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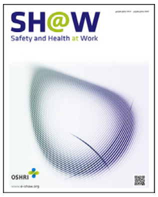

Original Article

A Method to Protect Mine Workers in Hot and Humid Environments

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A R T I C L E I N F O

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A B S T R A C T

Background: Work comfort studies have been extensively conducted, especially in the underground and meteorological fields resulting in an avalanche of recommendations for their evaluation. Nevertheless, no known or universally accepted model for comprehensively assessing the thermal work condition of the underground mine environment is currently available. Current literature presents several methods and techniques, but none of these can expansively assess the underground mine environment since most methods consider only one or a few defined factors and neglect others. Some are specifically formulated for the built and meteorological climates, thus making them unsuitable to accurately assess the climatic conditions in underground development and production workings.
Methods: This paper presents a series of sensitivity analyses to assess the impact of environmental parameters and metabolic rate on the thermal comfort for underground mining applications. An approach was developed in the form of a "comfort model" which applied comfort parameters to extensively assess the climatic conditions in the deep, hot, and humid underground mines.
Results: Simulation analysis predicted comfort limits in the form of required sweat rate and maximum skin wettedness. Tolerable worker exposure times to minimize thermal strain due to dehydration are predicted.
Conclusion: The analysis determined the optimal air velocity for thermal comfort to be 1.5 m/s. The results also identified humidity to contribute more to deviations from thermal comfort than other comfort parameters. It is expected that this new approach will significantly help in managing heat stress issues in underground mines and thus improve productivity, safety, and health.

1. Introduction

In contrast to other industries such as the building industry, in terms of the quantification of key parameters affecting human comfort, underground mine operators have seemingly paid more consideration to traumatic injury, dust, noise, gas exposures, infrared exposures in their operating processes but less attention to the thermal comfort of mine workers.

The "human thermal environment" is extremely unpredictable and cannot be conveyed in terms of temperature degrees. It cannot be adequately defined by any acceptable temperature ranges as well. Due to individual differences, it is not possible to specify a thermal environment which will gratify everyone. For example, a person walking upstairs in a cold environment while wearing a coat may feel too hot compared to someone sitting still while wearing a shirt in the same environment who may feel too cold.

According to Fanger [1], an environment can be said to achieve reasonable comfort when "at least 80% of its occupants are thermally comfortable". This means that thermal comfort can be assessed simply by surveying occupants to determine whether they are satisfied or dissatisfied with their environment. This, however, will generate problems since such survey will not be ideal for planning for comfort for all occupants.

Comfort assessment indices for the human body's thermal conditions in hot and humid climate comprise but are not limited to Dry-bulb and Wet-bulb temperatures [2], Effective Temperature (ET) [3,4], Wet-bulb Globe Temperature (WBGT) [5], Heat Stress Index (HSI), work and recovery heart rate, and body temperature [6]. Despite their heavy dependence for comfort analysis, some of these indices have not been reviewed for a very long period of time and are mostly based on subjective methods. For example, the International Organization for Standardization (ISO) 7243 [5]

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recommends a Wet-bulb temperature threshold limit value (TLV) of 32°C, but this is only based on responses of workers recorded over the past years. Equally, none of the above parameters can comprehensively assess the thermal status of miners for comfort. Furthermore, Dry-bulb or Wet-bulb temperatures, ET, WBGT, and HSI incline to focus on the environmental conditions without allowing for a worker's actual thermal status, as the heart rhythm or body temperature only shows the conditions of a human body without explicitly considering the complex interaction of human skin or respiration with the environment [7].

The ISO 7933-2004 standard [8] titled "Hot environments-Analytical determination and interpretation of thermal stress using calculation of the predicted heat strain," proposes limit values allowing the prediction of the physiological condition of a person when exposed to an environment described by the six primary parameters of air temperature, humidity, radiation, airflow velocity, metabolic rate, and clothing insulation. This paper uses the principles in the ISO 7933 standard to provide mine operators with a set of comparable methods that are well defined and simple to use, which is expected to enable them to protect mine workers more efficiently, promptly, and economically. A mathematical model was applied for assessing and predicting the comfort conditions in underground mines. Furthermore, a series of sensitivity investigations and analysis were performed to identify the impact of key environmental parameters and the metabolic rate on thermal comfort for underground mining applications.

1.1. Underground mine thermal environment

Mining at greater depths and the use of high-powered diesel machinery to increase production has forced a bigger burden on the mine ventilation systems to maintain acceptable and safe work conditions [9]. A decline of the climatic conditions experienced in these workings will also unfavorably affect the health and safety of the underground workforce. Underground mines are now being operated at considerable depths of over 2,000–3,000 m (6,500–9,800 ft). In addition, the heavy presence of diesel equipment has permitted improved production and development rates to be achieved at the cost of increased emissions of dust, gases, heat, and humidity [10].

The main objective of a mine ventilation system is to provide comfort to the mine workers and sufficient oxygen for diesel machinery by supplying sufficient air volumes to dilute and remove obnoxious gasses from the working areas. In similar fashion, the main objective of the study of underground thermal comfort conditions is generally to be able to determine the conditions for accomplishing human internal thermal neutrality. To do this, there arises the need to study the human body's response to certain environmental conditions [11].

