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Original Article

Challenges in Selecting an Appropriate Heat Stress Index to Protect Workers in Hot and Humid Underground Mines

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ABSTRACT

Background: A detailed evaluation of the underground mine climate requires extensive measurements to be performed coupled to climatic modeling work. This can be labor-intensive and time-consuming, and consequently impractical for daily work comfort assessments. Therefore, a simple indicator like a heat stress index is needed to enable a quick, valid, and acceptable evaluation of underground climatic conditions on a regular basis. This can be explained by the unending quest to develop a "universal index," which has led to the proliferation of many proposed heat stress indices.

Methods: The aim of this research study is to discuss the challenges in identifying and selecting an appropriate heat stress index for thermal planning and management purposes in underground mines. A method is proposed coupled to a defined strategy for selecting and recommending heat stress indices to be used in underground metal mines in the United States and worldwide based on a thermal comfort model.

Results: The performance of current heat stress indices used in underground mines varies based on the climatic conditions and the level of activities. Therefore, carefully selecting or establishing an appropriate heat stress index is of paramount importance to ensure the safety, health, and increasing productivity of the underground workers.

Conclusion: This method presents an important tool to assess and select the most appropriate index for certain climatic conditions to protect the underground workers from heat-related illnesses. Although complex, the method presents results that are easy to interpret and understand than any of the currently available evaluation methods.

1. Introduction

Hot and humid environments can negatively impact the performance, overall productivity, and most importantly the ability of the underground workforce to perform work in a safe manner [1]. Evaluations of the underground thermal environment are becoming more important due to the proliferation of health and safety problems related to adverse climatic conditions in underground miners [2]. These health and safety problems are normally in the form of thermal discomfort and heat-related illnesses such as thermal stress, heat cramps, heat rash, and heat stroke [3].

A heat stress index integrates personal, physiological, and thermal environment parameters into a single number for a "quantitative" assessment of exposing mine workers to heat stress [4–6]. Heat stress indices can be grouped into: (1) rational indices, which are based on calculations involving the heat balance equation; (2) empirical indices, based on objective and subjective strain assessments; and (3) direct indices, which involve direct measurements of environmental parameters such as dry-bulb temperature, wet-bulb temperature, relative humidity, and airflow velocity [6–8].

Since 1905, over 160 heat stress indices have been proposed for various thermal environments [9]. Fig. 1 shows the cumulative number of heat stress indices that were proposed from 1905 to 2012. The graph reveals two important facts about heat stress indices. First, there has been no single index that can be used as a "universal index" [7,8,10,11]. A universal index would be an index that includes a range of comfort limits based on different metabolic rates. Second, a large number of heat stress indices may bring confusion in choosing the appropriate one for a specific industry or

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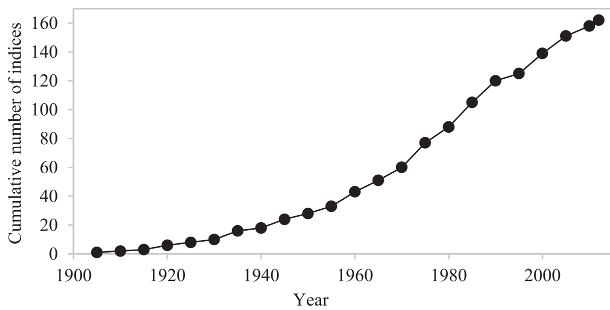

Fig. 1. Cumulative number of heat stress indices from 1905 to 2012.

work environment. The large number of available heat stress indices and the lack of a defined procedure to determine which index to be used for a particular climate have rendered comfort and environmental engineers to rely on guesswork in choosing an index for work climate evaluation. Many of the underground mines in the United States and worldwide can select an index while they are unaware of its limitations (observation of the authors from several underground gold mines in Nevada). This is partly occurring because measuring and collecting a large amount of physical and human-related parameters and subjecting them to complex climatic modeling are not simple and practical.

