A review of heat stress evaluation indices in extremely hot environments

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Abstract. Selecting appropriate evaluation indices to evaluate extremely hot environments has become an urgent problem to ensure the safety of workers' lives and improve labor productivity. The objective of this review is to compare relevant evaluation indices for assessing heat stress and to analyze the more effective ones applicable to the industrial environment by considering each one together. Based on extensive research on existing literature and relevant international standards, this paper introduces the definitions of heat stress and its influencing factors. Based on the actual needs of workers, analyze the existing heat stress indices from a practical standpoint, and summarize the definitions, advantages, and limitations of each index. As a result, this paper emphasizes that the relevant thresholds of thermal indices should be appropriately adjusted to suit different industrial environments. The hazards of extreme work environments can be reduced by developing new indices, charts, or related strategies. This review will provide a solid theoretical foundation for environmental control schemes for harsh working situations.

1 Introduction

As the global average temperature keeps going up, exposure to extreme heat is becoming more prevalent, and the risk of heat stroke and even death among workers due to compound extreme heat has increased significantly, particularly in northern China [1]. Heat exposure disproportionately affects those working in construction, steel mills, mining, metallurgy, and other industries, with an increased risk of heat-related illness (HRI) and decreased labor productivity. It is estimated that the resulting global GDP loss will be $2 trillion per year by 2030 [2]. When individuals' core body temperature surpasses 38°C, the most typical symptoms are heat cramps, heat syncope, heat edema, and heat exhaustion. When the temperature reaches 40°C and above, there is a risk of classical heat stroke or exertional heat stroke [3]. An evaluation of the work environment is necessary to protect workers from heat-related illness and death at work.

In China, hot environments usually refer to a living environment with a temperature higher than 35°C or a production environment with a temperature higher than 32°C [4]. Thermal environments are generally classified into dry and humid environments, and working in humid conditions produces greater physiological stress than in dry conditions [5]. More than 100 metrics have been used to assess the work environment and the physiological stress response exhibited by a person to that environment. The shift from simple indices based on linear equations to complex indices using computer software and the refinement from a single variable to multiple variables plays a crucial role in protecting operators in extremely hot environments.

2 Methodologies

The objective of this paper is to review the relevant thermal indices for extreme thermal environments, analyze the definition, applicability, and limitations of the thermal indices applicable to the conditions, and provide guidance for the selection of appropriate heat stress and strain indices by describing the concepts and influencing factors associated with extremely hot environments. In this study, extensive literature and books were reviewed and efforts were made to establish clear relationships between the multiple factors influencing heat stress and the relevant thermal indices. Relevant industry journals, conference proceedings, and books were processed by collecting information through screening, reading, and organizing. The keywords searched include heat stress, heat strain, extremely hot environments, environmental indices, and influencing factors. The databases used in this paper include Web of Science, Google Scholar, Science Direct, PubMed. The search time deadline was March 2022 and articles unrelated to the topic were excluded.

3 Assessment of heat stress

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3.1 Heat stress and heat strain

Heat stress and heat strain are not to be confused and it is necessary to distinguish between them. The Occupational Safety and Health Agency (OSHA) defines heat stress as the sum of the heat acting on the body generated by the environment and the body's own factors, indicating the degree to which excess heat in the body cannot be radiated to the surrounding environment. It is primarily determined by four environmental factors (air temperature, relative humidity, airflow rate, radiant heat from the sun, and other heat sources) and two individual factors (thermal resistance of clothing and activity level), with temperature and relative humidity playing a significant role [6]. The index that reflects the intensity of the thermal environments on the human physiological response is called the heat stress index. It is chiefly used to measure the level of heat stress in the event of high-risk heat illness and heat injury.

However, heat stress reflects the physiological responses induced when acting on the heat stress to which the body is subjected [7], reflecting the level of heat produced by the body in response to the metabolic rate of physical activity and the measures compensated to maintain its own heat balance, such as vasodilation, increased heart rate, and increased sweating.

3.2 Factors affecting heat stress and heat strain

Factors influencing heat stress and heat strain indices when exposed to extreme working conditions are shown in Table 1. The table focuses on field measurements to explore which factors pose a risk to the health status of workers, analyzing the specific relationships between different factors and whether there are potential intrinsic links.

<table>
<thead>
<tr>
<th>Factors</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Environmental parameters</td>
<td>Dry globe temperature, black globe temperature, dew point temperature, relative humidity, air velocity, heat generated by solar radiation, and other heat sources</td>
</tr>
<tr>
<td>Individual parameters</td>
<td>Age, gender, race, body fat, heat acclimation, working time, health status, clothing, activity intensity, smoking, hydration, medications, alcohol intake</td>
</tr>
<tr>
<td>Physiological parameters</td>
<td>Systolic blood pressure, diastolic blood pressure, heart rate, skin temperature, body core temperature, water loss, blood oxygen saturation, alveolar oxygen partial pressure</td>
</tr>
</tbody>
</table>

3.3 Evaluation indices related to extremely hot environments

There are three general types of indicators for assessing the thermal environment, which is used to define, predict and assess the physiological strain response of the thermal environment on the human body: direct, theoretical, empirical, and indices [7].

