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HOT ENVIRONMENT- ESTIMATION OF THERMAL COMFORT IN DEEP UNDERGROUND MINES

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ABSTRACT: Underground mines are a special type of environment which requires significant attention since they directly relate to miners' productivity, health and safety. With coal or ore exploitation into deep underground mine environments, high temperature and humidity creates risks because of large amounts of heat generated from geothermal heat, mining machines, groundwater and mine water. There have been many assessment methods for underground mine environment, such as dry-bulb temperature and wet-bulb temperature. However, none of the current methods can comprehensively evaluate the underground mine environment since most methods consider only one or a few defined factors and neglect others. In order to evaluate the human body's thermal status in terms of both personal and environmental viewpoints, this investigation firstly discusses the new upper limits of dry-bulb temperature with the support of some simulated results of indicators from ISO7933, and then adopts both mean skin temperature and dry-bulb temperature to establish a zone diagram. The calculation of mean skin temperature is based on the heat balance of the human body with the ambient environment. Then existent regulations on underground mine environments and some typical condition parameters in underground mines are applied to circumscribe different thermal zones. The established thermal zone diagram defines the preferable condition zone, acceptable condition zone, and prohibited zone. This method considers parameters from both the human body and the surrounding environment and hence offers a more comprehensive estimation.

INTRODUCTION

In comparison with other built environments in terms of the quantification of key parameters affecting air quality, underground mines have seemingly paid more attention to traumatic injury, noise, radon daughter exposure, infra-red exposures in pyrometallurgical processes (Donoghue, 2004) but less attention to human thermal comfort. Hot and humid environments are encountered in deep underground mines, where the virgin rock and air temperatures increase with depth due principally to the geothermal gradient, increasing air pressure from auto-compression of the air column, and groundwater. Mine water transfers heat and vapour to the air by evaporation, and the air receives the heat liberated by mining machinery and equipment as well as less important sources of heat including oxidation processes, human metabolism, explosive blasting, rock movement, and pipelines (Hartman, *et al.*, 1997).

In China the average temperature of the original rock in state-owned coal mines ranges between 35.9 and 36.8°C at the production level while the average mining depth was about 650 m by the year 2000, that would result in dry bulb temperatures exceeding 30°C and humidity of 95% to 100% in working faces (He, 2009). However, in Australian coal mines increasing strata temperatures at relatively shallow depths in combination with high surface ambient temperatures, e.g., in Queensland, have led to uncomfortably high ventilation temperatures on longwall faces. Wet bulb temperatures exceeding 30°C and humidity of 95% to 100% on longwall faces were reached due to the added heat from broken coal and rock on the face and in the goaf together with the heat dissipated by higher capacity longwall equipment (Mitchell, 2003). In South Africa, as the ore reserves for gold are now only to be found in deeper deposits, the current research contemplates depths of up to 5 km and beyond, and heat loads caused by increasing mining depths and the geothermal gradient. Webber-Youngman (2007) states that optimisation of energy resources through active control and predictive simulation modelling is possible, which could lead to establishing a safe, healthy and productive working environment in hot underground mines in South Africa.

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Currently widely-used evaluation indices for the human body's thermal conditions in hot and humid environment, include, but are not limited to dry and wet-bulb temperature, Effective Temperature (ET) (ASHRAE, 2005), Wet-bulb Globe Temperature (WBGT) (ISO7243, 1986), Heat Stress Index (HSI), work and recovery heart rate, body temperature (NIOSH, 1986). However, some of these indices have not been improved for a long period and are lack of theoretical basis. For example, the coal mine safety regulations of China, provide that the ambient dry-bulb temperature of working face should not be higher than 28°C (SAWS and SACMS, 2006), which is determined from practical working experience and have existed for tens of years. Furthermore, none of the above parameters can comprehensively reflect the thermal status of miners. For instance, dry or wet-bulb temperatures, ET, WBGT, and HSI tend to focus on the environmental conditions without considering a subject's actual thermal status, the rhythm of the heart or body temperature only shows the conditions of a human body without directly considering the interaction of human skin or respiration with the environment (Epstein and Moran, 2006).

