Heat stress evaluation at the working face in hot coal mines using an improved thermophysiological model

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ABSTRACT

With the increasing mining depths and the improving mining mechanization, coal miners in China have been exposed to increasingly hotter working conditions, especially in the working face where heat hazards are of high possibility. In this paper, a multi-segment thermos physiological model with an improvement in heat and moisture transfer through clothing was used to evaluate heat stress at the working face in hot coal mines. The improved thermos physiological model was firstly demonstrated with miners' thermal response data collected by field measurements, and then parametric simulations were done to evaluate the physiological influences of the relative humidity and the unsteady (cool-hot changing) air temperature along the working face. It is found that the cool-hot changing thermal environments significantly affect miners' physiological responses and thermal sensations, especially the air temperature changes around 24 °C~26 °C, and the heat stress can be relieved if a proper work-rest organization in a hot working face is addressed

Keywords: Coal Miner, Heat Strain, Underground Coal Mines, Thermal Physiology.

1. INTRODUCTION

Heat stress issues have been addressed in the mining industry of many countries like South Africa, Germany, India, Australia, the United States and Canada for the past decades [1-4]. In recent years, with the increasing mining depths and the improving mining mechanization, mine hazards, particularly mine fire and heat hazards have been becoming more frequent and serious in underground coal mines in China [5-8]. In some coal mines with a mining depth beyond 1000 m, the dry bulb temperature at the working face can reach 40 °C and the relative air humidity is up to 90%~100%. In such hot coal mines, even air conditioning system or other cooling measures are added, it is of great difficulty to control the maximum dry bulb temperature of some spots, like the back-end of a long working face (particularly the corner of return airways), down to 26 °C. Heat hazards to miners at the working face are therefore a high possibility.

In addition to the diversity of the tasks that miners perform at the working face, there is a high degree of variability of the environmental conditions from one location to another within a long working face, which depends on the operational conditions (i.e., use of machinery, use of water spray, etc.) and the accumulated heat dissipation from the rib, roof and the floor to the air flow. As far as we know, experimental studies in laboratory on evaluating heat stress in the working face of hot coal mines are rare, which is mainly on simulating a steady thermal condition [9], since it is of great difficulty in setting up a quite similar variable thermal condition (cool-hot

changing along the working face) in the laboratory, and the field measurement work is relatively scarce as it is quite hard to measure and acquire accurate miners' physiological response data on site [2]. In the past decades, heat stress indices, and mathematical thermoregulation models have been becoming popular to investigate heat strain problems of miners [10, 11].

Initially, the heat stress indices or empirical approaches, such as Effective Temperature (ET), Corrected Effective Temperature (CET), Predicted Four-Hour Sweat Rate (P4SR), Heat Stress Index (HSI), Wet Bulb Globe Temperature (WBGT) and so on, had been primarily applied to evaluate heat stress levels in hot mines because of the simple measurements and calculations [10,12-14]. Placed great emphasis on evaluating environmental conditions, heat stress indices cannot directly calculate the heat exchange between a person and the environment [15], and could not directly reflect miners' physiological strain, like the interaction of human skin or respiration with the thermal environment. Later, a number of heat stress evaluation methods based on heat balance equations taking into account both environmental conditions and personal conditions (ambient air temperature, radiant temperature, humidity, air speed, clothing, and metabolic rate) have been developed [15-22]. Based on heat balance equations, these models can estimate the increase of core temperature and maximum of sweat rates emitted during work and dehydration level, which can be used to predict thermal stress. Among aforementioned models based on heat balance equations of human body, the

Predicted Heat Strain (PHS) model has been widely used in evaluating heat stress levels in hot and humid conditions [20, 21]. Wu et al. used the PHS model to analyze the thermophysiological responses of miners under a variety of hot and humid conditions, and also determined accepted maximum exposed working time [22]. However, these existing models or heat stress indices for evaluating heat stress in hot mines have generally focused on steady-state conditions, and there are currently no models that address miners' physiological responses to cool-hot changing (unsteady or step-change) thermal conditions along the working face [11,18,19]. In addition, these existing models primarily evaluate heat strain and the sensation of the entire body, and cannot address local thermal analysis.

