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Sensitivity analysis of the effect of airflow velocity on the thermal comfort in underground mines

Pedram Roghanchi, Karoly C. Kocsis*, Maurice Sunkpal

Mining Engineering Department, University of Nevada, 1664 N. Virginia Street, Reno, NV 89557, USA

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ABSTRACT

Displeasure in respect to air volumes and associated airflow velocities are well-documented complaints in underground mines. The complaints often differ in the form that there is too little airflow velocity or too much. In hot and humid climates such as those prevailing in many underground mines, convection heat transfer is the major mode of heat rejection from the human body, through the process of sweat evaporation. Consequently, the motion of the mine air plays a pivotal role in aiding this process. In this paper, a method was developed and adopted in the form of a "comfort model" to predict the optimum airflow velocity required to maintain heat comfort for the underground workforce at different activity levels (e.g. metabolic rates). Simulation analysis predicted comfort limits in the form of required sweat rate and maximum skin wetness. Tolerable worker heat exposure times were also predicted in order to minimize thermal strain due to dehydration. The results indicate that an airflow velocity in the range of 1–2 m/s is the ideal velocity in order to provide a stress/strain free climate and also guarantee thermal comfort for the workers. Therefore, an optimal airflow velocity of 1.5 m/s for the miners' thermal comfort is suggested.

1. Introduction

The mining industry remains one of the most hazardous industries despite significant reductions in fatal injuries over the last century (Jacklitsch, Musolin, & Kim, 2016; Saleh & Cummings, 2011; Coleman & Kerkering, 2007). Underground mines in the United States and worldwide continue to become deeper and more mechanized as the presence of near-surface ore deposits decreases and the world demand for minerals continues to lead to production increases. A consequence of these changes in the underground mine environment is increased heat generation (Brake & Bates, 2002; Sheer, Butterworthm, & Ramsden, 2001). The main sources of heat in underground metal mines include auto-compression as air descends through vertical openings, strata heat (geothermic gradient), as well as heat from: machinery, mine water influx, explosive detonations, friction between falling rock, human metabolism, pipelines and oxidation (Brake & Bates, 2002; Carpenter, Roghanchi, & Kocsis, 2015; Kocsis & Hardcastle, 2010). In deep and hot mines, the removal of this heat is a top priority for mine operators as mine workers are at risk of suffering heat-related illnesses and injuries (Donoghue, 2004). It is imperative that the underground mine climatic conditions remain safe for human presence, as mine workers actively work in this environment. The hot and humid environment also has a negative impact on the efficiency of the underground workforce which may result in production decline (Xiaojie et al., 2011).

Ambient airflow velocity is acknowledged as one of the critical parameters to improve the thermal comfort of the mine workers, and it has been considered in all known comfort standards. Usually, minimum and maximum airflow velocity limits are determined and mandated in underground mines where mine personnel work and travel. To dilute most pollutants, a common minimum airflow velocity for airways where personnel work and travel is 0.3 m/s (MacPherson, 2009). However, in production workings, airflow velocities usually vary from 1 m/s to 3 m/s. The recommended maximum airflow velocity in the production areas is 4 m/s. Above airflow velocity of 4 m/s, significant discomfort can be experienced by the underground workers because of the impact of large dust particulars that are carried by the airflow (Berglund & Fobelets, 1987; Christensen, Albrechtsen, Fanger, & Trzeciakiewicz, 1984; Fanger & Christensen, 1986; Fanger & Pedersen, 1977; Griefahn, Mehnert, Bröde, & Forsthoff, 1997; Houghton & Yaglou, 1923;

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* Corresponding author.
E-mail addresses: proghanchi@unr.edu (P. Roghanchi), kkocsis@unr.edu (K.C. Kocsis), msunkpal@nevada.unr.edu (M. Sunkpal).