For wet bulb temperatures exceeding 30°C and humidity nearly saturated in working environments underground, it is necessary to improve and update the existing indices, like dry-bulb temperature, to determine what conditions can be regarded as acceptable, as well as the criteria and limits that should be adopted in assessing them. More importantly, an evaluation method that considers parameters from both the human body and the ambient environment is highly needed.

This paper aims to update the upper limit of dry-bulb temperature of working faces underground and develop a new method to comprehensively evaluate the thermal status of a miner in the underground environment by adopting the miner's metabolic rate, mean skin temperature and dry bulb temperature.

CALCULATION OF THE MEAN SKIN TEMPERATURE

When a human body is at heat balance with the ambient, the metabolic heat generation holds the following expression,

$$M=C+R+B+E+K+W, \text{ W/m}^2 \quad (1)$$

Where:

- M is the metabolic heat generation rate;
- C is convective heat exchange;
- R is radiative heat exchange;
- B is heat loss by respiration;
- E is evaporative heat loss;
- K is heat exchange by conduction; and
- W is the mechanical work.

According to field measurement and analytical studies, conduction heat loss and mechanical work attribute a relatively small portion to the underground mine environment (McPherson, 1992), so K and W become negative. Therefore Equation (1) may be simplified as,

$$M=C+R+B+E, \text{ W/m}^2 \quad (2)$$

Equation (2) can be expanded term by term (McPherson, 1992) into:

$$M = \frac{t_{sk} - t_a}{R_{cl} + 1/(f_{cl}h_c)} + f_{eff}\epsilon_{sk}h_r \left[t_{sk} - \frac{R_{cl}(t_{sk} - t_a)}{R_{cl} + 1/(f_{cl}h_c)} - t_r \right] + 1.7 \times 10^{-6} \times M(S_{out} - S_{in}) + \omega h_e f_{ec} (p_{sk} - p_a) \quad (3)$$

Where; t_{sk} is the mean skin temperature, t_a is dry-bulb temperature, R_{cl} is clothing thermal resistance, f_{cl} is factor of clothing area; h_c is convective heat transfer coefficient, f_{eff} is factor of effective radiation area; ϵ_{sk} is skin emissivity, h_r is the linearised radiative heat exchange coefficient, t_r is the mean radiant temperature, S_{out} - S_{in} is the difference of sigma-heat between exhaled and inhaled air, ω is skin wetness coefficient, f_{ec} is clothing permeability factor for vapour transfer, p_{sk} , p_a are the saturated partial vapour pressure at the skin and ambient, respectively (Waclawik and Branny, 2004).

Equation (3) is an implicit equation with respect to t_{sk} since h_r , ω , and e_{sk} all rely on t_{sk} . An iterative guess-correction numerical method may be applied to solve Eq. (3). Because a guessed t_{sk} may not satisfy Equation (3), the difference between metabolic heat generation and total heat loss is:

$$\Delta Q = M - (B + C + R + E) = M - \left\{ 1.7 \times 10^{-6} M (S_{out} - S_{in}) + \frac{t_{sk} - t_a}{R_{cl} + \frac{1}{f_{cl} h_c}} + f_r h_r \left[t_{sk} - \frac{R_{cl}(t_{sk} - t_a)}{R_{cl} + \frac{1}{f_{cl} h_c}} - t_r \right] + \omega h_c f_{ec} (p_{sk} - p_a) \right\} \quad (4)$$

The correction temperature may be based on the linearised change rate of ΔQ with respect to t_{sk} as,

$$\Delta t_{sk} = \Delta Q / (\partial \Delta Q / \partial t_{sk}) \quad (5)$$

With an appropriate guess of t_{sk} , Equation (3) can be solved by updating the mean skin temperature with Equation (5) until ΔQ approaches zero.

For the working faces of underground mines that hot and humid, the air humidity sometimes can be close to saturation. This paper selects 90% and 100% as the relative humidity values when calculating thermal comfort indexes of miners. Miners work underground under moderate or severe physical labor intensity, so 180, 200, 220, 240, 260, 280, 300 W/m² and excessive physical strength 320 and 340 W/m² are selected as the amount of miners' metabolic values. The miners wear thin pants and sleeved T-shirt, so $R_{cl} = 0.093$, $f_{cl} = 1.18$, and taking $v = 1$ m/s, $t_r = t_a$.