In this paper, the multi-segment UC Berkeley Thermophysiological Comfort model (BTCM) with an improvement in heat and moisture transfer through clothing is used to evaluate heat stress in unsteady environments (cool-hot changing) in the working face of hot coal mines. The improved BTCM is firstly validated with the thermal response data collected by field measurements in a hot coal mine. Based on the improved BTCM, emphasis has been put on the analysis and evaluation of physiological responses and heat of miners under the primary hot and humid conditions at the working faces in Chinese coal mines. Finally, some strategies for work organization in the working face proposed.

2. IMPROVED THERMOPHYSILOGICAL MODEL

In this paper, the multi-segment BTCM with an improvement in heat and moisture transfer through clothing is used to predict the heat strains for coal miners working in hot environment. The BTCM model has 16 body segments whose areas correspond to a widely used electrical manikin, each of which has five layers (core, muscle, fat, skin and clothing), and the BTCM can well deal with transient or unsteady conditions [23]. The heat and moisture transfer between the human body and environment for each segment is evaporation, radiation, convection, and conduction (where applicable). The clothing model considers the effect of clothing moisture absorption/desorption rate on heat transfer, as well as the effect of airspeed on the thermal and vapor resistance of clothing. However, the treatment of clothing insulation in the BTCM model has been insufficient for the purposes of predicting dynamic sensible and evaporative heat transfer for each body segment under a range of wind and walking conditions.

To tackle the aforementioned clothing layer issues of the BTCM model, Fu et al. presented two paths of heat and moisture transfer, i.e. between naked skin and environment, and clothed skin and environment [24]. With the improved implementation, the new BTCM model can address transient behavior due to absorption and desorption by clothing, and specific segment values for clothing insulation, vapor resistance, and the effects of air movement and walking. The improved BTCM model can predict the human thermal response, such as skin and core temperature for each segment, and can be used to predict perceived thermal sensation for different ambient levels, air temperatures and clothing ensembles in transient, non-uniform thermal environments.

The improved implementations of modelling of heat and moisture from skin and through clothing to the air are briefly described as follows. The sum of the fractions of naked and clothed areas of each segment is unity as shown in Eq (1).

$$F_{nude} + F_{clothed} = 1 \tag{1}$$

where F_{nude} and F_{closed} are the fractions of the naked and clothed area for each segment, respectively. When this segment is totally nude, the clothed fraction is zero.

2.1 Skin node

The heat storage of the skin node, $q_{skin,storage}$, is:

$$q_{skin,storage} = q_{fat} + M_{skin} - q_{skin-env} - q_{skin-clo} - q_{evap,\ skin-env} - q_{evap,\ skin-clo} \tag{2}$$

where q_{fat} and M_{skin} are the heat gain from fat and skin metabolic heat production, respectively. $q_{skin-env}$ and $q_{skin-clo}$ are the sensible heat losses from nude and clothed skin to the environment, respectively. $q_{evap,skin-env}$ and $q_{evap,skin-clo}$ are the latent heat exchanges from the naked and clothed skin, respectively. $q_{skin-env}$ is calculated as:

$$q_{skin-env} = A * F_{nude} * \left(h_c \left(T_{skin} - T_{air}\right) + q_{vf-skin}\right) \tag{3}$$

where A is the total skin surface area of the segment. T_{skin} and T_{air} are the skin and ambient air temperatures, respectively (°C). $q_{vf-skin}$ is the radiative heat transfer calculated by view factors, in W/m², which is described in [23]. h_c (W·m⁻²·°C⁻¹) is the coefficient of the convective heat exchange, $q_{skin-clo}$ is obtained by the temperature difference between skin and the clothing (T_{clo}). I_{clo} is the number of clo unit (1 clo = 0.155 m²KW⁻¹) for the intrinsic thermal resistance of the clothing:

$$q_{skin-clo} = A * F_{clothed} * \frac{\left(T_{skin} - T_{clo}\right)}{I_{clo}} \tag{4}$$

The latent heat exchange from the naked skin to environment, $q_{evap,\ skin-env}$ can be calculated by:

$$q_{evap,skin-env} = w * A * F_{nude} * \frac{\left(P_{skin} - P_{air}\right)}{R_{e,air}} \tag{5}$$

where P_{skin} and P_{air} are the partial vapor pressures at skin and in the air, respectively, in kPa. w is the skin wettedness, calculated by BTCM. $R_{e,air}$ (kPa·m²·W⁻¹) is the evaporative resistance of ambient air. $R_{e,air}$ is related to h_c through the Lewis constant for air (Le, 16.5 °C/kPa).

