THERMAL COMFORT FINDINGS: SCENARIO AT MALAYSIAN AUTOMOTIVE INDUSTRY

by

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This paper discusses the findings of thermal comfort assessment at Malaysian automotive industry. Nine critical workstations were chosen as subjects for the study in order to determine the thermal comfort among workers at Malaysian automotive industry. The human subjects for the study comprises of the operators from tire receiving, dashboard assembly, drum tester, body assembly, seat assembly, door check assembly, stamping workstation, engine sub assembly, and paint shop of the factory. The environmental factors such as wet bulb globe temperature, relative humidity, air velocity, illuminance were measured using BABUC A apparatus and thermal comfort measurement equipment. Through questionnaire survey, the demographic data of subjects and their perceptions on thermal comfort at each workstation were assessed based on ISO Standard 7730 and thermal sensation scale using predicted mean vote. Then, predicted percentage of dissatisfied is used to estimate the thermal satisfaction of occupants. The results indicated that most of the workstations of the automotive industry are considered as uncomfortable. Tire receiving station is considered having better working environment compared to other stations with lowest predicted mean vote index of 1.09 to 1.41 and predicted percentage of dissatisfied of 46%. Meanwhile, the engine sub assembly station and paint shop of assembly are considered the worst thermal environment with the predicted mean vote index values ranging between 2.1 to 2.9 and predicted percentage of dissatisfied values of 81% to 99%. Therefore, these two workstations are considered not comfortable because the thermal sensation scale is warm and almost hot.

Key words: *thermal comfort, wet bulb globe temperature, predicted mean vote, percentage of dissatisfied*

Introduction

Most of the industries in developing countries are concerned about improvement in the performance of workers, health, and safety. Anyhow, the manufacturing industries are characterized with improper design of workplace, unpleasant environment, poor human-machine system design, and inappropriate management programs [1]. The thermal comfort is defined as the condition of mind which expresses satisfaction with the thermal environment [2]. Fanger [3] suggested three conditions for comforts which are the body is in heat balance, mean skin temperature, and sweat rate are within limits required for comfort. Conditions required for heat balance can be derived from the heat balance equation. Mean skin temperatures and sweat rates that are acceptable for comfort have been derived from empirical investigation [4].

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Thermal comfort has great influence on the productivity and satisfaction of indoor building occupants [5]. Defining thermal comfort requires the need to consider the range of environmental and personal factors that will make occupants feel comfortable. Therefore, the best that can be realistically achieved is a thermal environment which satisfies the majority of people in the workplace, or "reasonable comfort" [6]. Thermal comfort is recognized as a key parameter for healthy and productive workplace. At the same time, lowering energy use in commercial building is vital if significant reduction in greenhouse gas emissions is to be achieved. Traditionally thermal comfort has been achieved at the expense of significant energy use for heating or cooling. In another major study, Taylor *et al*. [7] found that a well-designed building should be able to provide good thermal comfort, while simultaneously having low energy consumption.

Achieving thermal comfort is usually paramount in buildings involving people occupancy. In buildings the heating and cooling energy supply is provided by the HVAC system. The designed HVAC system should consider the working environment and type of activities performed indoors as well [8]. The use of HVAC systems for achieving the desired comfort conditions through complicated heat and moisture removal process has raised the possibility of thermal comfort problems in building. Thermal comfort problems have an immediate and direct impact on building occupant morale and productivity. Therefore immediate attention should be given to thermal comfort related complaints. Furthermore, minimum time and effort should be utilized for rectifying problems [8].

According to Fisk and Rosenfeld [9] productivity is one of the most important factors affecting the overall performance of any organization, from small enterprises to entire nations. Increased attention had been focused on the relationship between the work environment and productivity since the 1990. Laboratory and field studies showed that the physical and chemical factors in the work environment could have a notable impact on the health and performance of the occupants, and consequently on the productivity. Workplace environmental conditions, such as humidity, indoor air quality, and acoustics have significant relationships with workers' satisfaction and performance [10, 11]. Indoor air quality could have a direct impact on health problems and leads to uncomfortable workplace environments [12-14].

