Understanding the Human Thermal Balance and Heat Stress Indices as they apply to Deep and Hot US Mines

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Thermal heat stress may seriously affect the performance, overall productivity, safety and health of an individual and may decrease tolerance to other environmental hazards. Discomfort, heat illness and heat stroke are three phases of the reaction of the human body when exposed to an unstable heat balance in a hot and humid environment. Heat stroke is the most serious illness, which occurs when the core temperature of the human body exceeds the threshold temperature. Exceeding core temperatures can damage the thermoregulation functions of an underground worker and potentially generate irreversible damage to the brain and other organs. Heat stroke is a very serious illness, which carries a high risk of fatality when the underground climatic conditions are not immediately corrected.

The reaction of the human body to thermal variations involves a complex interrelationship between climatic factors and physiological responses. A heat stress index integrates personal, physiological, and environmental parameters into a single number for a quantitative assessment of thermal environments. Heat stress indices can be divided into three groups: rational, empirical and direct indices. Over decades, more than one hundred heat stress indices have been proposed for various thermal environments. No single heat index has given a holistic assessment of the human thermal environment. However, each heat stress index has special advantages that make it more suitable for use in its particular environment.

This paper aims to review and summarize the existing heat stress indices commonly used for assessing the heat stress conditions in underground mining environments. Heat stress indices will be categorized based on the thermal comfort parameters (dry-bulb temperature, wet-bulb temperature, black-globe temperature, wind velocity, metabolic rate, and clothing). The advantages and shortcomings of using a heat stress index for evaluation of an underground mine environment will be assessed. The physiological response of the human body to thermal stress will be made. Various modes of heat exchange events associated with the human body and its corresponding physiological reactions to hot and humid environments will also be analyzed. Furthermore, a discussion of the possibility of determining an empirical and/or rational index which would offer adequate protection for the underground workforce in the US will be made.

Keywords: Heat, Human Thermal Balance, Thermal Comfort, Energy Balance Equation, Heat Stress Index

1 Introduction

As the base and precious metal mines in the US become deeper, more productive and further mechanized, the underground workforce will be exposed to an increasingly hot and humid environment. Appraisal of the thermal environment is becoming more important due to significant effects of excessive heat on safety and health of the underground miners. These effects on individuals can be from thermal discomfort to heat-related illnesses such as thermal stress, heat cramps, heat rash, and heat stroke.

Assessment of the thermal environment includes an extensive monitoring of temperature and humidity with adequate thermal management protocols established for each underground mine. Controlling methods include reducing heat loads in the development and production workings and throughout the mine by means of ventilation, localized cooling systems, and refrigeration. The evaluation of the climatic conditions of an environment requires extensive measurements and modeling strategies. However, a simple tool is required to have a valid and acceptable evaluation of climatic condition on regular bases. A heat stress index integrates personal, physiological, and thermal environment parameters into a single number for a quantitative assessment of heat stress. 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; and (3) direct indices, which involve direct measurements of environmental variables. The use of a heat stress index makes it possible to evaluate and compare the climatic conditions in an underground mine during development and production processes. Over the decades, more than one hundred heat stress indices have been proposed for various thermal environments. No one single heat index has given a holistic assessment of the human thermal environment. However, each heat stress index has special advantages that make it more suitable for its particular environment.

Our goal is to identify and recommend heat stress indices that are more convenient for underground mining application. We identified twenty eight (28) heat stress indices suitable for an underground climatic assessment.

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In this paper, we discuss the effect of excessive heat on the human body, the thermal comfort, and energy balance equation. A review of the definition, history, and limitations of heat stress indices is also performed. We present a summary of international standards and regulations. The selection criteria available for underground mining applications are assessed and questioned.

2 Human Response to the Thermal Environment

Humans are comfortable within a very small range of core body temperatures. Biochemical processes in the 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. When the core temperature rises above 40°C (104°F), hyperthermia occurs, and hypothermia occurs below 35°C (95°F). Humans can tolerate extreme core temperatures below 35°C (95°F) or above 41°C (106°F) for only brief periods of time. To maintain the internal temperature within these limits, the human body exhibits very effective and in some instances specialized physiological responses to critical thermal stresses. These responses facilitate the conservation, production or elimination of body heat. This is achieved through finely controlled coordination of several body systems [1].

2.1 Human Heat Regulation

The various human body systems must synchronize their activities to perform physical activity. These systems have the capacity to adapt when exposed to the stresses of specific environments. 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. [2]. 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 [3]. The thermal exchange between a subject and the environment is equal to the difference between metabolic heat and thermal losses due to respiration and exchanges of heat through the skin surface.

