



Skin Temperature Distribution on Simulation Thermal Effects Under Construction Climate

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ABSTRACT

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Global warming is bringing more frequent and severe heat waves. Construction workers are particularly vulnerable to heat risk due to the job culture in the outdoor environment. Unrestrained heat has extreme effects on skin temperature, which will lead to low performance and also results to injuries and fatalities. This study aims to investigate the distribution of skin surface temperature under seven different thermal conditions involving variations in temperature and relative humidity. The computational simulation models based on real construction climate were developed. Simulation results showed the highest heat index (a combination of temperature/relative humidity) is at 34 °C/92% and 38 °C/83% and fall under extreme danger category. At this level, the models were experienced high heat/sunstroke continuous exposure. This study also indicated that skin temperature has significantly influenced by the hot and humid environment. It is hoped that this study is able to provide guidance and reference to the industry, especially the construction sector by providing appropriate control measures to overcome the issue of heat risk among workers.

1. Introduction

Tropical countries recognize as the region which have abundant of solar radiation and the relatively high air temperature and relative humidity levels. Hence, long periods of outdoor thermal discomfort are common [1,2]. Malaysia also located in a tropical region. Malaysia has a tropical rainforest climate with relatively high air temperature, relative humidity, and solar radiation. With 27 °C as yearly mean air temperature, the monthly mean maximum temperatures vary from 33.5 °C in March/April to 31.9 °C in December. On the other hand, the monthly mean minimum temperatures

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range from 23.1 °C in January to 24.3 °C in May. The relative humidity generally reaches a maximum above 90%, although its mean is between 70% and 90%. Likewise, with high rates of solar radiation (mean: from 14 to 16 MJ/m²d), the wind velocity is usually insignificant although during the monsoon seasons, it slightly increases [3,4]. To conclude, commonly high air temperature and relative humidity, intensified solar radiation, and generally over cast sky coverage as well as insignificant wind velocity besides heavy rainfalls distinguish the microclimate of this tropical region.

With the rapid development of construction in Malaysia, measures taken to adjust the environment have played an increasingly vital role in ensuring the health and safety of workers. Industrial workers are easier to expose to discomfort and pain during work [5]. Sun and Zhu [6] reviewed many studies on human physiological and psychological response to hot and humid environments. Their results indicated that high temperature and humidity can significantly reduce the temperature difference *in vitro* and *in vivo*, as well as affect metabolic heat diffusion, cause heart failure, increase oxygen consumption, and lead to the onset of other physiological responses. Kielblock *et al.*, [7] identified that the increase in ambient temperature and relative humidity inside a refuge chamber appreciably affects human metabolism. O'Nealet and Bishop [8] conducted experiments using multifarious, but simple, mental performance tests under hot and humid environments. The results showed that consciousness was one of the major factors that were obviously influenced by manual labor in hot and humid environments.

As part of the thermoregulatory process, the human body skin is constantly transferring heat with the surrounding environment. In a thermally comfortable state, substantial differences in the skin temperatures exist across the body, with higher temperatures at the head and torso and lower at the feet and hands. A human body heat loss is governed by a combination of several heat transfer mechanisms such as convection, radiation, respiration and evaporation. As technology has advanced, thermal manikins are the most realistic devices widely used for the assessment of heat and mass transfer from the human body to the environment. Their anatomic shape and their ability to sweat and move provide experimental conditions that are closer to the real human [9]. The number of thermal manikins available and the diversity of their use in research and measurement standards have increased continuously over the past 60 years [10,11]. In this time, the manikin technology has advanced either by improving precision [12] or by reducing production costs [13]. Thermal manikins have proved to be helpful to assess the indoor air quality [14,15], the spread of airborne particles [16-18], and also to calculate the human environment heat transfer coefficients used in numerical simulations of indoor spaces with occupants [19,20].

An evaluation of thermal conditions in industry can be done in one of the following; by using human subjects or by direct measurement of microclimate physical activities or by human shaped or called thermal manikins. Apart from experimental methods, there are usually used computational fluid dynamic (CFD) techniques. As a cost-efficient approach, CFD has been widely employed in the research area of heat transfer in thermal conditions. The human interacts closely with their surroundings by serving as obstacles of airflow, and the major heat source of thermal buoyancy flows [21]. In this work, the purpose of this paper is to investigate the distribution of skin surface temperature under different temperature and different relative humidity.