Taking all the conditions above into Equation (1) to Equation (5), the curves of mean skin temperatures under the condition of RH = 90% and RH = 100% are generated as shown in Figure 1.

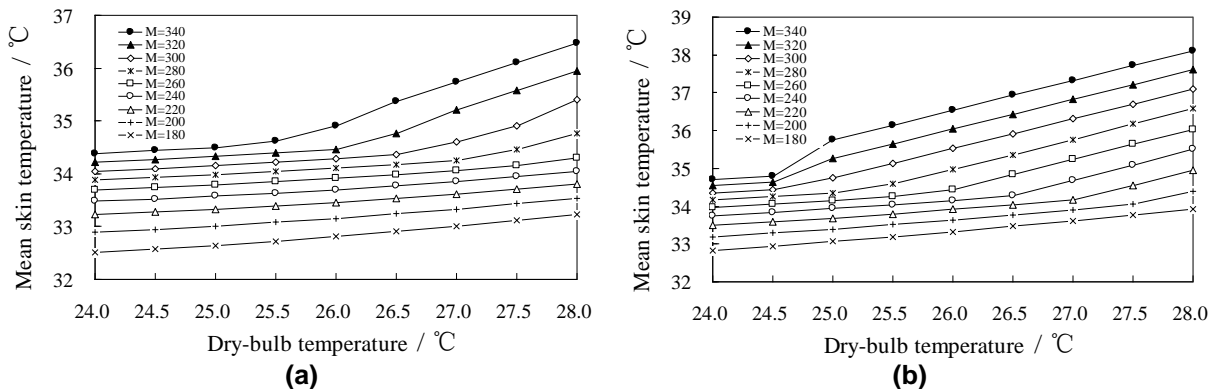


Figure 1 - Simulated results of mean skin temperature in the working face, (a) RH=90%, (b) RH=100%

A NEW INDICATOR OF DRY-BULB TEMPERATURE AND ITS VERIFICATION

From Figure 1, it can be seen that, when the ambient air relative humidity is 90% and the miners' metabolism is within the normal range, as long as the dry-bulb temperature does not exceed 28°C, the mean skin temperatures are below 36°C, which fully meets the thermal comfort requirements. When the relative humidity reaches saturation and the metabolism is lower than 260 W/m², as long as dry-bulb temperature is under 28°C, it can be seen that the mean skin temperature is below 36°C. A new upper limit of dry-bulb temperature is taken as 28°C.

ISO7933 provides the limit values of subjective heat stress indexes which can distinguish the miners who are acclimatised to the working environment or not, such as sweating rate, skin wetness, and upper limit of working time (ISO7933, 1989). When the indicators are below the warning line, a healthy worker may work without any danger. So this study selects sweating rate SW , skin wetness ω , and the upper limit of working time T_{up} as the subjective indicators to verify the new upper limit of air dry-bulb temperature, which gives:

$$SW = E/\eta \quad (6)$$

Where SW is sweating rate, g/h; η is sweat evaporation efficiency.

$$\eta = 1 - 0.5 \exp[-6.6(1 - \omega)] \tag{7}$$

$$\omega = E_{\text{req}} / E_{\text{max}} \tag{8}$$

Where E_{max} is the maximum evaporative heat loss, equivalent to the heat flux from all wet human skin; E_{req} is the evaporative heat dissipation for the human body. Because the breathing heat shares a very small proportion, so it is always be neglected, $E_{\text{req}} = M - (C + R)$.

$$T_{\text{up}} = 60 D_{\text{max}} / SW \tag{9}$$

Where D_{max} is the maximum dehydration capacity of a miner for one day, $D_{\text{max}} = 3900$ g for a miner who has adapted to the environment.

Table 1 lists the values of heat stress indexes of ISO7933 which are used to identify if workers are adapted to the environment (ISO7933, 1989).

