International Journal of Occupational Safety and Ergonomics

ISSN: 1080-3548 (Print) 2376-9130 (Online) Journal homepage: http://www.tandfonline.com/loi/tose20

The association between wet-bulb globe temperature and other thermal indices (DI, MDI, PMV, PPD, PHS, PSI and PSI_{hr}): a field study

Sajad Zare, Naser Hasheminejad, Mokhles Bateni, Mohammad Reza Baneshi, Hossein Elahi Shirvan & Rasoul Hemmatjo

To cite this article: Sajad Zare, Naser Hasheminejad, Mokhles Bateni, Mohammad Reza Baneshi, Hossein Elahi Shirvan & Rasoul Hemmatjo (2018): The association between wet-bulb globe temperature and other thermal indices (DI, MDI, PMV, PPD, PHS, PSI and PSI_{hr}): a field study, International Journal of Occupational Safety and Ergonomics, DOI: 10.1080/10803548.2018.1475957

To link to this article: https://doi.org/10.1080/10803548.2018.1475957

Published online: 11 Jul 2018.

International Journal of Occupational Safety and Ergonomics (JOSE), 2018
https://doi.org/10.1080/10803548.2018.1475957

The association between wet-bulb globe temperature and other thermal indices (DI, MDI, PMV, PPD, PHS, PSI and PSI_{hr}): a field study

Sajad Zare[a], Naser Hasheminejad[a], Mokhles Bateni[a], Mohammad Reza Baneshi[b], Hossein Elahi Shirvan[a] and Rasoul Hemmatjo[c]*

[a]*School of Public Health, Kerman University of Medical Sciences, Iran;* [b]*Institute for Future Studies in Health, Kerman University of Medical Sciences, Iran;* [c]*School of Public Health, Urmia University of Medical Sciences, Iran*

The current study aimed at comparing the correlation coefficients between wet-bulb globe temperature (WBGT) and a number of parameters, including the discomfort index (DI), modified discomfort index (MDI), predicted mean vote (PMV), predicted percentage of dissatisfaction (PPD), predicted heat strain (PHS), physiological strain index (PSI) and physiological strain index heart rate (PSI_{hr}). In total, 30 workers of a pelletizing factory participated in this study. Environmental parameters and workers' physiological parameters were measured in 10 working stations. The results showed that effective WBGT ($WBGT_{eff}$) strongly correlates with DI, MDI, PMV, PPD, PHS, PSI and PSI_{hr}. $WBGT_{eff}$ had the highest correlation coefficients with PMV, MDI, PHS and PSI_{hr}. Based on the obtained results, it was concluded that heat stress exceeded the standard limit for a number of indices in some of the working stations. Thus, some controlling measures should be taken to reduce heat stress in these stations.

Keywords: heat; thermal stress; thermal indices; dry temperature; wet-bulb globe temperature

1. Introduction

As a common phenomenon, many workers nowadays are exposed to hot working environments [1–4]. Exposure to heat and heat stress will have negative effects on individuals' health and will reduce their cognitive function and efficiency [5]. Because of human physiological limitations, exposure to excessive heat affects workers' performance and may threaten their health, leading to negative consequences like thermal fatigue, thermal cramp, heat stroke and heat rash [6,7]. Exposure to excessive heat also increases the amount of sweating [8], raises the likelihood of making work-related mistakes and accidents, and reduces the quality of duties performed by individuals. It is therefore crucial to pay close attention to workers who are exposed to heat [9]. Exposure to heat in Québec killed nine workers from 1983 to 2003 [10]. Heat stress, which is an interesting and complicated issue, is a natural stressor (unlike many other chemical and physical factors in the workplace) [11]. Human beings are warm-blooded living creatures that are capable of suitable adaptation while being exposed to heat [12]. Belding [13] argued that humans appropriately adapt themselves to heat, thus they can be classified as tropical creatures. In the past century, several indices were introduced to measure and/or predict thermal stress in hot environments [9]. There are nowadays over 60 known indices, with each of them having their own advantages and drawbacks [14]. When it comes to evaluating heat-related stress, three universal standards have been presented: (a) Standard No. ISO 7243:2017 [15] is used to monitor and control environments; (b) Standard No. ISO 7933:2004 [16] is utilized to assess the amount of heat exchange between the worker and the environment; (c) Standard No. ISO 9886:2004 [17] is exploited to monitor deep body temperature, skin temperature, heart rate and sweating. As a thermal stress index, the wet-bulb globe temperature (WBGT) is one of the simplest and most suitable procedures for assessing heat in various environments [18]. It is, however, relatively sensitive to air velocity. In addition, d'Ambrosio Alfano et al. [19] have recently reported some other flaws for this index.

Thermal comfort is defined as an individual's satisfaction with the thermal conditions in the workplace [20]. Some indices have been introduced to estimate thermal comfort, with all of them reporting a number which indicates the degree of dissatisfaction [21]. Some of these thermal comfort indices are the discomfort index (DI), modified discomfort index (MDI), predicted mean vote (PMV) and predicted percentage of dissatisfaction (PPD).

