2008-5435/14/63-26-32
INTERNATIONAL JOURNAL OF OCCUPATIONAL HYGIENE

IJOH 9: 26-32, 2017

ORIGINAL ARTICLE

Validity of Thermal Comfort Indices Based on Human Physiological Responses in Typical Open Pit Mines

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Received January 07, 2017; Revised January 29, 2017; Accepted February 21, 2017

This paper is available on-line at *http://ijoh.tums.ac.ir*

ABSTRACT

Working in hot environments is one of the common hazards in the workplaces, which can cause heat-related illnesses, affect workers' health and increase a risk of occupational injuries and accidents. The aim of this study was to assess and compare thermal comfort indices of humidex, Discomfort Index (DI), and ET with physiological responses in the open-pit mines in Tehran Province, Iran. This cross-sectional study was conducted in summer 2016 on 175 male workers in 12 construction materials mines in Tehran Province, Iran. Environmental and physiological parameters were measured simultaneously at three periods and thermal indices were determined as well. In this study, correlation coefficients of indices at different times of day were analyzed. Data were analyzed using SPSS 18 software and Pearson correlation. There was high correlation between thermal comfort indices with each other. All three indices used in this study had an appropriate relationship with core body temperature. Oral temperature had a greater correlation coefficient with thermal indices compared to the tympanic membrane temperature and skin temperature. Humidex had a high correlation coefficient with environmental parameters and physiological responses. The Humidex index is more valid than ET and DI indices. Humidex, among the studied indices, despite being simple, lack of need for sophisticated equipment to measure, low cost and easy interpretation can be used in open-pit mining.

KEYWORDS: *Heat stress, Thermal comfort indices, Physiological parameters, Open-pit mines*

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INTRODUCTION

Thermal comfort is defined as the absence of discomfort in the workers' environment, implying the condition when someone is not feeling either too hot or too cold. A number of factors have a substantial impact on the thermal comfort of an occupant's environment, so can be divided into personal and environmental factors. Personal factors include clothing, personal activity, and condition. Environmental factors comprise thermal radiation, temperature, air velocity and humidity [1].

The indicator of human thermal comfort is in principle called the thermal comfort index. A thermal comfort index method uses a model that provides a single number that represents the degree of discomfort caused by an environment. The model is based on research and integrates the relevant factors of the environment (temperatures, airflows, humidity, etc.) Surrounding a person in a way representing the comfort response of the person [2].

Some number of comfort indices for example Effective Temperature (ET), Heat index (HI), Discomfort Index (DI) and Humidex index have been deliberated and considered for the design of comfort in the mining environment. In this study, humidex, DI and ET indices were used[1].

Humidex is short for humidity index [3]. It is a temperature and humidity index, and one of the widely used experimental indices, which at first was recommended to use for both outdoor and indoor environments but studies indicated that this index is more appropriate for outdoor environments and the results obtained from analyzing the index in indoor environments are less than actual value. The index was developed at first in Canada and it was one of the heat indices used by meteorological organization to determine the presence or absence of heat stress and thermal comfort in a region and inform the public. This index combines the effect of temperature and humidity and weather feels of the average of persons will be described [4].

DI subsequent modification calculated with natural wet-bulb and dry-bulb temperatures does not include a consideration of radiant heat loading (globe temperature) but relies only upon the wet- and dry-bulb temperatures. However, a greater weighting is given to dry air temperature in an attempt to offset the absence of globe temperature. DI has high correlation coefficients with the effective temperature and sweating rate during rest and activity [5]. A number of studies investigated DI on diverse populations in different climatic conditions and development of this index was proposed to evaluate heat stress.

A strong correlation has been observed between the DI and wet-bulb globe temperature index in studies [5]. This index could simply calculate based on daily measured parameters in stations of meteorological agency[6].

Effective temperature index was developed based on measurements of environmental parameters in order to estimate the thermal strain. Effective temperature index was introduced at first to determine the relative effects of air temperature and humidity on the comfort of individuals and then was introduced as a heat stress index. This index expresses the feeling of warmth that is equal to how saturated environment and almost static air feels. Air velocity, in this case, is 0.12 m/s. The index is a compilation of dry-bulb temperature, wet-bulb temperature and air velocity [7].