3.3.1 Direct indices based on linear equations

The commonly used thermal indices for extremely hot operating conditions are shown in Table 2 and have been shown to correlate significantly with WBGT.

<table>
<thead>
<tr>
<th>Year</th>
<th>Index</th>
<th>Symbol</th>
<th>Formula</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957</td>
<td>Wet-bulb globe temperature</td>
<td>WBGT</td>
<td>Outdoor with solar radiation: WBGT = 0.7Ta + 0.2Tg + 0.1Tf Indoor or no solar radiation: WBGT = 0.7Ta + 0.3Tf</td>
<td>[12]</td>
</tr>
<tr>
<td>1957</td>
<td>Discomfort index</td>
<td>DI</td>
<td>0.4Ta + 0.4Tg + 8.3</td>
<td>[13]</td>
</tr>
<tr>
<td>1959</td>
<td>DI</td>
<td>0.5Ta + 0.5Tg</td>
<td>[14]</td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>Humidex</td>
<td>HD</td>
<td>Ta + 5.9 × (VP-10)</td>
<td>[15]</td>
</tr>
<tr>
<td>1984</td>
<td>Heat index</td>
<td>HI</td>
<td>−8.784695 + 1.61139411·Ta + 2.338549·RH − 0.14611605 · Ta − 1.2308094 · 10^{-3}·Ta^2 − 1.6424828 · 10^{-2}·RH^2 + 2.211732 · 10^{-1}·Ta · RH + 7.2546 · 10^{-6} · Ta · R^2</td>
<td>[16]</td>
</tr>
<tr>
<td>2001</td>
<td>Environmental stress index</td>
<td>ESI</td>
<td>0.63Ta + 0.03RH + 0.002SR + 0.0054 · (Ta · RH) − 0.073 · (0.1 + SR)^{-1}</td>
<td>[17]</td>
</tr>
</tbody>
</table>

(Note: Ta = wet bulb temperature (°C), Tg = black globe temperature (°C), Tf = dry bulb temperature (°C), RH = relative humidity (%), SR = solar radiation (W/m²), VP = 6.11 × 10^{0.0066·Ta[(237.7 + Ta) / 100]} × RH/100 (hPa))

WBGT has been recognized by the International Standards Organization (ISO) and is widely used in China, the US, and Japan. However, WBGT is relatively insensitive to wind speed and often underestimate the effect of wind speed. Therefore, WBGT is not suitable for assessing thermal environments with high wind speeds [18]. H.O. Ahmed et al. [19] concluded that the calculated WBGT index exceeds the threshold value specified by the standard and a supplementary assessment of HSI or TWL should be used. DI, HI and HD all depend on air temperature and relative humidity and are considered to be simpler and more direct indices than WBGT. However, HD cannot take into account factors such as radiation, metabolic heat, and airflow rate, and can be underestimated as a workplace hazard in extremely hot environments [20].

Researchers conducted real-time testing of indoor and outdoor construction sites and found that HI correlated more highly and reliably with WBGT than HD and that
HI could be used as a proxy for WBGT for extremely dry and hot areas [21].

ESI takes into account relative humidity, air temperature, and solar radiation and has been shown to be an alternative to WBGT for dry/hot/humid regions at different altitudes [17,22].

3.3.2 Theoretical indices based on the body heat balance equation

Thermal working limit (TWL) is calculated using the ‘TWL calculator’ based on the human body heat balance equation. The human body heat balance equation is [7]:

\[ S = (M - W) - (H_{res} + E + R + C + K) \text{ (W/m}^2\text{)} \]  

(1)

Where S represents body heat storage, which is the sum of heat production and heat loss; M-W represents total metabolic heat minus external mechanical work, when the body is at rest, the metabolic rate is 58W/m² (1met); K, C, R denote heat conduction, convection, and radiation heat exchange, respectively. E is sweat evaporation heat loss; and H_{res} is respiratory heat loss. S=0 means that the body is in thermal equilibrium. When S=0, the body produces greater heat and the body core temperature rises, and vice versa [23].

TWLs were widely used in the Australian underground mining industry and later extended to outdoor environments with radiant heat loads such as the construction industries. TWLs are generally used for workers who adjust their work schedule to their conditions to avoid heat stress [24].