It has been agreed that an ideal heat index is needed to accurately assess the climatic conditions on a regular basis and protect the workers in hot and humid conditions. Furthermore, this index would need to be user friendly and computationally straightforward for the environmental practitioners [12]. This research study posed the question of which index can be recommended for a particular climate and work condition? In this paper, a method is used to compare a thermal comfort model with some of the most widely used heat indices in underground mines. The method is applied to predict the “comfort zone” and to recommend an index based on its performance as close as possible to the “comfort zone.” The comparative analysis uses comfort data including air temperature, airflow velocity, humidity, and estimated physiological parameters such as clothing and activity rates.

2. Materials and methods

2.1. Thermal comfort

Humans are comfortable within a very small range of core body temperatures. Biochemical processes in the human body will not function if the temperature becomes too low or too high. At high temperatures, enzymes lose their activity and at low temperatures there is inadequate energy to continue metabolic processes [13]. Humans can tolerate extreme core temperatures below 35°C or above 41°C for only brief periods [13]. There are mechanisms by which the body can regulate its core temperature both at rest and during activity, and in both hot and cold or humid environments, along with health risks that are associated with physical activity in the aforesaid environments [14]. Through its intricate temperature regulation, the human body is able to reach a state of thermal equilibrium with the surrounding environment when the variation of internal energy at the body core level is equal to zero [15].

Assessment of “thermal comfort” must start with the appreciation that comfort is a state of mind. It is extremely difficult to classify the many factors that affect thermal comfort. The interaction between the physical demand imposed upon an individual, his/her physiological status, and his/her psychological attitudes must be considered in interaction with social customs, tangible perceptions, and the likes [16]. Because thermal comfort is rather subjective and restrictive, it is better to define a comfort zone within which most workers will be comfortable. This necessitates the need to define a “zone” in which most of the workers will consider comfortable, the so-called comfort zone. This comfort zone will be ascribed using the climatic and physiological parameters of the mine environment and some existing thermal comfort models.

2.2. Thermal comfort zone

Thermal comfort is the condition of mind which expresses satisfaction with the thermal environment [17,18]. Based on American Society of Heating, Refrigerating and Air-Conditioning Engineers definition, the “thermal comfort zone” is the condition that satisfies 80% of sedentary persons within the environment. According to Fanger [15], three parameters need to be satisfied for a person to be considered in the thermal comfort zone. These parameters are as follows: (1) the worker’s sweat rate needs to be within comfort limits; (2) the worker is in heat balance; (3) the worker’s mean skin temperature is within comfort limits. There are six main factors (air temperature, relative humidity, radiant temperature, air velocity, metabolic rate, and clothing) affecting the thermal comfort, which can be perceived as both environmental and personal [1,4,15].

2.3. Heat stress indices

The idea of the thermal index goes back to 18th century [4]. Without considering the dry-bulb temperature, perhaps the first published heat stress index was the wet-bulb temperature proposed by Haldane (1905) [10]. Since then a large number of heat stress indices have been proposed. Many of the earlier indices only included four environmental factors: effective temperature, equivalent temperature, operative temperature, and wet-bulb globe temperature (WBGT). Later, new indices took into account clothing and the metabolic rate as behavioral parameters.

Heat stress indices have been employed in different engineering applications. Presently, no one single index has gained universal acceptance. Belding [10] and Gagge and Nishi [11] pointed that having a unique valid system for rating heat stress is not possible because the interaction between the climatic parameters is complicated. Many of the current indices were developed for a specific use. Each heat stress index has special advantages that make it more suitable for a particular work environment. Despite extensive research work (Table 1), it is currently not possible to quantitatively compare the available heat indices using a valid method. Therefore, it is the user’s responsibility to examine each index and select the one that best suits the defined thermal climate and protects the mine workers.

Heat stress indices have several safety and health applications in the mining industry and other businesses. Among these applications, the following are mentioned:

- *Setting exposure limits or threshold limit values:* Perhaps, the most important application of a heat stress index is to define the maximum exposure time or safety limits [19].
- *Defining the comfort limits:* Another important application of a heat stress index is to define the comfort zone, which is applicable in the interest area (e.g., office, work area).
- *Determining the optimum control measures:* Heat stress indices can be used to evaluate and select the measures and available options of controlling heat such as air movement, air conditioning, work/break protocols.