In underground mines, there are many heat sources that cause the increase of temperature and humidity of air during its travel through mine airways and production workings. The mines' intake air temperature gradually increases as a function of depth, the level of mechanization, and the length the air travels through the underground openings. One of the main sources of heat in underground mines is the strata heat. The increase of strata temperature as a function of depth is known as the "geothermic gradient". Heat is transferred to the mine air from other sources as well, such as auto-compression (as air descends vertical openings), mining equipment (diesel/electrical), explosive detonation, human metabolism, and mine water thermal influx. There are several methods of controlling heat in an underground mine including the redesign of the primary/auxiliary ventilation systems, bulk/localized cooling, or refrigeration. Selecting the most suitable method depends on the level of heat to be removed, the location of the problem areas, and economic considerations [12,13].

2. Materials and methods

2.1. Thermal comfort

Thermal comfort is "the condition of mind which expresses satisfaction with the thermal environment" [3,4]. The environmental conditions required for comfort can be different for distinct individuals because there are variations both physiologically and psychologically from person to person. Hence, the best approach is to provide a thermal environment that satisfies the majority of people in the workplace. Based on ASHRAE's definition [4], the thermal comfort zone is the condition that "80% of sedentary or slightly active persons find the environment thermally acceptable." Three parameters need to be satisfied for a person to be in the thermal comfort zone as follows: (1) sweat rate is within comfort limits; (2) the body is in heat balance; and (3) mean skin temperature is within comfort limits [1].

It is extremely difficult to classify the many factors which affect thermal comfort: the interaction between the physical demand imposed upon the individual, his/her physiological status and his/her psychological attitudes must be considered in interaction with social customs, tangible perceptions, and the likes [14]. Restricting ourselves to thermal comfort is still subjective and difficult to satisfy all individuals with a simple environmental specification. Regardless of the difficulties in defining the thermal comfort zone, attempts to establish and define the parameters affecting the human thermal environment and its sensation to thermal comfort were made. By the end of the 19th century, four important components of the environment, namely temperature, humidity, airflow velocity, and the intensity of radiation, were recognized [15].

Undeniably, thermal comfort depends on the interaction between three groups of elements: environmental factors, clothing factors, and physiological factors. Fanger [1] established that the interaction of six fundamental factors can define the human thermal environment. Temperature, radiant temperature, humidity, and air movement are the four basic environmental variables. Behavioral factors are clothing and the metabolic rate (e.g., work intensity). These factors are summarized in Table 1.

Thermal comfort models are categorized into physiological and psychological [16]. The physiological models involve the self-regulatory function of the human body to varied thermal environments. These self-regulatory processes include vasoconstriction, shivering, vasodilation, sweating, and many more. Subjective ratings of climate discomfort and their equivalent physiological response are summarized in Table 2. Thermal physiological models range from the simplest one-node model to the complex three-dimensional finite element model, such as one-node model [17], two-node model [18], two-node model with transient response [19], 366 tissue nodes [20], and several others. The psychological thermal models predict both local and whole body thermal sensation. Examples of these psychological thermal models are: Whole Body Thermal State [21], Transient, Non-uniform or Uniform [22–24], Transient Thermal Sensation Model [25], and others.

The estimation of comfort requires a scientific model of the correlation between one or more climatic factors and the resulting comfort sensation that would be experienced by someone. As humans are often not the most logical or reliable of test subjects, such an association is difficult to experimentally determine; also, most testing is done on younger and healthier individuals, which is used to established standards. Consequently, most models are established on climatic data of large numbers of people subjected to many diverse conditions.

Table 1
Comfort parameters in the thermal balance Equation [1]

Terms in the thermal balance equation	Comfort parameters						
	M	I_{cl}	T_a	V	T_r	RH	clo
Metabolic power, M	●						
Mechanical power, W	●						
Respiratory convective heat loss, C_{res}	●		●				●
Respiratory evaporative heat loss, E_{res}	●					●	
Convective heat loss, C		●	●	●			●
Radiation heat loss, R		●			●		●

clo, clothing thermal resistance; I_{cl}, cloth index; M, metabolic rate; RH, humidify; T_a, ambient temperature; T_r, radiant temperature; V, air velocity.

Table 2
Five thermal effect zones associated with thermal comfort and sensation [7,27,28]

Vote	Thermal sensation	Zone of thermal effect	Comfort sensation	Total heat storage (S)
	Very hot	In-compensable heat zone	Very uncomfortable	$S \gg 0$
3	Hot	Sweat evaporation compensable zone	Uncomfortable	$S \approx 0$
2	Warm		Slightly uncomfortable	
1	Slightly warm	Vasomotor compensable zone	Comfortable	$S = 0$
0	Neutral			
−1	Slightly cool			
−2	Cool	Shivering compensable zone	Slightly uncomfortable	$S \approx 0$
−3	Cold		Uncomfortable	
	Very cold	In-compensable cold zone		$S \ll 0$

The central objective of most comfort models is to offer a single index that incorporates all the significant comfort conditions in order that two circumstances with dissimilar conditions, but with the same index would result in a very similar comfort perception [26]. The most intricate of these models are not normally the most precise, and the simplest are not usually the most reliable or provide a variable/imprecise result [27].

2.2. *Thermal comfort model development process*

The ISO has formed an integrated series of international standards for the assessment of human responses to various thermal environments. For hot environments, a three-tier approach is considered which involves a simple thermal index, such as the WBGT, which can be used for monitoring and control of hot environments [28,29]; a rational index, such as the required sweat rate (SW_{req}), which involves an analysis of the heat exchange between a worker and the environment [8]; and a standard for physiological measurement, which can be used in the establishment of personal monitoring systems of workers exposed to hot environments [30].