$$R_{e,air} = \frac{1}{h_c * Le} \tag{6}$$

The latent heat exchange from the clothed skin to the clothing, $q_{evap,\ skin-clo}$ is calculated as below. C_{H_2O} is the specific heat of water (4.2×10³J kg⁻¹°C⁻¹).

$$q_{evap,skin-clo} = A * F_{clothed} * \left[\frac{\left(P_{skin} - P_{air}\right)}{R_{e,tot}} + C_{H_2O} * m_{clo,cloth} \left(T_{skin} - T_{clo}\right)\right] \tag{7}$$

The heat absorbed by the clothing, m_{clo} is caluated from [24].

2.2 Clothing node

The stored heat within the clothing node is calculated as:

$$q_{clo,storage} = q_{skin-clo} - q_{clo-env} + q_{evap, skin-clo} - q_{evap,clo-env} \qquad (8)$$

where $q_{clo-env}$ and $q_{evap,clo-env}$ are the sensible and latent heat losses between the clothing and the environment, respectively.

$$q_{clo-env} = A * f_{clo} * F_{clothed} \left(h_c \left(T_{clo} - T_{air} \right) + q_{vf-skin} \right) \qquad (9)$$

$$q_{evap,clo-env} = A * f_{clo} * F_{clothed} * \frac{\left(P_{cloth} - P_{air} \right)}{R_{e,air}} \qquad (10)$$

For more details about the two paths through which heat is transferred from exposed or clothed skin to the ambient environment and the improvements of BTCM model in heat and moisture transfer through clothing, please refer to the reference [24].

3. RESULTS AND DISCUSSIONS

3.1 Validation of the improved BTCM model

The BTCM model has been validated against thermophysiological responses in transient, non-uniform thermal environments for office buildings, automobiles, and outdoors [23]. In this study, the improved BTCM model is further demonstrated with miners' thermal response data collected by field measurements at the working face in a hot underground coal mine. In the site measurement, we mainly measured the skin temperature of the workers. The strict safety management code in coal mines of China only allow fireproof and explosion-proof products to be used in underground coal mines. The strict safety code and the complex working condition in the working face restrict us to find a suitable measuring apparatus to measure the rectal temperature of the miners who are moving at work. This problem is common also in other dangerous environments as in glass industry and in technical spaces of ships as engine rooms [25]. The skin temperature is not as accurate as the core temperature to evaluate the heat accumulation within the body [26], while it can indicate physiological responses to some extent. Previous studies verify that in some cases skin temperatures can be used as an indicator to predict deep-body temperature and evaluate heat strain [19, 27].

The site measurements were done in a hot coal mine with an average mining depth of 800 meters. The length of the working face is about 240 meters and the coal seam is with an average thickness of 7 meters. The coal is extracted using fully mechanized longwall mining with sublevel caving technology. The geometric schematics of the site measurement at the working face are illustrated in Figure 1. Benefited from employing a mine cooling system, the air temperature along the working face is around 19.2 ℃ ~29.1 ℃. The relative humidity in the working face was pretty high and irregularly changes from 80% to 100% because of utilizing spraying systems. The air volume in the working face was approximately 1, 800 m³/min. Since the

cross-section shape of the working face is not completely the same and the objects in the working face (like conveyors, shearers, miners) resist the air flow, the measured air velocity in the working face varied from 1.49 m/s to 1.77 m/s, the mean radiation temperature is around 40 °C, which is mainly determined by the temperature of coal rig in the working face.
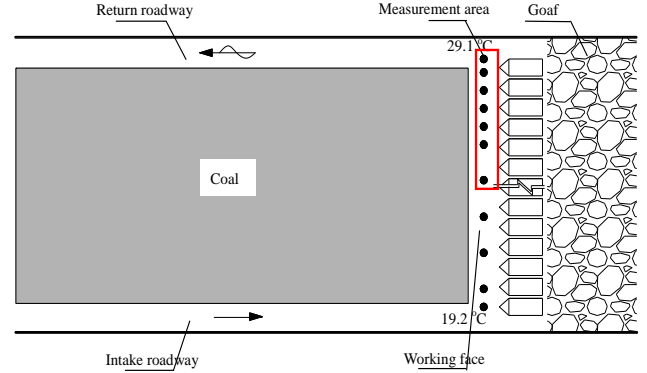