Since the outdoor jobs are commonly contractual, they are not covered by occupational health. Hence, in occupational health, it is necessary and undeniable to note the outdoor workers satisfaction and health, assessment of complications and adverse effects caused by heat, monitoring, and evaluation of possible heat stress in these individuals and worker's awareness about heat disorder as well as actions for prevention and control strategy [8]. Therefore, the first step in the prevention and management policies is to assess the risk of exposure to heat and identify employees exposed to heat. Several indicators have been presented to evaluate thermal comfort, but each of them has their own advantages and disadvantages. In this study, humidex, DI and ET indices were used to evaluate thermal comfort. On the other hand, the correlation of tympanic temperature and oral temperature with rectal temperature has been evaluated and approved in several studies and they have been introduced as an alternative for rectal temperatures in the cases that direct measurement of rectal temperature is not possible [3]. Moreover, the skin temperature is an important physiological parameter for the assessment of thermal comfort in a working man[1].

In this study, the tympanic temperature, oral temperature, and skin temperature were used as physiological responses.

MATERIALS AND METHODS

According to the climatic characteristics of different cities in Tehran Province, Iran and regarding climatic conditions prevailing in these areas in summer, construction materials open-pit mines were selected in three cities of Pakdasht, Ghods, and Damavand as the study areas to evaluate the thermal indices in summer 2016. Regarding the distribution of open-pit mines and cooperation of industry and mining organizations in every city, six mines from Pakdasht City, three mines from Damavand City, and three mines from Ghods City were selected.

Published online: March 28, 2017

In selecting the subjects, several parameters were considered such as heat adaptation, no history of cardiovascular disease, kidney disease, high blood pressure, fever and no medication taking. People with a history of less than one year of work experience in outdoor environments were excluded from the study. In total, 175 employees in mentioned three cities and three professional duties were selected and then included in the study. Written informed consent was received from all participants.

Environmental parameters including dry-bulb and natural wet-bulb temperatures using TIS10 device made in Iran, and relative humidity using TES1363 device made in Taiwan at three-hour intervals at 9, 12 and 15 o'clock were measured and recorded in the workstations of individuals. Relevant institutions confirmed calibration of all measurement devices before sampling. Overall, 594 environmental measures were recorded.

According to the measured environmental parameters, three indices of humidex, DI, and ET were calculated based on equations of 1, 2 and 3 respectively.

Humidex index is calculated from the following equation1. The index value is in the range from 20 °C to 54 °C (Table1)[4].

(Equation 1):

$$\text{Humidex} = T_{\text{air}} + 0.5555\left[6.11e^{5417.7530\left(\frac{1}{273.16}-\frac{1}{T_{\text{dew}}}\right)} - 10\right]$$

T_{air}=is the air temperature in °C
T_{dew}= is the dewpoint in °K

Table 1. Limit values and ranges of the Humidex index corresponding to rising thermal discomfort conditions[4]

Humidex range	Thermal discomfort level
29≤ hum≤ 20	Comfort
39≤ hum≤ 30	Some discomfort
45≤ hum≤ 40	Great discomfort, avoid exertion
54< hum≤ 46	Dangerous
<54	Heat stroke imminent

DI is calculated by Equation 2. Where, Tw and Ta are Mean values of wet and dry temperatures, respectively[6].

(Equation 2)

$$DI=0.5Tw+0.5Ta$$

Table 2. Recommended values for discomfort index[5]

DI values	Description
< 22	No heat stress is encountered
22-24	Most people feel a mild sensation of heat
24-28	The heat load is moderately heavy, people feel very hot, and physical work may be performed with some difficulties
>28	The heat load is considered severe, and people engaged in physical work are at increased risk for heat illnesses

Effective Temperature (ET) calculated by the following equation 3 [7].

(Equation 3):

$$ET = Ta - 0.4 \times (Ta - 10) \times \left(1 - \frac{RH}{100}\right)$$

T_a =air temperature (°C)
RH =relative humidity (%)

Table 3. Recommended values for effective temperature index [9].

Effective temperature (°C)	Description
<20	Cold
20-23.5	Comfort and relatively Standard
23.5-25	Thermal comfort zone
25-30	Lower thermal comfort zone
30-35	No thermal comfort zone
35-40	Discomfort
40-41.5	Severe discomfort

Simultaneously with measuring the environmental parameters, physiological parameters of oral temperature and tympanic temperature as the core body temperatures and the skin temperature were measured. The oral temperature was measured via a sublingual digital thermometer (Beurer model, Germany) with an accuracy of 0.1, and tympanic temperature was measured using a non-contact thermometer (Micro Life IR 120 model, China) with an accuracy of 0.1 °C in the range of 30-50 °C.The skin temperature was measured using a non-contact infrared thermometer (Manoli model, China).

