req} increases dramatically with the v_a increasing from 0m/s to 3m/s, while it increases slightly when the temperature increases from 32 ^{o}C to 37 ^{o}C. This may be because the body has developed the maximum sweating regulation for hot environments so that the effect of increasing temperature is not significant. By contrast, the air velocity would significantly enhance the convective heat transfer and evaporative heat dissipation. On real working sites, the improvements of thermal environments where the workers are exposed are limited by many technical and economic factors. However, from Fig. , the air velocity is more efficient at enhancing E_{req} and it is convenient to control and manage this on-site. Therefore, based on the prediction of body thermal status using the developed PHS_{HR} model, it can provide appropriate air velocity designs under different hot conditions, which would be beneficial for worker protection.

② *Heart rate VS exposure time*

As analyzed in Fig. 5, the exposure time would also have significant effect on human heat stress. More importantly, the permitted exposure time for workers is significantly affected by different work intensities. Here, Fig.   shows the fluctuation of T_{cr} of the human body with heart rates (being representative of different work intensities) and exposure time.

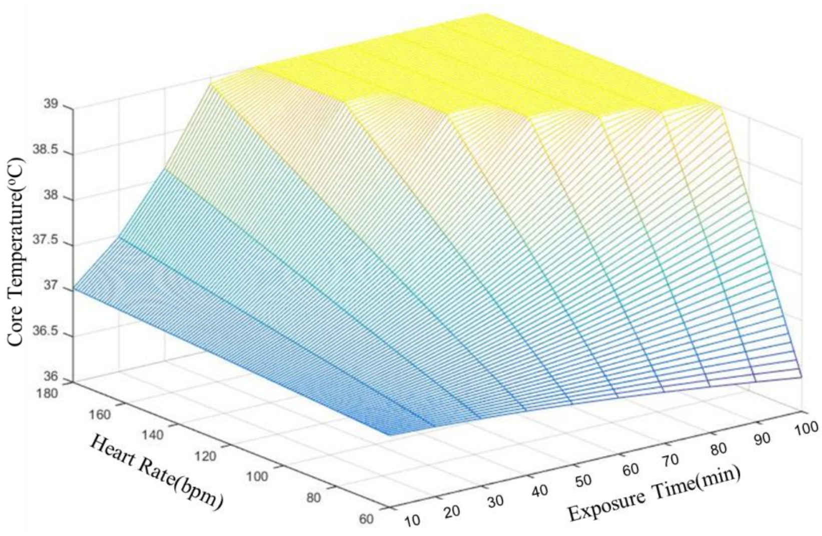

Fig. 7: The T_{cr} variation with the coupling impact of HR and time

The WHO[58] has recommended that the upper limit of the physiological core temperature is 39 ^{o}C in the case of continuously monitoring the workers' core temperatures. Accordingly, we took "T_{cr} <39 ^{o}C" as the upper limit during calculations using the PHS_{HR} model. From Fig. , if the HR is maintained below 110bpm, the permitted working time for the human body can be up to 100 minutes under the designed condition. However, when the heart rate exceeds 110bpm, the working time of 100 minutes fails to guarantee human health and safety. Besides, the metabolic rate, which is reflected by the real-time heart rate, also has a significant effect on the permitted exposure times. With the increasing metabolic rate, the permitted working time under the physiological threshold of T_{cr} (T_{cr} <39 ^{o}C) decreases rapidly. For example, the maximum working time is just about 30min when the heart rate is up to 180bpm. When the maximum working time is extended to 90 minutes, the permitted heart rate should be under 100bpm. As the exposure time for safety is important for working time management to prevent the occurrence of accidents at work, the developed PHS_{HR} model can provide the permitted working time with the dynamic changes of working intensities at individual levels once the heart rates of workers can be monitored simultaneously, which is superior to the present PHS model.

Overall, based on the outlines of the PHS model, the developed PHS_{HR} model can be applied to predict human thermal regulations in a variety of combinations of the seven variables in Eq.(19), and all outcomes related to heat exchanges in Table 6 can be obtained, making it convenient to be applied for the design, assessment, and improvement in specific high-temperature working environments (e.g. steel plants, construction sites, military, industry, and sports training, etc.). More importantly, with the recently emerged wearable and portable metabolic devices into the complex thermos-physiological models to develop the model individualization approaches[38], the developed PHS_{HR} model has adopted the physiological index - heart rate - which is easily obtained by the present technical instruments. Through monitoring the workers' real-time heart rates individually, the developed model can predict human heat stress easily in dynamic conditions at the personal level. This improvement ensures the risk evaluation for some heat-sensitive populations and provides the health protection in advance, which overcomes the inconvenient application of the PHS model in the ISO7933. Therefore, the developed PHS_{HR} model can be widely applicable for design, reconstruction guidance, evaluation standards, and policy administration.

6. Conclusions

A dynamic heart rate-based predicted heat stress model (PHS_{HR}) has been developed based on the framework of the PHS model in ISO 7933, achieving the real time risk assessment of heat stress. The validation of the model is conducted through human heat exposure experiments in a climate chamber. The main conclusions are drawn including the following aspects:

1) The instantaneous heart rate (HR) is introduced into the PHS model to predict the dynamic metabolic rates (M_i) over time. Based on this, the relation between M_i and HR_i is built and the various terms of heat exchange used in the heat balance equation (C, R, Cres, Eres, dS_{re}) are redefined as the function of the heart rate index.
2) The infinitesimal time unit Δt_i (x = 1, 2, 3 ... i) is introduced aiming to open the enclosed iteration calculation from t_i to t_{i+1} in the PHS model, and the terms (C, R, Cres, Eres, dS_{re}) are thus calculated with $\Sigma\Delta t_x$ (x = 1,2,3 ... i), which enables the dynamic outputs of physiological indices related to heat stress at any time according

to the changing environmental and personal parameters.

3) The developed PHS_{HR} model shows a similar trend to the original model, verifying the validity of the modified method introducing heart rate into PHS model. The developed PHS_{HR} has better sensitive responses in the dynamic situations where the real-time heart rates change significantly. Compared to the experimental data, the introduction of real-time heart rates contributes to the better prediction performance, especially with the metabolic rate changing over time.
4) The application of the developed PHS_{HR} model is discussed. The effect of the single and the multiple variables on human heat stress performances, such as E_{req}, the permitted exposure time, is quantified in the PHS_{HR} model, which makes it possible for application in the design, evaluation, and improvement of hot working environments.

Acknowledgements

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