3. Thermal comfort

Thermal comfort is the condition of mind which expresses satisfaction with the thermal environment [4]. The environmental conditions required for comfort are different for 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 ASHARE 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; (3) mean skin temperature is within comfort limits [3].

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 which affect thermal comfort; the interaction between the physical demand imposed upon the individual, his physiological status and his psychological attitudes must be considered in interaction with social customs, tangible perceptions and among other considerations [5]. Because thermal comfort is subjective, it is difficult to satisfy all individuals with a simple environmental specification.

Regardless of difficulties in defining the thermal comfort zone, attempts to define the parameters affecting the human thermal environment and its sensation to thermal comfort were made. By the end of the nineteenth century, four important components of the environment, temperature, humidity, air speed of movement, and the intensity of radiation, were recognized [6].

Undeniably, thermal comfort depends on the interaction between three groups of elements: environmental factors, clothing factors and physiological factors. Fanger [3] 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 metabolic rate.

Table 1. Thermal comfort parameters

Environmental	1.Dry bulb temperature (T_a)
	2. Black-globe temperature (MRT)
	3. Wind velocity (V)
	4. Relative humidity (RH)
Behavioral	5. Clothing (Clo)
	6. Metabolic rate (M)

Table 2. Five thermal effect zones associated with thermal and comfort sensation [2, 7, 8].

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	Uncomfortable	$S \approx 0$
2	Warm	compensable zone	Slightly uncomfortable	
1	Slightly warm			
0	Neutral	Vasomotor compensable zone	Comfortable	$S = 0$
-1	Slightly cool			
-2	Cool		Slightly uncomfortable	$S \approx 0$
-3	Cold	Shivering compensable zone		
	Very Cold	In-compensable cold zone	Uncomfortable	$S \ll 0$

4. Heat Balance Equation

Sustaining core temperature involves a balancing act between heat loss and heat production. The body is in a state of thermal equilibrium with its environment when it loses heat at the same rate as it gains heat. The relationship between the body's heat production and its heat gains and losses can be expressed mathematically using the first law of thermodynamics. This makes it possible to assess the human body's thermal balance with the following well-known equation (see table 3) [9]:

$$S = M - W - (C_{res} + E_{res} \pm C \pm R + E) \qquad (1)$$

where:

- M: Metabolic rate
- W: External work rate
- C_{res}: Respiratory convective heat loss,
- E_{res}: Respiratory evaporative heat loss
- E: Evaporation of the sweat
- C: Convection
- R: Radiation
- S: Heat storage in the body

When air is inhaled during respiration its temperature and humidity are at different levels with respect to the core of the body. The body's internal heat is transferred relative to the level of activity, to the external environment by convective (C_{res}) and evaporative (E_{res}) exchanges. Respiratory heat losses depend on the level of activity performed by the subject and the temperature and humidity of the air in the environment. Respired vapor loss, (E_{res}) comprises latent respiration heat loss (E_{rel}) and convective or sensible respiration heat loss (E_{rec}). Evaporative heat loss from skin surface (E_{sk}), is made of evaporative heat loss by skin diffusion (E_{dif}), and heat loss due to regulatory sweating (E_{rsw}) [9].

The human body external surface is characterized by thermo-conditions that are dissimilar from those of the neighboring environment. This prompts thermal exchanges between the subject and environment. These interactions are in the form of "sensible" heat losses: by convection (C), radiation (R), and conduction (K) and "latent" heat losses owing to sweat evaporation, (E) [10]

5. Heat Stress Index

The idea of the thermal index goes back to 18th century [11]. Without considering dry-bulb temperature, perhaps the first published heat stress index was wet-bulb temperature proposed by Hardlane [12]. Since then a large number of heat stress indices have been proposed. Many of the earlier indices only included four environmental factors, such as: Effective Temperature (ET), Equivalent Temperature (Eeq), Operative Temperature (OpT), and Wet-bulb Globe Temperature (WBGT). Later, new indices took into account clothing and metabolic rate as behavioral parameters. Furthermore, indices such as WBGT and ET were later modified to take into account the effect of clothing.

As shown in Fig. 1, over the years, more than 162 heat stress indices have been proposed by many authors for use in a specific climatic condition [13]. Fig. 1 shows the trend of heat stress indices proposed from 1905 to 2012. The trend is almost linear after 1950; approximately two heat stress indices were proposed each year. This indicates two important aspects of heat stress indices. First, the large number of indices demonstrate that none of these indices is valid as a universal heat stress assessment index. Belding [14] and Gagge and Nishi [15] mentioned that having a unique valid system for rating heat stress is not possible since the interaction between the climatic parameters is complicated. An index that integrates these parameters and correlates them with the physiological response of the body has not been developed.