Skin temperature was measured in four points of the body surface (ISO 9886, 4 points method) during the work and then means skin temperature was calculated in term of degree of centigrade as follows [10].

Mean skin temperature = (Right scapula .28) + (Neck .28)+ (Right shin .28) +(Left hand 0.16) (Equation 4)

To measure the tympanic membrane temperature, all measurements were conventionally performed in the right ear.

All factors such as earwax removal before measurement, straighten the ear canal by hand and the lack of using hearing protection device in measurement day was considered to measure correctly the tympanic membrane temperature.

In order to perform measurements, thermometer was first disinfected and then placed under the tongue close to bottom and the individual was asked to keep the mouth closed during measurement. Thermometer should be placed in the mouth for at least 5 min before the reading result; 15 min before the measurement, taking any kind of food, beverage and tobacco should be prevented.

Overall, 1575 measurements were recorded considering the number of individuals (n=175), number of measurements for variables per day (3 times) and 3 measured physiological parameters.

RESULTS

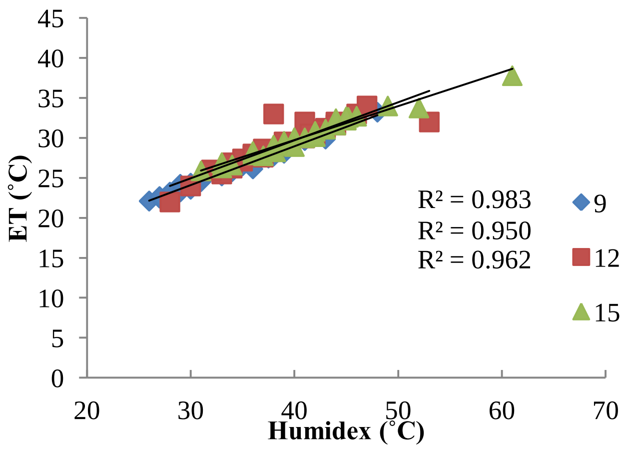
Demographic characteristics of the study population including means and standard deviation of age and work experience were respectively determined 36.8 ± 9.36 and 6.61 ± 5 yr. The mean metabolic rate was categorized in moderate metabolism range (264.2 to 313.33 watts) in accordance with the standard ISO-8996 2004. On the other hand, the thermal insulation of clothes was determined (0.79 ± 0.11 Clo) (0.58-1.12) in accordance with the standard ISO-9920 2007. The mean and standard deviation of other parameters such as environmental parameters, physiological parameters and thermal comfort indices in three measurement times have been presented in Table 4.

Table 4. Measurement results of environmental, physiological parameters and Thermal indices in three-measurement time

Variable	9 AM	12 PM	15 PM	M±SD
Environmental factors				
Dry-bulb temperature (ºC)	33.34±3.9	38.74±2.8	41±3.6	37.7±4.7
Natural wet bulb temperature (ºC)	20.71±2.7	22.27±2.7	23.12±2.45	22±2.32
Relative humidity (%)	20.57±7.7	13.73±6.4	12.5±6.3	15.6±7.2
Dew point (ºC)	6.82±6.5	5.24±7.7	5.55±8	5.87±6.2
physiological parameters				
Oral temperature (ºC)	36.26±0.47	36.4±0.55	36.5±0.47	36.37±0.37
Tympanic temperature (°C)	35.51±1.1	36.2±0.82	36.55±0.68	36.1±0.67
Mean skin temperature(°C)	34.7±1.6	35.46±1.5	35.9±1.3	35.35±1.24
Thermal indices				
HUMIDEX(°C)	33.76±5.3	38.6±5.5	41±6	37.8±5.4
DI(°C)	27.02±3	30.5±2.6	32.05±2.8	29.9±2.7
ET(°C)	25.9±2.6	28.85±2.2	30.16±2.6	28.3±2.75

The correlations between the indices at different hours of the day were studied (Fig. 1). A very good correlation has been seen at different times of day. The highest correlation coefficient among the indices was related to the early and middle hours (9 to 12). Humidex has shown the greatest correlation coefficients with all environmental parameters (wet-bulb temperature, dry-bulb temperature, dew-point temperature and relative humidity) (Table 5). On the other hand, Humidex had the highest correlation coefficient with oral temperature, skin temperature, and tympanic membrane temperature.

