

Research on the Estimation Method for Human Thermal Safety with Thermal Manikin

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Abstract. It is important to protect human safety in heat operation workshop and firefighting. The estimation method for human safety in heat environment is established in this paper. It is based on the bio-thermal response model and experimental simulation. Thermal cabin and infrared thermal radiation board are used to simulate the thermal environment. Human bio-thermal response, including body temperature and sweat rate, are calculated by model. The interactive process of the passive warming and sweat are simulated by NEWTON thermal manikin. Human safety state is estimated according to both hyperthermia and dehydration. This method is tested in 30°C~40°C thermal environment. It is concluded that the method can simulate the thermal response and estimate the thermal safety state of human in heat environment.

1. Introduction

It is necessary to estimate the safety state to protect human in thermal environment, such as heat operation workshop and firefighting. Human thermal safety can be estimated according to the bio-thermal index parameters, which are calculated by model referring the system of human-clothing-environment.

There are two methods to estimate human thermal safety. Thermal response model method obtains the bio-thermal index parameters by iterative calculation based on human-clothing-environment thermal system model [1]. The first typical model is the Stolwijk model which include six section and twenty-five units of body based on negative feedback theory in 1971 [2]. Charlie (2001) established the Berkeley model which improved Stolwijk model by more units of body, referring thermal exchange of blood and body units, referring thermal resistance and wet resistance, and so on [3]. Tanabe (2002) established the thermal comfortable model referring nonuniformity temperature environment based on multipoint heat control and computational fluid mechanics [4]. Thermal response model can obtain the thermal response of body temperature, sweat and breath rate. But it there are still some factors which need to be referred, such as air turbulence, local air disturbance, heat and material exchange of multi-layer clothing, body movement, and so on [5]. The other method estimates the thermal safety by human subject experiment or thermal manikin. But it is difficult for the human subject experiment in extreme thermal environment. The thermal manikin needs the specific experimental equipment which can



simulate human temperature and sweat [6]. Psikuta (2008) studied the thermal response including body temperature and sweat using one-section manikin [5]. Coca (2010) studied the human movement effect to thermal protective clothing using thermal manikin [7]. Most thermal manikins can't active adjust for environmental change [8]. But this type of methods become the highlight because the reliable performance of equipment, the repeatable thermal simulation result, and so on.

This paper establishes an estimation method for human thermal safety. This method combines the bio-thermal response calculation model and the thermal manikin experiment. The environment parameters in thermal cabin are obtained by sensors and the human thermal response for the next time step is calculated according to bio-thermal response model. Then the human thermal response, including the rising of body temperature and sweat absorption of heat are simulated by thermal manikin. The thermal safety state is estimated referring threshold values of body temperature and sweating dehydration.

2. Human thermal safety estimation method

2.1 Experimental platform

The Experimental platform include three parts: simulation system for human-clothing-environment, parameter measurement system and data collective/transportation/processing system. The simulation system for human-clothing-environment simulates the specific thermal environment using thermal cabin and heat radiation board, bio-thermal response using NEWTON thermal manikin, and it wears the clothing which realize the clothing effect. The parameter measurement system measures the thermal parameters of the environment and manikin. The data system includes the manikin control software-ThermalDAC, and bio-thermal response calculation model. It receives the real-time measurement parameters and calculates the thermal response parameters for the next time step and transport them to NEWTON thermal manikin. The experimental platform is as shown in Fig. 1.

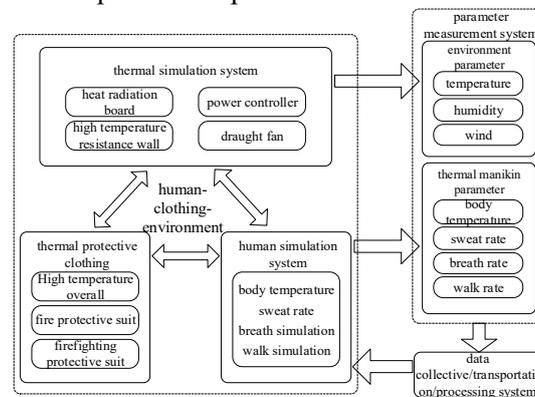


Figure 1. The Framework of the Experimental Platform

The NEWTON thermal manikin is comprised of manikin, skin layer, external system, environmental sensor and control software. The manikin and skin layer simulate the framework of human. The controllers and capillaries beneath skin layer simulate body heat and sweat. They are controlled by external system which comprised of the corresponding control box. The framework and function diagram of NEWTON thermal manikin is as shown in Fig. 2.