The method of evaluation and interpretation calculates the thermal balance of the body from the parameters of the thermal environment: air temperature (T_a), mean radiant temperature (T_r), partial vapor pressure (P_a), and airflow velocity (V_a), which are estimated according to ISO 7726 [31]. The physical characteristics of the workers exposed to these working circumstances, such as the metabolic rate (M) is estimated on the basis of ISO 8996, and the thermal characteristics of their clothing (clo) are estimated on the basis of ISO 9920 [32].

2.3. *Thermal comfort model elements*

The human body normally rejects heat to the environment using evaporative cooling and the heat transfer mechanisms of radiation, convection, and conduction [33,34] The relative roles of these heat transfer mechanisms are determined by the worker's metabolism, clothing, and activity level as well as by the surrounding environmental conditions of radiation, humidity, air temperature, and airflow velocity [1,35]. The acceptable value of each of these features is not fixed but can vary in conjunction with one or more of the others. It is possible for the human body to vary its own balance of losses, for example, through increased sweating or the insulating value of the clothing worn can be varied to a limited degree in order to compensate for conditions beyond the body's ability to make its own adequate adjustment.

The method is based on a comparison between the required sweat production as a result of the working conditions and the maximum physiologically achievable skin wettedness and sweat production. The standard requires calculating the sweat evaporation rate needed to maintain body thermal equilibrium, calculating the maximum sweat evaporation rate permitted to the ambient environment, and calculating the sweat rate required to achieve the necessary skin wettedness. The cooling efficiency of sweat as modified by the clothing worn is included in the calculation of the required skin wettedness. The model used in this study combines ISO 7933 [8,36] standards and the stress/strain limiting criteria described in them. The fundamental equations of the model are presented here.

The heat storage (S) of the body is given by the algebraic sum of the heat flows between the body and its environment. This model is developed by considering steady states; this is often taken as zero to assure comfort in the human body. Thermal interaction of the human body with the environment can be written as follows:

$$S = M - (C \pm R \pm B \pm E \pm K + W), \quad \mathrm{W/m^2} \tag{1}$$

This equation expresses the internal heat production of the body, which corresponds to the metabolic rate (M) minus the effective mechanical power (W), is balanced by the heat exchanges in the respiratory tract by convection and evaporation (B), as well as by the heat exchanges on the skin by conduction (K), convection (C), radiation (R), and evaporation (E), and by the eventual balance, heat storage (S), accumulating in the body. The different terms of Equation (1) are reviewed in terms of the principles of calculation. Heat is generated in the body by metabolism and can be lost to the

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environment by conduction, convection, radiation, and evaporation of moisture from the skin and respiration. Convective and radiative heat loss from clothed body to environment is calculated as:

$$C = h_{cl}(T_{sk} - T_{cl}) = \frac{T_{sk} - T_{cl}}{R_{cl}},\ \ \mathrm{W/m^2} \tag{2}$$

where, h_{cl} is clothing permeability index, W/(m^{2}K), T_{cl} is external temperature of the clothing, °C, R_{cl} is thermal resistance of the clothing, (m^{2}K)/W. T_{sk} is the mean skin temperature. The estimation of mean skin temperature is done using the equation developed by Hettinger et al (1986) [37], which is as follows:

$$\begin{aligned} T_{sk} = {} & 30 + 0.138\,T_a + 0.245\,P_a - 0.57\,V_a + 0.0128\,M \\ & - 0.553\,R_{cl},\ ^{\circ}\mathrm{C} \end{aligned} \tag{3}$$

Thermal resistance is the inverse of clothing permeability index and capturing this fact into Equation (2) will yield the following expression for convection heat loss.

$$C = h_c f_{cl}(T_{cl} - T_a),\ \ \mathrm{W/m^2} \tag{4}$$

where f_{cl} is the clothing factor (associated with the skin surface available for heat exchange) and h_c is heat dissipation coefficient related to the airflow velocity.

$$R = f_r \varepsilon_{sk} h_r (T_{cl} - T_r),\ \ \mathrm{W/m^2} \tag{5}$$

where ε_{sk} is the coefficient of skin emissivity, its approximate value falls between 0.95 and 0.97.

In most industrial situations, the effective mechanical power (W) as well as conduction heat loss (K) is small and can be neglected [15]. The heat flow by respiratory convection may be expressed, in principle, by Equation (5): The flux density of respiratory heat exchange is proportional to the difference between wet bulb temperatures of inhaled and exhaled air:

$$B = \frac{m(S_{out} - S_{in})}{F_{Du}} = 1.7 \times 10^{-6} \times M(S_{out} - S_{in}),\ \ \mathrm{W/m^2} \tag{6}$$

where $S_{out} - S_{in}$ is difference between the sigma-heat of inhaled and exhaled air, J/kg, $m = 1.7 \times 10^{-6} \times MF_{Du}$ is stream of mass of the inhaled air proportional to the metabolic heat production. M is the metabolic rate. F_{Du} is the surface area of the whole human body, m^2.

The maximum evaporative heat flow at the skin surface E_{max} is that which can be achieved in the hypothetical case of the skin being completely wetted. In these conditions, the evaporative resistivity of the layer separating the clothing and the air is calculated as:

$$R_e = \frac{1}{16.7 h_c F_{cll}} \tag{7}$$

$$E_{max} = \frac{(P_{sk} - P_a)}{R_e},\ \mathrm{W/m^2} \tag{8}$$

In the case of a partially wetted skin, the evaporation heat flow, E, in W/m^2 is given by [38]:

$$E = \omega E_{max},\ \ \mathrm{W/m^2} \tag{9}$$

E is the evaporative heat transfer rate and ω is the skin wettedness.

$$\mathrm{E} = \omega h_e f_{ec}(P_{sk} - P_a),\ \ \mathrm{W/m^2} \tag{10}$$

P_{sk}: saturation partial vapor pressure at the skin temperature, f_{ec}: clothing permeability factor for vapor transfer and h_e: Latent heat transfer coefficient, W/(m^{2}Pa).