Figure 1. The geometric schematics of the site measurement

Following approval of the experimental protocol from the Research Ethics Committee of China University of Mining and Technology, Beijing, six coal miners agreed to act for this study measurement. All subjects were aware of the protocol of the measurement. Before descending to the underground mine, all subjects underwent a basic medical examination for height, weight, body temperature, blood pressure and heartbeat. During the course of the measurement, one subject incurred a light swelter so that we stopped the measurement of his physiological responses and he went up to ground earlier. The physical characteristics of the rest five miner subjects (mean ± SD) were the following: age, 36.2± 2.5 years; working age, 13.2± 2.3 years; weight, 70.8±3.1 kg; height 171±3.8 cm. All workers passed health evaluation for fitness for work. During the field measurement, the five miner subjects dressed in 100% cotton short-sleeve shirt, short pants, helmet and leather boots were working in the working face, and the total thermal resistance of this mining ensemble is about 0.69 clo [28]. Three researchers walked back and forth along the working face to collect the skin temperatures at forehead, chest and armpit of the five subjects every thirty minutes. The duration of the site measurement was about three hours, during which the five miners moved and worked in an area (see the rectangle area in Figure 1) under an environmental condition that the air temperature was variable from 24.2 °C to 29. 1 °C, the air speed was around 1.5 m/s and the averaged relative humidity (RH) was around 90% (DHM2, Longtuo Instrument, Shanghai, China), the mean radiation temperature is about 39 ℃. The air volume and air velocity were calculated based on the site measurements using two mechanical air-flow meters (DFA, Zhongmei Group, China)

The labor intensity of miners at the working face using fully mechanized longwall mining with sublevel caving technology is not very intensive. In the simulation, we gave an averaged activity level of 1.5 met (weighted considering the rest instants since the miners do not keep working at all the working duration at the fully mechanized working face). In the simulation with the improved BTCM model, the miner subjects were exposed to a step-change thermal environment from 24.2 °C to 29. 1 °C with the air speed as 1.5 m/s, RH as 90%, and the mean radiation temperature as about 39 ℃. To well simulate and approximate the variable thermal

environment in the working face, the thermally step-change setup was changing approximately 2 °C per half an hour, i.e. staying in 24.2 °C for half an hour, and then shifting to 26.2 °C; then to 28.2 °C; then to 29.1 °C; then to 28.2 °C; then to 26.2 °C. In the simulation, 5 minutes for taking a rest in every thermal step phase of half an hour was implemented considering that miners normally have intermittent stop during the high-load work in the hot working face.

In the field measurement, the skin temperatures at forehead, chest and armpit of all subjects were recorded every thirty minutes. Data were presented as the average of the temperature monitors of all subjects, and the skin temperature (seen in Table 1) is weighted with forehead, chest and armpit temperature.

Table 1. Miner's mean skin temperatures weighted with measured forehead, chest and armpit temperature

Time /min	Miners' mean skin temperatures /°C					Mean_S /°C
	Miner1	Miner2	Miner3	Miner4	Miner5	
30	36.31	36.50	35.88	35.70	35.61	36.00
60	36.00	35.97	36.80	36.73	37.00	36.50
90	35.80	37.18	37.90	36.90	37.22	37.00
120	36.60	37.40	37.50	36.51	37.04	37.01
150	37.22	38.04	36.22	36.15	37.32	36.99

Note: Mean_S is the weighted skin temperature of the five subjects

Figure 2 shows the comparison of the mean measured skin temperature of five subjects and the predicted values of the improved BTCM model. The predicted skin temperatures are reasonably consistent with the measured data, with a maximum difference of 0.3 °C at 120th minute. It is indicated that the improved BTCM model can approximately simulate the physiological responses of miners at the working face in Chinese hot underground coal mines.
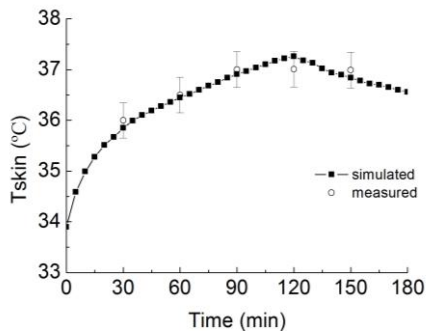