Table 1 - Indicators of heat stress and heat fatigue of ISO7933

Criteria	Non-acclimatised		Acclimatised	
	warning	danger	warning	danger
Maximum sweat secretion (g/h)	520	650	780g	1040
Dehydration (g)	2600	3250	3900	5200
Critical skin wetness	0.85		1	

Taking different conditions of temperature and humidity into Equation (6) to Equation (9) with different amounts of metabolism of miners, the curves of sweating rate, skin wetness, and upper limits of working time can be obtained, as shown respectively in Figure 2 to Figure 4.

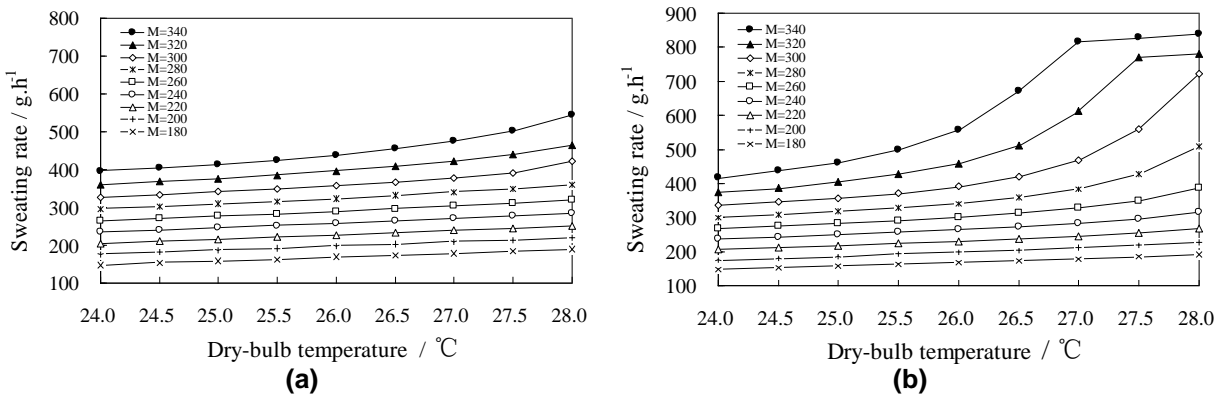


Figure 2 - Simulated results of sweating rate in the working face, (a) RH= 90%, (b) RH=100%

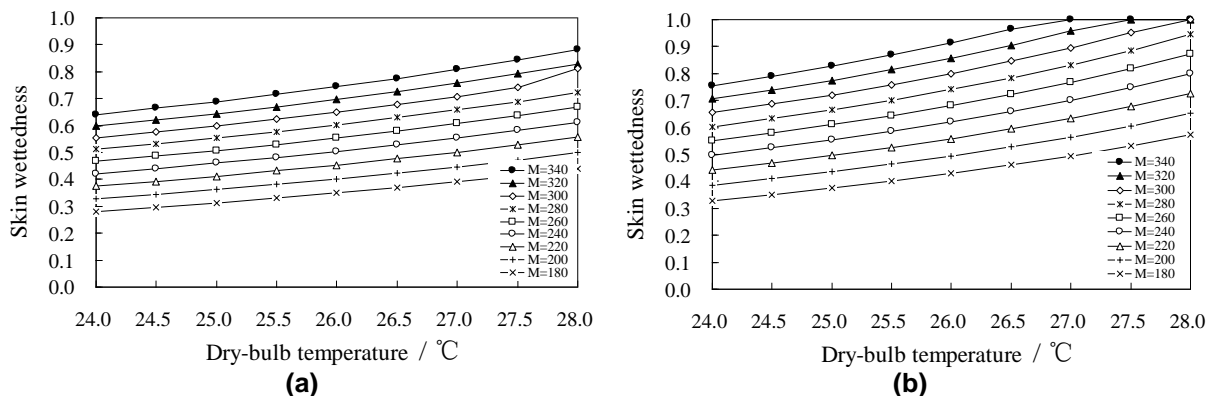


Figure 3 - Simulated results of skin wetness in the working face, (a) RH= 90%, (b) RH=100%

It can be seen from Figure 2 that when the relative humidity of the work environment is 90%, and the amount of metabolism generation by the miners is no more than 320 W/m², if the dry-bulb temperatures are below 28°C, the sweating rates of miners are below the warning lines of ISO7933 for the miners who are non-acclimatised to the environment, 520 g/h; When the relative humidity reaches saturation, the

working strength is less than 280W/m^2 , if the dry-bulb temperature is below 28°C , the indicator can also be met.