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Table 1
A literature review of the methods for quantitative comparison between existing heat stress indices.

Comparison method	Author(s)
Experiment Acclimatized and/or unacclimatized men and/or women Range of work and/or resting conditions Wide range of climatic conditions Different environmental and behavioral parameters	Lind and Hellon [22] Macpherson [4] Klemm and Hall [23] Ljunberg et al [24] Pulket et al [25] Morris and Graveling [26] Mairiaux and Malchaire [27]
Comparison between direct indices Summary of indices and their correlation to thermal comfort	Epstein and Moran [7]
Comparison between temperature–humidity indices Comparison between rational methods and temperature–humidity indices	d'Ambrosio Alfano et al [20]
Data analysis Large or small climatic databases as input parameters of climatic condition Assumed data	Beshir and Ramsey [28] Blazejczyk et al [29]
Rational method Concept of limiting metabolic rate Energy balance equation	Brake and Bates [8] Zuhairy and Sayigh [30]

- *Past exposures evaluation:* Heat stress indices can be also used to assess past exposures to heat in underground mines. For this purpose, more comprehensive indices can give better results.
- *Evaluation of safe work:* An index can be a good indication of the limits of safe work. Particularly, in sport, military, and mining industry settings, use of an appropriate index can help prevent heat- and cold-related illnesses.
- *Climate zone classifications:* Heat stress indices can be used to determine climate zones. These classifications are important to assure a safe and comfortable work environment.

There are some general limitations that should be taken into account for many of the heat stress indices, as follows:

- Many of the indices do not include a wide range of climatic conditions. These indices may be precise for a climatic condition (e.g., warm environment), but inappropriate for others. A good example is the scale of the "equivalent temperature index," which does not extend beyond 24°C. Therefore, an engineer may have to consider and work with more than one heat stress index if the work environment changes.
- Inbuilt errors exist in some of these indices. Several indices (e.g., direct indices) are developed based on algebraic or statistical models. There is some degree of error when these mathematical methods are applied. An example is the error of the "effective temperature index" scale in wind speed at high temperature [20].
- Important factors such as acclimatization cannot be included [4,21]. For a given level of heat stress, heat strain experienced by an acclimatized individual is different from an unacclimatized person. Many of the indices do not distinguish between acclimatized and unacclimatized persons in their application.
- Brake and Bates [1] state that most heat stress indices were developed for externally paced work. Increasing degree of mechanization of heavy tasks and new regulations result in informed workers that support self-pacing in thermally stressed climates.
- Averaging methods are not always physiologically valid. Many of the indices are developed based on thermal stress of the workers and averaging of large experimental data, although the reaction of the individuals to heat load can be modified by age, sex, etc. Furthermore, the response of a group of self-paced and acclimatized workers to heat will largely differ from a group of unacclimatized and less experienced workers.
- The validity and reliability of many indices are questionable. For example, the discomfort index was developed as a simplified version of WBGT [20]. In the WBGT index, globe temperature (GT) measures the combined effect of radiant heat, air temperature, and air speed. The discomfort index does not take into account the air speed by replacing GT with ambient temperature, which may cause significant errors in evaluating some climatic conditions.
- The primary purpose of evaluating the climatic conditions is to assess the work environment and redesign the control system (e.g., ventilation, cooling, work/break protocols) to meet safety, health, and comfort indicators for the mine workers [4]. None of the indices can take into account all the comfort determining factors and their interrelation. Consequently, the work environment should be assessed regularly, irrespective of how comprehensive is the index.