Figure 2. Comparison of field measurement data and predicted values of improved BTCM model

3.2 Effects of working thermal conditions

Previous studies clarified that the thermal conditions, such as ambient air temperature, radiant temperature, humidity, air speed, have great influence on heat stress [9-12]. From the site measurement, it is observed that the radiant temperature and air speed in the working face change slightly. Therefore, herein emphasis is placed on the analysis and evaluation of the effects of humidity and transient air temperature on heat stress in the working face. Parametric runs are made of thermal and sensation behavior to show the dynamic sensitivity of the sensible and vapor heat transfer of the miners.
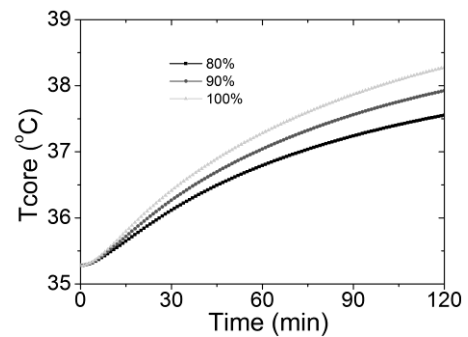
3.2.1 Effects of RH
The miners (dressed in an ensemble with 100% cotton short-sleeve shirt, short pants, helmet and leather boots with a total thermal insulation about 0.69 clo [28]) with the averaged working activity level of 1.5 met for 180 minutes in a hot environment at air temperature of 28 °C, the radiant temperature of 39 °C and air velocity of 1.5 m/s, was investigated. The predicted core (rectal) temperature and mean skin temperature were presented under different levels of RH (80 %, 90 % and 100 %). Figure 3 shows the distribution of the predicted averaged skin and core temperatures. It can be seen that the skin and core temperatures increase with the level of RH, and the skin temperature particularly goes up to 36 °C just after minutes of work, which is consistent with the measured skin temperature data of miners. The latent heat loss from skin by sweating can decrease with the increase of RH, seen from Equations (2-3). Therefore, the heat storage within the human body can increase with the level of RH, resulting in the increase of skin and core temperatures.
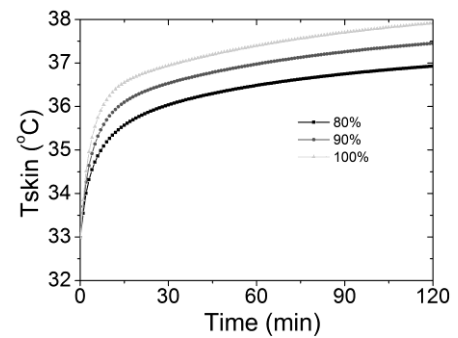
(a) Skin temperature

(b) Core temperature

Figure 3. The predicted skin and core temperatures under different levels of RH

3.2.2 Effects of temperature changes
In the working face, the miners should move back and forth with the mining advancing, and thus miners are working under an environment that the thermal condition is of periodic variation. In order to investigate the influence of non-uniform variable thermal environment on the heat stress, we arranged thermally step-change setup in the improved BTCM. To well approximate and simulate the variable thermal environment in the working face, the thermally step-change setups were addressed to change 2 °C per hour or per half an hour and changing extremely 4°C or 8 °C per 1 or 2 hours, respectively. Considering that the heat head in the deep coal mines could be getting more severe, two thermal environments, i.e. moderate and extreme thermal conditions, were implemented in the simulation. The different temperature step changes in simulation of moderate and extremely hot working faces in underground coal mines are shown in Table 2 and Table 3.

Parametric runs are made of thermal response in which the miners are exposed to moderate and extreme thermal environments seen in Table 2 and Table 3. In the simulation, the miners dressed in an ensemble with 100% cotton short-sleeve shirt, short pants, helmet and leather boots (total thermal insulation about 0.69 clo [28]) with the averaged working activity level of 1.5 met, were exposed for 300 minutes in total under the air velocity of 1.5 m/s and RH of 90 %.