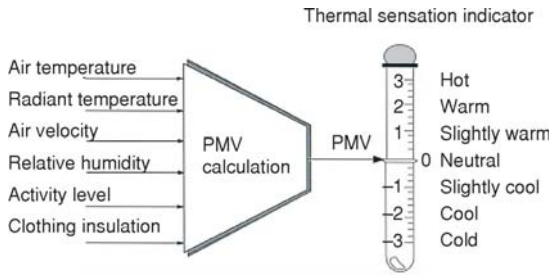

Figure 1. PMV and thermal sensation [8]

Predicted mean vote (*PMV*) is a parameter for assessing thermal comfort in an occupied zone based on the conditions of metabolic rate, clothing, air speed besides temperature, and humidity. According to Ho *et al.* [2], *PMV* values refer the ASHRAE thermal sensation scale that ranges from –3 to 3. Figure 1 summarizes the overall process of using the six variables associated with thermal comfort sensation to evaluate the *PMV* [15].

The general comfort eqs. (1)-(4) developed by Fanger [3] to describe the conditions under which a large group of people will feel in thermal neutrality is too complex and cannot be used in real time applications [4]:

$$PMV = (0.028 + 0.3033e^{-0.036M})\ \{(M - W) - 3.05[5.733 - 0.000699(M - W) - Pa] - \\ - 0.42[(M - W) - 58.15] - 0.0173\ M\ (5.867 - Pa) - 0.0014M\ (34 - T_a) - \\ - 3.96 \cdot 10^{-8} fcl[(T_{cl} + 273)^4 - (T_{mrt} + 273)^4] - fcl\ hc(T_{cl} - T_a)\} \quad (1)$$

where

$$T_{cl} = 35.7 - 0.028(M - W) - 0.155I_{cl}[3.96\cdot10^{-3}\text{fcl}[(T_{cl} + 273)^4 - - (T_{mrt} + 273)^4] - fcl\ hc(T_{cl} - T_a) \quad (2)$$

$$h_c = \begin{cases} 238(T_{cl} - T_a)^{0.25} \text{ for } 2.3(T_{cl} + T_a)^{0.25} \geq 121\sqrt{V_{air}} \\ 121\sqrt{V_{air}} \text{ for } 2.38(T_{cl} - T_a)^{0.25} \leq 121\sqrt{V_{air}} \end{cases} \quad (3)$$

The parameters are defined as follows: M [Wm^{-2}] is the metabolism, W [Wm^{-2}] – the external work, equal to zero for most activity, I_{cl} [clo] – the thermal resistance of clothing, *fcl* [°C] – the ratio of body's surface area when fully clothed to body's surface area when nude, T_a [°C] – the air temperature, T_{mrt} [°C] – the mean radiant temperature, V_{air} [ms^{-1}]– the relative air velocity, *Pa* [Pa] – the partial water vapour pressure, h_c [Wm^{-2}K^{-1}] – the convectional heat transfer coefficient, and T_{cl} [°C] – the surface temperature of clothing.

Furthermore, the equation for predicted percentage of dissatisfied (*PPD*) is given by:

$$PPD = 100 - 95\ \exp(-0.03353\ PMV^4 + 0.2179\ PMV^2) \quad (4)$$

Thermal comfort dissatisfaction of the occupants is usually estimated using PPD. Even though the thermal sensation vote is neutral, the *PPD* value is at 5%. *PPD* less than 20% is considered good and that means 80% of occupants are satisfied with the thermal environment [16]. Naturally ventilated buildings designs can perform efficiently in hot climate countries, like Malaysia because of their low evaporation rate, long hours of sunshine and high relative humidity [17]. Many published studies show that the human thermal sensation in a naturally ventilated environment is much better than that in a mechanically controlled thermal environment [18].

Malik and Hanim [19] have carried out study at two hotel lobbies which located at beach side and hill slope in Malaysia to determine whether the average air velocity can reduce the thermal discomfort. The environmental factors such as air velocity, air temperature, and relative humidity are measured for one week by using BABUC environmental data logger. The standard effective temperature is a temperature indicator that is used in this study as it takes the considerations of other climatic elements and not just relying on air temperature alone. Their study reveals that a drop of 1 °C would make significant difference in thermal comfort and also reduce the energy consumption and costs. Both set of data are within the Malaysian thermal comfort zone within the value of 24 °C to 28 °C as mentioned by Shukor [20].