Comparison between the heat stress indices based on Pierce two-node model

The National Institute for Occupational Safety and Health (NIOSH) published a revised recommendation standard in 2016 entitled "Occupational Exposure to Heat and Hot Environments," and proposed a selection criteria along with heat stress indices to be used in hot and humid environments. It recommends several heat stress indices including direct indices (e.g., dry-bulb temperature and wet-bulb temperature), rational indices (e.g., operative temperature, skin wetness, and Belding–Hatch heat stress index), and empirical indices (e.g., the effective temperature, WBGT, wet-globe temperature, and universal thermal climate index) [12].

It is not practical to review and compare all the available indices based on the aforementioned methods. In general, we know that measuring and collecting a large number of physiological and human-related factors are not simple and practical in the underground mines. To investigate the validity of a heat index for use under realistic underground mining conditions, a climatic model based on the mine climate data, including air temperature, relative humidity, airflow velocity, and the physiological parameters of the miners in the form of metabolic rate and clothing was developed and proposed for mine climate assessments. The radiant temperature was assumed to be equal to the air temperature in the algorithm of the model because the radiation heat transfer is negligible compared with convective and conductive heat transfers.

For this research study, the Pierce two-node model was selected, as its algorithm was straightforward and easy to understand as a computer application for thermal comfort assessments, specifically, for mining engineering applications. Other models of thermal comfort [15] are also worth considering.

The Pierce two-node model was developed at the John B. Pierce Foundation at Yale University. The model has been continually expanding since its first publication in 1970 [31]. The most recent version of the model appeared in the 1986 American Society of Heating, Refrigerating and Air-Conditioning Engineers Transactions [32]. In the Pierce two-node model solution, the human body is modeled as two concentric cylinders, where the inner cylinder represents the core of the human body, and the thin outer cylinder represents the skin shell [33]. The skin and core temperatures were calculated as a function of time by solving the heat balance at the core and skin nodes.

The rate of heat stored by the body (S) is given as the rate of metabolic heat production (M) minus the heat energy lost to the environment through the skin and respiratory tract, and the mechanical energy lost due to work as shown in equation (1):

$$M - W - Q_{sk} - F \pm C \pm R = S\left(\mathrm{W}/\mathrm{m}^2\right) \quad (1)$$

A simple expanded version of equation (1) is presented in equation (2), as follows:

$$M[(1-\eta) - 0.0173(P_{sat} - P_a) - 0.0014(34 - t_a)] - 16.7(0.06 + 0.94W_{rsw})h_c(P_{sk} - P_a)F_{pcl} - h(t_{sk} - t_a)F_{cl} = \Delta s \quad (2)$$

where

$$t_{sk} = 12.17 + (0.02t_a + 0.044t_r) + (0.194P_{sk} - 0.253v) + (0.003M) + 0.513t_{rec} \quad (3)$$

$$F_{pcl} = 1/(1 + 0.344hI_{cl}) \quad (4)$$

$$h_c = 0.608P^{0.6}v^{0.6} \quad (5)$$

$$h_r = 4.61(1 + (t_a + t_{sk})/546)^3 \quad (6)$$

$$h = h_c + h_r \quad (7)$$

$$F_{cl} = 1/(1 + 0.155h_cI_{cl}) \quad (8)$$

where

M = metabolic rate; η = efficiency; P_{sat} = saturation vapor pressure; P_a = actual vapor pressure; P = air pressure; t_s = air temperature; t_{sk} = skin temperature; t_r = radiant temperature; v = air velocity; W_{rse} = skin wetness; t_{rec} = rectal temperature; and h_c, h_r, h, F_{cl}, F_{pcl}, I_{cl} = constant coefficients.

Results

Several heat stress indices mostly used for work comfort evaluation in mines were studied. The exclusion criteria applied in selecting an index were that the index equation be unambiguously stated in the publication and that the required inputs are among our measured and estimated ventilation and climatic parameters such as relative humidity, air temperature, airflow velocity, barometric pressure, metabolic rate, and clothing. Indices with input parameters that formed variants of the measured parameters were also considered. Heat stress indices, mostly applied in underground mines, were calculated using the publications listed in Table 2.