The predicted heat strain (PHS) model allows the calculation of the maximum permissible exposure time in a short time by means of an iterative algorithm. It is this model that was applied by the international standard ISO 7933 to predict heat stress in workers in extremely hot environments, replacing the SW_{req} proposed in 1989. Lazaro et al. [25] conducted an experimental study on 10 Chinese male workers under different working conditions, and the measured skin and rectal temperatures were higher than the theoretical values based on the PHS model, overestimating the maximum permissible exposure time, and a correction to the PHS model is needed.

The standard effective temperature (SET) based on the two-node model not only measures heat exchange between the core and skin layers, as well as between the skin layer and the surrounding environment, but it also reflects thermoregulatory processes such as perspiration, vasodilation, contraction, and shivering. It has been included in ASHRAE Standard 55, both as an index of thermal comfort and for heat stress assessment in temperate regions. L. Ji et al.[26] proposed a new procedure for comparison between thermoregulatory models, using the root mean square error (RMSE) method to verify the accuracy of model combinations and to optimize the model constants. L. Ji et al. [27] investigated the elderly's reduced thermoregulatory activity and delay in generating thermoregulatory signals. The threshold and attenuation coefficients of thermoregulatory models were changed using numerical optimization to create a two-node physiological model appropriate to the elderly, but with limited prediction accuracy for skin temperature.

3.3.3 Empirical Indices

Universal thermal climate index (UTCI) is a tool for assessing heat stress based on a multi-node model and is defined as having a temperature equivalent to the human stress response in a real environment in a reference environment. It is commonly used in outdoor environments with low humidity and airflow rates [28]. This metric has been shown to correlate significantly with deep body temperature, skin temperature, and heart rate and has been applied in open-pit mines in Iran [29]. Conversely, in predicting the relationship between labor capacity and each of the heat stress indicators, the UTCI better predicted the labor capacity of subjects in the presence of wind (R² = 0.93) compared to WBGT [30]. ET is mathematically identical to the same perceived static saturated air temperature [31], which accounts for the influences of temperature, relative humidity, and wind speed, but tends to overstate heat stress owing to humidity overestimation as well as air flow rate underestimating. Later on, academics continued to update the ET, proposing CET, ET', SET, and other indices. It is primarily used to measure heat stress in an indoor environment.

3.4 ISO standards related to hot environments

In the ISO standards, there are three main indices applicable to the assessment of hot environments, they are ISO7243, ISO7933 and ISO9886. When WBGT exceeds the range specified in ISO7243, the heat stress can be further assessed based on ISO7793, and the predicted heat strain value can be calculated by the human body heat balance model. When assessing the individual or specific population in extremely hot environments. The pros and cons of hot environments standards can be found in Table 3[32–37].

<table>
<thead>
<tr>
<th>Standards</th>
<th>Indices</th>
<th>Details</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISO7243</td>
<td>WBGT</td>
<td>Heat stress levels in the human body and occupational exposure limits</td>
<td>Easy and convenient to obtain directly by measuring instruments</td>
<td>Requires 30 min to maintain stability, long measurement time; inaccurate dynamic environment measurement; unable to predict individual physiological state</td>
</tr>
<tr>
<td>ISO7933</td>
<td>PHS</td>
<td>Sweat rate, maximum permissible exposure time (D_{lim}), and prediction of heat strain</td>
<td>Taking into account environmental and personal factors</td>
<td>Complex calculation procedures and difficulty in measuring physiological parameters such as</td>
</tr>
</tbody>
</table>
4 Conclusion

For industrial buildings, WBGT is used in most countries and regions for indoor and outdoor environments as an indicator to assess heat stress and is simpler and more effective than other indicators. HD, HI and DI indicators can be used if it is difficult to measure the workplace in the thermal environment in which it is located. The PHS model is more advantageous when the physiological strain of a specific population needs to be investigated, but it is more complex for non-specialists to understand and will need to be further simplified in the future. ESI can be applied to dry hot/humid areas at different altitudes, HI is more suitable for dry and hot areas, TWL is generally used for self-paced workers, and SET takes into account more precisely the human physiological regulation mechanism and the heat exchange between the human body and its surroundings, and is more suitable for temperate regions. UTCI is more accurate in predicting the effects of wind on human physiological responses. ET index is more suitable for heat stress assessment in indoor environments.

Furthermore, the relevant standards applicable to hot environments and their applicable conditions are summarized to provide a reference basis for assessing the heat stress of workers in hot workplaces. It is a challenge to select a suitable indicator to assess heat stress because of the various climatic conditions in different regions and the different application ranges of the indices. This paper emphasizes that the relevant thresholds of thermal indices should be appropriately adjusted to suit different working environments according to local climatic characteristics. Many research scholars have found that other heat stress indicators can be combined to complement and achieve the prevention of heat-related disease risk in workers. In future research, heat stress indices applicable to actual hot workplaces can continue to be developed. It is also necessary to propose new methods and techniques for the general application of heat waves to the integrated effects of human physiology and psychology.

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References

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