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Abbreviations:

B	Heat exchanges in the respiratory tract by convection and evaporation
C	heat exchanges on the skin by convection
D_{max}	maximum tolerable dehydration
E	heat exchanges on the skin by evaporation
ε_{sk}	Skin emissivity
f_{cl}	Clothing area factor
f_{ec}	Clothing permeability factor for vapor transfer
f_{eff}	Effective radiation area factor
h_c	Convective heat transfer coefficient
h_r	Radiation heat exchange coefficient
K	heat exchanges on the skin by conduction
M	Metabolic rate
P_a	Saturated vapor pressure in the air
P_{sk}	Saturated vapor pressure on the skin
R_{cl}	Clothing thermal resistance
RH	Relative humidity
S	heat storage in the human body
$S_{out}-S_{in}$	Sigma heat exchange between inhaled and exhaled air
t_a	Ambient air temperature
T_{max}	TLV of allowable exposure time
t_r	Mean radiant temperature
t_{sk}	Skin temperature
v_a	airflow velocity
W	Effective mechanical power
ω	Skin wetness

McIntyre, 1979; Nevins, 1971; Toftum, 2002; Zhou, 1999). Particularly in underground metal and non-metal mines, where high airflow velocity may generate dust dispersion, which causes serious health hazards (Kurnia, Sasmito, & Mujumdar, 2014; Donoghue, 2004; MacPherson, 2009; Hartman, Mutmansky, Ramani, & Wang, 2012).

This paper is aimed at recommending optimal airflow velocities for the workers' thermal comfort in underground mines using an analytical solution to the human heat balance equation. This work uses the principles in the ISO 7933 (2004) standards and applies a mathematical model for assessing and predicting the comfort conditions in underground mines. A sensitivity analysis was also performed to demonstrate the importance of airflow velocity as a critical environmental parameter of thermal comfort for underground mining applications.

2. Materials and methods

Airflow is the average speed (with respect to location and time) of the air to which the human body is exposed (ISO 7730, 2005). Airflow velocity distribution is a key factor influencing heat and mass transfer in underground mines (MacPherson, 2009). Airflow velocity affects both convective and evaporative heat transfer coefficients, and thus influences thermal comfort conditions (McIntyre, 1979; Parsons, 2014). 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 (McIntyre, 1979; ISO 7730, 2005).

For decades air movement has been used as a strategy in hot and humid environments by mine ventilation and comfort engineers to increase the rate of the cooling of the occupants. For example, Humphreys (1977) developed an empirical equation to estimate the relative comfort temperature based on constant airflow velocity of 0.1 m/s and above. McIntyre (1979) found 28 °C to be the highest comfortable temperature at 1.4 m/s for male occupants and 1 m/s for female occupants. Rohles, Konz, and Jones (1983) found pleasant levels beyond what had been previously considered reasonable (up to 1 m/s at 29.5 °C). Spain (1984) found that an airflow velocity of 0.25 m/s provided comfort for air temperatures up to 27.8 °C, while 1 m/s provided comfort up to 29.4 °C. Holm and Engelbrecht (2005) uphold that air movement at temperatures below 37 °C cools the body while it begins to heat it at temperatures above 37 °C. Cândido, de Dear, Lamberts, and Bittencourt (2010) found that the minimally acceptable airflow velocity for Brazil's hot and humid climatic zone needs to be at least 0.4 m/s for 26 °C, reaching 0.9 m/s for operative temperatures up to 30 °C. As observed by Fountain and Arens (1993), the focus of most mine ventilation practitioners is often to deliver the required air volumes to the production workings. This is often done to the disadvantage of achieving the required airflow velocity for thermal comfort. However, apart from air quality, what is also desired at the workface by miners is comfort, safety, and satisfaction with their working environment.

The relationship between the body accumulating and rejecting heat through the processes of metabolism, convection, radiation and evaporation must be maintained at a dynamic state to ensure thermal comfort. This relationship is expressed in the human heat balance equation (Büttner, 1954; Höppe, 1999; Jacklitsch et al., 2016). The goal is to achieve an internal core temperature balance and avoid heat storage in the human body. According to field measurements and analytical studies, the attribute of conduction heat loss and mechanical work are a relatively small portion of the underground mine environment (MacPherson, 2009). Discounting the conduction effect of heat transfer in underground mines, the human heat balance equation used in the analysis is provided in Eq. (1), as follows:

