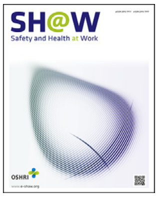
ARTICLE IN PRESS

Safety and Health at Work xxx (2017) 1–7

Contents lists available at ScienceDirect

Safety and Health at Work

journal homepage: www.e-shaw.org



Original Article

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

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ARTICLE INFO

Article history:
Received 19 January 2017
Received in revised form
6 March 2017
Accepted 5 April 2017
Available online xxx

Keywords:
climatic conditions
heat stress index
thermal comfort
underground mining

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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2093-7911/$ – see front matter
http://dx.doi.org/10.1016/j.shaw.2017.04.002

Please cite this article in press as: Roghanchi P, Kocsis KC, Challenges in Selecting an Appropriate Heat Stress Index to Protect Workers in Hot and Humid Underground Mines, Safety and Health at Work (2017), http://dx.doi.org/10.1016/j.shaw.2017.04.002

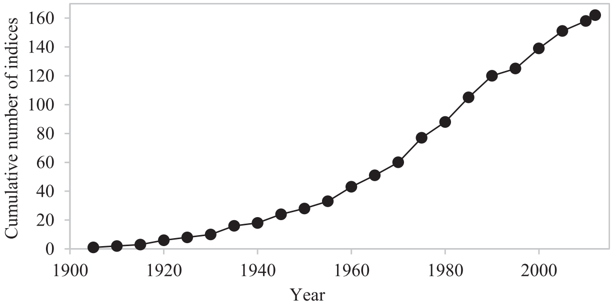

Fig. 1. Cumulative number of heat stress indices from 1905 to 2012.

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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