On the other hand, Jang *et al.* [21] conducted an evaluation of the optimal temperature in each cabin of the Korean maritime patrol vessels. Two methods were applied in this study, which are *PMV*/*PPD* and human factor. The ergonomic factors, human activities, and clothing were surveyed in cabins of 250, 1000, and 1500 ton vessels in this study. *PMV* and *PPD* were calculated to find the optimal air temperature for each cabin. In this calculation, they assumed that the mean radiant temperature of environment factors was equal to the dry bulb air temperature, and the relative air velocity was 0.0 m/s. Since there were different crew members at various vessels with different activities, various optimum temperatures are obtained at each cabin. Based on human factors, the optimum temperature was 23 °C and 29 °C. The results showed that the wheelhouse and accommodation can save 6 °C of energy in the case of *PMV*/*PPD* with demand controlled air conditioning.

The study by Toftum and Nielsen [22] pointed out that regular complains of draught were received from the employees who are working at cool or cold environments. In this study they have mentioned the previous study by Toftum [23] who conducted a field study among employees at various industrial spaces showed the existence of a relationship between the general thermal sensation and local thermal discomfort caused by convective cooling of the skin. In addition, they also figured out the findings of Kristensen and Christensen, [24] at meat processing

plants, a large numbers of complaints were received due to draught and coldness from the employees who are working at low temperature spaces.

Ajimotokan *et al.* [25] has performed a study at a beverage bottling plant to investigate the influence of indoor environment on workers' health, comfort, and productivity in Ilorin, Nigeria. In their study, they have reviewed the previous researcher's findings as evidence to say that health, comfort and performance of adults improved at higher ventilation rates [26-28]. The study reveals that evidence from review of complaints showed that continuous environmental stress affected workers' performance and decreases the productivity. Overall, a large number of workers experienced the sign of discomfort related to the environmental factors in the workplace.

Methodology

The automotive industry is considered the single largest manufacturing sector in the world [29]. Malaysia has obtained much recognition regionally and internationally for its outstanding achievement in automotive industry since the first national car, the Proton Saga was introduced in 1985 [30]. In Malaysia, the automotive industry is broadly classified into two major sectors which are manufacturing or assembly of motor vehicles and components as well as parts manufacturing such as body parts.

Both physical measurements and survey approaches have been conducted at all the nine workstations. These places are mechanically ventilated type except for door check assembly which equipped with an air-conditioning system. The plant has a central fan or local fans that provide air ventilation. The basic device used for the measurements was the BABUC A multi-data acquisition unit and thermal comfort measurement equipment as shown in figs. 2 and 3, respectively. These instruments were used to obtain the values of air temperature, air humidity, mean radiant temperature, relative air velocity, activity level (heat production in the body), and thermal resistance of the clothing. Meanwhile, the characteristics of the probes of equipment used (BABUC A) are described in tab. 1. It is expected that the sensitivity to error during the field measurement due to the inaccuracy of instruments minimized.

Figure 2. BABUC A Equipment (LSI, Italy)
Source: http://www.docknorte.com/ Productos/Analizadores/Meteorologicos/ IndoorMeteo.asp [31]

Figure 3. Thermal comfort measurement equipment

Table 1. Data acquisition system – characteristics of main probes (BABUC A) [32]

Probe	Operative range	Accuracy
Air temperature	–50 °C to 80 °C	± 0.17°C
Hot wire type of anemometer	0 to 50 m/s	±0.05 m/s for v_a = 0-0.5 m/s ±0.1 m/s for v_a = 0.5-1.5 m/s ±4% for v_a > 1.5 m/s
Black dull copper globe thermometer	–50 °C to 100 °C	±0.17 °C
Psychrometer	Temperature from –50 °C to 150 °C Relative humidity from 40% to 100%	Temperature ±0.13 °C Relative humidity ±2%
Radiometer	–150 W/m^2 to 1500 W/m^2	±3%
Double air temperature	–50 °C to 80 °C	±0.17 °C
Carbon dioxide	0 to 3000 ppm	±1 ppm

For this study, there were a total of 90 operators from nine workstations who became the subjects for survey approach. They are three workers from tire receiving station, ten workers from dashboard assembly station, twelve workers from body assembly, ten workers from seat assembly, four workers from drum tester assembly, twenty workers from door check assembly, twenty workers from stamping workstation, four workers from engine sub assembly, and seven workers from paint shop participated in the questionnaire survey. The demographic data such as age, gender, weight, height, marital status, and their perception on thermal comfort using thermal sensation scale were obtained by the questionnaire. All the workstations were observed well before setting up the measuring equipment at suitable locations which enables better data collection. In the same time, the equipment set up avoids disturbing the operator or other workers to perform their job. Most of the measurement starts off at the beginning of day shift at early morning around 8.00 a.m. until end of day shift at 5.30 p.m. The questionnaires were given to the workers during their break time.