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

Solving Eq. (1) iteratively by substituting the climatic parameters will determine the airflow velocities' range for comfort. In respect to the hypotheses made concerning heat transfer by conduction, mechanical power, and heat storage, the general heat balance Eq. (1) can be written as:

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

In most industrial situations, the effective mechanical power is small and can be neglected.

$$M = C + R + B + E, \quad \mathrm{W}\big/\mathrm{m}^2 \tag{3}$$

Several heat stress indices use either a fixed mean skin temperature or a prediction model, which incorporates some or all physical factors of the thermal environment as well as clothing insulation and metabolic rate. A fixed value is easy to use, however, in conditions with dynamic exposure to heat, this can result in its over- or under-estimation resulting in errors in the heat balance analysis. A lot of the methods available for predicting skin temperature have inherent limitations. Some are developed for resting subjects while others are formulated based on an insignificant amount of sample data. Some others lack comprehensiveness. In this study, the mean skin temperature was estimated from the linearized regression equation proposed by Mairiaux, Malchaire, and Candas (1987) presented in Eq. (4). This equation is among very few equations that consider all six thermal comfort parameters for the calculation of mean skin temperature. For underground mining purposes, a predictor must involve a working subject and be able to predict with accuracy and precision over a wide range of environmental conditions. A calculation of skin temperature was needed in which all the thermal comfort parameters could be taken into account. This is particularly important for having mean skin temperature included in iteration cycles in order to have more accurate results.

$$t_{sk} = 30 + 0.138\, t_a + 0.254\, P_a - 0.57\, V_a + 0.0128\, \mathrm{M} - 0.553\, R_{cl} \tag{4}$$

The expanded form of Eq. (1) is shown in Eq. (5) and the definitions of the terms and their interdependence, as well as the mode of heat exchange that affects each term, are illustrated in Table 1. The dominant effect of the airflow velocity in terms of the comfort equation and its influence on the convective and evaporative heat exchange modes is also established (see Table 2).

$$M = \frac{t_{sk} - t_a}{R_{cl} + {}^{1}\!/\!(f_{cl} h_c)} + f_{eff}\,\varepsilon_{sk}\left[t_{sk} - \frac{R_{cl}(t_{sk} - t_a)}{R_{cl} + {}^{1}\!/\!(f_{cl} h_c)} - t_r\right] + 1.7 \times 10^{-6} \times M(S_{out} - S_{in}) + \omega h_e f_{ec}(P_{sk} - P_a), \quad \mathrm{W}\big/\mathrm{m}^2 \tag{5}$$

The method relied on the conventional fact that the evaporation effect of sweat is the main means by which heat is dissipated from the human body in hot climates. This heat rejection process is highly dependent on the airflow velocity. Also, dehydration, required sweat rate, and skin wetness that limit the criteria of ISO 7933 (1989; 2004) have been adopted in the method.

E_{req}, is the evaporation heat flow required to maintain thermal equilibrium with respect to the miners' body and, therefore, for 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:

Table 1
The interrelationship between terms in the human comfort equation and airflow velocity, modified from (Fanger, 1970).

Parameters	Mode of heat generation	Airflow velocity V (m/s)
M	Chemical	○
t_a	Convection	●
t_{sk}	Convection	●
R_{cl}	Convection	●
f_{cl}	Convection	●
h_c	Convection	●
f_{eff}	Radiation	○
ε_{sk}	Radiation	○
h_r	Radiation	○
t_r	Radiation	○
S_{out} -S_{in}	Evaporation	○
ω	Evaporation	●
f_{ec}	Sweat Evaporation	●
P_{sk}	Sweat Evaporation	●
P_a	Sweat Evaporation	●

● Interrelationship with air velocity; ○ No interrelationship with air velocity.