The method evaluated each heat stress index to determine whether it conforms to the ascribed comfort zone in the Pierce two-node model. The modeling results of several cases for varying activity rates of 100 W/m^2, 150 W/m^2, 200 W/m^2, 250 W/m^2, and 300 W/m^2, and airflow velocity from 0.1 m/s to 1.5 m/s, relative humidity from 0% to 100%, skin wettedness of 0.5 to 1, efficiency of 5% to 15%, and air temperature from 0°C to 50°C were studied. A nonacclimated worker is assumed to wear coverall and the underground environment was assumed to be a uniform environment ($T_a = T_r$). Based on these criteria, an "appropriate" index or set of indices was selected to be used in the prevailing mine climate and physiological conditions (Table 3). Any heat index algorithm can be used with any preferred activity and airflow velocity rate, to be assessed for acceptability.

Figs. 2 and 3 give visual valuations of how each particular heat stress index is performing relative to the generated comfort zone and provide a clear indication on the ability of the index to protect the mine workers. Contour plots depicted in Fig. 2 demonstrate that, in uniform environments ($T_a = T_r$), with airflow velocity of 1.5 m/s and for an activity rate of 200 W/m^2, the "discomfort" index in general deviates from the comfort zone. Furthermore, the "effective temperature" index does not perform very well relative to the comfort zone. However, the "humidex" heat index tends to perform quite well especially at higher humidity rates, which are typical of deep and hot underground mines. In terms of index performance relative to the comfort zone under these climatic and physiological conditions, the result of the simulation shows that the WBGT index seems to perform better than the other three indices and will therefore be an ideal candidate to be selected for assessing the comfort of the mine workers at metabolic rate of 200 W/m^2. Furthermore, the graphs show that the heat stress indices tend to be noisier relative to the comfort zone compared with the results obtained in the first case. This obviously reflects the heavy impact of an increased metabolic rate (e.g., work intensity) on the comfort of mine workers. At the metabolic rate of 250 W/m^2, however, all of the aforementioned indices failed to predict the comfort zone, particularly at high relative humidity, which is the case in most of underground operations (Fig. 3).

Recommended selection criteria

The problem with NIOSH [12] selection criteria is that no existing index meets all the requirements proposed by the NIOSH. On the one hand, direct and empirical indices have relatively simple measurement and calculation procedures. They, however, as shown

Table 2
Most widely used simple heat indices in mining industry.

No.	Index formula	Author(s)
1	Wet-bulb temperature	Haldane [34]
2	Discomfort index (DI) $= 0.4 \times \mathrm{tw} + 0.4 \times \mathrm{ta} + 8.3$	Thom [35]
3	Wet-globe temperature (WGT) = WBGT − 2	Botsford [36]
4	Discomfort index (DI) $= 0.5 \times \mathrm{tw} + 0.5 \times \mathrm{ta}$	Sohar et al [37]
5	Modified discomfort index (MDI) $= 0.75 \times \mathrm{tw} + 0.3 \times \mathrm{ta}$	Epstein and Moran [7]
6	Discomfort index (DI) $= \mathrm{ta} - (0.55 - 0.0055 \times \mathrm{RH}) \times (\mathrm{ta} - 14.5)$	Kyle [38]
7	Thermohygrometric index (THI) $= 0.55 \times \mathrm{tw} + 0.2 \times \mathrm{t_{dew}} + 5.3$	Schoen [39]
8	Humidex $= \mathrm{ta} + (5/9) \times (\mathrm{e} - 10)$	Masterton and Richardson [40]
9	Wet bulb globe temperature (WBGT) $= 0.7 \times \mathrm{tw} + 0.3 \times \mathrm{ta}$	Minard et al [41]
10	Effective temperature (ET) $= \mathrm{ta} - 0.4 \times (\mathrm{ta} - 10) \times \left[1 - \left(\frac{\mathrm{RH}}{100}\right)\right]$	Houghton and Yaglou [42]
11	New effective temperature (NET) $= \frac{37-(37-\mathrm{ta})}{(0.68-0.0014\times\mathrm{RH})} + \{1/[1.76 \times 1.4 \times \mathrm{v}^{0.75} - 0.29 \times \mathrm{ta} \times (1 - 0.01 \times \mathrm{RH})]\}$	Gagge et al [31]
12	Thermal strain index (TSI) $= \frac{1}{3} \times \mathrm{tw} + 3/4 \times \mathrm{ta} - 2 \times \mathrm{v}^{0.5}$	Lee [19]

RH, relative humidity; WBGT, wet-bulb globe temperature.

