Analyzing Heat Stress Among Metal Casting Workers Using Selected Thermal Indices: A Pilot Study During Winter Climatic Conditions

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Abstract Excessive hot environments are usually widespread in metal casting industries, where higher ambient temperature and radiant heat exposure could impose subsequent suppression on workers' well-being and negatively impacts the work productivity. The six main agents of thermal stress include four environmental factors (air temperature, radiant temperature, air velocity, and relative humidity) and two personal factors (metabolic rate and clothing worn), which influence the heat exchange mechanism between the worker and its surroundings. The present study aimed to analyze the thermal exposure level in different work sections of the metal casting industry during the winter climatic conditions. Three different widely used thermal indices, i.e., wet bulb globe temperature (WBGT), tropical summer index (TSI), and discomfort index (DI), have been utilized to evaluate the heat stress exposure level under distinct foundry work sections. Further, descriptive and inferential statistics have been used to analyze the evaluated parameters. Results revealed higher thermal exposure levels associated with the furnace and molding work sections as compared to fettling and CNC machining sections. Although, during the selected time period, heat indices were not exceeding the threshold limit values (TLVs) under the respective work sections.

Keywords Work environment · Casting workers · Thermal indices · Exposure assessment

1 Introduction

Metal casting workers are exposed to harsh work conditions due to the high heat industrial work environment and subjected to intensive physical workload, which imposes significant thermal stress on the workers' health [1]. There are several environmental factors (air temperature, relative humidity, air velocity, and radiation) and

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personal factors (clothing worn and muscular activity), which affect the thermal ambience of a person [2]. In foundries, there are various work activities such as high heat furnace work operations, metal pouring and molding tasks, fettling operations, and manual material handling, which require a higher level of physical work activity [3]. A hot work environment imposes thermal stress, which causes thermophysiological effects on the workers' bodies (such as a rise in core body temperature, heart rate, and increased sweating) [1]. India is a diverse country with extreme climatic conditions ranging from tropical and subtropical regions, and there is a huge unorganized sector [4]. Most of India's north and northeast regions are subjected to humid subtropical climates, whereas a humid and hotter tropical climate is found in Southern India. Climatic zones like tropical and subtropical regions with higher air temperature and humidity values may cause greater risks of heat-related illness and safety threats to workers employed in developing countries with low and medium incomes [5, 6]. In developing countries like India, fewer resources are available on the combined effect of workplace heat exposure and climatic conditions [7]. Extreme hot environments are usually widespread in foundries, iron and steel industries, and several other industrial work sectors. A prolonged period of heat exposure with a poor work environment will affect the production level, and at the same time, it will negatively impact the workers' performance [8, 9].

For assessing heat stress, several indices have been developed over the past century, including the environmental factors and personal factors or a combination of both. Heat stress indices can be divided into three different categories, i.e., rational indices (based on the heat exchange equation), empirical indices (relating to objective and subjective strain), and direct indices (involving direct measurements) [10]. The present study research question was to assess whether the foundry indoor industrial heat stress exposure levels exceed the permissible limits/threshold limit values (TLVs) during the winter climatic conditions. So, the present study aimed to assess the environmental parameters followed by evaluating the heat stress exposures levels under distinct foundry work locations during the winter climatic conditions; to have better insights into the indoor workplace heat exposure experienced by the workers engaged in several foundry work activities. Further, descriptive and inferential statistical analysis has also been performed for the evaluated parameters.

