SHIBAJI DEY
and
NETAI CHANDRA DEY

Determining factors affecting thermal comfort in underground coal mine

Thermal comfort in underground mining is one of the important factors in daily mining operations so does its monitoring and measurement. In Indian mining condition very insignificant research investigations have been done, therefore, for better productive mines, determination of thermal comfort is necessary. Thermal stress along with its comfort factors has been taken into consideration for this study. Two different thermal comfort indices i.e. predicted mean vote (PMV) and predicted per cent of dissatisfied (PPD) are fixed as the indicators of thermal comfort. Total 20 participants were taken for the study to assess the thermal comfort during their regular mining shift hours. Correlation statistics is also applied for finding out the interrelationship between PMV, PPD, and different thermal comfort factors. The result shows several positive and negative correlation score of low to medium for most of the thermal stress factors. Among those, few factors are found with very strong correlation. A positive correlation between PMV and heat generation due to metabolism (r = 0.99) has been found while strong negative correlations between PMV vs. heat exchange by convection in breathing(r=–0.88) and evaporative heat exchange in breathing(r=–0.99) have been identified. It can be concluded that not a few but several factors are responsible for alteration in thermal comfort. It is also found from mine A (r=0.60) and Mine B (r=0.53) data set that the PMV and PPD have a medium strong correlation. Identification of thermal comfort factors is important to frame appropriate workload and a proper thermal comfort model for workers.

Keywords: *Underground mine; thermal comfort; predicted mean vote (PMV); predicted per cent of dissatisfied (PPD); wet bulb globe temperature (WBGT).*

1. Introduction

In modern mining ecosphere, mining of minerals becomes essential as the energy demand is increasing gradually [1]. Extraction of high gross calorific value (GCV) coal is also aimed at fulfilling the demand of thermal power plant which is the source of 56% energy in India [2]. There are tremendous opportunities for underground coal mining in India, though bulk share of Indian coal production comes from opencast coal mines. Consequently, an average of only 150-250 meter of underground coal bed is mined till date. In India, there is 51.09 billion tonnes of coal reserves present as per the study of the different scientific organizations [3]. The Ministry of Coal, Government of India is giving emphasis on the underground mechanization rapidly for having high production rate in mines, as well as they are planning to increase overall coal production (both from opencast and underground) to 1 billion tonnes per year out of which significant amount is expected to get from underground mines by 2026 [4]. With high aspiration there are also several challenges present in Indian mining. Though, mining especially; the underground mine operation is observed to be the toughest working experience as several issues like hot and humid workplace [5,6], presence of different ergo stress factors [7] alongwith low rate of efficiency and musculoskeletal disorders (MSD) related problems [8] play as the key antagonist factors in day to day underground mining operation. Different research studies both in India [9] and abroad [10] have shown presence of different psycho-physiological stress factors in underground mines. There are several stress factors present in mining, but out of them, heat stress related issues are found vulnerable in almost every mine in the world. Compared to mines abroad, Indian mines are mostly shallow in nature but the problem regarding thermal stress or heat stress is found very frequent and significant. There are several control measures available to deal with, but most important is to have significant data about the heat stress pattern during the mining operation. It is very true that there have been very insignificant numbers of research undertaken to address the heat stress problem in underground mines in India. There may be the cause of having shallow mines, but in the future, this stress control measures will be highly required. However, heat stress and thermal comfort are interrelated to each other. Thermal comfort can also be demonstrated by the term 'state of the mind' which expresses the comfort of an individual in the working environment. Therefore, thermal comfort estimation in Indian mines could emerge as one of the most important tools in mining environmental research which may mirror the thermal stress during mine unit operations under a given set of working environment. Moreover, thermal stress measurement

Mr. Shibaji Dey, Doctoral Scholar; and Prof. (Dr.) Netai Chandra Dey, Professor (Mining) Dept. of Mining Engineering. IIEST Shibpur

is more important where a continuous type of operation is taking place. Different kind of continuous operation in mining is present; therefore a continuous measurement of thermal comfort is required to figure out the stress coming out from heat stress variables. Consequently, to find out the interrelationship between different thermal comfort factors has been a priority since long.