Table 2
Variation range 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	–
Airflow Velocity, v_a (m/s)	0–4	–
Clothing Insulation (clo)	0–1	0.093
Metabolic Rate, M (W/m^2)	200–340	200, 250, …, 340

$$E_{req} = M - (C + R + B) \tag{6}$$

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

$$\omega_{req} = \frac{E_{req}}{E_{max}} = \frac{M - (C + R + B)}{h_e f_{ec}(P_{sk} - P_a)} \tag{7}$$

The maximum wetness is 1.0 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, by taking into account the fraction of sweat that trickles away because of large variations in local skin wetness. The required sweat rate is given by:

$$SW_{req} = \frac{E}{\eta} \tag{8}$$

where η is sweat evaporation efficiency and is dimensionless. Under very humid conditions the sweat evaporation efficiency is given by the following relationship:

$$\eta = 1 - \frac{\omega^2}{2} \tag{9}$$

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

$$SW_{max} = 2.62M - 148 \quad \textit{For acclimatized workers} \tag{10}$$

$$SW_{max} = 3.27M - 186 \quad \textit{For un–acclimatized workers} \tag{11}$$

T_{max} is calculated based on D_{max} for one working shift. Maximum water loss (dehydration) in the range of 7.5% of the body mass, should be reduced by 33% in order to protect 95% of the workers (Malchaire, Kampmann, Havenith, Mehnert, & Gebhardt, 2000), was applied. In this analysis, an amount of 3900 g (5.2%) is assumed as the upper limit of dehydration for a working shift of 8 h.

$$T_{max} = \frac{D_{max}}{SW}, \quad (\mathrm{hr}) \tag{12}$$

The data represents, empirically, what prevails in hot underground mine climates. The analysis has been performed for an acclimatized/un-acclimatized miner, and all conditions are below the limiting criteria of ISO 7933 (2004). The boundary limits of thermal comfort were determined by the maximum sweat rate criteria, the maximum skin wetness criteria, and the maximum dehydration criteria in the form of maximum exposure limit time. These indices were predicted for underground conditions with dry-bulb air temperatures (t_a) varying from 10 °C to 50 °C, and one of the other parameters varying in the ranges that are indicated in Table 3. A mathematical model was developed in MATLAB and plots were generated to calculate the maximum sweat rate, skin wetness, and exposure limit possible for different air velocity values. Considering the air temperature results at airflow velocity of 0 m/s

Table 3
Air velocity effect on air temperature requirement of sweat rate with varying humidity at a metabolic rate of 250 W/m^2 for an acclimatized worker with coverall.

$M = 250$ 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 (1285.5 g/h) (°C)								
50	34.56	36.00	36.47	36.57	36.48	36.29	36.03	35.72	35.38
60	32.64	34.01	34.47	34.56	34.49	34.30	34.06	33.77	33.45
70	30.17	31.45	31.86	31.95	31.88	31.71	31.48	31.20	30.90
80	27.96	29.13	29.52	29.60	29.53	29.36	29.15	28.89	28.60
90	25.72	26.80	27.16	27.22	27.15	26.99	26.78	26.54	26.27
100	26.15	27.25	27.60	27.66	27.58	27.40	27.19	26.93	26.64

as the benchmark, airflow velocity was increased to 4 m/s in increments of 0.5 m/s. For the maximum allowable sweat rates, skin wetness, and exposure limit times, the corresponding air temperatures were recorded. These temperatures are the maximum allowable comfort temperatures in an underground environment.

3. Results

Several relevant scenarios have been studied to identify an optimized relative airflow velocity in order to maximize thermal comfort in underground mines. Considering the air temperature results at airflow velocity of 0 m/s as the benchmark, decreased dry-bulb air temperature requirements as a function of increased airflow velocities, were computed. For instance, Fig. 1 shows the results generated by means of simulation exercises of tolerable exposure times at a constant activity rate of 250 W/m^2 and relative humidity (RH) of 60%, 80%, and 100%. These graphs clearly show that the safe exposure time is greatly improved when the airflow velocity is increased from 0 m/s to 1 m/s (in red). There is an insignificant improvement in tolerable exposure time when the air velocity increases from 1 m/s to 2 m/s. Beyond 2 m/s increasing airflow velocity would negatively affect thermal comfort. When the relative humidity is above 80%, high airflow velocities would again work against thermal comfort. This is the case in most underground mines, particularly in working areas where the relative humidity exceeds 80%.