The DI, which was proposed by Thom [22], is calculated by the use of two environmental parameters, namely dry temperature and wet temperature. Sohar [23] modified this index in 1962. The MDI is the result of 80 years of

*Corresponding author. Email: r.hemmatjo@yahoo.com

modification on thermal indices and is calculated by taking dry temperature and wet temperature into account [24]. The PMV and PPD have also been introduced to report thermal comfort. The PMV, presented by Fanger in 1970 [25], is the most appropriate index for determining thermal comfort in environments with medium heat. The following six factors are taken into consideration in calculating this index: metabolism, clothing, environmental temperature, air velocity, relative humidity and average radiation temperature. The PPD was formulated based on the PMV and is used to assess the average heat sensation of a large group of people [26]. In order to avoid complication in using meteorological data and applying instruments inappropriately for calculating the effective WGBT ($WBGT_{eff}$), a modern thermal stress index, like predicted heat strain (PHS), can be utilized [27]. PHS, which is a rational index, is based on balanced body heat and sweat rate required to maintain a stable central temperature [28]. In hot environments, the human body has a response known as strain, which can be measured through physiological parameters [29]. Moran et al. [30] introduced the physiological strain index (PSI) to assess heat stress. It is the best known experimental index and measures physiological strain based on deep temperature and heart rate. A modified version of this index is the physiological strain index heart rate (PSI_{hr}), which is calculated by comparing variations in heart rate in working and resting conditions [31].

Pelletizing is an important industry in which workers are required to be exposed to a lot of heat sources in the working stations. Few studies have compared various thermal stress indices in such settings. The present study was designed to fill this lacuna in the literature by:

- determining environmental parameters of the workplace;
- assessing workers' physiological parameters;
- calculating $WBGT_{eff}$, DI, MDI, PMV, PPD, PHS, PSI and PSI_{hr};
- measuring the correlation between $WBGT_{eff}$ and environmental/physiological parameters;
- measuring the correlation between $WBGT_{eff}$ and thermal indices including DI, MDI, PMV, PPD, PHS, PSI and PSI_{hr}.

2. Materials and methods

2.1. *Research design*

The present study, which adopted a cross-sectional, descriptive-analytical design, was carried out in the summer of 2016. The participants came from a pelletizing factory located in the southeast of Iran. Environmental parameters of the workplace and participants' physiological parameters were measured in different stations along the furnace, with measurements being conducted on different days. Furthermore, based on workers' medical records, the selected participants were completely healthy and did not use any drugs. They were also non-smokers and were not infected by cardiovascular diseases.

2.2. *Participants*

The selected participants worked at the furnace of the pelletizing factory. The mean ± *SD* of their age, working experience and body mass index respectively was 4.05 ± 31.75 years, 31 ± 7 years and 25.26 ± 2.15. Furthermore, in line with Standard No. ISO 8996:2004 [32], the participants' metabolic rate was set at 90–140 W/m^2.

2.3. *Sampling procedure*

In order to study physiological parameters, random sampling was adopted for selecting participants:

$$N = \frac{(Z(1-(\alpha/2)) + Z(1-\beta))^2}{((1/2)\ln((1+r)/(1-r)))^2} + 3$$
$$N = \frac{(1.96 + 1.28)^2}{(0.69)^2} + 3 = 25, \quad (1)$$

where $Z = Z$ value; $\alpha =$ type 1 error; $\beta =$ type 2 error; $r =$ correlation coefficient; $N =$ sample size. According to Equation (1), 25 workers should be selected. However, in order to enhance the validity and reliability of the study, 30 participants were chosen.

2.4. *Measuring environmental parameters*

In order to measure environmental parameters including dry temperature, natural wet temperature, radiation temperature, relative humidity and dew point, a calibrated $WBGT_{eff}$ meter (model Casella-1232342; Casella, UK) was used. On the other hand, a Kipp and Zonen solar radiometer (model SR11-TR; Hukseflux, The Netherlands) and a thermo anemometer (model VT 50; Kimo, Canada) were respectively used to assess solar radiation and air velocity.

2.5. *Measuring physiological parameters*

Physiological parameters (i.e., heart rate and deep temperature) were measured in two phases through calibrated devices in line with Standard No. ISO 9886:2004 [17]. In the first phase, the workers rested for 30 h. Then, after 20 and 30 min, their physiological parameters including deep temperature (as indicated by tumble curtain temperature) and heart rate were assessed, followed by calculating the mean score of these two measurements. In the second phase, after 40 and 60 min of work in their corresponding stations, workers' physiological parameters were assessed and the mean scores of these two measurements were calculated. Heart rate was assessed using a Polar Sports Clock (model V800; Polar, Finland) and tumble curtain temperature was measured using a tympanic thermometer (model FT 78; Beurer, Germany).

2.6. Measuring heat stress indices

2.6.1. Wet-bulb globe temperature

The WBGT, commonly used to assess heat stress, was developed by the US navy [33]. According to Standard No. ISO 7243:2017 [34,35], $WBGT_{eff}$ is calculated based on measurements of natural wet temperature, radiation temperature and dry temperature. If the environment is heterogeneous and the heat load varies in different heights, it is necessary to measure $WBGT_{eff}$ at three heights: ankle, abdomen and heart [35]. The amount of metabolism for each occupation is calculated according to Standard No. ISO 8996:2004 [32]. Then, the weighted average time for the amount of metabolism for all responsibilities of each occupation is calculated.

2.6.2. Discomfort index

The DI was introduced by Thom in 1959 [22]. It is calculated based on two environmental parameters, namely dry temperature (T_a) and wet temperature (T_w) [2].

2.6.3. Modified discomfort index

Moran et al. [33] proposed the MDI in 1999. This index is calculated using wet temperature (T_w) and dry temperature (T_a).

2.6.4. Predicted mean vote

The PMV, which was suggested by Fanger in 1970 [25,29], is one of the main temperature-physiological indices which is frequently used in both urban and regional planning studies as well as meteorological research projects. This index is used to predict the collective perception of a group of individuals positioned in the same environmental condition. Six factors (i.e., dry temperature, mean radiation temperature, relative humidity, wind speed, metabolic rate and clothing insulation) are used to calculate the PMV. The value of this index is reported on a 7-point scale that ranges from −3 to +3, with 0 being the ideal value indicating neutral thermal perception. Ray Man version 1.2 is used to calculate the PMV.