The heat generation and thermal stress in underground mines are mostly coming out from different machinery operation, rock movement, auto compression, body heat release and most importantly with increasing geothermic gradient. The current study is aimed at (1) identifying and demonstrating the status of thermal stress indices and (2) finding out the interrelationship between thermal stress indices and different heat stress factors.

2. Materials and method

2.1 Selection of workplace and participants

Selection of mines is done based on some scientifically chosen criteria. Out of significant number of mines visited in different subsidiaries of Coal India limited, only 2 mines (Mine A and Mine B) are having almost similar air velocity at working face, same geo-mining condition, but having different working mine depth which have been incorporated in the study. Mine A has depth of cover 150 meter while for Mine B depth of cover is 320 m. Moreover, mines taken for the study is having same gassiness i.e. degree I gassiness.

Total 20 male miners (10 participants from each mine) are selected for the study. Participants for determining thermal comfort are included based on some basic criteria. The basis for selection of the participants is:

- Participants in the BMI range of 18.5 - 25 kg/m^2 [11] and BSA in the accepted range of 1.9 m^2 [12] are considered healthy and have been included for this study.
- It has been ensured that the workers with no physiological disorder or do not have any previous report of illness.
- Participants having almost the same resting heart rate (RHR) at surface before starting their work.
- Participants have the experience of familiarization of his particular work for minimum of 1 year i.e. only acclimatized persons are included.
- Participants having normal resting electrocardiography (RECG) are selected.
- Participants having given their choice to join the study are selected.
- The full assessment is conducted with the basis of written permission given by the general manager of the concerned area and the colliery officials.

2.2. Thermal comfort model and its determination

For assessment of thermal comfort indices like predicted mean vote (PMV) and predicted per cent of dissatisfied (PPD), there are several established formulas (Eq. 1-9) present [13]. These formulas are used to estimate PMV and PPD during work. The determination of PMV and PPD is done and analyzed based on the environmental data of each hour during shift. The formulas used are shown below as equation nos. 1 to 9. Equation no. 1 which is used here for estimation of PMV has been estimated using equation nos. 2 to 8 while estimation of PPD is done through the help of the value obtained from equation no.1.

$$PMV=(0.303e^{-2.100M}+0.028)\times[(M-W)-H-E_c-C_{res}-E_{res}] \quad ...1$$

where,

PMV = Predicted mean vote

M = Metabolic rate (W/m^2)

W = Effective mechanical power (W/m^2)

H = Sensitive heat loss

E_c = Heat exchange by evaporation on the skin

C_{res} = Heat exchange by convection in breathing

E_{res} = Evaporative heat exchange in breathing.

$$H=3.96\times10^{-8}\times f_{cl}\times[(t_{cl}+273)^4-(t_r+273)^4]-f_{cl}\times h_c\times(t_{cl}-ta) \quad ...2$$

$$E_c=3.05\times10^{-3}\times[5733-6.99\times(M-W)-p_a]-0.42\times[(M-W)-58.15] \quad ...3$$

$$C_{res}=0.0014\times M\times(34-t_a) \quad ...4$$

$$E_{res}=1.7\times10^{-5}\times M\times(5867-p_a \quad ...5$$

$$H_c=10.4\sqrt{V}(\text{for forced convection}) \quad ...6$$

$$f_{cl} = I_{cl} > 0.5\ \text{clothing} = 1.05+0.1\ I_{cl} \quad ...7$$

$$t_{cl} = 35.7-0.028\times\frac{M}{AD_u}-0.155\times I_{cl}\times[3.96\times10-8\times f_{cl}\times\{(t_{cl}+273)^4-(t_{mrt}+273)^4\}+f_{cl}\times h_c(t_{cl}-t_a)] \quad ...8$$

where,

I_{cl}=clothing insulation (m^2K/W)

