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Jie Yang
Donghua University

Guowen Song
Iowa State University, gwsong@iastate.edu

Liwen Wang
Donghua University

Yun Su
Donghua University

Chunhui Xiang
Iowa State University, chxiang@iastate.edu

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Research Article

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Keywords: heat stress, chemical protective clothing, human thermal model, physiological response, thermal protection

Jie Yang,[1] Guowen Song,[1] Liwen Wang,[1] Yun Su,[1,2] Rui Li,[1] Chunhui Xiang[1]
[1]Department of Apparel, Iowa State University, USA
[2]College of Fashion and Design, Donghua University, China

Correspondence: Guowen Song, Department of Apparel, Events, and Hospitality Management (AESHM), Iowa State University, Ames, IA 50011, USA, Tel 51 5709 9052, Email gwsongsgs@gmail.com

Introduction

Chemical protective clothing (CPC) is designed to effectively eliminate the interaction of hazardous chemical/biological agents with the human body.[1] However, thermal protection and thermal comfort are two major conflicting factors for protective clothing.[2] CPC with low vapor permeability greatly restricts heat dissipation mechanisms, which creates heavy heat strain burden and reduce task efficiency as well as range-of-motion, especially when wearers are exposed to hot environments with high level of working intensity.[3–5] It is therefore necessary to investigate the human physiological responses and heat stress associated with CPC for reducing heat-related illness and improving task efficiency.

Human trials were performed to investigate heat stress through indices such as tolerance time, heart rate, heat storage, and sweating rate.[6–8] However, these previous studies dealing with heat stress in CPC focused on specific task, garment, and environment. Additionally, the results of these studies were not transferable to wearers in other garments or environmental conditions.[4] It is necessary to develop a systematic approach to evaluate physiological responses under different human-clothing-environment systems and assist the selection and design of CPC. Thus, a mathematical model is proposed in this study to evaluate physiological responses and heat stress level in CPC.

A human thermal model,[9] considering wearer characteristics, clothing properties, and environmental conditions, was applied to determine physiological responses under transient conditions. Manikin tests were conducted to measure thermal insulation and evaporative resistance of CPC, which were used as inputs to the thermal model. Based on the recommended upper limit of core temperature, the maximum exposure time of wearers was eventually evaluated taking account of activity level, clothing properties, and environmental conditions. Additionally, the effects of ambient temperature and relative humidity on physiological responses and heat stress were evaluated.

Methods

Manikin test

A 'Newton' sweating thermal manikin (Thermetrics, Seattle, USA) was applied to measure thermal insulation and evaporative resistance of clothing strictly following the standard ASTM F1291[10] and ASTM F2370,[11] respectively. The temperature, heat flux, and sweating rate of each zone can be controlled independently through the software Therm DAC8 (Thermetrics, Seattle, USA). The manikin can be operated by temperature/heat flux/thermal comfort mode. For measurements of evaporative resistance, a tight-fitted knitted fabric was dressed as 'skin' that wicks water from sweating pores and distribute water throughout the manikin surface.[12] The walking motion system of the manikin generated walking movements ranging from 0 to 1.3m/s. The software Therm DAC8 recorded the ambient temperature, relative humidity, wind speed, manikin temperature, heat flux, sweating rate, and walking speed.

The thermal insulation of clothing was calculated by the following equation:

$$R_c = \frac{T_s - T_a}{H} \tag{1}$$

Where R_c is the thermal insulation, $m^2{}^{\circ}C/W$; T_s is the surface temperature of manikin, ${}^{\circ}C$; T_a is the ambient temperature, ${}^{\circ}C$; H is the heat flux generated by manikin, W/m^2.

The evaporative resistance of clothing was expressed as

$$R_e = \frac{P_{sat} - P_{amb}}{H - \left[\left(T_s - T_a \right) / R_c \right]} \tag{2}$$

Where R_e is the evaporative resistance, $Pa{}^{\circ}C/W$; P_{sat} is the

saturation vapor pressure at skin, *Pa*; P_{amb} is the ambient vapor pressure, *Pa*.

A type of CPC was selected to measure the clothing properties by a sweating thermal manikin in climate chamber. The thermal insulation and evaporative resistance of the CPC were 0.098 m^2 *°C/W* and 22.7 *Pa °C/W*, respectively.