Results and discussion

The tire receiving station is located close to the loading ramps and very much influenced by the environment. This is because this station is very close to main door and windows. The door and windows are always open during work. On dry and sunny days the temperature will be much higher and will disturb the workers even more. The influence of rain to the temperature is very large. The highest temperature measured was close to 28 °C. The humidity is again influenced by rain. The humidity was about 75% in the morning. When the rain started, it went to a maximum value of 92% and kept at this range until the rain has stopped. Then it decreased slowly to values around 70%. The obtained relative humidity exceeds the recommended value of 50% to 60% thus the conditions were uncomfortable for the workers. This workstation was not comfortable because the *PMV* index is around 1.07 to 1.41 and the *PPD* is 27% to 46%. That means the highest *PPD* in this station is 46%, so, 54% of occupants are likely to be satisfied. The calculated metabolic rate is 116 W/m^2 as the activity is moderate. The value of clothing insulation used is 0.8 clo for short sleeves and light working trousers. The survey result shows that this workstation is hot and the response of the relative humidity is also very high. Two out of three workers feel very much affected by the humidity, feel uncomfortable and think the conditions and the productivity could be improved. They also feel that illuminance at the station was sufficient to fulfill the job.

The dashboard assembly station was located more to the center of the plant. The air is continuously exchanged by some fans in the roof of the plant, but the climate at this station is not really affected by any outside circumstances. The factors are more or less influenced by the closed environment. The *PMV* index is 1.97 to 2.13 while the *PPD* is 82%. That indicates, another 18% of occupants are likely to be satisfied with the environment. The metabolic rate calculated was 116 W/m^2 due to the moderate activity. The value of clothing insulation was 0.8 clo for short sleeves and light working trousers. The answers to the questions of the survey are correlated with measured values. The impression on the temperature being too high is not that strong compared to the answers given at the tire receiving station. The measured relative humidity ranges between 50% and 70%. The average of 60% is definitely lower than the relative humidity measured at the tire receiving station. The impression of the workers matches with the measured data. The illuminance at this station was sufficient. The workers support this by quoting the conditions are sufficient, but also saw potential for improvements.

The Seat Assembly station directly located at the center of the plant. So, the influence of the environment outside the plant is less affecting. The *PMV* index is around 1.93 to 2.15. However the *PPD* achieved is 83% and only 17% of occupants are likely to be satisfied. The metabolic rate calculated was 116 W/m^2 as the activity were moderate. The value of clothing insulation was 0.8 clo for short sleeves and light working trousers. The temperature measured was quite high at this station. The personal impression of the workers supports this fact. Most of them feel "much" or "very much" affected according to the survey. The survey showed, that the impression of the workers is not that high than at other stations. Most of them quoted neutral. Some responded much affected and some not much. The results range between all possible answers, tending to neutral. The illumiance was not that strong but seemed sufficient for the workers. The evaluation of the survey shows behavior that corresponds to the measured values.

On the measurement day at the drum tester station, the climate was calm with only scattered clouds. The measurement devices were deployed in a pit, below the floor level. The clothing value is 1.1 clo with the metabolic rate is 100 W/m^2. The *PMV* index is 2 while the *PPD* is around 74% to 79%. So, only 21% of occupants are satisfied with this environment. The temperature seems to be very uncomfortable at the drum tester station. The answers to the questions about the temperature are all much or very much. The measured temperature at this station is not high compared to other stations, but it seemed to affect the workers a lot. The humidity was not as much affecting as the temperature. The answers about the humidity show, that the humidity was not a burden for the workers. The illuminance is no real problem at this station. Most of the operators comment, that the illumination is sufficient. The conditions did not seem to disturb the workers much.