F_{cl}=clothing surface area factor

T_a=air temperature (°C)

T_r=mean radiant temperature (°C)

P_a=water vapor partial pressure (kilo-pascal)

T_{cl}=clothing surface temperature (°C)

V= air velocity (m/min)

$$PPD=100-95\times e^{-(0.03353\times PMV4+0.2179\times PMV2)} \quad ...9$$

Thermal comfort model of PMV-PPD was first adopted by Fanger, hence it is widely known as Fanger's comfort model. Consequently, it is adopted by ASHRAE as standard 55 [15]. There is comfort scaling of PMV where +3 PMV is used as the reference value for hot zone and value of -3 is considered for a cold zone. Value of 0 is considered as neutral.

2.3. Statistical analysis

Pearson student's 't' test for independent variables is done to determine whether there are any significant differences between the variables within the selected mine groups. The statistical design is planned to study the effect of an independent variable on a single dependent variable. All sets of thermal stress variables (of different thermal comfort factors) have been considered for Pearson's 't' test while the mean and standard deviation is calculated for each set of data. Difference between mean values has been found from two different sets of data tested by one tail paired 't' test (homoscedastic) with a significant level of 'α' = 0.05. Null hypothesis (H_0) is proposed as there is no significant difference between the group means.

Statistical correlation test has been performed to further strengthen the test results. The test is done by using Microsoft office excel 2010 data analysis tool pack to predict and figure out the exact correlations between thermal comfort factors. Positive or negative correlation in the range of 0.7 to 1 has been considered as strong correlation, 0.3-0.7 as medium strong correlation and below 0.3 score is considered as weak correlation [16].

3. Results

3.1. Thermal comfort condition at different mines

As the thermal comfort is the derivative of several heat stress factors, mines under the study have shown different thermal comfort values. PMV and PPD value which is used as the indicator of thermal comfort has been found with 24.6% higher data values in case of Mine A and 36.3% in case of Mine B compared to the reference value of hot zone (Table 1).

Though, no significant differences are observed between two mines in case of PMV (M=3.74, SD=0.82; M=4.09, SD=0.65; p-value=0.15) and PPD values (M=99.28. SD=1.70; M=99.97, SD= 0.05; p value=0.10), it is observed that a medium strong correlation between PMV and PPD do exist for both Mine A (r=0.60) and Mine B (r=0.53). It is also established that the PMV score can influence PPD condition during work.

TABLE 1: PMV AND PPD VALUES OF TWO SELECTED MINES

Parameters	Mine A(N=10)	Mine B(N=10)	Pearson's students' t-test (one tail homoscedastic)
PMV	3.74+0.82 (2.55-5.29)	4.09+0.65 (3.30-5.42)	0.15(NS)
PPD	99.28+1.70 (94.5-100)	99.97+0.05 (99.83-100)	0.10(NS)

Moreover, both of the two mine environments are measured with high wet bulb globe temperature (WBGT) values compared to the reference value (Table 2) of OSHA (M=27.21, SD=0.45 for Mine A; M=27.78, SD=0.51 for Mine B) and a significant difference (p=0.001) between two mine WBGT has been observed. It is seen in previous research study that the workload of miners in India mostly identified in the category of moderate-heavy workload [17]. Moreover, higher ambient temperature and relative humidity in both of the mine working site have been observed. For moderate to heavy continuous workload, it is better to have WBGT in the range of 25-26.7°C (Table 2). From the higher WBGT (Fig.1), PMV (Figs.2 and 3) and PPD score (Table 1) it is clearly understood that mining environmental condition is hectic to survive in case of long continuous job type, therefore; almost 100% population feel discomfort or dissatisfied during mining operation.

