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Study of heat stress and thermal environment in construction sites

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ABSTRACT

Heat stress is a recognized hazard for construction workers. To ensure safety and health of the workers, it is important to study the heat stress and thermal environment in construction sites, and develop practical solutions to avoid adverse health effects and accidents. In typical construction sites, the employees have to work long hours in thermally stressful environments, and with heavy physical workload, especially during summer time. As a result, they are at high risk and this may pose special hazards of heat stress. This research examines different kinds of heat stress indices and standards in the world. The result indicates that wet bulb globe temperature (WBGT) is a major factor affecting the level of heat stress because the rate of evaporation from human body is limited when WBGT increases. It is also found that some indexes provide little common agreement for the exposure limit and time; some can only be used for preliminary heat stress evaluation. In general, metabolic rate is the most difficult part to estimate in the heat stress equation for construction workers. It is concluded that engineering and administration method is the most effective way to control heat stress. Moreover, training and education for the employees are critical to preventing accidents in construction sites.

Keywords: Heat stress, thermal environment, construction sites, Hong Kong.

在建築地盤的熱應力和熱環境之研究

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摘要: 熱應力是公認危害建築工人的因素。為確保工人的安全和健康，研究建築地盤的熱應力和熱環境是很重要的，因為它可以幫助制定切實可行的解決方案，以避免影響健康和出現意外事故。在典型的建築地盤，僱員須長時間在緊張的熱環境和沉重的工作量下工作，尤其是在夏天。因此，他們在這樣高風險中，可能會帶來特殊的熱應力危害。本研究探討世界上不同類型的熱應力指標和標準。結果表明，暑熱壓力指數（濕球黑球溫度，WBGT）是一個主要因素影響熱壓力的程度，因為當人體的暑熱壓力指數增加，蒸發的速率是有限的。同時還發現，一些指標很少提供共同協議的接觸限值和時間;有的只能用於初步熱應力評估。一般情況下，代謝率是估計建築工人在熱應力方程的最困難的部分。結論是工程和管理方法是最有效的方法來控制熱應力。此外，培訓和教育員工是預防在建築地盤事故的關鍵所在。

關鍵詞: 熱應力，熱環境，建築地盤，香港。

1. Introduction

Heat stress is a recognized hazard for construction workers (CSAO, 2000; Hsu, *et al.*, 2008; Labour Department, 2007). Since Hong Kong's weather is very hot and humid, especially during summer, there are frequent reports of workers suffering from heat strokes or other heat related health effects (Labour Department, 2009; Leung, Yip and Yeung, 2008; Shafie, *et al.*, 2007). To ensure safety and health of the workers, it is important to study the heat stress and thermal environment in construction sites, and develop practical solutions to avoid adverse health effects and accidents.

In Hong Kong, large number of workers in construction sites have to work long hours in thermally stressful environments, and with heavy physical workload. They are at high risk and this may pose special hazards of heat stress (CSAO, 2000). It is necessary for the workers to adopt adequate preventive measures in order to control and limit the risk. Bernard and Cross (1999) have studied the heat stress for complex exposures in metal industries with aluminum smelters and developed guidelines for the heat stress management. Miller and Bates (2007) have evaluated the thermal work limit as a workable strategy for managing heat stress for the protection of workers in thermally stressful environments. Yoopat, *et al.* (2002) have assessed the thermal environment and physiological strain in tasks associated with airport, construction, and metal jobs in Thailand. There is an urgent need to develop a better understanding and an effective policy on heat stress management for construction workers in Hong Kong and other similar cities.

This research examines different kinds of heat stress indices and standards in the world so as to evaluate their characteristics, advantages and disadvantages. By studying the basic principles of heat stress and investigating the practical conditions at the construction sites in Hong Kong, it is possible to identify suitable methods for assessing the heat stress and thermal environment. It is hoped that the research findings can help people determine proper preventive and control measures.

2. Heat Stress Control Principles

According to OSHA (1999), heat stress is the general name of several medical conditions such as heat exhaustion, heat cramps and heat stroke. When the body is unable to cool itself by sweating, several heat-induced illnesses can occur, and can even result in death. In fact, the current understandings of the physiological effects of workers in thermally stressful environments were developed from a large number of significant laboratory and field studies (Beshir and Ramsey, 1988). But, assessing the thermal stress and expressing the stress in terms of physiological and psychological strain is complex (Epstein and Moran, 2006).