2.6.5. Predicted percentage dissatisfied

The PPD predicts the percentage of the people who felt more than slightly warm or slightly cold (i.e., the percentage of the people who were inclined to complain about the environment). Using the 7-point scale of thermal sensation (−3 to +3) postulated by Fanger [25], all those who responded ±2 and ±3 were declared uncomfortable. Conversely, those who responded ±1 and 0 were declared comfortable. The percentages of subjects who responded ±2 and ±3 were determined for each class of PMV; that variable has been called the PPD.

2.6.6. Predicted heat strain

The PHS model can be considered a rational model, because it calculates heat exchange between the human body and environment [36]. The PHS index is based on the thermal balance equation which uses measured environmental parameters in a series of equations to predict the body response to the heat stress as a rise in core temperature. In this study, Malchaire Analysis version 2.4.12 was utilized to calculate PHS.

2.6.7. Physiological strain index

The PSI, which was introduced by Moran et al. [30], considers deep body temperature (T) and heart rate (HR) in the resting and working conditions. PSI values vary from 0 to 10, with 0 indicating lack of strain and 10 demonstrating the highest level of thermal strain.

2.6.8. Physiological strain index heart rate

The PSI_{hr} is calculated by considering variations of heart rate in the working and resting conditions. The PSI_{hr} ranges from 0 to 5, with 0 indicating lack of strain and 5 demonstrating the maximum level of thermal strain [14].

2.7. Statistical analysis

The collected data were analyzed by SPSS version 20 using statistical tests such as the Pearson correlation coefficient and linear regression.

2.8. Ethical considerations

Ethical approval was obtained from the Ethics Committee of Kerman University of Medical Sciences (ID: IR.KMU.REC.1395.43). All participants signed a consent form.

3. Results

3.1. Mean and standard deviation of environmental variables

Table 1 presents the mean and standard deviation values for the 30 environmental parameters in the 10 working stations. The highest dry temperature (T_a) and natural wet temperature (T_{nw}) were recorded at the beginning of side layer chute, while the highest $WBGT_{eff}$ was registered in the station of slide rail checking. Also, the greatest value of relative humidity (RH) belonged to the disk corridor. Conversely, the lowest dry temperature (T_a) and natural wet temperature (T_{nw}) were observed in the furnace chamber.

Table 1. Mean ± *SD* of environmental variables measured in the 10 working stations.

Measuring station	T_a (°C)	T_g (°C)	T_{nw} (°C)	RH (°C)	Dp (°C)	SR (w/m^2)	V (m/s)
Beginning of side layer chute	0.6 ± 43.8	0.8 ± 42.2	1.0 ± 29.1	0.4 ± 31.9	0.4 ± 23.5	0.0 ± 200.0	0.0 ± 1.0
Grate bar supply	0.8 ± 40.1	0.8 ± 42.3	1.2 ± 27.0	0.4 ± 34.7	0.4 ± 21.5	0.0 ± 200.0	0.0 ± 1.0
Burners	0.5 ± 39.5	0.8 ± 41.1	1.2 ± 27.1	0.4 ± 36.7	0.4 ± 22.1	0.0 ± 200.0	0.0 ± 1.0
Slide rail checking	0.8 ± 41.3	0.4 ± 43.8	0.8 ± 27.5	0.0 ± 34.2	0.0 ± 21.7	0.0 ± 200.0	0.0 ± 1.0
Furnace corridor	0.8 ± 39.0	0.8 ± 39.4	0.8 ± 25.2	0.0 ± 31.0	0.0 ± 18.0	0.0 ± 200.0	0.0 ± 1.0
Furnace chamber	0.7 ± 27.3	0.6 ± 27.1	0.4 ± 20.4	0.0 ± 48.6	0.0 ± 15.7	0.0 ± 200.0	0.0 ± 1.0
Disk corridor	0.4 ± 31.5	0.8 ± 31.9	0.8 ± 24.8	0.0 ± 53.3	0.0 ± 21.2	0.0 ± 200.0	0.0 ± 1.0
Rate feeder	0.8 ± 32.3	0.5 ± 33.7	0.8 ± 24.2	0.0 ± 49.2	0.0 ± 20.4	0.0 ± 200.0	0.0 ± 1.0
Mixer	0.7 ± 32.4	0.8 ± 34.2	0.8 ± 25.1	0.0 ± 53.6	0.0 ± 21.9	0.0 ± 200.0	0.0 ± 1.0
Raw pellets alley	0.8 ± 31.3	0.8 ± 33.5	0.8 ± 21.1	0.0 ± 32.9	0.0 ± 14.2	0.0 ± 800.0	2.1 ± 5.2

Note: Dp = dew point; RH = relative humidity; SR = solar radiation; T_a = dry temperature; T_g = radiation temperature; T_{nw} = natural wet temperature; V = velocity.

Table 2. Mean ± *SD* of physiological parameters and workers' metabolic rate in the 10 working stations ($N = 30$).