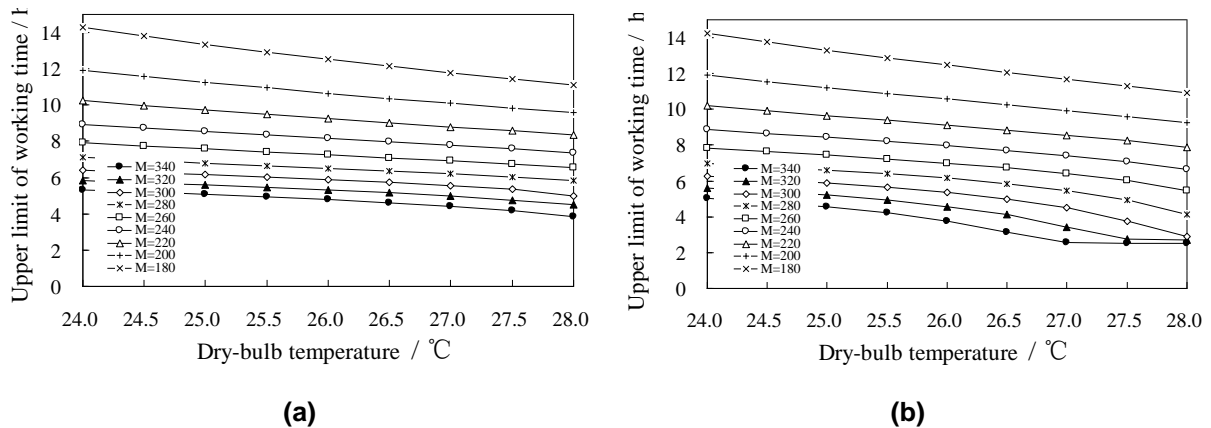


Figure 4 - Simulated results of upper limit of working time, (a) RH= 90%, (b) RH=100%

Figure 3 shows that when the relative humidity of the environment is 90%, and the amount of metabolism generation of miners is no more than 300W/m^2 , if the dry-bulb temperatures is below 28°C , the skin wetness of miners is below the warning and danger lines of ISO7933 for the miners who are non-acclimatised to the environment, 0.85; When the relative humidity reaches saturation, the working strength is less than 260W/m^2 , if the dry-bulb temperature is below 28°C , the indicator can also be met.

Figure 4 shows that when the relative humidity of environment is 90%, the amount of metabolism generation of miners stay at less than 280W/m^2 , if the dry-bulb temperatures below is 28°C , the working time of miners underground can meet the rule of six hours for one working day, especially, miners' working time underground with metabolism of 300W/m^2 might reach five hours; When the relative humidity reaches saturation, and the working load is less than 260W/m^2 , if the dry-bulb temperature is below 28°C , the indicator can also be met.

To sum up, when the relative humidity is 90%, and the amount of the miners' metabolism generation is approximately less than 300W/m^2 , if the dry bulb temperature does not exceed 28°C , these three indicators of heat stress mentioned above can meet the thermal comfort conditions; When the relative humidity reaches saturation, and the working strength is no more than 260W/m^2 , and the dry-bulb temperature does not exceed 28°C , the three indicators mentioned above can also be satisfied. As a result, they verify the correctness of the new upper limit of dry bulb temperature that can be extended to 28°C in China.

CIRCUMSCRIPTION OF THERMAL ZONES

According to Fanger's theory (Fanger, 1972) on human body, skin temperature is closely related to thermal sensation and hence it can be a key parameter to indicate a human body's thermal status. There are seven parameters that can exert impacts on a person's heat balance, therefore on skin temperature. They are metabolism (M), work (W), clothes thermal resistance (R_{cl}), air temperature (t_a), mean radiant temperature (t_r), air velocity (v), water vapour pressure (p_a), where the former three parameters reflect a human's personal condition, whereas the latter four or any of their combinations indicate the surrounding environmental condition. It seems possible to apply the skin temperature to describe a person's thermal status.