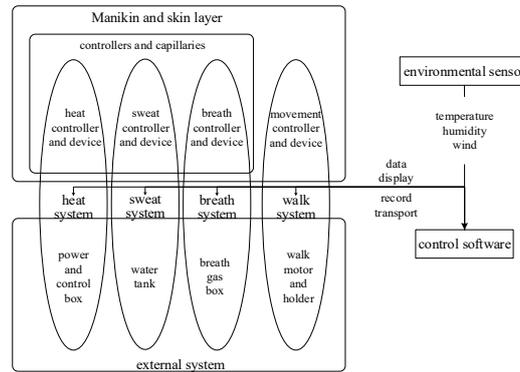


Figure 2. The Framework and Function Diagram of NEWTON Thermal Manikin

2.2 Experimental method

The thermal manikin and heat radiation board are deposited in the thermal cabin. The specific thermal environment is made by heat radiation board. The environment and manikin parameters are measured by environment sensors and thermal manikin. Then the response for the specific thermal stress is calculated by the data processing system. According the calculation result the thermal manikin can simulate the thermal response, including body temperature and sweat rate. Referring to the threshold temperature and sweat dehydration the safety state can be estimated.

The experimental process is: (1) activate the heat radiation board and the environmental temperature rises; (2) thermal manikin temperature rises as the heat accumulates; (3) activate the sweat and evaporation as the body temperature rises; (4) estimate the safety state according to the body temperature and sweat. The process is as shown in Fig. 3.

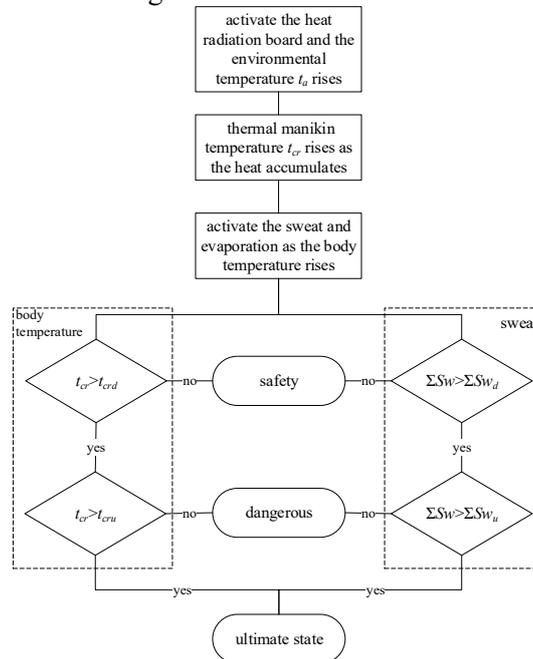


Figure 3. The Experimental Process Diagram

2.3 Bio-thermal parameters calculation

The bio-thermal response model given by ISO 7933 [9] is used to calculate the parameters. Three steps are executed as follows:

(1) The maximum evaporative heat flow at the skin surface E_{max} (W/m^2) and the required evaporative heat flow E_{req} (W/m^2) are calculated as follows:

$$E_{\max} = \frac{P_{sk} - P_a}{R_{cl}} \quad (1)$$

$$E_{\text{req}} = M - dS_{\text{eq}} - W - Cres - Rres - C - R \quad (2)$$

whereas p_{sk} and p_a are saturated water vapour pressure at skin temperature and water vapour partial pressure respectively, kpa; R_{cl} is the total evaporative resistance of clothing and boundary, $\text{m}^2 \cdot \text{kpa}/\text{W}$; M is metabolic rate, W/m^2 ; dS_{eq} is body heat storage rate for increase of core temperature associated with the metabolic rate, W/m^2 ; W is effective mechanical power, W/m^2 ; $Cres$ and $Rres$ are respiratory convective heat flow and evaporative rete respectively, W/m^2 ; C and R are convective and radiative heat flow respectively, W/m^2 . p_{sk} , p_a and R_{cl} are obtained by measurement, while M and W are setted based on the practical situation.