Table 2. Temperature step changes of moderate thermal environment (case 1)

Air temperature /^{o}C	28	26	24	22	20	22	24	26	28
Time duration of Option 1/h	1	0	1	0	1	0	1	0	1
Time duration of Option 2 /h	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Table 3. Temperature step changes of extreme thermal environment (case 2)

Air temperature /^{o}C	34	30	26	22	18	22	26	30	34
Time duration of Option 1 /h	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Time duration of Option 2 /h	1	0	1	0	1	0	1	0	1
Time duration of Option 3 /h	1	2	0	0	0	0	0	0	2

Case 1: Moderate thermal environments

There are two suggested options of temperature step changes, i.e. with the air temperature from 28 ^{o}C to 20 ^{o}C, and back to 28 ^{o}C, in moderate thermal environments seen in Table 2. Figure 4 shows the distribution of predicted averaged skin and core temperatures in moderate thermal environments. It can be seen that the change of skin temperature is along with the heat loss to the environment (seen in Figure 5). The skin temperature in the end is basically the same. The heat loss, normally through convection and radiation in moderate thermal environments, is determined by the difference of the skin and air temperatures. It is also shown that the time when the change of skin temperature is from decrease to increase is consistent with the transition time of heat loss, for the air temperature from 20 ^{o}C to 22 ^{o}C. This is corresponding to the change of core temperature. The core temperature at the 180th minute is nearly the same when the air temperature is changing from 20 ^{o}C to 22 ^{o}C. Therefore, the prediction of human thermal response is very important to show thermal physiology and heat transfer to the environment, when working in the thermal condition with the change of the air temperature near from 20 ^{o}C to 22 ^{o}C. When working under a changing moderate thermal condition, it is observed from Figure 4 that the core temperature of the miners does not exceed 38.0 ^{o}C, below which no physical damage would be expected [29].

Thermal sensation model of BTCM for non-uniform and transient environments were developed, validated against the chamber experiments [30]. The model predicts the thermal sensation for the subjective responses to the environment from skin and core temperatures. The sensation scale is a 7-point scale to accommodate extreme environments: 4-"very hot", 3-"hot", 2-"warm", 1-"slightly warm", 0-"neutral", -1-"slightly cool", -2-"cool", -3-"cold", -4-"very cold" [31].

Figure 6 shows the thermal sensations of miners under the moderate thermal environments. There is not much difference between the two options when the air temperature is changing from 28 ^{o}C to 24 ^{o}C and back from 24 ^{o}C to 28 ^{o}C, or changing from 22 ^{o}C to 20 ^{o}C and back from 20 ^{o}C to 22 ^{o}C. However, the thermal sensation is near -1 ("slightly cool") at the 120th minute and is close to 1 ("slightly warm") at the 240th minute, with a bigger changing rate of time of duration (Option 2). The thermal sensation is still about 3 ("hot") at the 120th minute, and near 4 ("very hot") at the 240th minute under the thermal environment of Option 1. It is indicated that the air temperature ranging from 22 ^{o}C to 24 ^{o}C is one of the key control factors to relieve heat strains and

improve the tolerance during physical work in hot underground coal mines. The ventilation system is suggested to supply the air flow of around 24 ^{o}C to keep a neutral thermal condition for working, but it is of great difficulty to control the thermal condition around 24 ^{o}C at the full working face in hot coal mines. It is a practicable advice that the miners can shift by turns to move to the thermal area of air temperature at 24 ^{o}C to take a short rest or move on to other work tasks need done at the 24 ^{o}C area.

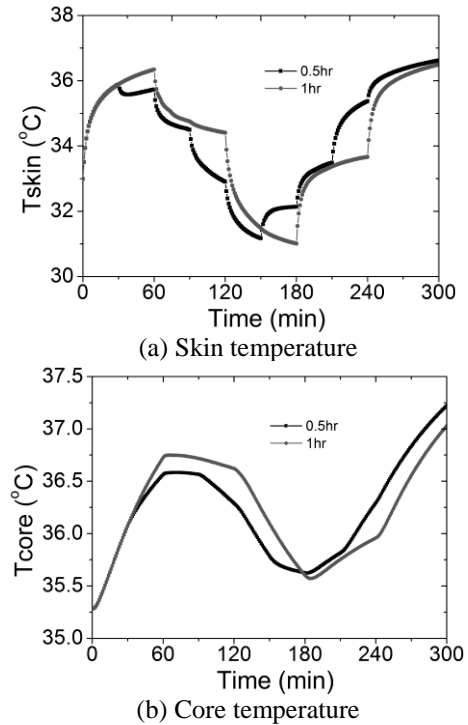(a) Skin temperature

(b) Core temperature

Figure 4. The predicted skin and core temperatures under the moderate thermal environments