The body assembly station was located again close to a gate at the side of the plant. The influence of the outside environment is again stronger then at those stations at the assembly belt in the center of the plant. The day started sunny and dry. The *PMV* index value at the body assembly station is between 1.76 and 2.1. Meanwhile, the *PPD* is around 65% to 81%. So, 19% are likely to be satisfied by the worker. At this station, the workers had to wear long sleeves. The metabolic rate was also 116 W/m^2 and the clothing insulation value was 1.1 clo. In conclusion, this station is not comfortable because the thermal sensation is warm. Due to the further distance from the gate and windows the station has less air flow. The temperature impression seems to be warmer than it actually is. The temperature is once again quoted as hot. Many workers rate the disturbance caused by the temperature as very high. The need to wear shirts with long sleeves, gloves and protectors against the spraying sparks while welding caused a stronger influence from temperatures. The humidity is also rated as high. Most of the workers answered to the questions about the relative humidity, that they feel affected and much disturbed by it.

The paint shop assembly station activities are to paint the metal parts, plastics parts or combination of both parts. Therefore, the metabolic rate was 93 W/m^2 (light industry) and the clothing insulation value was 0.9 clo. The relative humidity is almost constant throughout the day. It ranges around 60% to 80%. High humidity was observed during morning session and it started to reduce before the lunch break. However, after the lunch break, the relative humidity started to increase again due to rainy weather outside the working area. The finding was also consistent with the air temperature profile recorded. The radiant temperature profile is also consistent with the air temperature profile recorded during the experiment. Low radiant temperature is observed during the morning session and started to increase after 11:00 a. m. This is consistant with increasing air temperature inside the working area and also starting oven operation temperature for drying of the products. The results *PMV* index at paint shop assembly station is between 2.1 and 2.8. Meanwhile, the *PPD* is around 81% to 98%. Overall, this station is not comfortable at all because the thermal sensation is warm and almost hot.

At the door check assembly, the measurement were conducted for two days with two different brand sections. On the first day, for brand A door check assembly section was measured. During the measurement the climate is good not cloudy. The workers do their work in the room that has air conditioning. The temperature increased constantly. At the beginning of the measurement, the temperature is 23 °C and after 2:30 p. m., the temperature increased until the measurement ended. The highest temperature in this station is 28 ºC. The average of relative humidity is 50%. The metabolic rate is 69.6 W/m^2 for light industry which has standing or seated and hand works. The clothing value is 0.75 clo for underpants, shirt, trousers, socks, and shoes. The *PMV* index shows higher about 1.29 which is slightly warm meanwhile the *PPD* is 60%. That indicates the rest 40% of occupants are satisfied with the comfort level in that environment. On second day, brand B door check assembly section was measured. During the measurement, the average of humidity in this station is 50%. The temperature showed an increase at 1 pm about 29 ºC. After 3 p. m., the temperature decreased because of cloudy weather. Since the activity is similar as for brand A, at this station the metabolic rate is 69.6 W/m^2 with clothing value is 0.75 clo. The *PMV* index shows higher about 1.55 which is slightly warm, while the *PPD* is 54% higher. That means the rest 46% of occupants are satisfied with the comfort level at that environment.

The stamping workstation is located near the door behind the plant. This station used natural ventilation and assisted by a fan. At the beginning of measurement, the relative humidity is 64% and decreased until measurement ended. The temperature also escalated until 30 ºC. Since more radiance is emitted the air velocity decreases. The metabolic rate is 81.2 W/m^2 for moderate activity while standing. The clothing value is 0.75 clo for underpants, shirt, trousers, socks. and shoes. The *PMV* and *PPD* also shown this station is slightly warm with the *PMV* index of 1.84 and the *PPD* of 69%. That shows 31% of occupants are satisfied with this station environment.

At the engine sub assembly station, the effect of environment to the workers should be considered as standard. The environmental monitoring station had been collecting online data for 6 hours and 30 minutes. The overall pattern of the result shows a normal and harmless condition of environment. During the measurement, there are some variation in terms of illuminance and radiant temperature. This is due to heavy rain and changes in lighting. The natural light source had been closed and replaced by ceiling lighting that is obviously better. The air temperature is slightly raised before raining. The recommendation from ASHRAE is the air temperature is should be between 19 °C and 26 °C. The actual result of 29 °C showed that the working area is out of comfort in terms of room temperature. The metabolic rate was 93 W/m^2 (light industry)

and the clothing insulation value was 0.9 clo. The *PMV* index at engine sub assembly station is between 2.1 to 2.9 meanwhile, the *PPD* is around 81% to 99%. In conclusion, this station is not comfortable because the thermal sensation is warm and almost hot.