2. Methodology

2.1 Experimental Facility

Climate chamber, as shown in Figure 1 with sizing of 4.07 m (L) × 4.07 m (W) × 2.5 (H) was used as the simulated working environments. In this study, we adopted seven temperature levels with a combination relative humidity. The designed conditions of simulation for the study construct based

on the design of experiment method and based real case of construction industry climate indicated in Table 1.

Table 1
 Studied thermal conditions set up

No.	Temperature, °C	Relative Humidity, %
1	25	70
2	27	50
3	27	78
4	32	70
5	34	74
6	34	92
7	38	83

This study simulates the manual lifting task at construction industry. In the construction industry, the subjects are demanded to lift a sandbag manually. Therefore, in this study, the weight of the sandbag used is 10 kg to follow the guideline with much lower weight than the maximum [22].

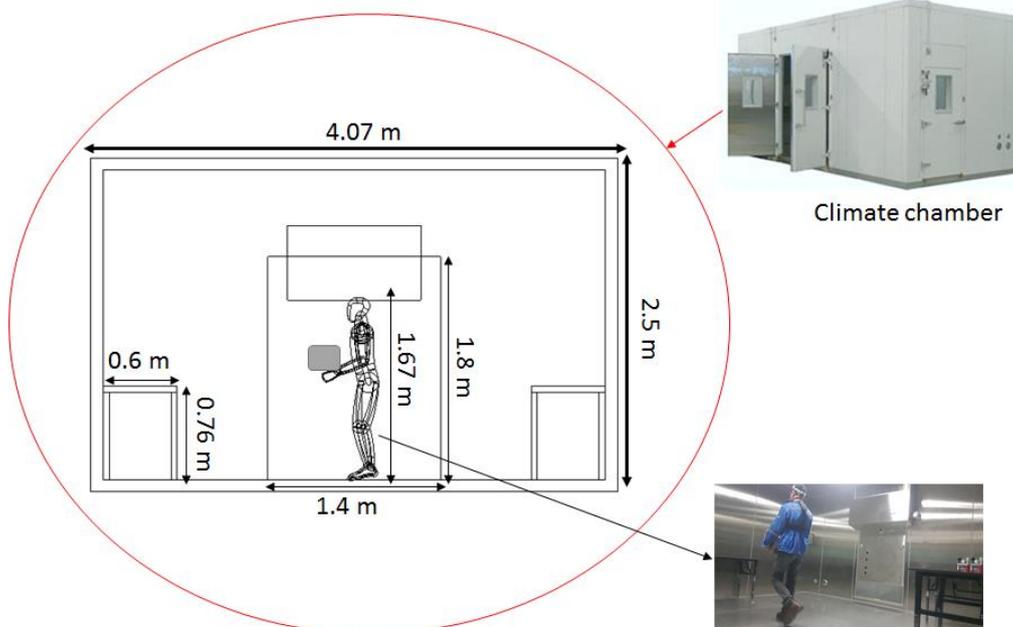


Fig. 1. Computational domain

2.2 Boundary Conditions of CFD Model

Figure 2 present the boundary setting of the working environment. In this study, the ANSYS CFD software program was used to explore a three-dimensional model with steady-state, three-dimensional and non-isothermal conditions assumptions. Thus, the RNG k- ϵ turbulence model was applied to model air turbulence as described in a study by Chen [23], which examined indoor air flow under different turbulence models and concluded that the RNG k- ϵ model was the most accurate model in terms of flow separation, streamline curvature, and flow stagnation.

The boundary conditions in the initial set of the simulations were chosen according to the conditions in the experiment by Nilsson *et al.*, [24,25]. The walls were modelled as no-slip walls with constant, and the evaluated value of wall emissivity was 0.9. The boundary conditions (Figure 2) at

the inlet were the velocity of 0.1 m/s with mean turbulence intensity of 6% (experimental data, [26]). The air was evacuated through two circular openings on the wall.