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Table 3
Recommended heat indices for comfort assessment based on various metabolic rates.

Metabolic rate (W/m^2)	Appropriate heat stress index
100	ET, NET, TSI, WBGT, Humidex, THI, DI (1962), DI (1959), DI (1990), DI (1959), THI, DI (1968), DI (1998), DI (1963)
150	NET (RH < 80), TSI (30 < RH < 70), ET, WBGT, Humidex, THI (RH > 50), DI (1959), DI (1998), DI (1963), DI (1959) (RH < 60)
200	Humidex, DI (1959), NET (RH < 50), TSI (20 < RH < 40), ET (RH < 50), WBGT (RH < 80), THI (RH < 50)
250	Humidex, DI (1959), NET (RH < 50), TSI (20 < RH <40), ET (RH < 50), WBGT (RH < 70), DI (1959)
300	Humidex (RH < 50), DI (1963) (RH < 50), DI (1959)

DI, discomfort index; ET, effective temperature; NET, new effective temperature; RH, relative humidity; THI, thermohygrometric index; TSI, thermal strain index; WBGT, wet-bulb globe temperature.

in this study, do not incorporate the physiological comfort parameters for evaluating total strain. This is because many of these indices are developed using statistical and simple mathematical methods and are not based on the energy balance equation. On the other hand, rational indices may be more comprehensive and accurate compared with other types of indices. However, the measurement and calculation procedures are complex and difficult to comprehend. Consequently, many of the underground mines in the United States and worldwide may select an index while they are unaware of its limitations.

In extreme hot and humid conditions often faced by mine workers, the heat index used for comfort evaluation must be carefully selected. It should provide protection for the mine workers as much as possible. To optimize this selection process, it is recommended that index selection be classified based on two phases of mining, namely: (1) planning and design phase; and (2) operational phase. This is essential because a well-assessed thermal condition in the planning and design phase will minimize the burden of managing heat stress in the operational phase. Furthermore, through this approach a more complex and complete analysis can be carried out in the planning and design phase as opposed to the operational phase, where it is essential that the index should be specifically selected for the local conditions and should not be complicated. In view of this premise, the following factors are suggested to be considered when selecting an index based on the two discussed phases.

Planning and design phase

- The index should be applicable for the purposes of underground mine climatic guidelines;
- The accuracy of the heat stress index must be proven by means of previous applications, or use;
- The purpose of using a heat stress index is to evaluate comfort limits, safe work limits, and/or to determine the optimum control method;
- All major factors contributing to the heat load during mining activities should be included in the work comfort assessment;
- The included factors should have a valid weight in relation to the total heat strain;
- Interpretation of the results should be straightforward.