Measuring station	T_w (°C)	T_r (°C)	HR_w (bpm)	HR_r (bpm)	Metabolic rate (W/m^2)
Beginning of side layer chute	0.8 ± 38.2	0.4 ± 36.8	0.4 ± 131.3	0.8 ± 83.0	13.8 ± 140.0
Grate bar supply	0.8 ± 37.2	0.8 ± 37.0	0.9 ± 116.0	0.8 ± 74.0	12.1 ± 135.0
Burners	0.8 ± 38.0	0.8 ± 37.1	0.4 ± 120.0	0.4 ± 78.6	21.3 ± 132.5
Slide rail checking	0.8 ± 38.0	0.8 ± 37.0	0.4 ± 121.0	0.4 ± 80.6	19.7 ± 137.5
Furnace corridor	0.8 ± 37.8	0.8 ± 36.9	0.4 ± 109.6	0.4 ± 76.6	24.2 ± 110.0
Furnace chamber	0.8 ± 37.7	0.8 ± 37.0	0.4 ± 88.6	0.82 ± 73.0	8.5 ± 90.0
Disk corridor	0.8 ± 37.8	0.4 ± 37.3	0.4 ± 93.6	0.82 ± 80.0	16.9 ± 110.0
Rate feeder	0.8 ± 37.9	0.8 ± 36.9	0.4 ± 98.6	0.82 ± 71.0	28.1 ± 112.5
Mixer	0.8 ± 38.1	0.8 ± 37.1	0.8 ± 102.0	0.82 ± 82.0	11.6 ± 110.0
Raw pellets alley	0.8 ± 37.9	0.8 ± 37.0	0.8 ± 89.0	0.82 ± 69.0	15.9 ± 102.5

Note: HR_r = heart rate in the resting condition; HR_w = heart rate in the working condition; T_r = deep body temperature in the resting condition; T_w = deep body temperature in the working condition.

Additionally, the lowest RH value was recorded in the furnace corridor. The mean scores of environmental variables in various stations were significantly different from each other ($p < 0.001$).

3.2. *Mean and standard deviation of physiological parameters and workers' metabolic rate*

Table 2 presents the mean and standard deviation values for workers' physiological parameters and metabolic rates in various working stations. The highest deep body temperature (T_w), heart rate (HR_w) and metabolic rate were observed at the beginning of side layer chute. On the contrary, the lowest deep temperature (T_w), heart rate (HR_w) and metabolic rate were recorded in the furnace chamber.

3.3. *Mean scores for $WBGT_{eff}$, DI, MDI, PMV, PPD, PHS, PSI and PSI_{hr}*

According to Table 3, the highest values of $WBGT_{eff}$, DI, PMV and PSI were recorded at the beginning of side layer chute. But the greatest value of PHS was registered in the slide rail checking, while its lowest value was observed in the furnace chamber. Moreover, the mean scores of environmental variables in various stations were significantly different from each other ($p < 0.001$).

3.4. *The correlation between effective $WBGT_{eff}$ and environmental/physiological parameters and other indices*

Table 4 presents the correlation coefficients for the relationships between $WBGT_{eff}$ and environmental/physiological parameters. According to the obtained results, the strongest correlation belonged to the association between $WBGT_{eff}$ and natural wet temperature (T_{nw}) ($R = 0.96$). In contrast, $WBGT_{eff}$ had the weakest relationship with deep temperature in the resting condition (T_r) ($r = 0.06$). It should be noted that $WBGT_{eff}$ had a high slope coefficient with deep temperature in the working condition (T_w) ($a = 1.3$).

The results of Pearson correlation indicated that $WBGT_{eff}$ had a high correlation with other indices, with the strongest association being registered with the PMV ($r = 0.95$) (Table 4). However, the highest slope coefficient was recorded for the relationship between $WBGT_{eff}$ and PSI_{hr} ($a = 5.44$). It should be noted that the mean score of $WBGT_{eff}$ was significantly different from those of other indices ($p < 0.001$).

Table 3. Mean ± *SD* for $WBGT_{eff}$, DI, MDI, PMV, PPD, PHS, PSI and PSI_{hr}.

Measuring station	$WBGT_{eff}$	DI	MDI	PMV	PPD	PHS	PSI	PSI_{hr}
Beginning side layer chute	0.6 ± 33.2	1.6 ± 34.5	1.2 ± 34.0	0.21 ± 4.7	0.0 ± 100.0	12.4 ± 496.0	0.1 ± 4.8	0.1 ± 2.5
Grate bar supply	0.8 ± 31.8	0.4 ± 33.1	0.8 ± 32.5	0.21 ± 4.2	0.0 ± 100.0	15.4 ± 451.0	0.2 ± 3.8	0.0 ± 1.9
Burners	0.4 ± 31.9	0.4 ± 33.1	0.7 ± 32.5	0.05 ± 3.9	0.0 ± 100.0	10.8 ± 425.0	0.2 ± 4.1	0.0 ± 2.0
Slide rail checking	0.8 ± 32.6	0.4 ± 33.7	0.4 ± 32.3	0.4 ± 4.4	0.0 ± 100.0	6.2 ± 548.3	0.0 ± 4.0	0.1 ± 2.0
Furnace corridor	0.6 ± 29.2	1.2 ± 31.7	0.6 ± 30.7	0.09 ± 3.8	0.0 ± 100.0	6.2 ± 358.3	0.2 ± 3.3	0.1 ± 1.5
Furnace chamber	0.8 ± 22.1	4.8 ± 26.6	2.1 ± 25.2	0.00 ± 1.2	0.0 ± 35.0	6.2 ± 118.3	0.4 ± 2.4	0.0 ± 0.8
Disk corridor	0.8 ± 27.0	0.74 ± 28.3	0.8 ± 28.2	0.00 ± 2.3	0.0 ± 88.0	8.8 ± 199.9	0.0 ± 2.3	0.0 ± 0.7
Rate feeder	0.8 ± 27.1	1.1 ± 28.4	0.8 ± 27.8	0.00 ± 2.3	0.0 ± 88.0	8.1 ± 240.0	0.0 ± 3.1	0.1 ± 1.2
Mixer	0.8 ± 27.8	0.6 ± 29.6	0.8 ± 28.5	0.00 ± 2.4	0.0 ± 91.0	8.1 ± 250.0	0.0 ± 3.0	0.1 ± 1.1
Raw pellets alley	0.8 ± 24.6	0.8 ± 27.1	0.8 ± 25.2	0.05 ± 1.9	0.0 ± 72.0	8.1 ± 230.0	0.1 ± 2.8	0.1 ± 0.9

Note: DI = discomfort index; MDI = modified discomfort index; PHS = predicted heat strain; PMV = predicted mean vote; PPD = predicted percentage dissatisfied; PSI = physiological strain index; PSI_{hr} = physiological strain index heart rate; $WBGT_{eff}$ = effective wet-bulb globe temperature.