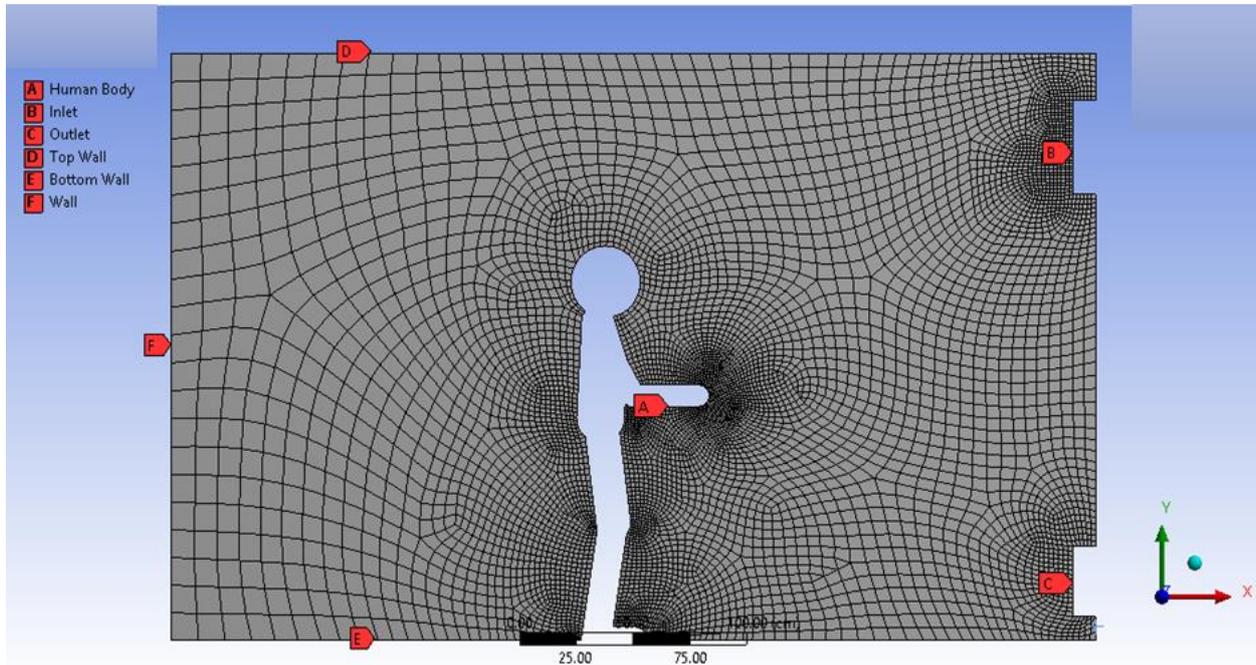


Fig. 2. Mesh with boundary conditions

2.3 Numerical Methodology

The flow of air in the climate chamber was considered as steady, incompressible, low-velocity turbulent flow. The governing equations include the mass conservation, momentum conservation, energy conservation and species diffusion equations are as follows [27]

$$\frac{\partial \rho}{\partial \tau} + \frac{\partial \rho u_i}{\partial x_i} = 0 \quad (1)$$

$$\frac{\partial \rho u_i}{\partial \tau} + \frac{\partial \rho u_j u_i}{\partial x_j} = \frac{\partial \tau_{ji}}{\partial x_j} + \rho f_i \quad (2)$$

$$\frac{\partial \rho t}{\partial \tau} + \frac{\partial \rho u_i t}{\partial x_i} = \frac{\partial}{\partial x_i} (k + ki) \frac{\partial t}{\partial x_i} + S_h \quad (3)$$

$$\frac{\partial \rho m_l}{\partial \tau} + \frac{\partial \rho u_i m_l}{\partial x_i} = \frac{\partial}{\partial x_i} \left(D_l \frac{\partial m_l}{\partial x_i} \right) + S_l \quad (4)$$

where ρ is air density, u_i is the velocity. f_i is unit mass force, τ_{ji} is air Viscous stress. k is heat conductivity coefficient, ki is thermal conductivity due to the effect of turbulence, m_l is the mass of component, l per unit volume, D_l is diffusion coefficient, S_l is the rate of formation of components per unit volume. The convergence of the solution and relevant variables were monitored and the solution was completed when there were no changes between iterations (Figure. 3). In addition, the effects of conservation were also checked. Constitutive equations were proposed to describe the flow and heat transfer mechanism such as power-law fluid model in various of shear stress according to power function of strain rate [28].