2 Work Methodology

In the present study, three widely used heat stress indices have been considered to evaluate the heat stress exposure level under indoor industrial work conditions during the last month of the winter season (February 2021) in two different foundry units located in Ambala, India. The environmental measurements were monitored using Kestrel 5400 Heat stress tracker Pro (Nielsen-Kellerman Co.; USA) placed on a tripod at 1.1 m floor surface height as per ISO 7243 standard [11]. The equipment was allowed to stabilize for a minimum of 15 min, after which the monitored readings were considered for evaluation purposes. The environmental variables were

Fig. 1 Monitored work sections (furnace, molding, fettling, and CNC machining)

monitored during the afternoon time period (1:00 PM–3:30 PM) under four different work sections, i.e., fettling, molding, furnace, and CNC machining, as depicted in Fig. 1. From the monitored variables, respective heat stress indices were evaluated to analyze the associated risk exposure levels. Further descriptive and inferential statistics have also been performed on the evaluated variables.

2.1 Considered Heat Stress Indices

Wet bulb globe temperature (WBGT): WBGT is an empirical index; which is a widely used and validated heat stress index [11], for assessing hot work environments considering the combined effects of air temperature, humidity, air velocity, and radiation by measuring natural wet bulb temperature (T_{nw}), dry bulb temperature (T_a), and radiant effects using globe temperature (T_g) for both indoor and outdoor work conditions.

For indoor work environment;

$$\text{WBGT} = 0.7T_{nw} + 0.3T_g \tag{1}$$

For outdoor environment;

$$\mathrm{WBGT} = 0.7T_{\mathrm{nw}} + 0.2T_{\mathrm{g}} + 0.1T_{\mathrm{a}} \tag{2}$$

Tropical summer index (TSI): TSI, based on the Indian climatic conditions, gives an equivalent temperature of still air at a constant relative humidity of 50%, which provides a similar thermal sensation experienced by a user as the actual environment under consideration [12]. It is expressed by a mathematical relation as shown in Eq. (3):

$$\mathrm{TSI} = 0.308 * T_{\mathrm{wb}} + 0.745 * T_{\mathrm{g}} - 2.06\sqrt{V_{\mathrm{ar}} + 0.841} \tag{3}$$

where T_{wb} is the wet bulb temperature (°C), T_{g} is globe temperature (°C), and V_{ar} is airspeed (m/s).

Discomfort index (DI): The development of a direct indices tool called the "discomfort index" based on wet bulb temperature (T_{wb}) and dry bulb temperature (T_{db}) with some correction factor relates to the thermal degree of discomfort perceived by the user in a work environment [13].

$$\mathrm{DI} = 0.5(T_{\mathrm{db}} + T_{\mathrm{wb}}) \tag{4}$$

where T_{d} = dry bulb temperature (°C) and T_{w} = wet bulb temperature (°C)

3 Results and Discussion

3.1 Environmental and Individual Variables

During field visits and manual observations, the clothing insulation values (in "clo"; 1 clo equals to 0.155 m^2 C/W) varied between 0.7 clo and 0.91 clo (based on the observed clothing worn by employed workers and recommended ISO 9920 standard [14]). Further, ISO 8996 standard provides information about the metabolic rate (in W/m^2) based on the physical work activities [15, 16]. Based on the ISO 8996 guidelines, the metabolic rate for workers employed in a high heat work environment like casting industries was classified as follows; fettling: 190 W/m^2, molding: 165 W/m^2, furnace work: 135 W/m^2, and CNC: 100 W/m^2. The monitored environmental variables (relative humidity, dry bulb temperature, globe temperature, wind speed, and natural wet bulb temperature) under different work sections were analyzed using statistical analysis to draw logical conclusions. Tables 1 and 2 depict the descriptive statistics results for the monitored environmental variables. It was observed that furnace and molding sections were exposed to higher ambient temperatures than fettling and CNC machining work sections. At the same time, higher RH values were