Human thermal model

A human thermal model proposed by Yang et al.[9] was applied to predict the physiological responses such as core temperature, skin temperature, sweating rate, and blood flow rate under various conditions. The model divided the human body into 20 segments, and each segment was comprised of four layers including core, muscle, fat, and skin layer. The central blood compartment exchanged heat with all other nodes through convection. The thermal model contained three systems: a passive system predicted heat transfer within the human body and that with its environment through evaporation, radiation, convection, and conduction; an active system simulated human thermoregulation through sweating, shivering, vasoconstriction, and vasodilation; a clothing system calculated the effect of clothing properties on heat exchange between human body and environment.

The heat balance equation of each node except for the central blood compartment was given by following.[13]

$$C_{i,j}\frac{dT_{i,j}}{dt} = Q_{i,j} - B_{i,j} + D_{i,j-1} - D_{i,j} - Res_{i,j} - (Rad_{i,4} + Con_{i,4} + Eva_{i,4})$$

(3)

Where *i* is the number of body segments; *j* is the number of node layers; *C* is the heat capacity, *Wh/°C*; T is the temperature, *°C*; *t* is the time, *h*; *Q* is the heat production, *W*; *B* is the heat exchange between each node and central blood compartment, *W*; *D* is the conductive heat exchange to neighbor layers within the segment, *W*; Res, Rad, Con, and Eva are the heat loss through respiration, radiation, convection, and evaporation, respectively, *W*.

$$C_{81}\frac{dT_{81}}{dt} = \sum_{i=1}^{20}\sum_{j=1}^{4} B_{i,j}$$

(4)

Where C_{18} and T_{81} are the heat capacity and temperature of the central blood node, respectively.

The evaporation at skin surface was comprised of heat exchange by water vapor diffusion and sweat evaporation, the details of the calculation can be found in the literature.[14] The sensible heat exchange including convection and radiation between the skin and environment was calculated by the following.[14]

$$Q_{cl} = \frac{\left(T - t_o\right)A}{I_{cl} + \dfrac{1}{\left(h_c + h_r\right)f_{cl}}}$$

(5)

Where *T* is the skin temperature, *°C*; t_0 is the operative temperature, *°C*; A is the surface area of the segment, m^2; I_{cl} is the thermal insulation of clothing, m^2 *°C/W*; h_c and h_r are the convective and radiative heat transfer coefficient, respectively, W/ m^2 *°C*; f_{cl} is the clothing area factor, NA.

Active system calculated the human thermoregulation including vasoconstriction, vasodilation, shivering, and sweating. Warm and cold signals from the receptors arrived at the hypothalamus and then appropriate effector commands were issued.[15] In the work of Stowijk,[13] the warm and cold signals were calculated through temperature difference between each node and its set-point. The detailed information of the calculation of vasoconstriction, vasodilation, shivering, and sweating can be found in the literature.[13,14]

Heat stress prediction

Core temperature is one of the most important physiological response parameters and is a critical indicator of heat stress. Maximum exposure time can be evaluated by the core temperature reaching a defined maximum value. The ISO 7933[16] recommended a maximum core temperature of 38.0°C. Some studies[17–19] used 38.5°C as the maximum core temperature, and Xu et al.[20] applied 39.0°C as the threshold value. In this work, the endurance time was calculated by the length of time until the core temperature reaches 38.5°C.

Results and discussion

The thermal model required inputs of human/clothing/environment parameters such as metabolic rate, thermal insulation, evaporative resistance, ambient temperature, relative humidity, and wind speed. Different environmental conditions and metabolic rate were selected to simulate human thermal responses, shown in Table 1.