Second, the large number of indices generates confusion. Many of these indices were developed for specific climatic conditions. There may be limitation(s) that make these indices inadequate for other climatic conditions. Therefore, it will be difficult for users to choose an appropriate index, since no one single index includes all environmental and behavioral factors and conditions.

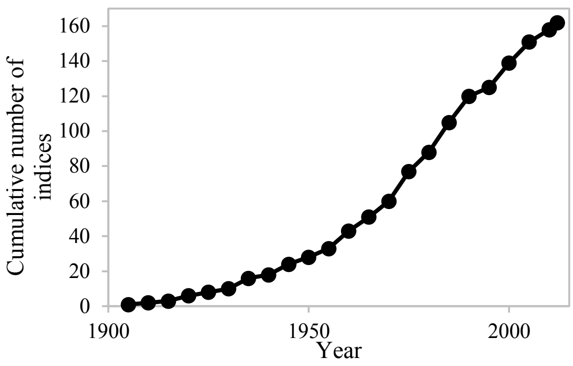

Fig. 1. Cumulative number of indices from 1905 to 2012

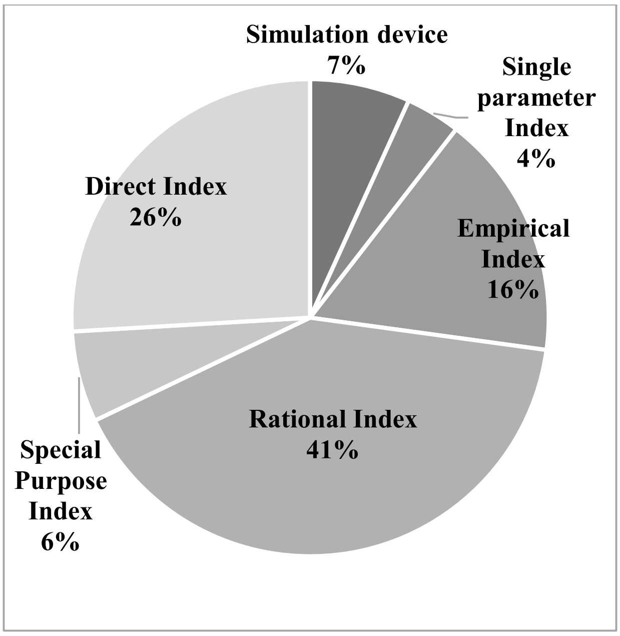

Fig. 2. Heat stress indices classification [13]

Table 3. The terms of the energy balance equation can be logically expressed as a function of the thermal comfort parameters [2]

Terms in the thermal balance equation	Comfort Parameters					
	M	Clo	T_a	V	MRT	RH
Metabolic power, M	●					
Mechanical power, W	●					
Respiratory convective heat loss, Cres,	●	●	●			
Respiratory evaporative heat loss, Eres	●					●
Convective heat loss, C		●	●	●		
Radiation heat loss, R		●			●	

6. Limitations of Heat Stress Indices

Heat stress indices can be divided into three groups:

1. Rational, based on energy balance equation
2. Empirical, based on objective and subjective strain
3. Direct, based on direct measurements of parameters.

Presently, no one single index can be used as universal valid index for all thermal environments. Many of these indices were developed for a specific use. It is thus the user's responsibility to examine each index and choose the one that best suits the defined thermal climate.

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

1. 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 75 ºF. Therefore, an engineer may have to work with more than one heat stress index if the environmental condition changes.

2. Inbuilt errors exist in some of these indices. Several indices (in particular 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 'Effective Temperature Index' scale in wind speed at high temperature [16].

3. Important factors such as acclimation (the process of becoming adjusted to an environment) cannot be included [6, 17]. In a given level of heat stress, heat strain experienced by an acclimated individual is different from a non-acclimated person. Many of the indices do not distinguish between acclimated and un-acclimated subjects in their application.

4. Brake & Bates [18] states 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.

5. Averaging method is not always physiologically valid. Many of the indices are developed based on thermal stress of the workers and averaging of large experimental data. Though, the reaction of the individuals to heat load can be modified by age, gender, etc. The response of a group of self-paced, acclimated workers to heat will differ from a group of non-acclimated, less experienced workers.