Table 1 Monitored environmental parameters (mean (SD)) in foundry work sections

Parameters	Relative humidity (%)	Air temp. (in Celsius)	Globe temp. (in Celsius)	Air velocity (in m/s)	Natural wet bulb temp. (in Celsius)
Work-section					
Fettling	**40.61** (1.112)	**31.29** (0.233)	**31.35** (0.404)	**0.220** (0.239)	**22.01** (0.218)
Furnace	**36.40** (0.932)	**32.89** (0.217)	**36.28** (0.742)	**1.615** (3.771)	**21.25** (0.403)
Molding	**37.46** (0.987)	**32.66** (0.267)	**33.26** (0.117)	**0.154** (0.172)	**22.47** (0.283)
CNC	**40.30** (1.437)	**30.48** (0.869)	**30.08** (0.521)	**0.077** (0.129)	**21.36** (0.402)

The average values of the monitored variables have been presented in bold

Table 2 Range values for monitored environmental parameters

Parameters	Relative humidity (%)	Air temp. (in Celsius)	Globe temp. (in Celsius)	Air velocity (in m/s)	Natural wet bulb temp. (in Celsius)
Work-section					
Fettling	38.1–42.9	30.7–31.7	30.2–32.1	0.05–1.2	21.6–22.5
Furnace	35.0–39.4	31.4–33.3	33.6–37.3	0.05–29.5	20.5–22.2
Molding	36.2–39.0	32.1–33.1	33.0–33.5	0.05–0.7	21.9–22.9
CNC	38.2–42.5	28.9–31.6	29.5–31.7	0.05–1.0	20.8–22

accountable to the fettling and CNC section compared to the furnace and molding sections. However, the highest values of globe temperature were observed under the furnace work section followed by molding section; due to the radiant heat exposure. Air velocity was found to be higher under the furnace section due to the heavy-duty pedestal fan installed near the furnace zone. The least value of air velocity was observed under the CNC work section. Figure 2 shows the variation among monitored variables (mean values) under the different work sections.

3.2 Evaluated Heat Stress Indices

From the analyzed variables, considered heat stress indices (i.e., WBGT, TSI, and DI) were evaluated as given in Tables 3 and 4. Higher values of heat stress indices were observed under the furnace and molding sections as compared to other work sections; with least values accountable to the CNC section. During the selected time period (winter season), fewer variations were observed under the distinct work sections, and also, the indices values were not exceeding the permissible limits. Figure 3 depicts the bar graphs, comparing evaluated heat stress indices mean values under the four distinct work sections.

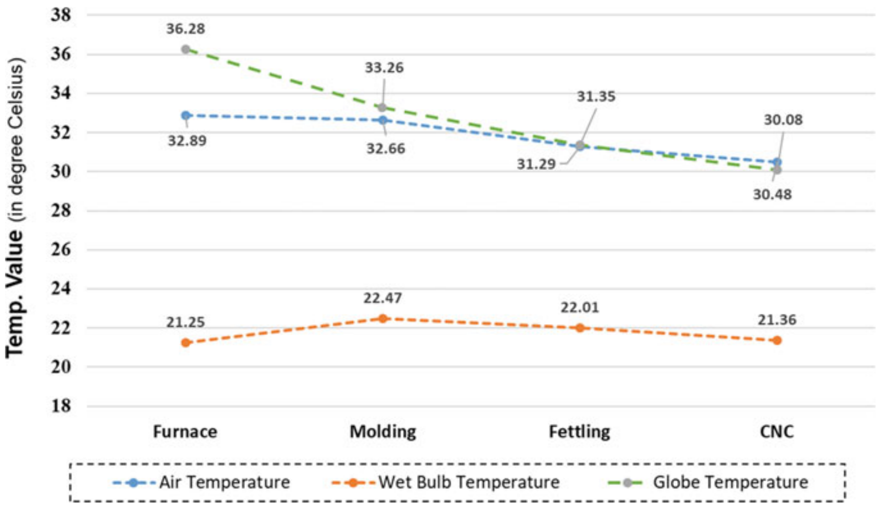

Fig. 2 Environmental parameters mean values under different work sections

Table 3 Evaluated heat stress indices (mean (SD)) (in °C)