Case 2: Extreme thermal environments

There are three suggested options of temperature step changes, with the air temperature from 34 ^{o}C to 18 ^{o}C, and then back to 34 ^{o}C, in extreme thermal environments as seen in Table 3. Figure 7 shows the distribution of the predicted averaged skin and core temperatures of miners in extreme thermal environments. It can be observed that the skin temperature at the 180th minute is nearly the same, which is 31.7 ^{o}C, 32.1 ^{o}C and 31.9 ^{o}C for the three options, respectively. The skin temperature is also almost the same at

the 120th minute for the first two options, 37.1 °C and 37.0 °C, respectively. The change of skin temperature is along with the heat loss to the environment (seen in Figure 8), for the comparison of the time integration of the heat loss. However, when the air temperature changes from 18 °C (cool) to 34 °C (hot), the skin temperature is increasing with a bigger gradient from Option 1 to 3. The heat loss through the convection and radiation is then decreasing, for the smaller difference of the skin and air temperatures as well among the three options. It is also shown that the core temperature is also decreasing with a bigger gradient from Option 1 to 3, when the air temperature changes from 34 °C (hot) to 18 °C (cool). Therefore, the cooling effects of cool air on core temperature can be easily achieved for the Option 1 and Option 2, considering its slighter change corresponding to the change of air temperature.
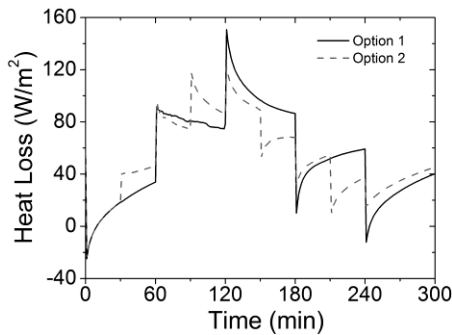
Figure 5. The predicted heat loss under the moderate thermal environments
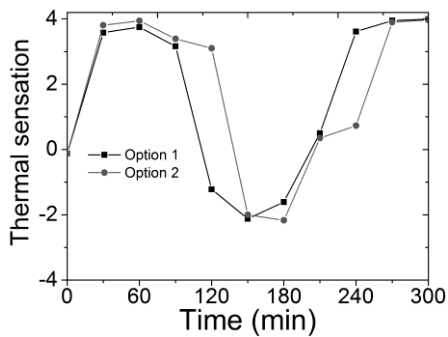

Figure 6. The predicted thermal sensation under the moderate thermal environments

In addition, from Figure 7, it is shown that it apparently prolongs the exposure time when the core temperature of the miners exceeds 38.0 °C under the condition that the miners work under a hot-cool changing thermal condition. This working way relieves the heat strain of miners in a hot working face.
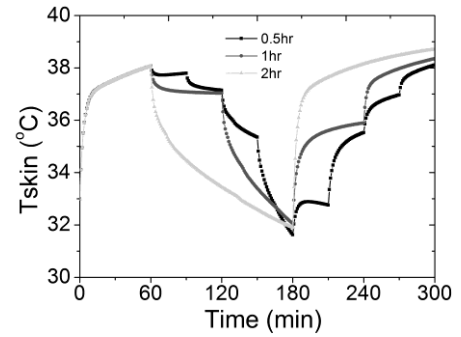
(a) Skin temperature
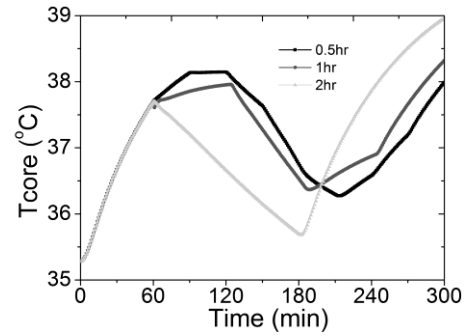
(b) Core temperature

Figure 7. The predicted skin and core temperatures under the extreme thermal environments

3.3 Work organization advices

For realizing a moderate thermal environment like aforementioned Case 1 or an extreme thermal environment like Case 2 in the working face, the required cooling capacity of the mine cooling system significantly.