Usually heat stress is readily associated with high environmental temperatures and humidities (Leithead and Lind, 1964). Individual response of the workers in construction sites can be affected by environmental factors such as ambient temperature, air movement, relative humidity, radiant heat and so on. However, it is difficult to predict who will be suffering from heat stress because of the different personal risk factors like weight, age, physical condition, medical record, i.e. heart disease and high blood pressure.

In order to prevent heat stress to occur, it is necessary to evaluate the heat stress risk and formulate a safe and effective management system (Bernard and Cross, 1999; CSAO, 2000). Heat stress assessment should be carried out in order to consider and implement effective preventive measures. Appropriate environment control, administrative control and worker monitoring are essential for preventing accidents and reducing adverse health effects. Moreover, training and education for the employees is a key element to tackle the problem of heat stress so that they can fully understand what heat stress is, how it affects their health and safety, and how it can be prevented. It should be noted that it is the responsibility of both employee and employer to control the heat stress.

3. Heat Stress Indices

Heat stress indices can be categorized into three groups: “rational indices”, “empirical indices”, or “direct indices” (Epstein and Moran, 2006). The first two groups are sophisticated indices, which involve environmental and physiological variables. However, they are difficult to measure and calculate; it is not recommended for the daily use. The latter group comprise of simple indices, which are based on the measurement of basic environment variables. Table 1 shows a comparison of four common types of heat stress indices.

Table 1. Comparison of four heat stress indices

Index	Devised by	Merits	Limitations
Effective temperature scales [direct indices]	Houghton and Yaglou (1923)	- Good physiological index	- Error increase as environmental condition increase - Insufficient weight of low air movement in hot and humid environment
Wet bulb globe temperature (WBGT) [direct indices]	Yaglou and Minard (1957)	- Simplicity - Does not required extensive instrumentation - Good physiological index	- Requires careful evaluation of people's activity, clothing and many other factors
Predicted four-hour sweat rate (P_4SR)	McArdle, *et al.* (1947)	- No upper limit of the amount of heat stress - Good measure of physiological strain	- The longer expose, the lower accuracy result
Belding-Hatch index [rational indices]	Belding and Hatch (1955)	- Simplicity	- Less accuracy than P_4SR - Discrepancy of 40% total heat load

3.1 Effective Temperature Scales

The primary objective of using the effective temperature (ET) scale is to assess the subject comfort with the combined of wet bulb temperature, dry bulb temperature and the air velocity (Houghton and Yaglou, 1923).

$$ET = DBT - 0.4 \times (DBT - 10) \times (1 - RH) / 100 \quad (1)$$

where DBT = dry bulb temperature (℃) and RH= relative humidity (%)

In order to make allow for the radiant heat, corrected effective temperature (CET) can be used. CET is either found from the graphs or calculated from the following equations.

For normal: $$CET = (1.21\,GT - 0.21\,WBT) / [1 + 0.029\,(GT - WBT)] \quad (2)$$

For basic: $$CET = (0.944\,GT - 0.056\,WBT) / [1 + 0.022\,(GT - WBT)] \quad (3)$$

where GT = globe thermometer temperature (℃)
WBT = wet bulb temperature (℃)

3.2 Wet Bulb Globe Temperature

Wet bulb globe temperature (WBGT), devised by Yaglou and Minard (1957), is by far the most widely used heat stress index throughout the world. The advantage of using the WBGT is simplicity since it does not require additional instrumentation. WBGT can be calculated in the following manner.

(a) For outdoor conditions: WBGT = 0.2 GT + 0.1 DBT + 0.7 WBT (4)

(b) For indoor conditions: WBGT = 0.5 GT + 0.7 WBT (5)

where DBT = dry bulb temperature (°C)

WBGT can be assessed using a heat stress monitor (see Figure 1). The monitor will measure dry bulb temperature, wet bulb temperature, radiant heat and globe thermometer temperature to determine WBGT. Two important standards (ISO 7243 and ACGIH) are provided to evaluating the heat stress (ISO, 1989).