The results of Humidex index analyses indicated 63% relatively discomfort zone, 27.9% severe discomfort zone with avoiding activities and 9.1% dangerous zone. The analysis of DI index results indicated that 78.9% of measurements showed a severe heat load, and people involved in physical labor were at increased risk of heat illness. 92.2% of the measurements revealed discomfort at higher than 24 °C. Concerning of ET index measurements, the results showed 13.1% thermal comfort zone, 56.6% lower comfort zone and 30.3% no thermal discomfort.



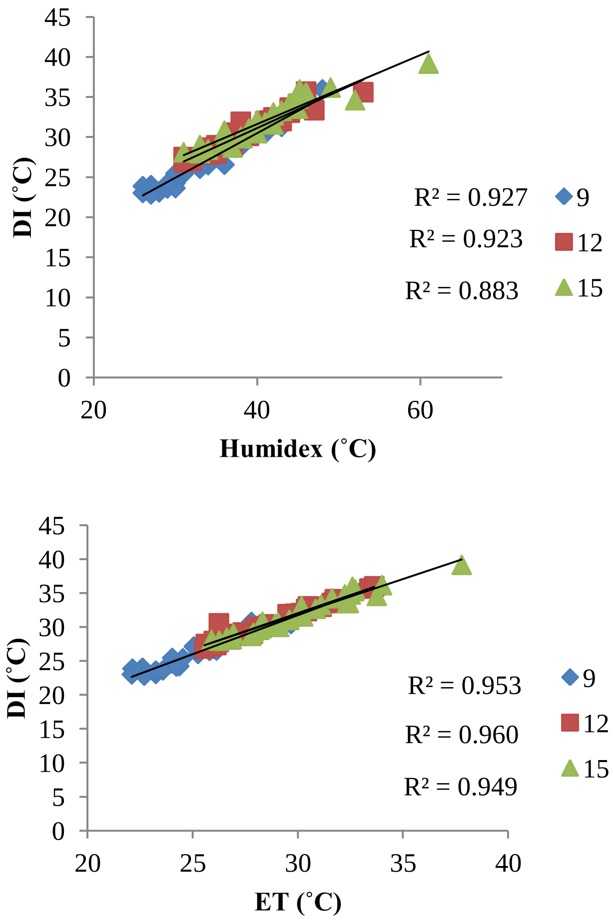


Fig.1. The correlations between the indices at different hours of the day

Table 5. Relationship between the environmental, physiological parameters and the Thermal indices

	Variable	**HUMIDEX** (ºC)	**DI** (ºC)	**ET** (ºC)
	Environmental factors			
Dry-bulb temperature (ºC)	R	0.921	0.915	0.890
	P-value	0.001	0.001	0.001
Natural wet bulb temperature (ºC)	R	0.924	0.905	0.750
	P-value	0.001	0.001	0.001
Relative humidity (%)	R	0.400	0.319	0.300
	P-value	0.001	0.011	0.018
Dew point (ºC)	R	0.800	0.710	0.740
	P-value	0.001	0.001	0.001
	physiological parameters			
Oral temperature (ºC)	R	0.560	0.514	0.478
	P-value	0.001	0.001	0.001
Tympanic temperature (°C)	R	0.477	0.477	0.438
	P-value	0.001	0.001	0.001
Mean skin temperature(°C)	R	0.450	0.416	0.315
	P-value	0.001	0.001	0.012
	thermal comfort indices			
HUMIDEX(°C)	R	1.000	0.954	0.980
	P-value	0.001	0.001	0.001
DI(°C)	R	0.954	1.000	0.895
	P-value	0.001	0.001	0.001
ET(°C)	R	0.980	0.895	1.000
	P-value	0.001	0.001	0.001

Published online: March 28, 2017

DISCUSSION

One of the most basic steps in assessment of the risk of exposure to heat stress understands the thermal conditions and identification of risk, performed by valid heat stress indices.