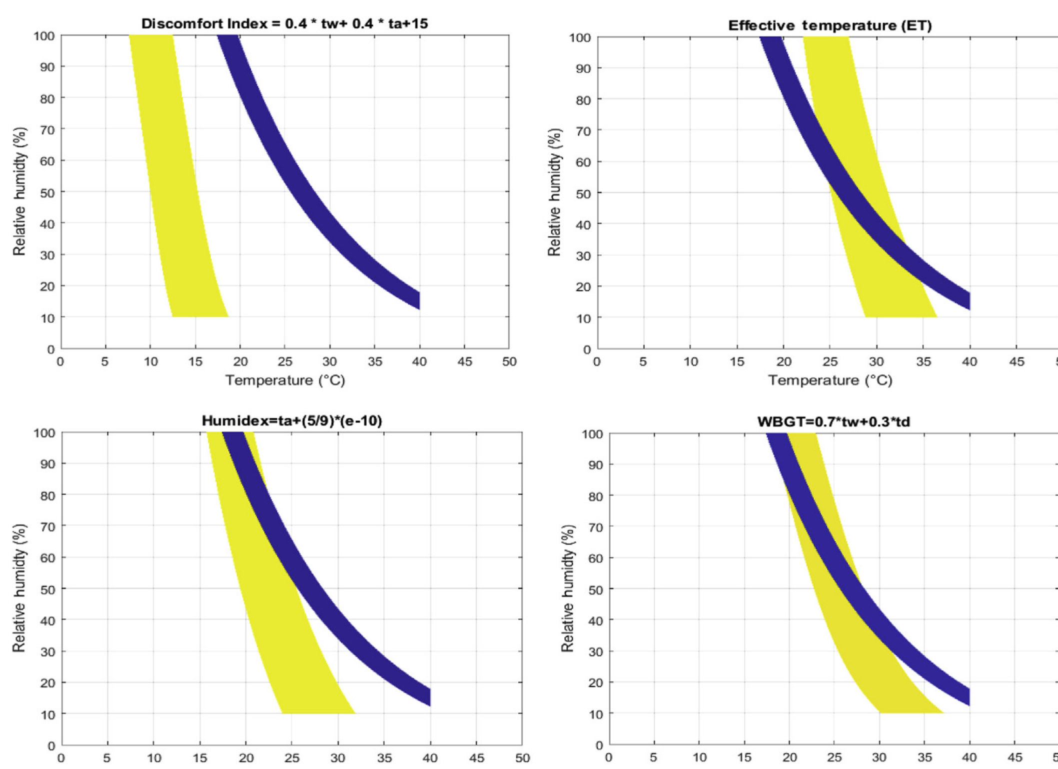

Fig. 2. Convergence between selected heat stress indices (yellow) and comfort zone (blue). $M = 200\ W/m^2$; $V = 1.5\ m/s$; $W_{rse} = 0.7$; clothing: coverall.

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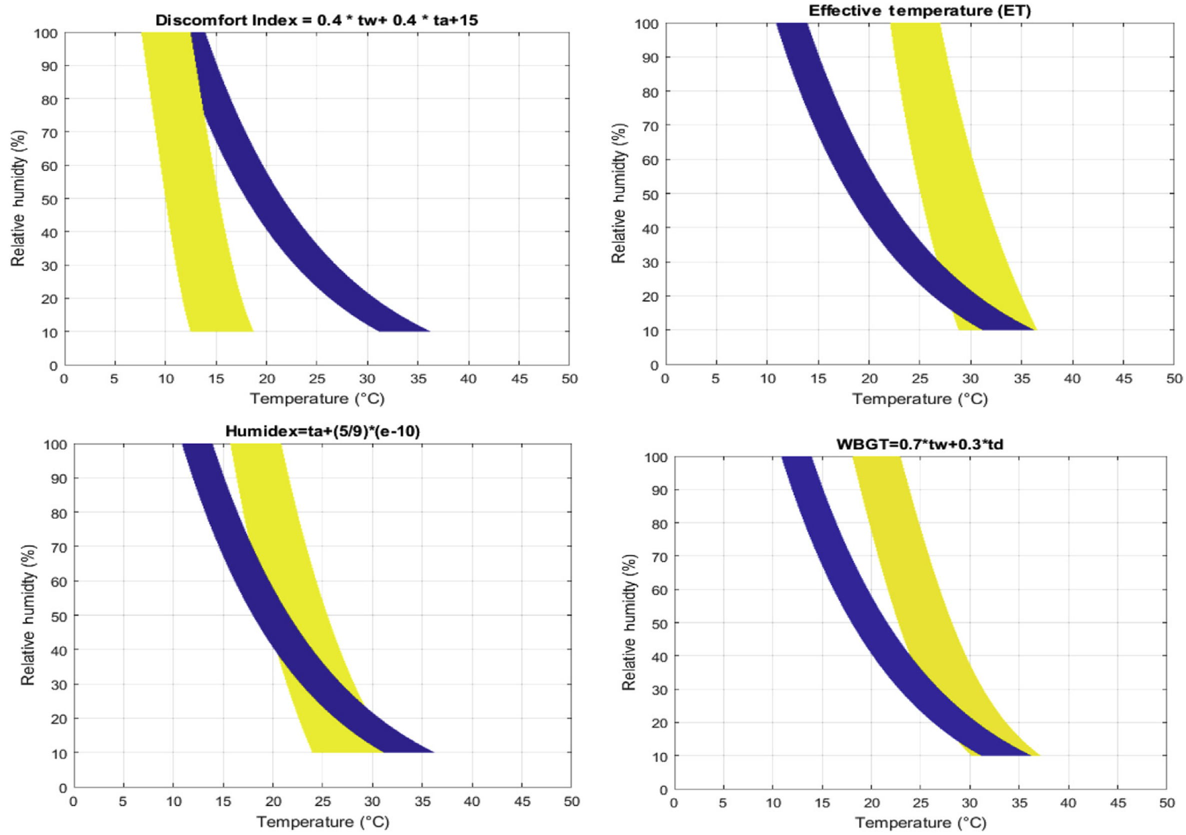