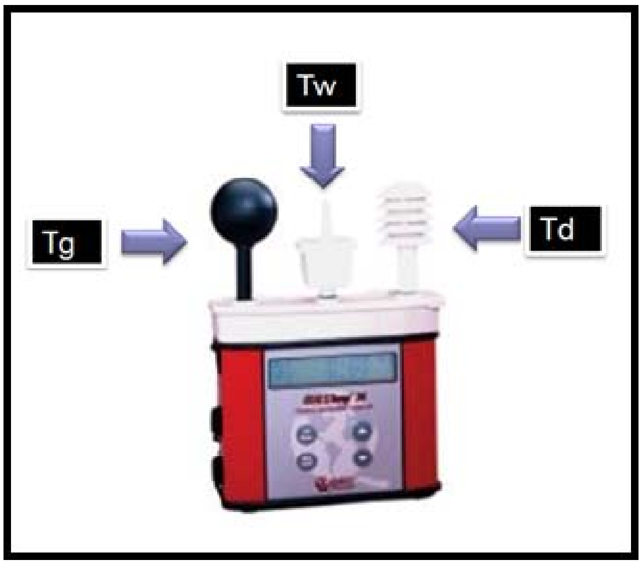

Figure 1. Heat stress monitor [Source: www.questtechnologies.com]

3.3 Predicted Four-hour Sweat Rate (P4SR)

Predicted four-hour sweat rate (P4SR) was devised empirically by McArdle *et al.* (1947) from the result of series experiment on young acclimatized naval ratings based on the amount of sweat produced in four hours. It applied to relatively wide ranges of combinations of DBT, WBT, GT, air movement, metabolic heat production and clothing. Leithead and Lind (1964) point out that the procedure of using P4SR is rather complicated, but a number of investigations have confirmed that the results of P4SR are quite accurate. There is an upper limit of sweat that can be produced. Once excess this limit, sweat rate will no longer be increased. The safe limit of P4SR for healthy and acclimatized young men is about 4.5 liters. For non-acclimatized men, the value of P4SR will be lower.

3.4 Belding-Hatch Index

Belding-Hatch index, or heat stress index (HSI), is defined as the ratio of evaporative cooling required for maintaining heat balance ($E_{reqired}$), to the maximum evaporative cooling possible (E_{max}) under the given conditions (Belding and Hatch, 1955).

$$HSI = (E_{reqired} / E_{max}) \times 100\% \quad (6)$$

This can be expressed as a function of metabolic rate, air and wall surface temperatures, air movement and vapour pressure (Auliciems and Szokolay, 2002). HSI indicates the level of heat stress, with a value of 100 being considered the maximum value that can be tolerated for working hours a day (say, 8 hours per day). The scale is thought to be reliable for still air between 27 ℃ and 35 ℃, 30-80% RH and for higher temperature with lower humidity.

4. Heat Stress Analyses

In construction sites, there are many occupations and they require different metabolic rate ranging from low to very heavy. To investigate the risk of heat stress, the site workers with heavy physical workload were taken. For example, concreter, bar bender and fixer, general welder, electrical fitter and carpenter were selected. The outdoor air temperature was assumed to vary between 25 ℃ and 35 ℃ to represent thermally stressful environments.

4.1 Metabolic Rates

Since the empirical indices (like ET and WBGT) do not consider the metabolic rate, a rational index, HSI, is used for the analysis here. Radiation and convection losses were found in order to calculate the required evaporation rate. The HSI was then determined by dividing the required evaporation rate by the maximum evaporate rate. Figure 2 shows the calculation results of HSI for different metabolic rates, from rest (65 $W.m^{-2}$) to very high (290 $W.m^{-2}$).