Table 4. Results of Pearson correlation coefficient investigating the relationship between $WBGT_{eff}$ and environmental/physiological parameters and other indices.

Environmental/physiological parameter	Correlation (*r*)	R^2 (%)	Slope	*p*
T_a	0.9	91.6	0.6	<0.001
T_g	0.9	9.0	0.6	<0.001
T_{nw}	0.9	92.7	1.2	<0.001
RH	0.5	27.9	–	<0.001
Dp	0.7	61.7	0.9	<0.001
SR	0.3	14.8	–	0.036
T_w	0.3	9.7	1.3	0.940
T_r	0.0	0.0	0.3	0.725
HR_w	0.9	88.7	0.2	<0.001
HR_r	0.6	37.2	0.4	<0.001
DI	0.8	72.6	0.9	<0.001
MDI	0.9	89.7	1.0	<0.001
PMV	0.9	91.1	2.8	<0.001
PPD	0.8	73.1	0.1	<0.001
PHS	0.9	88.6	0.0	<0.001
PSI	0.8	72.7	3.8	<0.001
PSI_{hr}	0.9	84.2	5.4	<0.001

Note: Dp = dew point; DI = discomfort index; HR_r = heart rate in the resting condition; HR_w = heart rate in the working condition; MDI = modified discomfort index; PHS = predicted heat strain; PMV = predicted mean vote; PPD = predicted percentage dissatisfied; PSI = physiological strain index; PSI_{hr} = physiological strain index heart rate; RH = relative humidity; SR = solar radiation; T_a = dry temperature; T_g = radiation temperature; T_{nw} = natural wet temperature; T_r = deep body temperature in the resting condition; T_w = deep body temperature in the working condition; $WBGT_{eff}$ = effective wet-bulb globe temperature.

Figure 1 shows the degree of correlation and regression line between $WBGT_{eff}$ and other indices including the DI, MDI, PMV and PPD.

Figure 2 illustrates the amount of correlation and regression line between $WBGT_{eff}$ and other indices including the PHS, PSI and PSI_{hr}.

4. Discussion

This study was conducted among 30 workers in a pelletizing company in southeast Iran. The aim was comparing the correlations between $WBGT_{eff}$ and the DI, MDI, PMV, PPD, PHS, PSI and PSI_{hr}. The results indicated that $WBGT_{eff}$ has a high correlation with some environmental parameters including dry temperature (T_a), ($r = 0.95$), radiation temperature (T_g) ($r = 0.95$) and natural wet temperature (T_{nw}) ($r = 0.96$). These strong correlations can be attributed to the parameters that are used to calculate $WBGT_{eff}$. Furthermore, $WBGT_{eff}$ had a high correlation with one of the physiological parameters, namely heart rate (HR_w) ($r = 0.94$).

The results further revealed that $WBGT_{eff}$ has a close connection with the DI, MDI, PMV, PPD, PHS, PSI and PSI_{hr}. The correlation coefficient between $WBGT_{eff}$ and