Table 2 is shows the summary of key findings of thermal comfort assessment at nine different workstation in Malaysian automotive industry.

Table 2. Summary of key findings of thermal comfort assessments at Malaysian automotive industry

Workstation	Summary of thermal comfort assessment result
Tire receiving	*PMV* index value: 1.07-1.41 *PPD* value: 27%-46% Metabolic rate : 116 W/m^2 Clothing rate: 0.8 clo for short sleeves and light working trousers Overall: This workstation was not comfortable and only 54% of occupants are likely to be satisfied
Dashboard assembly	*PMV* index value: 1.97-2.13 *PPD* value: 82% Metabolic rate : 116 W/m^2 Clothing rate: 0.8 clo for short sleeves and light working trousers Overall: This workstation was not comfortable and only 18% of occupants are likely to be satisfied
Body assembly	*PMV* index value: 1.76-2.1 *PPD* value: 65% - 81% Metabolic rate : 116 W/m^2 Clothing rate: 1.1 clo for long sleeves Overall: This station is not comfortable because the thermal sensation is warm
Seat assembly	*PMV* index value: 1.93-2.15 *PPD* value: 83% Metabolic rate : 116 W/m^2 Clothing rate: 0.8 clo for short sleeves and light working trousers Overall: This station is not comfortable because only 17% of occupants are likely to be satisfied
Drum tester assembly	*PMV* index value: 2 *PPD* value: 74% -79% Metabolic rate: 100 W/m^2 Clothing rate: 1.1 clo Overall: This station is not comfortable because only 21% of occupants are satisfied with this environment
Door check assembly	<u>For brand A</u> *PMV* index value: 1.29 *PPD* value: 60% Metabolic rate: 69.6 W/m^2 Clothing rate: 0.75 clo for underpants, shirt, trousers, socks and shoes Overall: This station is not comfortable because only 40% of occupants are satisfied with this environment <u>For brand B</u> *PMV* index value: 1.55 *PPD* value: 54% Metabolic rate: 69.6 W/m^2 Clothing rate: 0.75 clo for underpants, shirt, trousers, socks and shoes Overall: This station is not comfortable because only 46% of occupants are satisfied with this environment
Stamping workstation	*PMV* index value: 1.84 *PPD* value: 69% Metabolic rate: 100 W/m^2 Clothing rate: 0.75 clo for underpants, shirt, trousers, socks and shoes Overall: This station is not comfortable because only 21% of occupants are satisfied with this environment

Table 2. (continuation)

Workstation	Summary of thermal comfort assessment result
Engine sub assembly	*PMV* index value: 2.1-2.9 *PPD* value: 81% to 99% Metabolic rate: 93 W/m^2 Clothing rate: 0.9 clo Overall: This station is not comfortable because the thermal sensation is warm and almost hot
Paint shop of assembly	*PMV* index value: 2.1-2.8 *PPD* value: 81% to 98% Metabolic rate: 93 W/m^2 Clothing rate: 0.9 clo Overall: This station is not comfortable because the thermal sensation is warm and almost hot

Conclusions

Among the nine workstations that are involved in this study, the tire receiving station is considered having better working environment compared to other stations. This is due to the tire receiving station obtained the lowest *PMV* index scale which is between 1.07 and 1.41 with 54% of occupants satisfied with the environment. Even though, the environment is still not within the recommended comfort range based on ISO 7730-1994 which has *PPD* less than 10% and PMV between –0.5 to +0.5. The door check assembly condition is almost similar for brand A and brand B with both using air conditioning but still obtained different *PMV* and *PPD* values. On the other hand, engine sub assembly station and paint shop of assembly are considered the worst thermal environment with the *PMV* index values ranging between 2.1 to 2.9 and 2.1 to 2.8 respectively. The *PPD* values are nearly 81% to 99% at both workstations therefore these two workstations are considered not comfortable at all because the thermal sensation scale is warm and almost hot. In conclusion, low awareness on the importance of environmental ergonomics among industrial members and workers caused poor thermal comfort conditions in the Malaysian automotive industry. Therefore, serious attention is needed to emphasize on thermal comfort conditions at Malaysian automotive industry in order to provide better working environment for workers. As a result, it would help increase the productivity of workers at the Malaysian automotive industry. Finally, further researches are recommended by optimizing the environmental parameters and setting up the working environment accordingly in order to improve the thermal comfort conditions in Malaysian automotive industry.

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