Table I Environmental conditions and activity intensities for simulation

Cases	Ta (°C)	RH (%)	Q (W/m²)	V (m/s)
Case 1	30	40	300	0.5
Case 2	30	70	300	0.5
Case 3	40	40	300	0.5
Case 4	40	70	300	0.5
Case 5	30	40	400	0.5
Case 6	30	70	400	0.5
Case 7	40	40	400	0.5
Case 8	40	70	400	0.5

Effects of environmental conditions on physiological responses and heat stress

The mean skin temperatures were simulated by the human thermal model under different ambient temperature and relative humidity at the metabolic rate of 300W/m² (Case 1-4), shown in Figure 1. It was clear that the mean skin temperatures showed a positive correlation with the ambient temperature and humidity. The model predicted higher mean skin temperatures at the relative humidity of 70% than those at the relative humidity of 40% under both 30°C and 40°C ambient temperatures, which was in consistent with the results from Nicol[21] where high humidity increased discomfort. The effect of humidity is particularly important in hot environments in which the evaporative heat loss predominates. Besides, it can be explained by the fact that evaporative heat loss was determined by the vapor pressure difference between the skin and the environment.[1] When the environment temperature was higher than the skin temperature, evaporation would become the only way to dissipate heat from the human body to the environment. The higher the ambient humidity, the less evaporative

heat exchanged with the environment. The mean skin temperatures significantly increased when the ambient temperature rose from 30°C to 40°C, and the peak value of mean skin temperature difference between the 30°C and 40°C environment was 0.69°C (RH=40%) and 0.72°C (RH=70%), respectively. The mean skin temperature at the ambient temperature of 40°C increased at a rate much higher than that at the ambient temperature of 30°C, which was 0.039, 0.044, 0.093, and 0.097°C/min during the first 15min for case 1 to case 4. At the ambient temperature of 30°C, the skin temperature was higher than the environment temperature leading to heat dissipation to the environment. When the human body was exposed to the ambient temperature of 40°C, the human body absorbed heat from the environment by radiation and convection.
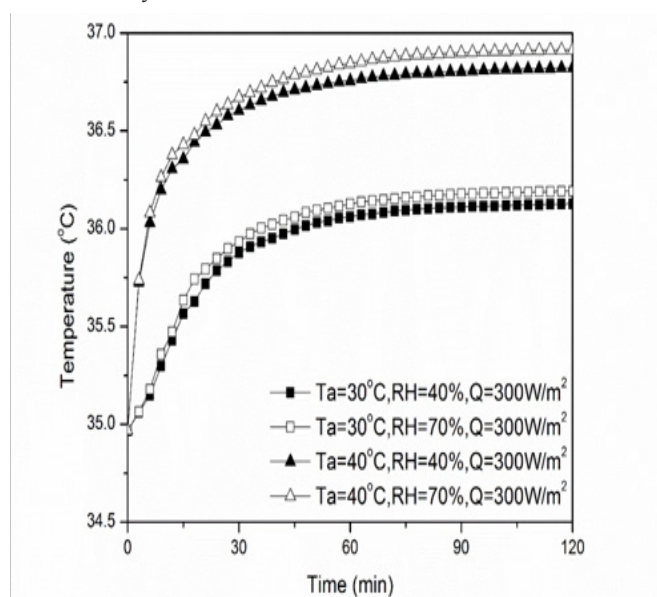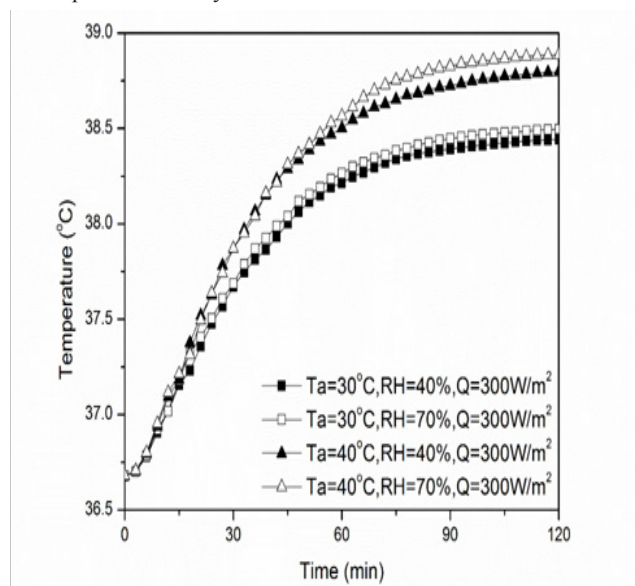

Figure 1 Mean skin temperatures simulated for case 1 to case 4.