Fig. 2 presents the required sweat rate production for work comfort at a metabolic rate of 250 W/m^2, and relative humidity of 60%, 80%, and 100%. The maximum effect in respect to air motion is achieved at airflow velocities of 1 m/s and 2 m/s. Any increase in airflow velocity above 2 m/s would reduce the ambient air temperature. Within this interval of 1 m/s to 2 m/s, an optimum benefit in respect to air motion for thermal comfort is achieved at 29 °C, 28.5 °C, and 27.1 °C respectively. Fig. 3 assesses the workers' comfort based on the required skin wetness at a metabolic rate of 250 W/m^2, and at 80% and 90% relative humidity. Optimum benefits with respect to air motion are reached at airflow velocities between 1 m/s and 2 m/s. Again, above 2 m/s, increasing airflow velocity has a negative impact on the comfort level of the workers. For example, at a relative humidity of 80%, an airflow velocity of 1 m/s provides comfort for air temperatures up to 30.9 °C, while 4 m/s provides comfort up to 29.1 °C (Fig. 3, center).

The same results were also generated through model runs for climatic conditions where the relative humidity varied from 50% to 100%, and the metabolic rates from 200 W/m^2 to 340 W/m^2. When the airflow velocities are within 1 m/s and 2 m/s, thermal comfort can be achieved. Increasing the airflow velocities above 2 m/s would only reduce high air temperatures. This airflow velocity range is not affected by the metabolic rate of the worker and the relative humidity of the surrounding environment. Since higher airflow velocities would generate discomfort because of impact by large dust particles, this analysis validates the statement that work comfort can be achieved if the airflow velocity is maintained between 1 m/s and 2 m/s.

The results of the sensitivity analysis are shown in Tables 3 and 4. At the metabolic rate of 250 W/m^2, considering the air temperature results at 0 m/s as benchmark temperature, an increase in the maximum allowable temperature requirements were computed as the airflow velocity was increased from 0 m/s to 4 m/s. Results from model runs showed that the maximum possible required ambient air temperature for comfort, with respect to the sweat rate of the worker, is achieved at the airflow velocity of 1.5 m/s. Beyond 1.5 m/s, the effect of airflow velocity on the required ambient temperature is reversed. This illustrates that the optimum effect of airflow velocity on the worker's sweat rate for comfort is achieved at 1.5 m/s, after which increasing the airflow velocity would lower the ambient temperature but at a disproportional rate.

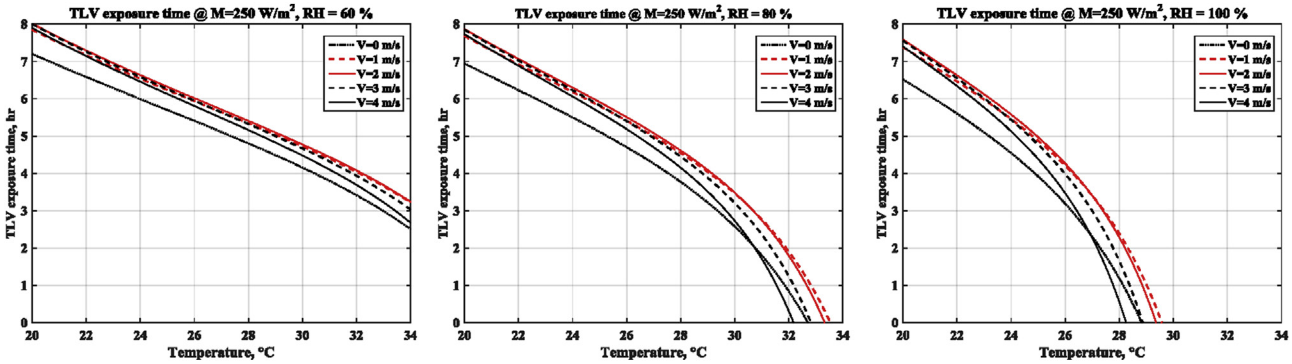

Fig. 1. Simulation results showing tolerable exposure time at a metabolic rate of 250 W/m^2, and relative humidity of 60% (left), 80% (center), and 100% (right).