A person's mean skin temperature is dependent on the complicated heat transfer governing equation that involves the aforementioned seven parameters in implicit format. However, such implicit heat transfer equation is very hard to be applied to tell the miners' thermal status. Diagrams can provide a convenient method of assessing human body's thermal comfort. Figure 5 illustrates the concept of a thermal zone diagram, where the horizontal and vertical coordinates represent parameter 1 and 2, respectively, while curve 1 represents the effect of the rest parameters (concentrated to parameter 3) to the correlation of parameter 1 and 2. An acceptable zone can be defined with the circumscription of line 1, line 2 and curve 1, which means lines 1 and 2 are the upper limits of the acceptable conditions, respectively, and curve 1 is the lower limit. If a miner and the underground environment hold conditions within the acceptable zone, it implies this miner can work without inducing thermal symptoms.

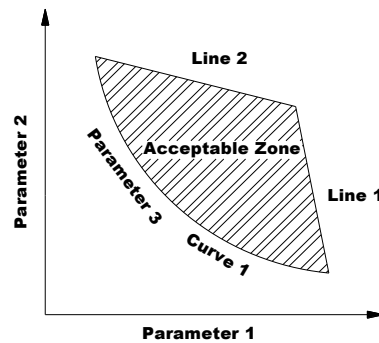


Figure 5 - The concept of a thermal condition zone diagram

The following summarises the development of a thermal zone diagram in underground mine environment using dry-bulb temperature as parameter 1, mean skin temperature as parameter 2, and other parameters concentrating to parameter 3. From Equation (3), it can be seen the mean skin temperature is dependent on M , t_a , R_{cl} , t_r , v , and p_a . It is noted that air velocity, v , determines convective heat transfer coefficient, whereas water vapour pressure p_a , affects evaporative heat loss. These six parameters are usually in certain ranges in typical underground mine environment, so they can be applied to circumscribe thermal zones in terms of t_{sk} . The six parameters are discussed briefly as follows.

Metabolic production M

Underground manual work is usually moderate or heavy, with average metabolic rates normalised at 245 W/m^2 or 340 W/m^2 respectively (Mcpherson, 1992). In this paper, the metabolic rate level of 300 W/m^2 may be considered as the upper limit.

Dry-bulb temperature t_a

Article 102 of the Chinese Coal Mine Safety Regulations sets the upper limit of airflow temperature at 26°C in working faces. If the air temperature in working faces exceeds 30°C miners should cease work (SAWS and SACMS, 2009). According to the former analysis, the average temperature of 28°C is set as the upper limit of air dry-bulb temperature.

Clothes thermal resistance R_{cl}

Thin trousers and long-sleeved shirt which are commonly worn in underground workings are selected to assess the effective thermal resistances of clothing ensembles. This thermal resistance is $0.093 \text{ (m}^2\text{K)/W}$ and its typical corresponding area factor is 1.18 (Mcpherson, 1992).

Mean radiant temperature t_r

The mean radiant temperature depends on the actual thermal status of rocks, heat release of mining machines and airflow condition. In underground mine, the mean radiant temperature will not differentiate much from the ambient air temperature due to strong flow condition and thus extensive heat transfer between hot surfaces and the ambient air in typical mines. Therefore one may set $t_r = t_a$ for simplicity.

Air velocity v

In order to condition underground mine air temperature, and also to dilute methane, carbon dioxide and other harmful gases, air velocity underground is usually maintained in the range of 0.25 m/s to 4 m/s (SAWS and SACMS, 2009). This paper has set 0.25 m/s as the lower limit and 4 m/s as the upper limit for airflow velocity to be considered.

Water vapour pressure p_a

Water vapour pressure affects latent heat transfer. Air in working faces is nearly saturated, with relative humidity commonly ranging from 90% to 100%. Water vapour fraction pressure can be calculated from relative humidity.

Evaporative heat loss E

Latent heat transfer in underground mines is mainly in the form of sweat evaporation. To prevent dehydration and thermal fatigue, ISO7933 requires the maximum allowed amount of dehydration for manual workers $D_{max} = 3900$ g (equivalent to sweating heat release of 1.5 kWh/m^2 (Waclawik and Branny, 2004) for a working day (6-8 hours) (ISO7933, 1989). Hence in this paper, we chose $E=1.5 \text{ kWh/8h}=187.5 \text{ W/m}^2$ as the upper limit.