With regards to the hypotheses made concerning the heat transfer by conduction, mechanical power, and heat storage, the general heat balance Equation (1) can be written as:

$$M - (C \pm R \pm B \pm E \pm K + W) = 0,\ \ \mathrm{W/m^2} \tag{11}$$

$$M = C \pm R \pm B \pm E,\ \mathrm{W/m^2} \tag{12}$$

The required evaporative heat flow, E_{req}, is the evaporation heat flow required for the maintenance of the thermal equilibrium of the miners' body and, therefore, for the heat storage to be equal to zero. It is defined as the difference between the metabolic rate and the sum of convective and radiation heat transfer and is given by: Respiratory heat exchange is often ignored [39].

$$E_{req} = M - (C + R) \tag{13}$$

The required skin wettedness, ω_{req}, is the ratio between the required evaporative heat transfer and the maximum evaporative heat flow at the skin surface:

$$\omega_{req} = \frac{E_{req}}{E_{max}} = \frac{M - (C + R + B)}{h_e f_{ec}(P_{sk} - P_a)} \tag{14}$$

The maximum wettedness is 1 for acclimatized workers and 0.85 for non-acclimatized workers.

The calculation of the required sweat rate is made on the basis of the required evaporative heat flow, but taking into account of the fraction of sweat that trickles away because of the large variations in local skin wettedness. The required sweat rate is given by:

$$SW_{req} = \frac{E}{\eta} \tag{15}$$

η is the sweat evaporation efficiency and is dimensionless. Under very humid conditions, it is given by:

$$\eta = 1 - \frac{\omega^2}{2} \tag{16}$$

The rate of sweat production can be expressed (W/m^2) multiplying SW by 0.6726, i.e., $1\ \mathrm{W}/_{\mathrm{m}^2} = 1.4868\ \mathrm{g}/_{(\mathrm{hm}^2)}$.

The maximum sweat rate is a function of the metabolic rate (M in watts) according to [8]:

$$SW_{max} = 2.62\,M - 148,\ (\mathrm{g/hr}) \quad (Un - acclimatized\ worker) \tag{17}$$

$$SW_{max} = 3.27\,M - 186,\ (\mathrm{g/hr}) \quad (Acclimatized\ worker) \tag{18}$$

The TLV of allowable exposure time (T_{max}) is calculated based on the maximum tolerable dehydration (D_{max}) for one working day. The limit on duration of exposure is computed for an average subject on the basis of a maximum water loss (dehydration) of 7.5% of the body mass and has to be reduced by 33% in order to protect 95% of the miner population [40]:

$$T_{max} = \frac{D_{max}}{SW},\ (\mathrm{hr}) \tag{19}$$

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3. Results

3.1. Sensitivity analysis for thermal comfort

It is imperative to study and understand the sensitivity of environmental and physiological conditions on miners' comfort so that when air temperature, humidity, mean radiant temperature, air velocity, metabolic rate, and/or clothing is out of the comfort range, adjusting one or more of the other conditions will restore comfort with the addition of little or no energy. The sensitivity of these climatic and personal factors were tested using the thermal limit criteria of ISO 7933 [8,36], required sweat production, required skin wittedness, and safe duration of exposure (from the dehydration limit criteria) as the control signals. These limits are derived from the heat balance equation.

A mathematical model was developed in MATLAB based on equations that explained thermal model elements, and plots were generated to calculate the maximum sweat rate and skin wettedness different air velocity values. The boundary limits of thermal comfort were determined by the maximum sweat rate criteria and the maximum skin wettedness criteria. These indices were predicted for underground conditions with air temperatures varying from 10°C to 50°C, and one of the other parameters varying in the ranges indicated in Table 3. A constant clothing insulation "clo" value of 0.093 was used for this assessment. This is equivalent to the miners' uniforms (e.g., coveralls) degree of insulation.

3.1.1. Airflow velocity

Airflow velocity is the average speed (with respect to location and time) of the air to which the body is exposed. Airflow velocity is a key factor influencing heat and mass transfer. It affects both the convective heat transfer coefficient and the evaporative heat transfer coefficient, thus influencing the thermal comfort conditions [40]. The reaction of a person to air movement is likely to be a complicated phenomenon as it depends on the climatic parameters, including temperature, humidity, clothing worn, metabolic rate, and resulting skin temperature.

Considering the air temperature results at an air velocity of 0 m/s as the benchmark, decreasing air temperature requirements as a function of increasing airflow velocities were computed. Fig. 1 shows the results of simulation of the maximum sweat rate for acclimatized and non-acclimatized workers as a function of air temperature, relative humidity, and air velocity at the metabolic rate of 200 W/m^2. As air velocity increases from 0 m/s to 4 m/s, there is a corresponding increase in air temperature until a velocity of 1.5 m/s is reached. Above 1.5 m/s, the effect of air velocity on air temperature reverses and decreases as the velocity increases. This illustrates that the optimum effect of air velocity on sweat rate for comfort is achieved at 1.5 m/s after which increasing air velocity is purposely done to lower air temperatures (Table 4).

The percent of skin wettedness is altered by the airflow velocity, which is a function of the evaporative heat coefficient, expressed as $(h_e = 16.5 \times 10^{-3} h_c,)$, where h_c is the convective heat transfer coefficient and is dependent on air velocity $(h_c = 8.7v^{0.5})$. Just like in the sweat rate, the optimum air velocity effect on skin wettedness occurred at 1.5 m/s (see Table 5).

