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

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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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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:

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

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:

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

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

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

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

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