3.2. INTERRELATIONSHIP BETWEEN PMV AND THERMAL COMFORT FACTORS

From the analysis of different factors and sub-factors as associated with thermal comfort at workplace, some correlations with PMV have been found. Correlation between PMV (M=3.92, SD=0.74) and body surface area (M=1.69, SD=0.03; r=0.47) [Fig.4], heart rate ratio (M=1.6, SD=0.05; r=0.20) [Fig.5], heat convection rate (M=3.97, SD=0.23; r= –0.25) [Fig.6], heat generation due to metabolism (M= 149.2, SD=20.05; r=0.99) [Fig.7], heat exchange by convection in breathing (M=2.79, SD=0.21; r=–0.84), evaporative heat

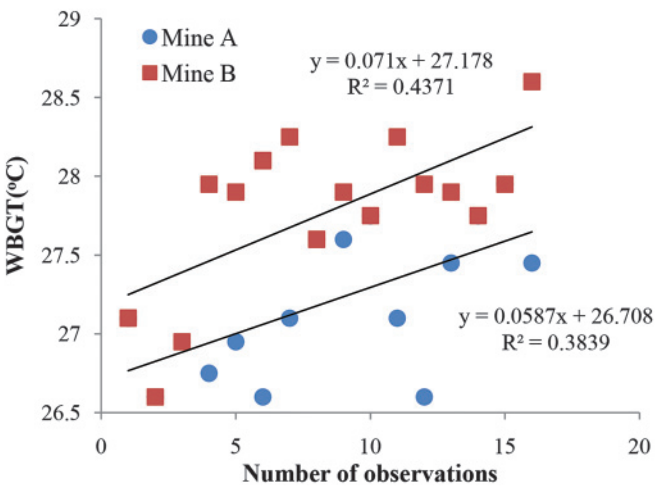

Fig.1 WBGT values at two different mine sites

TABLE 2: WBGT REFERENCE VALUES OF DIFFERENT WORKLOAD

Work rest regimen	Workload		
	Light	Moderate	Heavy
Continuous work	30.0°C (86°F)	26.7°C (80°F)	25.0°C (77°F)
75% Work, 25% rest, each hour	30.6°C (87°F)	28.0°C (82°F)	25.9°C (78°F)
50% Work, 50% rest, each hour	31.4°C (89°F)	29.4°C (85°F)	27.9°C (82°F)
25% Work, 75% rest, each hour	32.2°C (90°F)	31.1°C (88°F)	30.0°C (86°F)