Table 3
Range of variation of the climatic parameters in the solution process

Parameter	Range	Constant value
Relative humidity, RH (%)	50–100	50, 60,….100
Mean radiant temperature ($t_r = t_a$), (°C)	10–40	
Air velocity, V(m/s)	0–4	0, 1.5, ….4
Clothing insulation (clo)	0–1	0.093
Metabolic rate, M (W/m^2)	200–340	200, 220, …340

The analysis shows that the miners' comfort increased with increasing airflow velocity and decreasing air temperature as a result of achieving the necessary sweat production. Airflow velocity affects body heat transfer by convection and evaporation. Below 50% relative humidity (RH), the mine air is dry and the airflow velocity will increase moisture removal at the skin surface, increasing cooling due to evaporative processes. In hot and humid environments (50–80% RH), airflow velocity will accelerate the evaporation of sweat by moving saturated air away from the skin and replacing it with unsaturated air. Above 80% RH, there is very little evaporative potential as the air blowing past is already close to saturation, making air movement relatively ineffective.

3.1.2. Relative humidity

High levels of RH can work against the evaporative cooling effects of sweating and leave the body prone to over-heating. Humans are sensitive to slight temperature changes yet cannot perceive differences in RH levels within the range of 25–60%, which is the primary reason that this range is often cited as the baseline [41]. If relative humidity falls outside this range, there are notable effects. When RH gets too high, discomfort develops either due to the feeling of the moisture itself [3] which is unable to evaporate from the skin or due to increased friction between skin and clothing with skin moisture [3]. When RH gets too low, skin and mucous surfaces become drier, leading to complaints about dry nose, throat, eyes, and skin [41]. Workers and people in general tend to acclimate to low humidity after months to a year. The air in the mine workings is nearly saturated, with RH commonly ranging from 90% to 100%. The moisture content of the air (X) can be determined if we know the dry-bulb temperature of the air, the barometric pressure (P), and the pressure applied by the water vapor (e).

Tables 6 and 7 present the sensitivity analysis of humidity on required sweat rate and skin wettedness. With a benchmark RH of 50% the corresponding decrease in air temperature requirements were calculated. Fig. 2 and Table 6 indicate that increasing the airflow velocity will not improve the air temperature requirement as long as the humidity increases. At an air velocity of 4 m/s and a saturated climate, there is the highest demand for lower temperatures. This also verifies the fact that with humidity being constant, air temperature variations appear minor with increasing velocity. At constant velocity, however, the air temperature requirement is much more significant with increasing humidity. Thus, it can be concluded based on this analysis that humidity has a much significant impact on work comfort than airflow velocity.

3.1.3. Metabolic rate

The activity level or work intensity is the metabolic rate that controls the generated heat inside the human body as we perform physical activities. Hence, the metabolic rate depends on the activity level and the fitness level of the worker. The estimated metabolic rate for various activity levels is depicted in Table 8 [29].

The metabolic rate is the energy released per unit time by the oxidation processes in the human body and is dependent on the amount of muscular activity. Metabolic rates vary according to the activity performed. It is often measured in met [1 met = 50 kcal/h/m^2] and is proportional to the body weight, activity level, body surface area, health, sex, age, amount of clothing, surrounding thermal conditions, and atmospheric conditions. Typically, the metabolic rate for a normal adult with a surface area of 1.8 m^2 at rest (seated and quiet) is evaluated at 1.0 met or an equivalent of 60 W/m^2 [42].

The sensitivity analysis of metabolic rate on a worker's sweat rate production and skin wettedness is depicted in Tables 9 and 10.