The model predicted the core temperature for case 1 to case 4, displayed in Figure 2. Similar to the mean skin temperature, the simulated core temperatures showed a positive correlation with the ambient temperature and relative humidity. At the ambient temperature of 30°C, the simulated core temperatures at the humidity of 70% were slightly higher than those at 40%, and the similar trend was observed at the ambient temperature of 40°C. However, a larger difference of peak core temperature between case 3 and case 4 was observed compared with that of case 1 and case 2. It was probably due to the sweat evaporation which played an important role in human thermoregulation, particularly in the hot environment.

The core temperatures increased quickly in the first 30 min, it approximately increased by 1.0°C for case 1 and case 2, and 1.2°C for case 3 and case 4, respectively. At the end of the exposure, the core temperature was 38.44, 38.49, 38.80, and 38.89°C, respectively. The core temperature in case 1 and case 2 did not exceed the 38.5°C, while that in case 3 and case 4 exceeded the threshold value of 38.5°C recommended in the literature.[17,18] Therefore, the ambient temperature was a major factor affecting the heat stress. On the one hand, the human body gains heat from ambient through convection and radiation in the hot environment. On the other hand, the rate of metabolic heat production in the hot environment was higher than that in the normal environment.[9] Based on the recommended core temperature limit, the maximum exposure time was 60min for case 3 and 57min for case 4.

It can be concluded that the maximum exposure time should be longer when exposed to the dry environment than to the humid environment.

Figure 2 Core temperatures simulated for case 1 to case 4.

Effects of metabolic rate on physiological responses and heat stress

The model predicted the mean skin temperatures for case 5 to case 8, displayed in Figure 3. It was obvious that the simulated mean skin temperatures for case 5-8 was much larger than those in corresponding case 1-4. The heat storage in human body increased with the increasing of metabolic rate, causing the rise of mean skin temperature. In the first 15min, the increase rate of mean skin temperature for the case 5 to case 8 was 0.060, 0.067, 0.11, and 0.12°C/min, respectively. The case 8 had the highest increase rate of mean skin temperature caused by the high ambient temperature and humidity. Compared with the mean skin temperature increase rate in case 1 to case 4, the mean skin temperature increase rate at metabolic of 400W/m² approximately increased by 50% and 20% at the ambient temperature of 30°C and 40°C, respectively. The peak value of mean skin temperature occurred at the end of the exposure, and the difference of mean skin temperature peak value between case 1 and case 5, case 2 and case 6, case 3 and case 7, and case 4 and case 8 was 0.43, 0.47, 0.40, and 0.42°C, respectively. Thus, the mean skin temperature increase rate in a more humid environment (RH=70%) was slightly higher than that in a less humid environment (RH=40%) when the metabolic rate increased from 300 to 400W/m². According to (Figure 1) (Figure 3), the ambient temperature and metabolic rate greatly influenced the mean skin temperatures than the ambient humidity did.

The model predicted the core temperatures for case 5 to case 8, displayed in Figure 4. The core temperatures increased sharply during the first 30min, and the increase rate of core temperature was 0.043, 0.046, 0.046, and 0.053°C/min, respectively. The case 8 had the highest increase rate of core temperature, which displayed the same trend with case 4. The temperature difference between case 5 and case 6 was much lower than that between case 7 and case 8, which can be explained by the sweating evaporation of human body. The maximum core temperature during the exposure for case 5 to case 8 was 38.95, 39.02, 39.31, and 39.42°C, respectively. When the metabolic rate

increased from 300 to 400W/m^2, the maximum core temperature in case 5 to case 8 was nearly 0.5°C larger than that in case 1 to case 4 regardless of the change of ambient temperature and humidity.
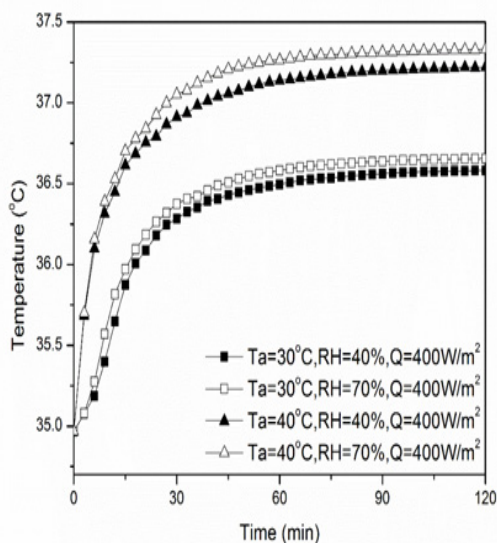