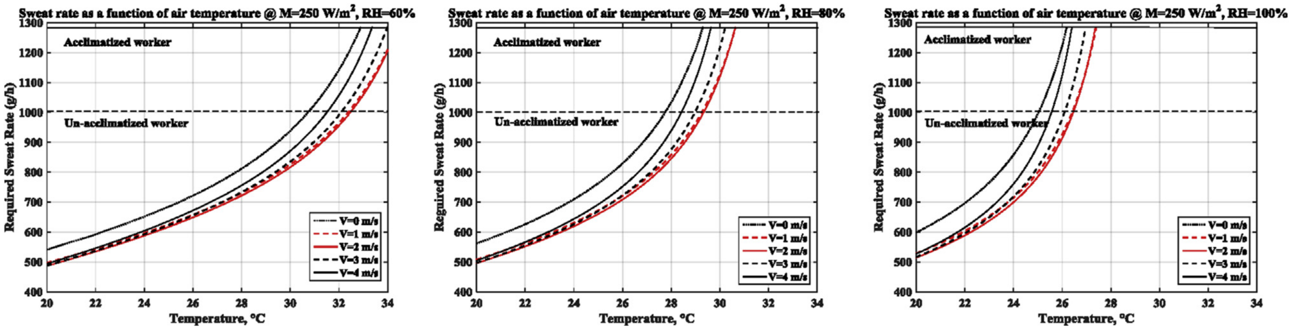

Fig. 2. Simulation results showing allowable sweat rate at a metabolic rate of 250 W/m^2, and relative humidity of 60% (left), 80% (center), and 100% (right).

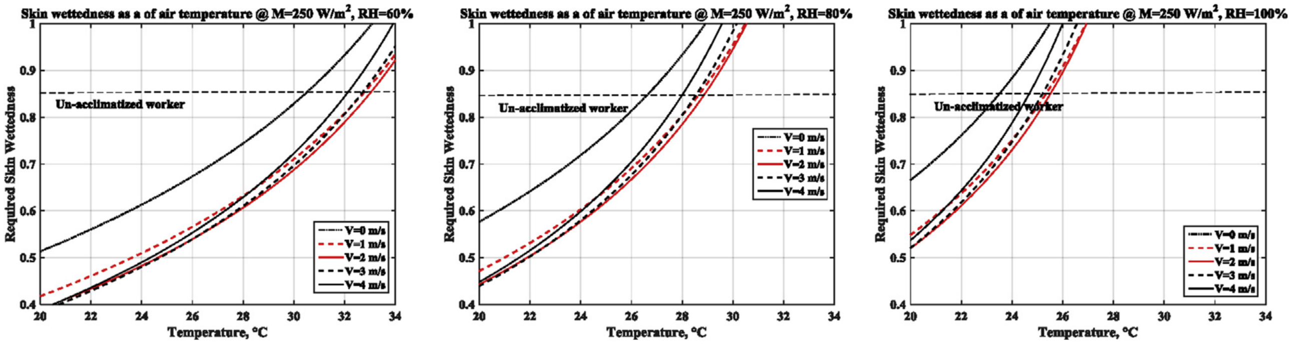

Fig. 3. Simulation results showing skin wetness at a metabolic rate of 250 W/m^2, and relative humidity of 60% (left), 80% (center), and 100% (right).

Table 4
Air velocity effect on air temperature requirement of skin wetness with varying humidity at a metabolic rate of 250 W/m^2 for an acclimatized worker with coverall.