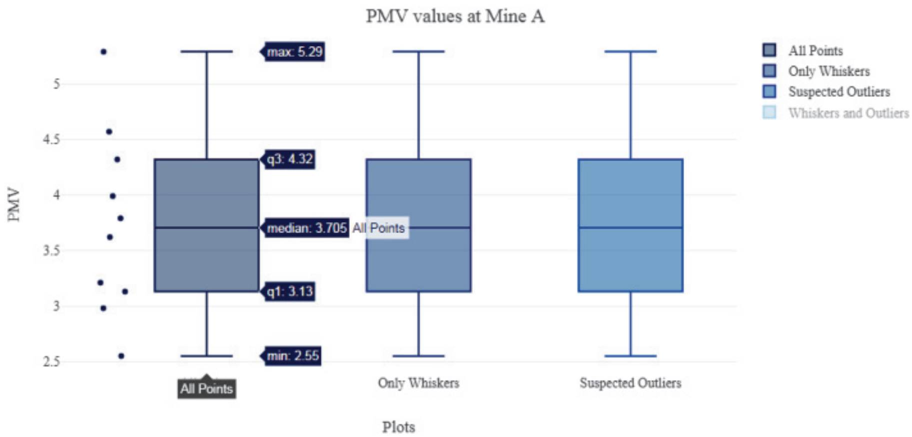

Fig.2 PMV value at mine A

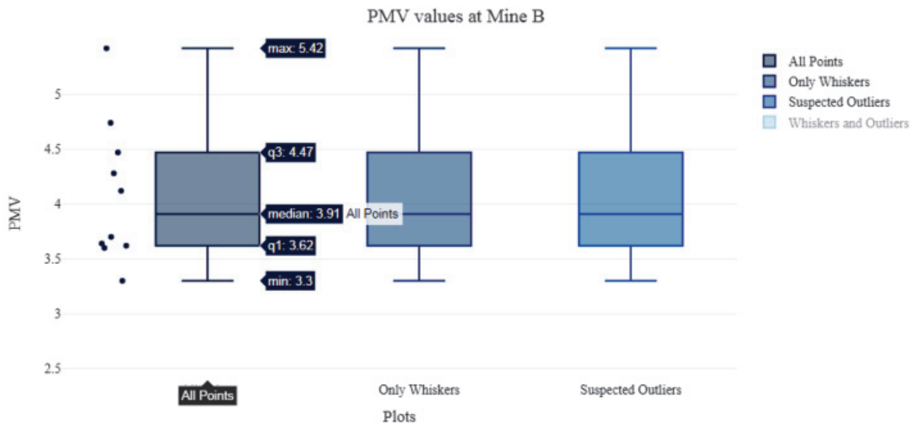

Fig.3 PMV value at mine B

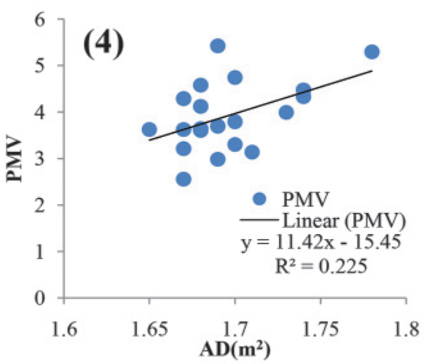

Fig.4 Interrelationship between AD and PMV

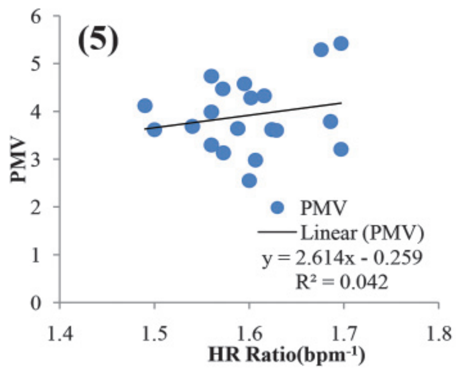

Fig.5 Interrelationship between hr ratio and PMV

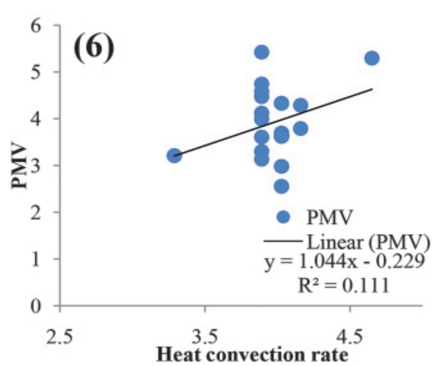

Fig.6 Interrelationship between heat convection rate and PMV

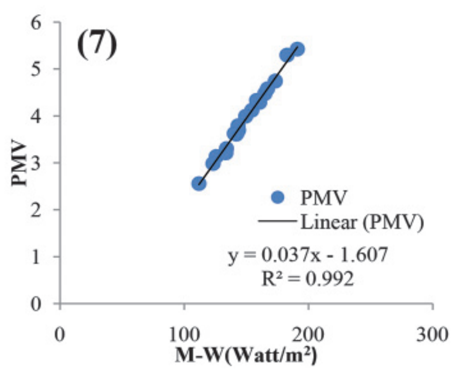

Fig.7 Interrelationship between M-W and PMV

exchange in breathing (M=31.90, SD=2.56; r=–0.88), evaporative heat loss (M=–23.94, 8.9; r=–0.99), air velocity (M=0.15, SD=0.01; r=–0.34), sensitive heat loss (M=–1.59, SD=1.83; r=–0.14) are identified as important factors in underground mining for thermal comfort.