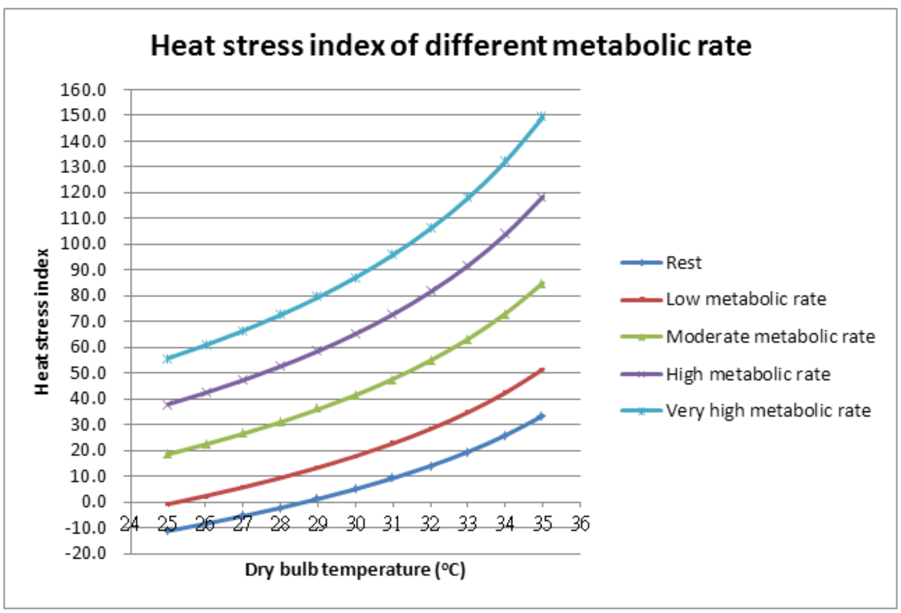

Figure 2. Heat stress index (HSI) calculated for different metabolic rates

From Figure 2, HSI does not indicate very stressful effect (HSI < 70) for all the metabolic rates when the outdoor DBT is not exceeding 28 ℃. As the curves show exponential grows, the HSI will increase dramatically when DBT increases beyond 28 ℃. Since some site workers like bar benders and fixers have heavy physical work (large metabolic rate), their risk of heat stress become very high when the DBT exceed 28 ℃.

4.2 Comparing Different Indices for Heat Stress

The characteristics of different indices for heat stress against DBT variation have been studied by setting GT equal to 32 ℃, WBT equal to 26 ℃, RH equal to 70% and wind speed equal to 1 m/s. Figure 3 shows the results for six types of indices: WBGT, CET, ET, operative temperature (OT), net effective temperature (NET) and equivalent temperature (EqT).

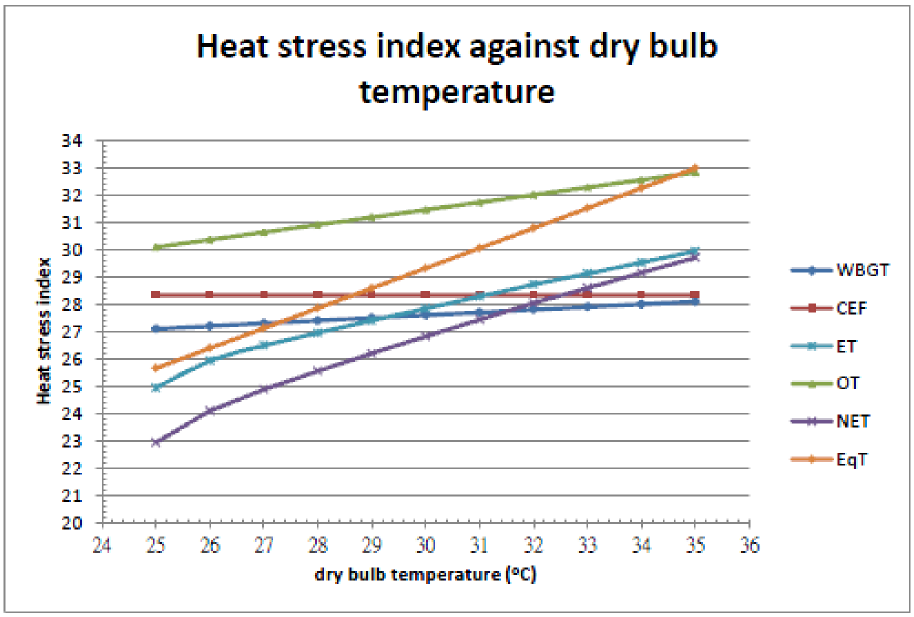

Figure 3. Characteristics of different indices for heat stress against DBT variation

From Figure 3, it can be seen that WBGT, OT, NET and EqT increase quickly when the DBT increases. As expected, CET and ET change very little when the DBT increases. The DBT is an important environmental factor because it can greatly affect the core temperature of the human body. Figures 4 and 5 shows the characteristics of different indices for heat stress against the variation of globe temperature (GT) and wind speed (WS), respectively.