Indices →	WBGT	DI	TSI
Work-section ↓			
Fettling	**24.81** (0.175)	**26.65** (0.171)	**28.02** (0.256)
Furnace	**25.76** (0.360)	**26.57** (0.245)	**30.65** (1.482)
Molding	**25.70** (0.219)	**27.56** (0.186)	**29.65** (0.205)
CNC	**23.97** (0.357)	**25.92** (0.623)	**27.03** (0.472)

The average values of the monitored variables have been presented in bold

Table 4 Range values for evaluated heat stress indices (in °C)

Indices →	WBGT	DI	TSI
Work-section ↓			
Fettling	24.45–25.09	26.25–26.95	27.30–28.71
Furnace	25.17–26.36	26.05–27.30	22.45–32.23
Molding	25.29–26.05	27.20–27.80	29.18–30.01
CNC	23.47–24.55	25.10–26.80	25.69–28.34

3.3 Scatterplots and Correlation Analysis

Further, Pearson product moment correlation was performed using IBM SPSS 26.0 software package for the evaluated heat stress indices. Highest association was observed among WBGT and TSI (r – value = 0.861; p-value < 0.01) followed

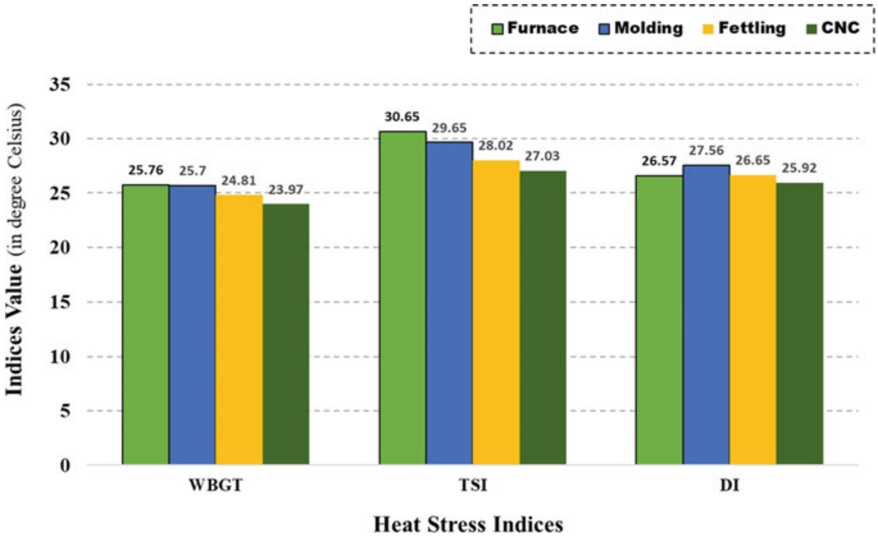

Fig. 3 Evaluated heat stress indices (mean values) under different work sections

Table 5 Correlation analysis for respective heat indices

Bivariate correlation analysis			
	WBGT	DI	TSI
WBGT	1	0.751**	0.861**
DI	0.751**	1	0.474**
TSI	0.861**	0.474**	1

**Correlation is significant at the 0.01 level (2-tailed)

by WBGT and DI (r − value = 0.751; p-value < 0.01) indices; as given in Table 5. Although, the least association was observed between TSI and DI (r − value = 0.474) indices. Figure 4 depicts the scatterplots and regression lines for the relationship among respective indices. The results showed a strong relationship between WBGT and TSI (R^2 − value = 0.741) followed by WBGT and DI (R^2 − value = 0.564) indices. However, the least association was observed among TSI and DI (R^2 − value = 0.225) indices.