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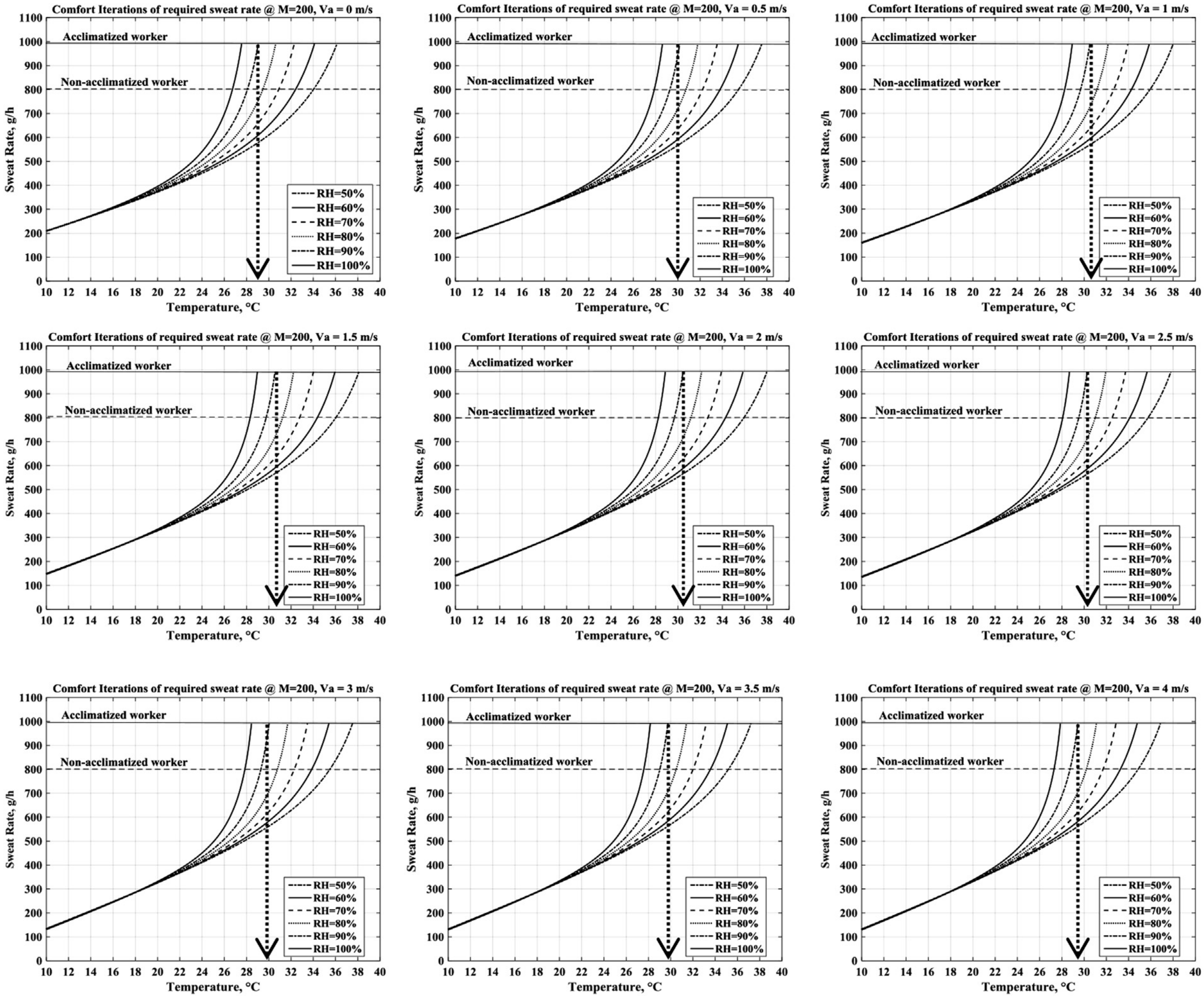

Fig. 1. Sweat rate analysis as a function of air temperature, air velocity, and relative humidity at M = 200 W/m^2. The air temperature requirement to achieve the maximum sweat rate decreases by increasing the air velocity.

The highlighted column at 200 W/m^2 activity rate is taken as the benchmark from which the air temperature requirement is calculated. In Table 9, as the metabolic rate increases, there is increasing demand to maintain lower air temperatures in order to achieve the sweat production necessary for comfort. At 90% RH, the maximum sweat production is achieved at an ambient air temperature of 30°C. As the metabolic rate increases, the air temperature requirement is decreased to ~28°C. So, with higher metabolic rates miners are more thermally sensitive; consequently, the risk of discomfort is higher.

As shown in Table 10, the generation of more heat as a result of higher activity rates requires lower air temperatures to promote heat rejection in the form of sweating. This is achieved by convective heat transfer from the heated skin into the passing cooler air. The analysis indicates that increasing metabolic rates demand lower air temperatures to maintain comfort for the miners.

Therefore, at greater activity rates, the air temperature should be lower to ensure comfort. The human body can handle higher temperatures at lower metabolic rates. The impact of metabolic rates on thermal comfort is critical. As metabolic rates increase, we

Table 4
Air velocity effect on air temperature requirement of sweat rate with varying humidity at a metabolic rate of 200 W/m^2

M = 200 W/m^2	Air velocity (V), m/s								
	0	0.5	1	1.5	2	2.5	3	3.5	4
Relative humidity (RH), %	Maximum allowable temperature for an acclimatized worker based on maximum sweat rate (991.2 g/h) (°C)								
50	34.53	35.97	36.44	36.54	36.45	36.26	36.00	35.69	35.35
60	32.82	34.2	34.66	34.75	34.68	34.49	34.25	33.96	33.63
70	31.23	32.55	32.98	33.07	33.00	32.82	32.59	32.30	31.99
80	29.74	30.98	31.40	31.48	31.41	31.23	31.00	30.73	30.42
90	28.31	29.49	29.89	29.96	29.88	29.71	29.48	29.21	28.91
100	26.93	28.06	28.42	28.48	28.40	28.22	28.00	27.73	27.44

M, metabolic rate.

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Table 5
Air velocity effect on air temperature requirement of skin wettedness with varying humidity at a metabolic rate of 200 W/m^2

M = 200 W/m^2	Air velocity (V), m/s								
	0	0.5	1	1.5	2	2.5	3	3.5	4
Relative humidity (RH), %	Maximum allowable temperature for an acclimatized worker based on maximum skin wettedness (°C)								
50	37.27	38.95	39.52	39.66	39.60	39.41	39.16	38.85	38.50
60	34.67	36.21	36.72	36.83	36.77	36.59	36.34	36.00	35.70
70	32.46	33.89	34.36	34.46	34.38	34.20	33.96	33.66	33.34
80	30.51	31.85	32.28	32.37	32.29	32.11	31.87	31.58	31.26
90	28.73	30.00	30.40	30.47	30.39	30.21	30.00	29.70	29.39
100	27.08	28.28	28.66	28.73	28.64	28.46	28.23	27.95	27.65

M, metabolic rate.