The results in Figure 4 (the slope of the lines) indicate that GT is very influential to OT and EqT, but will not affect the other indices so much. As for Figure 5, the wind speed affects NET and EqT, very much but has no effect on the other four indices.

A summary of the overall characteristics of the six different indices for heat stress is given in Table 2. This information can help people understand better how to apply and evaluate the indices for heat stress analysis.

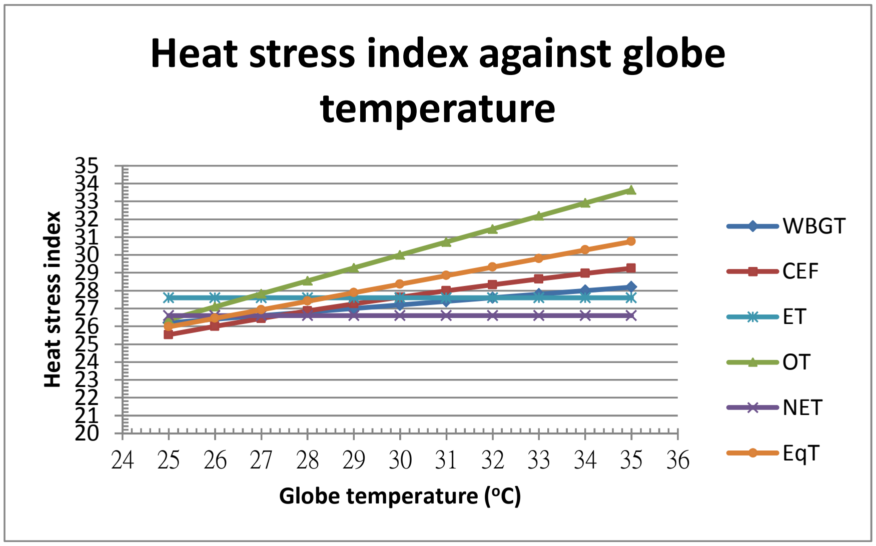

Figure 4. Characteristics of different indices for heat stress against GT variation

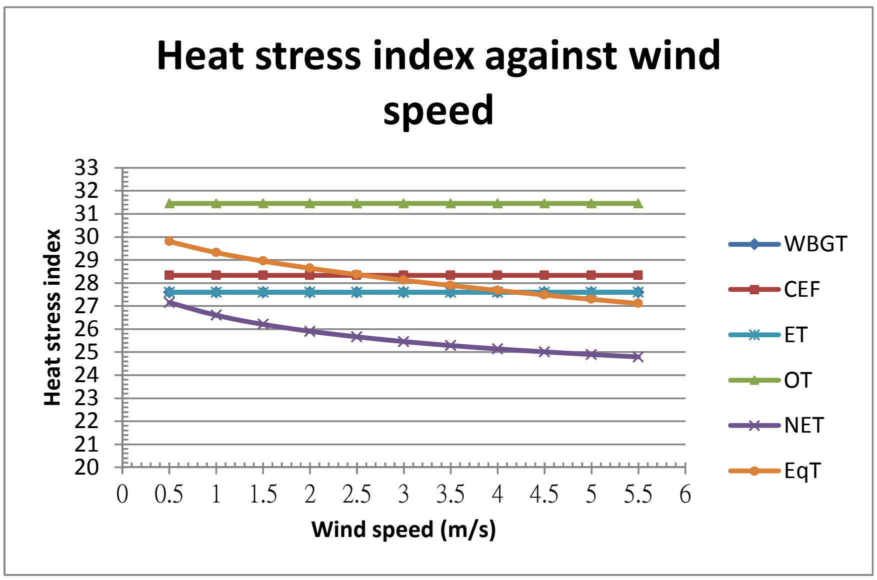

Figure 5. Characteristics of different indices for heat stress against wind speed variation