4 Conclusion

Heat stress is often an unacknowledged occupational health hazard, especially in developing countries. In developing countries like India, fewer resources are available on the combined effect of workplace heat exposure and climatic conditions. For

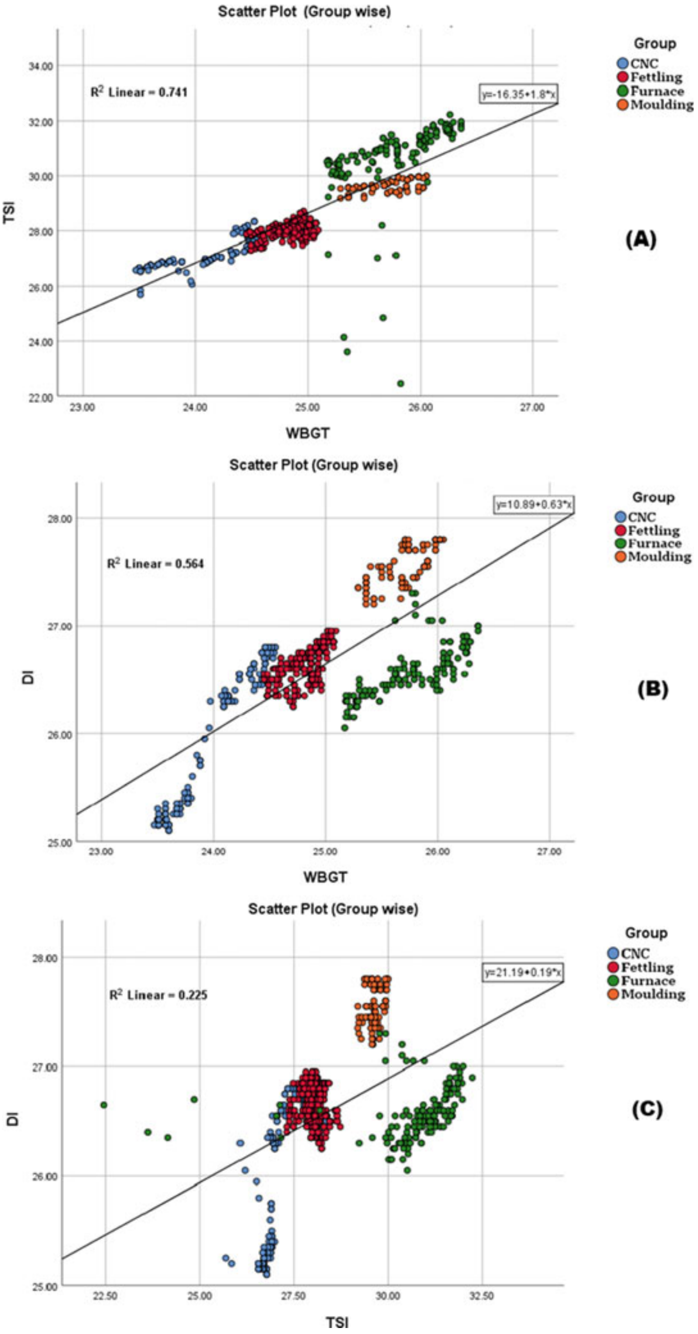

Fig. 4 Scatterplots depicting the relationship between respective indices **a** TSI versus WBGT, **b** DI versus WBGT, **c** DI versus TSI

heat stress assessment, several indices have been developed over the past century, including the environmental factors and personal factors or a combination of both. The present study assessed the heat stress exposures levels under different foundry work sections during the winter climatic season utilizing widely used heat indices. Strong positive association was observed among WBGT and TSI ($r -$ value $= 0.861$; p-value < 0.01) followed by WBGT and DI ($r -$ value $= 0.751$) indices. Although, the least association was found for TSI and DI ($r -$ value $= 0.474$). Results revealed that the heat stress exposure levels were not exceeding the threshold limit values (TLVs) during the selected climatic condition. However, higher values of globe temperature and heat indices were observed under the furnace and molding sections compared to other work sections, with the least values accountable to the CNC machining section. Although a futuristic study could also be performed, having a comparative analysis of heat stress parameters under the different foundry work sections during the winter and hot summer climatic seasons.

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