Table 6
Relative humidity effect on air temperature requirement of sweat rate with varying humidity at metabolic rate of 200 W/m^2

M = 200 W/m^2	Air velocity (V), m/s								
	0	0.5	1	1.5	2	2.5	3	3.5	4
Relative humidity (RH), %	Maximum allowable temperature for an acclimatized worker based on maximum sweat rate (991.2 g/h) (°C)								
50	34.53	35.97	36.44	36.54	36.45	36.26	36.00	35.69	35.35
60	32.82	34.20	34.66	34.75	34.68	34.49	34.25	33.96	33.63
70	31.23	32.55	32.98	33.07	33.00	32.82	32.59	32.30	31.99
80	29.74	30.99	31.40	31.48	31.41	31.23	31.00	30.73	30.42
90	28.31	29.50	29.89	29.96	29.88	29.71	29.48	29.21	28.91
100	26.93	28.06	28.42	28.48	28.40	28.22	28.00	27.73	27.44

M, metabolic rate.

Table 7
Relative humidity effect on air temperature requirement of skin wettedness with varying humidity at metabolic rate of 200 W/m^2

M = 200 W/m^2	Air velocity (V), m/s								
	0	0.5	1	1.5	2	2.5	3	3.5	4
Relative Humidity (RH), %	Maximum allowable temperature for an acclimatized worker based on maximum skin wettedness (°C)								
50	34.67	36.21	36.72	36.83	36.77	36.59	36.34	36.00	35.70
60	32.46	33.89	34.36	34.46	34.38	34.20	33.96	33.66	33.34
70	30.51	31.85	32.28	32.37	32.29	32.11	31.87	31.58	31.26
80	28.73	30.00	30.40	30.47	30.39	30.21	30.00	29.70	29.39
90	27.08	28.28	28.66	28.73	28.64	28.46	28.23	27.95	27.65
100	34.67	36.21	36.72	36.83	36.77	36.59	36.34	36.00	35.70

M, metabolic rate.

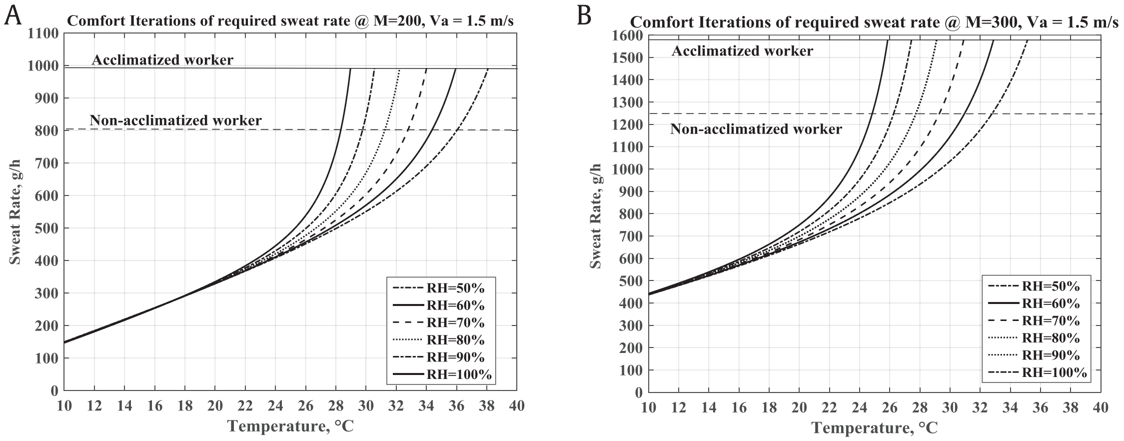

Fig. 2. Decrease of maximum allowable comfort temperature as a function of relative humidity at the metabolic rate of (A) 200 W/m^2 and (B) 300 W/m^2.

Table 8
Estimate of metabolic rate for activity [29]

Rating	Activity	Metabolic rate, M
0	Resting	$M \leq 65$ W/m^2
1	Low metabolic rate	$65 < M \leq 130$ W/m^2
2	Moderate metabolic rate	$130 < M \leq 200$ W/m^2
3	High metabolic rate	$200 < M \leq 260$ W/m^2
4	Very high metabolic rate	$M > 260$ W/m^2

produce more heat. This excess heat needs to be dissipated so that we do not overheat. Sweat production and thus its evaporation becomes an increasingly important factor to maintain thermal comfort.

3.2. Maximum worker exposure time

The combination of environmental conditions and workloads encountered by underground miners may result in unacceptable physical stress and strain. The safety and health conditions of the underground workers must be the top limiting factor rather than other targets and indicators when operating in thermally stressful environments. Harsh environmental conditions demand that a safe exposure time limit is set. The safe exposure time correlates to the maximum dehydration that can be tolerated under the defined comfort conditions.

Upper tolerable limits of maximum sweat loss or dehydration must also be set. Dehydration will occur when the climatic conditions are such that drinking during the period of exposure cannot replenish the amount of water lost [43]. The ISO 7933 recommends a tolerable dehydration limit of ranging from 3.5% to 7.5% of the body weight (75 kg) of an average miner. In this analysis, an amount of 3900 g (5.2%) is assumed as the upper limit of dehydration for a work shift of 8 hours.