Table 2. Summary of the overall characteristics of the six different indices for heat stress

Indices	DBT	WBT	RH	GT	WS
WBGT	*	****	--	**	--
CET	*	***	--	***	--
ET	***	--	***	--	--
OT	**	--	--	****	--
NET	****	--	***	--	**
EqT	****	--	--	***	**

Note: DBT = Dry bulb temperature, WBT = Wet bulb temperature, RH = relative humidity, GT = Globe temperature, WS = Wind speed

* Change of Heat stress index 0-2

** Change of Heat stress index 2-4

*** Change of Heat stress index 4-6

**** Change of Heat stress index 6-8

5. Discussions

A number of heat stress indices were studied and compared in the previous sections. It is found that HSI and P4SR involve a number of different parameters and the evaluation procedure is complicated. Therefore, it is not recommended at this stage to adopt them for the assessment of heat stress in construction sites. The other indices which are less complicated can be considered. An analysis of thermal stress of climate in Hong Kong will be helpful to understand the practical situation and determine the proper strategy (Yan, 1997).

5.1 Very Hot Weather Warning

In Hong Kong, an operating procedure is used by the Hong Kong Observatory for alerting the public of stressful weather in order to prevent people from suffering heat stress (Chan, Lun and Pang, 2011; Li and Chan, 2000). The system called "Very hot weather warning" has been implemented since late 1997 in order to alert the public to take necessary precautions with the extreme temperature. The net effective temperature (NET) was chosen by the Hong Kong Observatory as one information for considering the issue of "Very hot weather warning". The NET is expressed as follows (where T is the ambient temperature). Usually, the highest NET occurs in the summer from May to September and the lowest NET is in winter.

$$NET = 37 - \frac{37 - T}{0.68 - 0.0014RH + \left(\frac{1}{1.76 + 1.4v^{0.75}}\right)} - 0.29T(1 - 0.01RH) \tag{7}$$

When Hong Kong was preparing and hosting the 2008 Olympic equestrian events, Hong Kong Observatory has carried out heat stress analysis and developed a measurement and warning scheme for the horses based on WBGT (Wong and Lee, 2008). It is believed that the approach from this scheme can also be applied to human being.

5.2 Suggestions for Hong Kong

ET and CET cannot reflect all the important factors of outdoor heat stress since it is designed mainly for the indoor condition and only includes two parameters. OT and EqT ignore the effect of the wet bulb temperature which affects the rate of sweating. Therefore it might underestimate the actual situation. As a result, WBGT is selected as the heat stress index for the construction sites. WBGT can be applied to assess both indoor and outdoor condition as it includes two equations to evaluate the difficult conditions (Bernard and Hanna, 1988).

The common standards for heat stress (ISO, 1989 & 2004) often set different exposure limits related to WBGT. It is necessary to find out suitable data for setting the limits in the Hong Kong's situation. In fact, the WBGT-index can be used for a fast diagnosis of hot environments like construction site. For a detailed analysis, the required sweating rate (SWreq) index is recommended because it is a comprehensive index based on ISO (2004).

6. Conclusions

Increasing concern about the risk of heat stress for workers and the simultaneous needs for evaluating the thermal environment in construction site make it necessary to set up some rules or provide some guideline for controlling and managing the heat stress. Different heat stress indices can be applied to meet the situation. In Hong Kong, the most suitable index at present is the WBGT as it was derived from the relative humid condition and the equation is easy to understand and apply.

Possible measure should be carrying out when excess the limit of the heat stress. Engineering and administration control is the most fast and efficiency way to control the heat stress. In the long run, a suitable health and training project should be provided for the workers in the construction site as education is the key to enhance the knowledge of heat stress for the workers so that they can know the early symptoms of the heat stress and the remedy measure can be done immediately.

The measures to manage heat stress in construction sites will not only ensure safety and health but will also enhance the productivity of the workers (Mohamed and Srinavin, 2005; Mohamed and Srinavin, 2002; Srinavin and Mohamed, 2003).

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