Table 2 summarises all thermal condition parameters discussed above to circumscribe thermal zones.

Table 2 - Summary of thermal condition parameters in underground mine environment

Parameters	M/Wm^{-2}	$t_a = t_f/^\circ\text{C}$	R_c /m^2KW^{-1}	f_{cl}	$v /m s^{-1}$	E/Wm^{-2}
Values	≤ 300	≤ 28	0.093	1.18	0.25-4.0	≤ 187.5

RESULTS AND DISCUSSIONS

Figure 6 illustrates the plotted thermal zone diagram, where the abscissa shows the dry-bulb temperature and the vertical coordinates the corresponding mean skin temperature. The entire region is divided into five sub-zones, i.e., zone I, II, III, IV, V separated by curve 1, 2, 3, 4 and SW. Zone I is the region below curve 1 and a part of SW, which represents the most favorable condition in underground mines, because at the condition portrayed by curve 1 ($v=4 \text{ m/s}$ and $RH=90\%$) it favors heat release from the human body, whereas curve SW represents the mean skin temperature under the maximum sweating heat release of 187.5 W/m^2 to avoid excessive dehydration. Therefore, zone I represents that if the dry-bulb temperature is within 28°C , and the mean skin temperature is lower than the prescribed temperature on curve 1 and curve SW, there should be no heat stress risks.

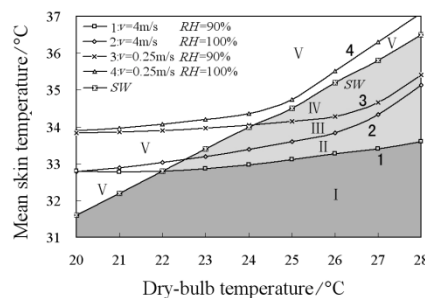


Figure 6 - Thermal zone diagram in underground mines (plotted under metabolism production of 300 W/m^2)

Above zone I is Zone II, which is circumscribed by curve 1, 2 and a part of curve SW. Curve 2 represents the condition when the ambient air reaches saturation at 4 m/s . Zone III is confined by curve 2, 3 and a part of SW, where curve 3 is at the lower limit of air velocity at 0.25 m/s , but at a relative humidity of 90%. Similarly, Zone IV is confined by curve 3 and a part of SW. Curve 4 represents the most adverse condition, because the air movement was very slow with saturation state on this curve. Curve 4 is above curve SW, although the mean skin temperature in actual sites may possibly fall between curve SW and 4, it has violated the regulation of the maximum allowable dehydration prescribed on curve SW. Zone V represents the prohibited status for miners, and under any circumstances, the mean skin temperature should not fall in zone V for a long time to prevent miners from any heat stress.

In summary, from the viewpoint of human thermal condition, zone I represents the most preferable working condition for miners, where heat stress symptoms should not emerge; From zone II to zone IV, the mean skin temperature increases, therefore the risks for heat stress symptoms also increase although they are still in the acceptable zone; Under any circumstance, the mean skin temperature should not be in Zone V for safety. As Figure 6 was plotted under the maximum allowable metabolic

rate, the evaluation of a miner's thermal condition under other smaller metabolic rates with Figure 6 will be conservative.

CONCLUSIONS

This paper analyses and summarizes the thermal stress evaluation indexes of ISO7933, from the simulated results of mean skin temperatures of different environmental humidity and labour intensity, it can be recommended that the upper limit of dry-bulb temperature of working faces in China Coal Safety Regulations could be extended from 26°C to 28°C under certain environmental conditions. The accuracy of the new indicator is verified by simulation results of subjective evaluation indicators, including sweating rate, skin wetness and the upper limit of working time.

In order to evaluate the human body's thermal status from both personal and environmental conditions, this investigation has adopted both mean skin temperature and dry-bulb temperature to establish a zone diagram. Existing regulations on mine environments and some typical condition parameters in underground mines are applied to develop a diagram of thermal condition zones, which define the preferable condition zone, acceptable condition zone, and prohibited zone for workers working in underground mines. The thermal zone diagram method may also be used for evaluating building environments.

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