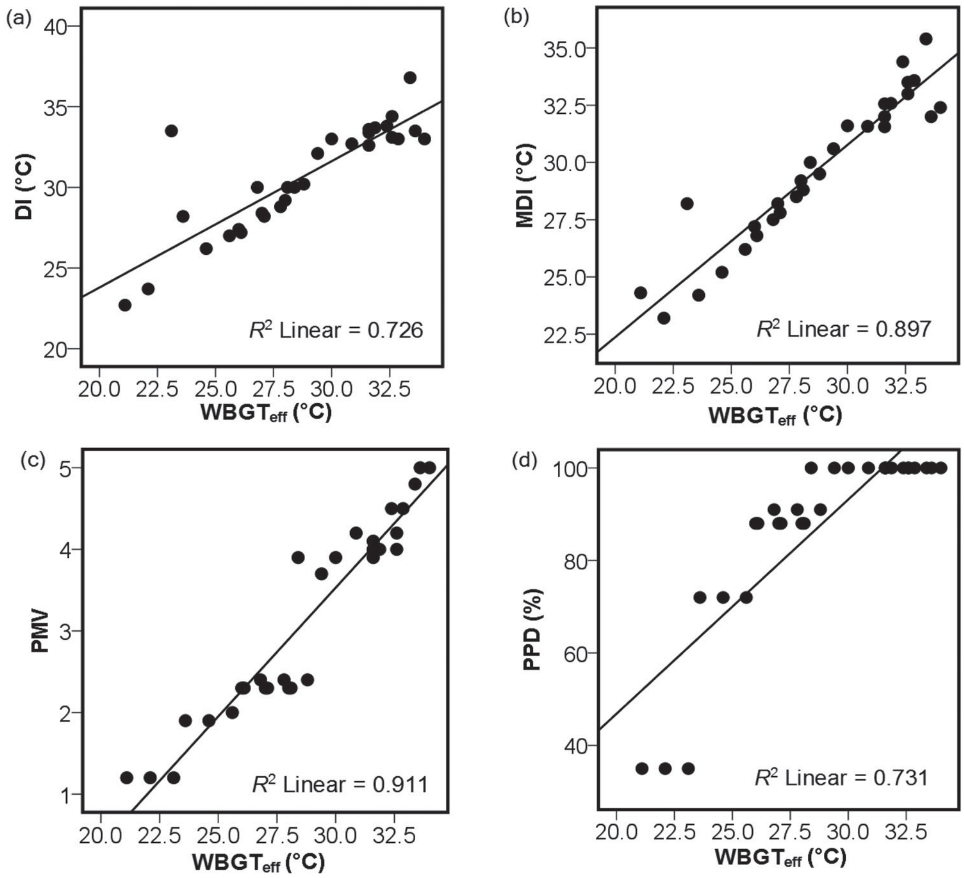

Figure 1. Degree of correlation and regression line between WBGT$_{eff}$ and other indices including (a) DI, (b) MDI, (c) PMV and (d) PPD.
Note: DI = discomfort index; MDI = modified discomfort index; PMV = predicted mean vote; PPD = predicted percentage dissatisfied; WBGT$_{eff}$ = effective wet-bulb globe temperature.

DI was 0.85. Epstein and Moran [2] also demonstrated a strong correlation between WBGT$_{eff}$ and the DI ($r = 0.95$). Similarly, Yang and Chan [37] reported a strong relationship between WBGT$_{eff}$ and the DI ($r = 0.84$) and MDI ($r = 0.79$). In the current study, a high correlation was also detected between WBGT$_{eff}$ and the MDI ($r = 0.94$).

The findings further showed strong correlations between WBGT$_{eff}$ and two other thermal comfort indices, i.e., PMV ($r = 0.95$) and PPD ($r = 0.85$). Kwon and Parsons [38] have also illustrated that WBGT$_{eff}$ is strongly connected with the PMV and PPD. Their findings are similar to our results.

The obtained results indicated that, based on Standard No. ISO 7243:2017 [35] for an adapted individual (28 °C), workers who perform their duties in several stations – at the beginning of side layer chute, under grate bar supply furnace, burners, slide rail checking and furnace corridor – are exposed to excessive heat stress, hence appropriate measures should be taken to reduce this stress (Table 3).

In recent years, some studies have made attempts to examine the correlation between WBGT$_{eff}$ and some physiological parameters. For example, Jafari et al. [39] reported correlation coefficients of 0.85 and 0.56 between WBGT$_{eff}$ and the PSI and PSI$_{hr}$, respectively. In the current study, higher correlation coefficients were observed between WBGT$_{eff}$ and the PSI ($r = 0.85$) and PSI$_{hr}$ ($r = 0.91$). Moreover, Golbabaie et al. [40] showed that the correlation coefficient between WBGT$_{eff}$ and the heart rate was 0.73. They argued that WBGT$_{eff}$ is an appropriate, applicable index for assessing heat in hot and humid environments. Also, Monazzam Esmaielpour et al. [41], who studied heat stress indices among workers, reported a correlation coefficient of 0.73 between WBGT$_{eff}$ and the heart rate. In our study, nonetheless, a stronger correlation was detected between WBGT$_{eff}$ and the heart rate ($r = 0.94$).

Brake and Bates [42] showed that deep temperature of people working in industrial and mining sectors increased during a workshift, exceeding the standard limit (38 °C). In the current study, it was observed that workers' deep temperature (T_w) was over the standard limit at the beginning of side layer chute and mixer.