The analysis of DI index results indicated that 78.9% of measurements showed severe heat load, and people involved in physical labor were at increased risk of heat illness. 92.2% of the measurements indicated discomfort at higher than 24 °C.

The results of study in the spring and summer seasons in the nine climatic zones throughout IRAN showed that the DI was different in various seasons and climatic zones (P<0.001). Besides, based on the recommended values of discomfort index, 28.8% of the measurements in the spring indicated no discomfort. On the contrary, 76.4% of the measured values in the summer season showed a serve heat load and persons engaged in physical labor were at increased risk of heat-related illness. Regardless of the season, 76.4% of the measured values showed discomfort level of over 24 °C[6].

In summer 2007, in the Athena city were investigated the mortality by analysis of four factors including discomfort index, heat load Index (HL) index, Actual Sensation Vote and Thermal Sensation-Ginovi method. The results revealed very high levels of DI and HL indexes, indicating extreme heat stress during the last ten days of June and July [11].

DI index is easy to interpret and explain the thermal comfort. Meteorological Organization parameter can be used to calculate this index. Some studies were used DIto assess thermal comfort and heat stress [5-6].

In the case of ET index, the measurements results showed 13.1% thermal comfort zone, 56.6% low thermal comfort zone and 30.3% thermal discomfort zone. Analysis of the results of Humidex measurements demonstrated 63% relatively discomfort zone, 27.9% severe discomfort zone with avoiding activities and 9.1% dangerous zone.

Indices used in this study were analyzed by correlation coefficient at different times of the day. According to Fig. 1, very good correlation coefficient has obtained in all cases at different times of day. Based on the results presented in Table 5, Humidex has shown the highest correlation coefficient with environmental parameters (Natural wet bulb temperature, dry-bulb temperature, dew-point temperature and relative humidity). On the other hand, Humidex has the highest correlation with oral temperature (r=0.56), tympanic membrane (r=0.477) and skin temperature (r=0.450).

Although Humidex was firstly used to predict the weather but because it is convenient and simple to use and does not need complicated devices to measure, so its application was considered in assessing the heat stress in indoor and outdoor environments. Investigating the mortality rate in Italy was concluded that high prevalence of mortality is associated with high levels of humidex [12]. The results of Santee's study showed very good correlation between predicted rectal temperature and Humidex index [13-14].

Humidex in moderate thermal conditions provides a better assessment to estimate thermal conditions of environment. The correlation between Humidex and WBGT was obtained very high in both desert and semi-desert regions, while Humidex showed a moderate correlation with tympanic temperature [3]. Regardless of the climate, Humidex could use as a substitute for WBGT in the studied range of temperature and humidity and it is consistent with the tympanic temperature as a physiological response to heat stress, which is consistent with the findings of the present study.

In another study, was done in oil terminals in southern regions of Iran, evaluation of heat stress using WBGT, ET, and CET" demonstrated that the mean and standard deviation of the indices in outdoor environments were obtained respectively 29.76±3.51, 28.03 ± 4 and 29.36 ± 3.51. All three indices used in this study have a good and appropriate correlation with core body temperature [15].

The highest correlation among physiological parameters and heat indices were respectively related to oral temperature (r=0.476, -0.56), tympanic membrane temperature (r=0.438, -0.477) and skin temperature (r=0.315, -0.450). All three indices used in this study have a good and appropriate correlation with core body temperature. Several indices were studied such as rectal temperature, tympanic temperature, sublingual temperature, heart rate, heart rate recovery, and physiological strain index in two sets of clothes. Among the mentioned indices, tympanic temperature and the sublingual temperature could be used as the best indices for evaluating the heat strain in the workplace [16]. A significant relationship between heat stress index and sublingual temperature were indicated in workers [15-16].

CONCLUSION

All three indices used in this study had a good and appropriate correlation with the core body temperature. There was the maximum correlation between Thermal comfort indices and oral temperature. Humidex indicated a high correlation with environmental parameters and physiological responses. The Humidex index is

Published online: March 28, 2017

more valid than ET and DI indices. Humidex, among the studied indices, despite being simple, lack of need for sophisticated equipment to measure, low cost and easy interpretation can be used in open-pit mining.

ACKNOWLEDGEMENTS

This research has been supported by Institute for Environmental Research (Grant No.94-01- 46-28540).The authors declare that there is no conflict of interests.

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Published online: March 28, 2017