$$dS_{\text{eq}} = c_{sp} (t_{\text{cr,eq } i} - t_{\text{cr,eq } i-1}) \times (1 - \alpha_{i-1}) \quad (3)$$

$$Cres = 0.01516M (t_{\text{ex}} - t_a) \quad (4)$$

$$Rres = 0.00127M (59.34 + 0.53t_a - 11.63p_a) \quad (5)$$

$$C + R = \frac{t_{sk} - t_a}{I_{cl}} \quad (6)$$

whereas c_{sp} is specific heat of the body, $\text{W}/(\text{m}^2 \cdot \text{k})$; $t_{\text{cr,eq } i}$ is core temperature as a function of the metabolic rate at time t_i , $^{\circ}\text{C}$; α_i is skin-core weighting at time t_i ; t_{ex} , t_a , t_{sk} are the temperatures of expired air, air and skin respectively, $^{\circ}\text{C}$.

(2) The predicted sweat rate at time t_i , sw_i (W/m^2) is calculated as follows:

$$sw_i = sw_{i-1} \cdot e^{-\frac{1}{10}} + sw_{\text{req}} \left(1 - e^{-\frac{1}{10}} \right) \quad (7)$$

whereas sw_{req} is required sweat rate, W/m^2 . It depends on E_{req} and E_{\max} .

(3) The rectal temperature $t_{\text{re},i}$ ($^{\circ}\text{C}$) is calculated as follows:

$$t_{\text{re},i} = t_{\text{re},i-1} + \frac{2t_{\text{cr},i} - 1.962t_{\text{re},i-1} - 1.31}{9} \quad (8)$$

whereas $t_{\text{cr},i}$ is core temperature at time t_i , $^{\circ}\text{C}$

$$t_{\text{cr},i} = \frac{1}{1 - \frac{\alpha_i}{2}} \left[\frac{dS_i}{c_{sp}} + t_{\text{cr},i-1} - \frac{t_{\text{cr},i-1} - t_{\text{sk},i-1}}{2} \alpha_{i-1} - t_{\text{sk},i} \frac{\alpha_i}{2} \right] \quad (9)$$

t_{re} is usually used to represent t_{cr} [10]. Therefore, sw_{req} and t_{re} can be calculated according to body and environment parameters.

3.Result and analysis

In state of comfortable, the temperature $t_{\text{sk}}=34^{\circ}\text{C}$ is set as the initial skin temperature. The temperatures of heat radiation board are set as 30°C , 32°C , 34°C , 36°C , 38°C and 40 respectively. Then the human thermal response is investigated in 4 hours and the safety state is estimated according to body temperature and sweat. The thermal response of t_{re} for different heat radiation t_{rad} is as shown in Fig. 4.

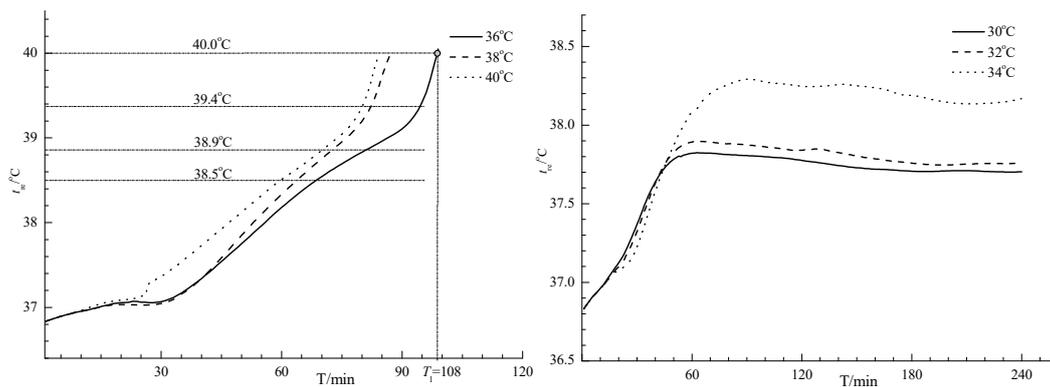


Figure 4. Thermal response of t_{re} for t_{rad}

1. t_{re} rises more rapidly as t_{rad} rises.
2. For t_{rad} is 30°C and 32°C, t_{re} rises first and then gets lower, and get in a steady state at last. This means body can adapt this thermal stress. For t_{rad} is 34°C, t_{re} fluctuates at last. This means it's the critical thermal stress for body. And $t_{rad}=34^{\circ}\text{C}$ agrees with the critical steady value theoretically. For t_{rad} is 36°C, 38°C and 40°C, t_{re} rises rapidly until it gets up to the critical effect value of ISO 7933 model ($T_1=108$ min). This thermal stress is beyond ISO 7933 model.
3. Human body is dangerous when t_{re} reaches dangerous value. As 38.5°C, 38.9°C and 39.4°C [11] are the physical, safety and tolerance upper limit respectively, the dangerous time can be calculated as Table 1.