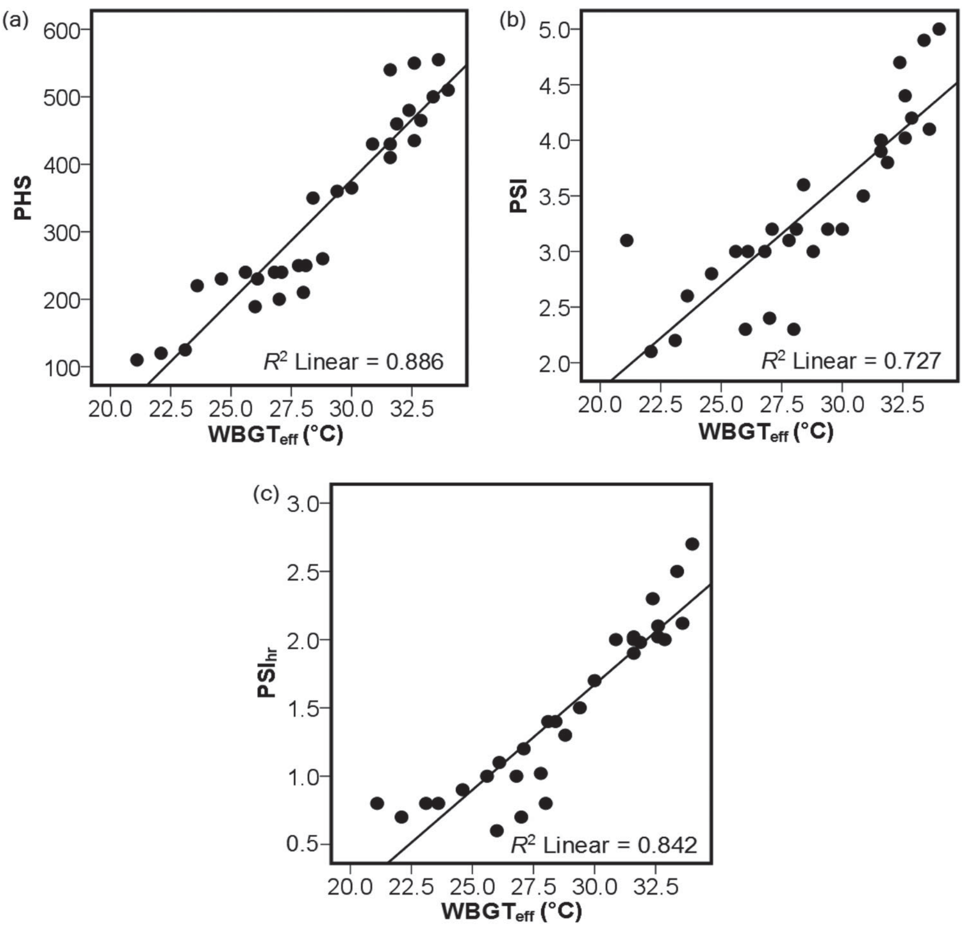

Figure 2. Degree of correlation and regression line between $WBGT_{eff}$ and other indices including (a) PHS, (b) PSI and (c) PSI_{hr}.
Note: PHS = predicted heat strain; PSI = physiological strain index; PSI_{hr} = physiological strain index heart rate; $WBGT_{eff}$ = effective wet-bulb globe temperature.

5. Conclusion

These findings indicate that values of $WBGT_{eff}$, DI, PMV and PSI were higher at the beginning of side layer chute. But the greatest value of the PHS was registered in the slide rail checking, while its lowest value was observed in the furnace chamber. Furthermore, the deep body temperature (T_w), heart rate (HR_w) and metabolic rate were higher at the beginning of side layer chute. The results also showed that $WBGT_{eff}$ had the highest correlation with the PMV, MDI, PHS and PSI_{hr}. On the other hand, the highest slope coefficient was recorded between $WBGT_{eff}$ and the PSI_{hr}. This shows that the PSI_{hr} has fewer variations compared to $WBGT_{eff}$ at different rates in various ranges of ambient conditions. Also, significant differences were observed between the mean score of $WBGT_{eff}$ with those of the DI, MDI, PMV, PPD, PHS, PSI and PSI_{hr} ($p < 0.050$). Therefore, these findings show that heat stress exceeds the standard limit in some working stations. Thus, some controlling measures should be taken to reduce heat stress in these stations.

Acknowledgements

The authors are deeply grateful for the support provided by this center and the research deputy of Kerman University of Medical Sciences.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The current study was the output of a research project (code number: 950061) which was financially supported by by the Kerman University of Medical Sciences.

ORCID

Mokhles Bateni http://orcid.org/0000-0002-9569-8821

References

[1] Lu S, Peng H, Gao P. A body characteristic index to evaluate the level of risk of heat strain for a group of workers

with a test. Int J Occup Saf Ergon. 2014;20(4):647–659. doi:10.1080/10803548.2014.11077074

[2] Epstein Y, Moran DS. Thermal comfort and the heat stress indices. Ind Health. 2006;44(3):388–398. doi:10.2486/indhealth.44.388

[3] Zare S, Hasheminejad N, Shirvan HE, et al. Comparing Universal Thermal Climate Index (UTCI) with selected thermal indices/environmental parameters during 12 months of the year. Weather Clim Extrem. 2018;19:49–57. doi:10.1016/j.wace.2018.01.004

[4] Hemmatjo R, Motamedzade M, Aliabadi M, et al. The effect of artificial smoke compound on physiological responses, cognitive functions and work performance during firefighting activities in a smoke-diving room: an intervention study. Int J Occup Saf Ergon. 2017:1–8. doi:10.1080/10803548.2017.1299995

[5] Hemmatjo R, Motamedzade M, Aliabadi M, et al. The effect of various hot environments on physiological responses and information processing performance following firefighting activities in a smoke-diving room. Saf Health Work. 2017;8(4):386–392. doi:10.1016/j.shaw.2017.02.003

[6] Golbabaei F, Zakerian SA, Dehaghi BF, et al. Heat stress and physical capacity: a case study of semi-professional footballers. Int J Public Health. 2014;43(3):355–361.

[7] Hansen E, Donohoe M. Health issues of migrant and seasonal farmworkers. J Health Care Poor Underserved. 2003;14(2):153–164. doi:10.1353/hpu.2010.0790

[8] Tang Y-M, Wang D-G, Li J, et al. Relationships between micronutrient losses in sweat and blood pressure among heat-exposed steelworkers. Ind Health. 2016;54(3):215–223. doi:10.2486/indhealth.2014-0225

[9] Yaglou C, Minaed D. Control of heat casualties at military training centers. Arch Ind Health. 1957;16(4):302–316.

[10] Bourbonnais R, Zayed J, Lévesque M, et al. Identification of workers exposed concomitantly to heat stress and chemicals. Ind Health. 2013;51(1):25–33. doi:10.2486/indhealth.2012-0095

[11] Hemmatjo R, Motamedzade M, Aliabadi M, et al. The effects of multiple firefighting activities on information processing and work performance in a smoke-diving room: an intervention study. Hum Factors Ergon Manuf. 2017;27(6):261–267. doi:10.1002/hfm.20709

[12] Sawka MN, Wenger CB, Pandolf KB. 1996. Thermoregulatory responses to acute exercise-heat stress and heat acclimation. In: Fregly M, Blatteis CM, editors. Handbook of Physiology, Section 4, Environmental Physiology. New York (NY): Oxford University Press, 1996 p. 157–185.

[13] Belding H, editor. Strains of exposure to heat. Standards for occupational exposures to hot environments, proceedings of symposium. Cincinnati (OH): NIOSH; 1976.