Fig. 3 shows an example of TLV exposure time based on varying metabolic rate at air velocity of 1.5 m/s and RH of 60% and 80%. In Fig. 3, as long as the air temperature stays at 27°C, the activity level in the environment should not exceed 200 W/m^2 for the 8 hours

Table 9
Decreasing air temperature requirement as a result of increasing metabolic rate and humidity at constant air velocity of 1.5 m/s using sweat production rate criteria

Metabolic activity (W/m^2)								Humidity (%)
200	220	240	260	280	300	320	340	
Air temperature (°C)	Maximum allowable temperature for an acclimatized worker based on maximum sweat rate (°C)							
36.50	36.00	35.50	34.90	34.20	33.50	32.80	32.10	50
34.80	34.20	33.60	32.90	32.30	31.60	30.90	30.10	60
33.10	32.50	31.80	31.20	30.50	29.80	29.10	28.40	70
31.50	30.90	30.20	29.60	28.90	28.20	27.50	26.70	80
30.00	29.30	28.70	28.00	27.30	26.60	25.90	25.20	90
28.50	27.80	27.20	26.50	25.90	25.20	24.50	23.80	100

Table 10
Decreasing air temperature requirement as a result of increasing metabolic rate and humidity at an air velocity of 1.5 m/s using skin wettedness criteria

Metabolic activity (W/m^2)								Humidity (%)
200	220	240	260	280	300	320	340	
Air temperature (°C)	Maximum allowable temperature for an acclimatized worker based on maximum skin wettedness (°C)							
39.65	38.91	38.14	37.37	36.56	35.70	34.93	34.07	50
36.83	36.11	35.37	34.61	33.84	33.05	32.25	31.42	60
34.45	33.75	33.02	32.28	31.53	30.76	29.98	29.17	70
32.37	31.67	30.96	30.23	29.50	28.74	27.97	27.18	80
30.48	29.79	29.09	28.37	27.65	26.90	26.14	25.36	90
28.73	28.03	27.35	26.64	25.93	25.19	24.44	23.67	100

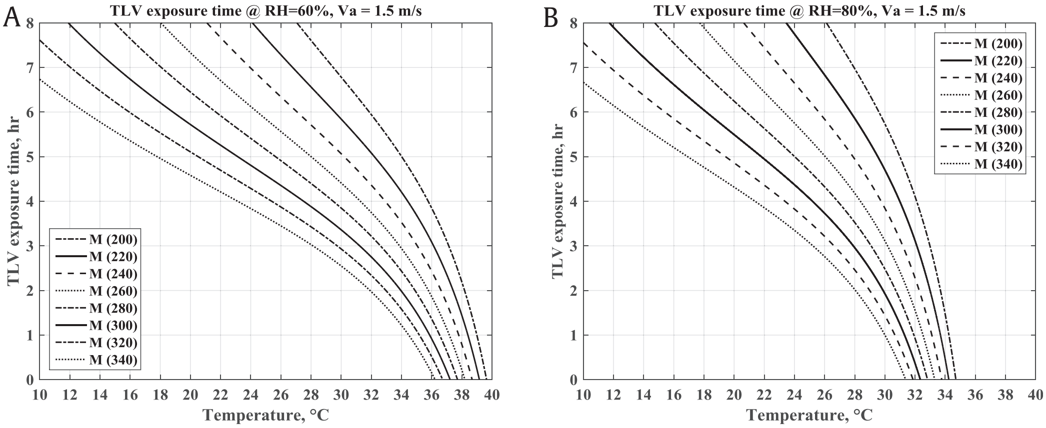

Fig. 3. Maximum worker exposure analysis as a result of increasing metabolic at an air velocity of 1.5 m/s and relative humidity of (A) 60% and (B) 80%.

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continuous work per 8-hour shift. In other words, the safe working time is shorter than 8 hours for metabolic rates greater than 200 W/m^2. Considering constant environmental condition, mandatory work-rest regimens should be placed using an appropriate heat stress index to avoid heat storage in the worker's body, which may result in heat stress risks and illnesses. Enabling self-paced working through empowerment of workers may also be considered to decrease the severe effect of heat exposure to workers' body.

4. Conclusions

This study analyzed the effects of changing humidity, air velocity, and metabolic rate along with air temperature on the thermal comfort of miners. Two key techniques were used in this study to authenticate the research. A detailed analysis of the various heat exchanges between the environment and the human body was carried out and quantified into a mathematical model for comfort analysis. The thermal comfort was then analyzed using the ISO 7933 required sweat rate, skin wittedness, and maximum safe exposure time indices. The technique included the use of the two stress criteria of maximum skin wettedness and maximum sweat rate and the strain criteria of maximum dehydration. The required sweat rate cannot exceed the maximum sweat rate attainable by the subject. The required skin wettedness cannot exceed the maximum skin wettedness attainable by the subject. These two conditions are dependent on the level of acclimatization of the subject to the work environment. Finally, irrespective of the thermal balance, the dehydration level must be limited to a maximum value desirable to maintain the hydro-mineral equilibrium of the body. The study results can be usefully summarized into the following points:

- From the simulated results based on the thermal parameters of the environment, upper working limits of air temperature, activity, humidity, and air velocity can be determined and recommended.
- Maximum exposure times to minimize strain due to dehydration can also be predicted. The study also makes it possible to manipulate the environmental parameters to obtain a value for maximum exposure time.
- Optimum air temperatures for thermal comfort are achieved at air velocities of 1.5 m/s. When the air motion across the skin increases, thermal comfort will increase and that the optimum air velocity for comfort is 1.5 m/s.
- The analysis also observed that humidity contributes a lot more to deviations from comfort. It is followed by activity level and then airflow velocity. Note that in this study, values for clothing (clo) are kept constant, and T_a is equated to T_r.

The required sweat rate cannot exceed the maximum sweat rate attainable by the subject. The required skin wettedness cannot exceed the maximum skin wettedness attainable by the subject as well. These two conditions are dependent on the level of acclimatization of the subject to the work environment. Finally, whatever the thermal balance, the dehydration level must be limited to a maximum value desirable to maintain the hydro-mineral equilibrium of the body.

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Conflicts of interest

The authors declare no conflicts of interest.

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