Though, in some cases very weak correlation (r<0.3)score have been found, it may be so as the PMV and PPD values are the derivatives of several sub-factors. There are different factors which are interrelated to thermal comfort and it is the factors, not a single factor which controls the thermal comfort at mine working environment. Out of the different factors identified, heat generation due to metabolism (Fig.7), heat exchange by convection in breathing, evaporative heat exchange in breathing, air velocity, evaporative heat loss are important factors to control thermal comfort at mines.

4. Discussion

It is a matter of concern that the concept of thermal comfort in underground mines is still in the developing stage. In India research regarding thermal comfort factors is insignificant in number till date. From the study it is understood that the thermal comfort is a complex system which is interconnected with several factors and sub factors during mine unit operation. In underground mines where the type of operation is performed mostly in a continuous manner, determination of thermal comfort is very much important. It could play decisive in the selection of spell time and gaining maximum productivity out of a working shift. It is seen from the current study, a shallow mine of 150m depth has shown the higher PMV value. Moreover, WBGT has been measured 1.9% higher than the reference value for mine A and 4.1% higher for mine B in case of a moderate continuous job, for heavy it is 8.84% and 11.1% higher respectively [18]. Therefore, continuous work in heat stress condition is somewhat unbearable in a long term basis as per the current assessment. In mining condition, it is observed that relative humidity and air vapour pressure also high along with high ambient temperature and low air velocity. It is a phenomenon that thermal comfort factors and its indices mostly depend on different heat convection and conduction rate between air and body. Increase in air temperature during work coupled with higher air vapour pressure could further resist the heat release. However, body surface area, metabolic demand during work also act as important factors in thermal comfort. Additionally, the depth of cover of mines can also be included as a thermal stress factors as with geothermic gradient heat production will be increasing gradually. PMV value for the current two mines under study is found 24.6% and 35.3% higher compared to the reference value for mine A and mine B respectively. Hence, in bigger depth mines the thermal stress (PMV) will be increased further to increase the discomfort rate among mine workers as the PPD of mine A (r=0.60) and mine B (r=0.53) have been found correlated with PMV values.

However, conceiving countermeasure against adverse thermal stresses for higher depth mines seems to be the need as the future of coal mining in India will be shifted towards bigger depth underground mines. From the study, both weak and strong correlations are found with some factors which could be very essential in controlling and managing thermal stress down the mines. It is also pertinent here that several factors and its' correlation with thermal comfort indices have been found mostly in the zone of weak to middle strong correlation. Only a few among those factors are found with very strong correlation where a positive correlation between PMV and heat generation due to metabolism (r=0.99) has been found while a strong negative correlation between PMV vs. heat exchange by convection in breathing(r=-0.88) and evaporative heat exchange in breathing(r=-0.99) have been identified.

However, weak and strong correlation between factors advocates that there are several factors contributing to thermal comfort. Proper identification and fixation of those factors can increase the work efficiency of miners at workplace; simultaneously increasing rate of air velocity could bring down the thermal stress significantly. Proper monitoring of identified contributing factors like heat generation due to metabolism,exchange by convection in breathing,evaporative heat exchange in breathing, air vapor pressure, air, and skin temperature would be very helpful to bring down the thermal stress at the mine site. Additionally, fixation of work-rest scheduling according to the thermal stress values could be helpful for the mining workplace to make mines more productive and heat tolerable for a continuous type of mining operations.

5. Conclusion

Thermal comfort measurement in mining is very important insight as work output and productivity are closely interrelated with thermal stress factors. There is several thermal stress factors identified and correlated to PMV value both negatively and positively. It is found that in deeper underground mines, under the rising heat stress condition, factors like metabolic demand, different type of evaporative and conductive heat loss and other allied heat stress factors are important to manage thermal comfort during continuous mine unit operations as the discomfort of individual is found correlated to identified thermal comfort factors.

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