6. The validity and reliability of many indices are questionable. For example, Discomfort Index (DI) was developed as a simplified version of WBGT [16]. In the WBGT index, globe temperature (GT) measures the combined effect of radiant heat, air temperature, and air speed. DI does not take into account air speed by replacing GT with ambient temperature, which may cause significant error in evaluating some climatic conditions.

7. The primary purpose of evaluating climatic conditions is to assess the environment and re-design it so that to be to meet safety, health and comfort of workers [6]. None of the indices can take into account all the comfort determining factors and their interrelation. Therefore, the environment should be assessed on regular bases irrespective of the comprehensives of the applied index.

7. Selection Criteria

Thermal assessment of the underground mine environment, particularly in active areas, should be done routinely by ventilation engineers. The choice of an index for this purpose is of great importance and critical.

An index should be simple to use, accurate for moderate to hot climates and involve minimal manpower and instrumentation in measurements, calculations and interpretation of results.

The following criteria should be satisfied when an index is used for assessing thermal environment in underground mines:

1. Applicability in the chosen industry should be confirmed;
2. All major heat load contributing factors in mining conditions should be included;
3. Measurements, calculations and interpretation should be simple;
4. The included factors should have valid weight in relation to the total strain;
5. The index should be applicable for the purposes of mine climatic guidelines or limits [17, 18].

No existing index meets all these requirements. On the one hand, direct and empirical indices have relatively simple measurement and calculation procedures. They however do not encompass the physiological comfort parameters for evaluating total strain. This is because many of these indices are developed using statistical and simple mathematical methods and not upon the energy balance equation. On the other hand, rational indices may be more comprehensive and accurate compared with other types of indices. The problem is that the measurement and calculation procedures are complex and difficult to comprehend.

8. Comparison and Selection of Heat Stress Indices

Several research studies looked to assess, compare and select the most appropriate heat stress index for a particular application. These attempts can be grouped into comparison methods including:

(1) Experiment: Examination of acclimated and/or un-acclimated individuals in different range of activity and climatic conditions and study of physiological and behavioral responses of human body to hot-humid environments (e.g. [20, 21]).

(2) Comparison: Based on thermal comfort parameters (e.g. [8, 20]).

(3) Climatic data analysis: Analysis of climatic condition with assumed data or climatic databases as input parameters of (e.g. [21, 22]).

(4) Rational methods: Use of different rational methods to examine the accuracy and applicability of heat stress indices (e.g. [23, 24]).

There are other research projects and comparison methods not mentioned in this paper.

9. Summary and Discussion

As the increasingly mechanized underground mines in Northern Nevada become deeper, the issue of heat becomes a significant problem. Hot and humid environments can seriously affect the performance, overall productivity and most importantly the ability of the underground workforce to perform work in a safe manner. Therefore, thermal assessment of the underground mine environment, particularly in the active areas, should be performed regularly by ventilation engineers.

It is not practical to review and compare all the available indices based on the mentioned methods. Generally, we know that in underground mine environments, it is not practical to measure and collect a large number of physiological and human-related factors. A discussion shall be made to debate how accurate a heat stress index should be for the underground mine environments. An investigation of the accuracy of simple indices (e.g. mostly direct indices) may lead to a simple index which is at least precise in its range and accuracy.

The large number of available heat stress indices and shortcomings of current selection criteria would make it difficult to choose an applicable index. Many of the underground mines in the US and around the world choose an index while they are unaware of its limitations. The current criteria do not specify the use of standard instruments and their calibration procedures, which could be a significant source of error. The small size of the black globe (often less than the standard 150 mm) used in the measurement of GT is a typical example.

In the next stage of the NIOSH project, we are working on a new evaluation and selection method for the mining industry to make it easier to choose a heat stress index for thermal climatic assessments. A comprehensive but simple selection criterion seems to be necessary mainly for underground mining application.

Our goal is to define and recommend one or more indices that can effectively protect the underground workers in hot US mines. It will be difficult to suggest one index that can be used in the western US mines, only. Though, it can be a fairly acceptable guideline to show the performance and safeguard of these heat stress indices in various climatic conditions. Based on this principle, we can define heat stress indices for any type of climatic condition including the base and precious metal mines in USA.

So far, for the precious metal mines in western USA we selected 28 heat stress indices (10 direct indices, 8 empirical indices and 10 rational indices) for comparisons. In each particular index we have defined the parameters as well as the weight of each parameter based on model sensitivity. We are presently comparing these heat indices based on:

1. Weights of each parameter
2. Simplicity and applicability
3. Instrumentations and requirements
4. Validity of indices using maximum rate of sweating

By developing our comparison model, we can then compare any other index that contains thermal comfort parameter(s).

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