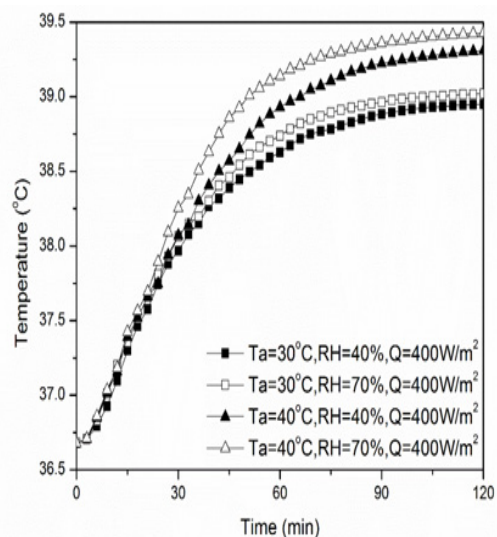**Figure 3** Mean skin temperatures simulated for case 5 to case 8.

Figure 4 Core temperatures simulated for case 5 to case 8.

The maximum exposure time was evaluated based on the parameters in case 1 to case 8, shown in Figure 5. The longest exposure time was observed for case 1 with 129min, followed by the case 2 with 126min, and the shortest exposure time was found for case 8 with only 36min. It can be concluded that the maximum exposure time was mostly influenced by the ambient temperature and metabolic rate. Therefore, working in a hot environment with heavy activity level can greatly reduce maximum exposure time. Although the maximum exposure time was affected by the relative humidity, the increased relative humidity from 40% to 70% caused approximately 3-6min decreased in maximum exposure time. Therefore, intolerable heat strain would easily occur in a hot environment. Additionally, the physical load could further enhance heat stress raising the risk of danger to wearers' health and safety.[20]
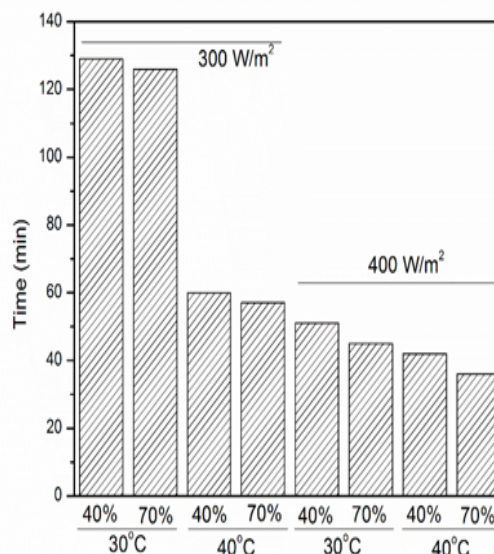

Figure 5 Maximum exposure time under the parameters for case 1 to case 8.

Conclusion

A human thermal model was applied to evaluate physiological responses under different environmental conditions and activity intensities when wearing a typical CPC. Based on the recommended core temperature threshold, the maximum exposure time of wearer was evaluated. The results indicated that the ambient temperature and metabolic rate significantly increase heat stress, while relative humidity only slightly affects the physiological responses and heat stress. The current model was capable of predicting maximum exposure time under different environmental conditions, which can be used for human safety assessment.

Many factors such as activity intensity, clothing properties, air gap size, and environmental conditions affect physiological responses and heat stress. The CPC should be designed not only to offer chemical protection but also to improve thermal comfort. In this work, the effects of activity intensity and environmental conditions were analyzed. In the future work, the effects of clothing properties and air gap size on heat stress will be investigated to improve the understanding of thermal comfort of CPC and wearer performance. A 3-D body scanning system will be applied to measure the air gap between skin and clothing, and the influence of air gap thickness on heat transfer and heat stress will be analyzed.

Acknowledgements

Conflict of interest

Author declares there is no conflict of interest in publishing the article.

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