M = 250 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 wetness (°C)								
50	34.95	36.53	37.06	37.19	37.13	36.96	36.72	36.43	36.10
60	33.11	34.58	35.07	35.17	35.12	34.94	34.71	34.38	34.09
70	31.83	33.23	33.69	33.79	33.71	33.54	33.30	33.01	32.69
80	29.1	30.38	30.79	30.88	30.80	30.62	30.40	30.12	29.82
90	27.51	28.73	29.11	29.18	29.10	28.93	28.73	28.44	28.14
100	25.13	26.24	26.60	26.66	26.58	26.41	26.20	25.94	25.66

4. Discussion

The heat exchange between the skin/clothing boundaries and the surrounding ambient air has an important influence on thermal comfort. In hot climates, as the body tries to cool itself, the flow of air across the body will assist evaporative cooling through sweat production. In high humidity climates, the air envelope surrounding the body may become saturated with moisture, however, by displacing the air next to the body and replacing it with fresh, less moist air, sweat evaporation will be sustained. Air movement increases the rate of heat loss by evaporation. For continued heat loss, the evaporated water vapor must be free to move away from the human body. All this leads to the continued cooling process of the body, and the higher the velocity of air, the more effective the cooling process is.

At present, ventilation practitioners are focused on delivering adequate air volumes to production workings. However, it is not explicit whether enough effort is put into ensuring that an adequate airflow velocity is also maintained to provide thermal comfort for the mine workers. The consequences of heat stress can be detrimental to mine workers. When the human body has difficulty losing heat, thermal stress and strain may take hold. This can expose the mine workers to heat-related illnesses as a result of discomforts such as lassitude, headache, nausea, dizziness, uneasiness, and eventually fainting. Consequently, a stable state of human comfort needs be assured. Securing this degree of climatic improvement should be the aim of mine ventilation engineers and environmental professionals.

This study was intended to demonstrate the importance of airflow velocity in maintaining comfort limits in underground mining environments. Despite surface climatic control strategies (where there is natural ventilation in many circumstances), the only means for adjustment of the thermal condition in underground mines is through the use of an artificial ventilation system (fan). When cooling systems are not employed, airflow velocity is the only parameter that a ventilation engineer can modify in order to maintain an acceptable thermal environment. This is important, mainly, because most of the time, merely adjusting the auxiliary ventilation system in the problem area will efficiently dilute the heat generated during production operations. This can involve moving the duct system, changing the duct or fan size, switching to a forcing or overlap system, etc. If the required air volume is more than the existing primary system can supply, other measures may need to be taken to increase the airflow. These may include regulating the airflow in other areas of the mine to increase air volume delivery to the desired area, adding booster fans underground and/or upgrading surface fans.

The results of this study agree with the maximum and minimum airflow requirements that are recommended in mine ventilation literature. Air motion across the skin accomplishes cooling through both convective energy transfer and latent energy transfer (evaporation of perspiration from the skin). If the air temperature is less than the skin temperature, it will significantly increase convective heat losses. This occurs because an increased amount of air is coming in contact with warm skin. With little or no air movement, the air close to the skin quickly heats up to the ambient temperature, and air movement occurs only when it becomes more buoyant. So, the comfort temperature is highly dependent on the airflow velocity. The required sweat rate cannot exceed the maximum sweat rate attainable by the subject. The required skin wetness cannot exceed the maximum skin wetness attainable by the subject. 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 that is desirable for maintaining the hydro-mineral equilibrium of the body.

In hot and humid environments where the relative humidity varies from 50% to 100%, increasing the airflow velocity will accelerate the evaporation of sweat by moving the saturated air away from the skin and replacing it with unsaturated air. Furthermore, at a relative humidity of 20% (dry conditions), the airflow velocity will accelerate moisture removal at the skin surface increasing cooling due to evaporative processes. Above 80% relative humidity (humid conditions) there is very little evaporative potential as the ambient air is already close to saturation, making air movement relatively ineffective.

5. Conclusions

The design or re-design of primary and/or auxiliary ventilation systems to provide acceptable working conditions should be explored before refrigeration is considered, as the cost savings could be significant. This study analyzed the effect of air velocity with air temperature on the thermal comfort of miners. The technique included the use of a two stress criteria of maximum skin wetness and maximum sweat rate, and the strain criteria of maximum dehydration. In this study, airflow velocities of 1 m/s and 2 m/s, which will guarantee thermal comfort, were determined by means of climatic modeling and simulation exercises. Based on the pattern of the results, the authors recommend an optimal airflow velocity of 1.5 m/s throughout production workings.

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