[14] Brake R, Bates G. A valid method for comparing rational and empirical heat stress indices. Ann Occup Hyg. 2002;46(2):165–174. doi:10.1093/annhyg/mef030

[15] Parsons K. Heat stress Standard ISO 7243 and its global application. Ind Health. 2006;44(3):368–379. doi:10.2486/indhealth.44.368

[16] d'Ambrosio Alfano FR, Palella BI, Riccio G. The role of measurement accuracy on the heat stress assessment according to ISO 7933: 2004. WIT Trans Biomed Health. 2007;11:115–124. doi:10.2495/EHR070131

[17] International Organization for Standardization (ISO). Ergonomics – evaluation of thermal strain by physiological measurements. Geneva; ISO; 2004. Standard No. ISO 9886:2004.

[18] Hemmatjo R, Zare S, Heydarabadi AB, et al. Investigation of heat stress in workplace for different work groups according to ISO 7243 standard in Mehr Petrochemical Complex, Assaluyeh, Iran. J Paramed Sci. 2013;4(2):108–112.

[19] d'Ambrosio Alfano FR, Malchaire J, Palella BI, et al. WBGT index revisited after 60 years of use. Ann Occup Hyg. 2014;58(8):955–970. doi:10.1093/annhyg/meu050

[20] Sunkpal MN. Assessing thermal comfort in deep underground mines [master's thesis]. Reno (NV): University of Nevada, Reno; 2015.

[21] Kralikova R, Sokolova H, Wessely E. Thermal environment evaluation according to indices in industrial workplaces. Procedia Eng. 2014;69:158–167. doi:10.1016/j.proeng.2014.02.216

[22] Thom EC. The discomfort index. Weatherwise. 1959;12(2): 57–61.

[23] Sohar E, Tennenbaum J, Robinson N. A. Comparison of the cumulative discomfort index (cum. di) and cumulative effective temperature (cum. et), as obtained by meteorological data. Biometeorology. 1962; 395–400.

[24] Haberley BJ. Human trials to evaluate thermal performance specifications for private bushfire shelters [master's thesis]. Sydney (NSW): University of Wollongong; 2013.

[25] Fanger PO. Thermal comfort. Analysis and applications in environmental engineering. Copenhagen: Danish Technical Press; 1970.

[26] International Organization for Standardization (ISO). Ergonomics of the thermal environment – analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria. Geneva: ISO; 2005. Standard No. ISO 7730:2005.

[27] Holmér I. Climate change and occupational heat stress: methods for assessment. Glob Health Action. 2010;3(1): 5719. doi:10.3402/gha.v3i0.5719

[28] International Organization for Standardization (ISO). Hot environments – analytical determination and interpretation of thermal stress using calculation of required sweat rate. Geneva: ISO; 2004. Standard No. ISO 7933:2004.

[29] Varley F. A study of heat stress exposures and interventions for mine rescue workers. Transactions. 2004;316:133–142.

[30] Moran DS, Shitzer A, Pandolf KB. A physiological strain index to evaluate heat stress. Am J Physiol. 1998;275(1 Pt 2):R129–R134. doi:10.1152/ajpregu.1998.275.1.R129

[31] Jafari MJ, Hoorfarasat G, Salehpour S, et al. [Comparison of correlation between wet bulb globe temperature, physiological strain index and physiological strain index based on heart rate with heart rate and tympanic temperature on workers in a glass factory]. Saf Promot Inj Prev (Tehran). 2014;2(1):55–64. Persian.

[32] International Organization for Standardization (ISO). Ergonomics of the thermal environment – determination of metabolic rate. Geneva: ISO; 2004. Standard No. ISO 8996:2004.

[33] Moran D, Shapiro Y, Epstein Y, et al. A modified discomfort index (MDI) as an alternative to the wet bulb globe temperature (WBGT). In: Hodgdon JA, Heaney JH, Buono MJ, editors. Proceedings of the 8th International Conference of Environmental Ergonomics: Environmental Ergonomics VIII; 1998; San Diego, CA. [Place unknown]: International Society for Environmental Ergonomics; 1999. p. 77–80.

[34] Parsons K. ISO standards on physical environments for worker performance and productivity. Ind Health. 2018;56(2):93–95. doi:10.2486/indhealth.56-93

[35] International Organization for Standardization (ISO). Hot environments: estimation of the heat stress on working man. Geneva: ISO; 2017. Standard No. ISO 7243:2017.

[36] Wang F, Gao C, Kuklane K, et al. Effects of various protective clothing and thermal environments on heat strain of unacclimated men: the PHS (predicted heat strain) model revisited. Ind Health. 2013;51(3):266–274. doi:10.2486/indhealth.2012-0073

[37] Yang Y,Chan AP-c. Role of work uniform in alleviating perceptual strain among construction workers. Ind Health. 2017;55(1):76–86. doi:10.2486/indhealth.2016-0023

[38] Kwon J, Parsons K. Heat and cold stress indices for people exposed to our changing climate. In: Yoo SD, editor. EKC2008 Proceedings of the EU–Korea Conference on Science and Technology; 2008 Aug 28–31; Heidelberg. Berlin: Springer; 2008. p. 467–476.

[39] Jafari MJ, Assilian Mahabadi H, Khodakarim S, et al. Heat stress in an open-pit iron ore mine and its relationship with physiological strain. Health Saf Work. 2016;6(4): 51–62.

[40] Golbabaie F, Monazam Esmaieli MR, Hemmatjou R, et al. [Comparing the heat stress (DI, WBGT, SW) indices and the men physiological parameters in hot and humid environment]. Iran J Health Environ. 2012;5(2):245–252. Persian.

[41] Monazzam Esmaielpour M, Golbabaei F, Khodayari F, et al. Survey of the productivity loss due to heat stress in different tasks of farmers in Darreh Shahr city. Health Saf Work. 2015;5(3):63–74.

[42] Brake DJ, Bates GP. Deep body core temperatures in industrial workers under thermal stress. J Occup Environ Med. 2002;44(2):125–135. doi:10.1097/00043764-200202000-00007