From the analysis and discussion in Section 3.2.2, it is known that the thermal responses and thermal sensation of the miners are affected by the periodically changing thermal condition, especially when the air temperature changes around 24 °C~26 °C. In the working faces of some deep hot mines, it is highly energy consuming to make the thermal environment below 26 °C, and sometimes it is of great difficulty to control the air temperature of the working face below 30 °C due to the complex geothermal feature or the technical bottleneck of underground cooling measures. Under such circumstances, the miners can shift by turns to go to the thermal area of air temperature around 22 °C~ 24 °C to take a short rest or switch to other work tasks need done at the 22 °C~24 °C area. In this way of work organization, the heat stress can be relieved to some extent.
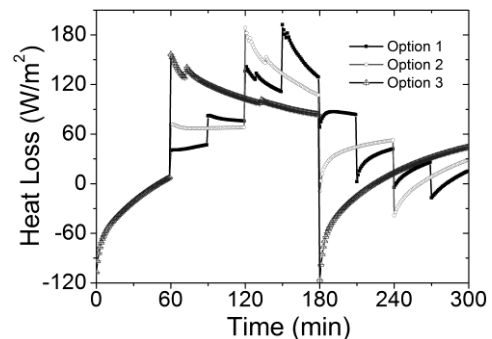

Figure 8. The predicted averaged heat loss under the extreme thermal environments

4. CONCLUSIONS

In this study, the improved BTCM validated with field measurement data in a hot coal mine, was used to evaluate thermalphysiological responses of miners in changing thermal environments at the working face of a variety of hot and humid conditions. Emphasis was placed on evaluating the influences of the relative humidity and cool-hot changing air temperature on human thermoregulation. It is found that: a) the skin and core temperatures of the miners increase fast with the level of high RH, and the skin temperature particularly goes up to 37 ºC very quickly; b) the unsteady (cool-hot changing) thermal condition significantly affect miners' thermal responses and thermal sensations, and the heat stress can be relieved if a proper work organization in a hot-cool changing working face is addressed; c) the air temperature around 22 ºC~24 ºC is one of the key control factors to from heat strain and improve the thermal tolerance during high-load physical work in hot underground coal mines.

For the miners' health in terms of heat stress, it is suggested that the air flow of 22 ºC ~24 ºC in the working face supplied by the air conditioning system or other cooling measures, whereas for the extreme hot coal mines, the miners should shift by turns to the thermal area of air temperature around 24 ºC to take a short rest or switch to other work tasks at the 24 ºC area, which is helpful to achieve heat strain relief.

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NOMENCLATURE

F_{nude}	fractions of the naked area for each segment
F_{closed}	fractions of the clothed area for each segment
q_{fat}	heat gain from fat metabolic heat production
M_{skin}	heat gain from skin metabolic heat production
$q_{skin\text{-}env}$	sensible heat losses from nude to the environment
$q_{skin\text{-}clo}$	sensible heat losses from clothed skin to the environment
$q_{evap,skin\text{-}env}$	latent heat exchanges from the naked
$q_{evap,skin\text{-}clo}$	latent heat exchanges from the clothed skin
A	total skin surface area of the segment
T_{skin}	skin temperature
T_{air}	ambient air temperature
$q_{vf-skin}$	radiative heat transfer calculated by view factors, W/m^2
h_c	coefficient of the convective heat exchange, $W \cdot m^{-2} \cdot {}^{\circ}C^{-1}$
$q_{skin-clo}$	obtained by the temperature difference between skin and the clothing
I_{clo}	number of clo unit for the intrinsic thermal resistance of the clothing
P_{skin}	partial vapor pressures at skin, kPa
w	skin wettedness, calculated by BTCM
$R_{e,air}$	evaporative resistance of ambient air, $kPa \cdot m^2 \cdot W^{-1}$
$q_{evap, skin-clo}$	The latent heat exchange from the clothed skin to the clothing
C_{H_2O}	specific heat of water ($4.2 \times 10^3 J\ kg^{-1}{}^{\circ}C^{-1}$)
m_{clo}	heat absorbed by the clothing
$q_{clo\text{-}env}$	sensible heat losses between the clothing and the environment
$q_{evap,clo\text{-}env}$	sensible and latent heat losses between the clothing and the environment