Building and Environment 135 (2018) 318–329

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

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

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ARTICLE INFO

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

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 $\Delta t_i$, 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.

## 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 °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 1000 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 °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 °C-38.2 °C is suggested to be the upper limit for light work while a value of 39.2 °C is the upper limit for heavy work [24]. In

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https://doi.org/10.1016/j.buildenv.2018.03.014
Received 25 January 2018; Received in revised form 10 March 2018; Accepted 10 March 2018
Available online 12 March 2018
0360-1323/ © 2018 Published by Elsevier Ltd.

**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 ($W/m^2 \cdot °C$) |
| C | convective heat losses ($W/m^2$) |
| R | radiative heat losses ($W/m^2$) |
| $C_{sp}$ | specific heat of the body (J/kg°C) |
| 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 (°C) |
| $T_{cl}$ | mean temperature of the outer surface of the clothed body (°C) |
| $T_{cr,eq}$ | core temperature as a function of the metabolic rate (°C) |
| $T_{cr,i}$ | core temperature at time point "i"(°C) |
| $T_{sk}$ | skin temperature (°C) |
| $T_{re}$ | rectal temperature (°C) |
| $T_{sk,0}$ | the initial skin temperature of the subject at resting status (°C) |
| $T_{sk,i}$ | the skin temperature at the time point "i" (°C) |
| $T_{sk,eq}$ | skin temperature as a function of the metabolic rate (°C) |
| $T_{sk,eq,x}$ | the ideally stable skin temperature at the time point "x"(°C) |
| MST | mean skin temperature (°C) |
| $t_a$ | mean air temperature (°C) |
| RH | relative humidity (%) |
| $t_r$ | mean radiant temperature (°C) |
| $v_a$ | mean air velocity (m/s) |
| $t_i$ | time point after $i*\Delta t$ (s) |
| $\Delta t$ | time infinitesimal |
| x | intermediate variables, $1 < x < i$ |
| i, i-1 | time point |
| $\alpha$ | proportion of core part in body weight, normally at 0.22 |
| $\varepsilon sk$ | average emissivity of skin |
| $\rho$ | density ($kg/m^3$) |
| $\sigma$ | Stefan-Boltzmann constant ($W/m^2 \cdot K^4$) |
| $\sigma*\varepsilon sk*Ar/AD$ | constant value, normally taken as $4.234923*10^{-8}$ |
| Mean | mean value of the data |
| SD | standard deviation |

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 780 g/h-1040 g/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 they 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

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