Fig. 3. Convergence between selected heat stress indices (yellow) and comfort zone (blue). M = 250 W/m^2; V = 1.5 m/s; W_{rse} = 0.7; clothing: coverall.

Operational phase

- The index should be applicable for the purposes of underground mine climatic guidelines;
- The purpose of using a heat stress index is to set exposure limits or threshold limit values under a wide range of environmental conditions;
- All the contributing factors should be measurable or reasonably assumed;
- The measurements, measuring instruments and protocols, and interpretation of the collected data, and results should not interfere with worker's performance;
- Measurements and calculations should be simple;
- Interpretation of the index should be straightforward.

Discussion and Conclusions

Which heat index is the most appropriate? The relationship between the comfort zone and the heat indices is simple and easy to comprehend. An almost superimposed relationship defines an "ideal" index for the conditions that describe the comfort zone and index. The primary appeal of heat indices should be *simplicity*. It is more likely that mine ventilation engineers and the mining crew in general will approve a thermal index due, in part, to the fact that the index can be presented in a format that they can understand and apply. That is, if the index is simple. Unfortunately, simple outputs also limit the appropriateness of the value to a specific or special case. The necessity of using numerous modifications to simple indices to adjust for various conditions, to a large extent, negates the apparent advantage of indices.

The comfort model used measured and estimated comfort parameters and compared output data generated from model runs with the measured ventilation and climatic parameters such as airflow velocity and activity rates. The computer algorithm for this model is based on the numerical solution of the heat balance equation and the heat transfer coefficients recommended by the Pierce two-node model. Furthermore, the environment engineers are provided a tool to assess, identify, and recommend a simple but appropriate index to be applied underground through the use of this simulation method described in this paper. The model run results depicted various responses of heat indices to different climate and physiological conditions. The results can be used to propose various suitable heat indices for work comfort evaluation. Although complicated, the method provides an avenue for simple indices to be evaluated based on a comprehensive set of comfort parameters instead of their conventional reliance on the climate and mostly on two parameters only, the air temperature and humidity.

In conclusion, although there are many heat stress indices, there has never been a well-defined method or process to select an appropriate index for a particular underground climate. This has limited mine environmental engineers to select a heat stress index/indices based largely on intuition and guesswork. This method presents an important tool to assess and select the most appropriate index for certain climatic conditions to protect the underground workers from heat-related illnesses. Although complex, the method presents results that are easy to interpret and understand than any of the currently available evaluation methods. It also gives the added advantage that simple indices can be assessed based on physiological comfort parameters. However, more research work is needed to further enhance the method and validate the climatic

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model to accurately assess the climatic conditions and select the most appropriate and safe index that will protect the mine workers.

Conflicts of interest

The authors declare no conflict of interest.

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