Table 1. Body temperature dangerous time for t_{rad} .

$t_{rad}/^{\circ}\text{C}$	physical upper limit time/min	safety upper limit time/min	tolerance upper limit time/min
30	-	-	-
32	-	-	-
34	-	-	-
36	69	83	95
38	64	74	83
40	60	71	81

Estimate the safety state according to sw situation as Fig. 5.

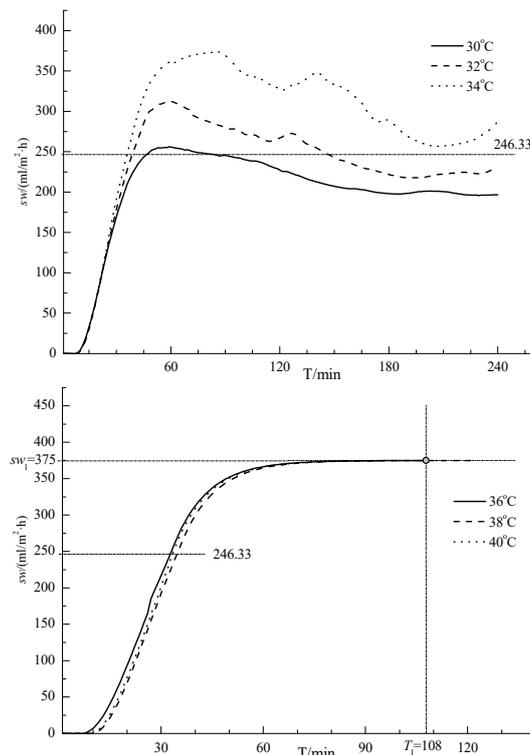


Figure 5. Thermal response of sw for t_{rad}

1. sw rises more rapidly as t_{rad} rises.
2. For t_{rad} is 30°C and 32°C, sw rises first and then gets lower, and get in a steady state at last. This means body can adapt this thermal stress. For $t_{rad}=34^\circ\text{C}$, t_{re} fluctuates at last. This means it's the critical thermal stress. For t_{rad} is 36°C, 38°C and 40°C, sw rises rapidly until it gets up to the critical effect value of ISO 7933 model, $sw=375$ ml/(m²/h) ($T_1=108$ min). In This thermal stress is beyond ISO 7933 model.
3. Body will be in dangerous state when the sweat gross is 0.01% of body weight, 246.33 ml/(mh). Then the sw dangerous time for different t_{rad} can be calculated as Table 2.

Table 2. Sweat dangerous time for t_{rad} .

$t_{rad}/^\circ\text{C}$	dangerous time/min
30	47
32	39
34	36
36	33
38	35
40	33

The sweat dangerous time gets shorter as the t_{rad} rises when the body can adapt to the thermal stress. The sweat dangerous time will be the same when the body can not adapt to the thermal stress. This means the sweat critical values are the same for different t_{rad} when thermal stress is beyond the adaption ability of body.

4. There is a critical value for the total water loss of body, Σ_{sw} . They are 2% of body weight (1400g) for dangerous state, 5% (3500g) for injury state [12]. The Σ_{sw} dangerous time for different t_{rad} as Table 3.

Table 3. Σ_{sw} dangerous time for t_{rad} .

$t_{rad}/^{\circ}\text{C}$	dangerous time/min	Injury time/min
30	127	662
32	95	606
34	52	521

4. Discussion and conclusion

There are some disadvantages of theoretical calculation and experimental stimulation for the safety estimation of human body in thermal environment. This paper establishes an estimation method for human safety. This method integrates theoretical calculation and experimental stimulation with thermal manikin. It can simulation the real thermal response including body temperature and sweat situation. According to these bio-thermal parameters the thermal state can be estimated.

Some work needs to be improved. NEWTON thermal manikin, which is used in this method, is comprised of 20 body sections. The body temperature is calculated by the mean value of the 20 body sections. In the same way the sweat rate is calculated. For more precise, every body section, including the corresponding temperature and sweat rate should be calculated respectively.

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