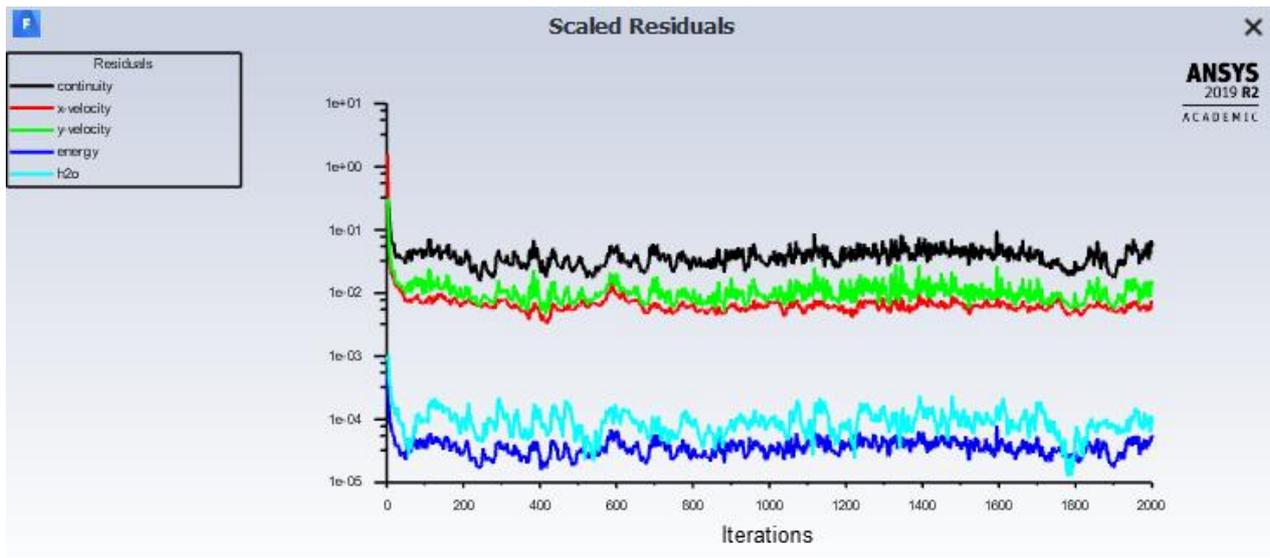


Fig. 3. Solution convergence

3. Results

In Figure 4, the left side of the plot shows the scale of airflow temperature in °C. The effects of supply temperature and relative humidity, flow pattern measuring parameters are investigated. The contour plot in the fluid domain is colour coded and related to the CFD colour map, ranging from 25.0 to 37.0 °C. Figure 4(a) present the air temperature supply is 25 °C, and this figure shows that the temperature increases to the behind of the manikin from the supply level. As observed, the temperature around the manikin range between 32.2 to 37.0 °C. For this case study, the lower temperature was observed near the inlet, which is 26.2 °C. The gradient of the temperature increase with the distance from the inlet where the heat source (manikin) exist is strongly higher than the gradient in the space of the environmental chamber. It was also observed that the temperature near the wall behind the manikin was higher than the area near the inlets, which is 33.4 °C and 28.6 °C.

Figure 4(b) present the air temperature supply is 27 °C, and this result shows that the temperature increases slowly to the behind of the manikin from the supply level. As observed, the temperature around the manikin range between 35.0 to 37.0 °C. For this study, the lower temperature was observed near the inlet, which is 26.8 °C. The gradient of the temperature increase with the distance from the inlet where the heat source (manikin) exist is strongly higher than the gradient in the space of the environmental chamber. It was also observed that the temperature near the wall behind the manikin was higher than the area near the inlets, which is 34.0 °C and 28.9 °C.

Figure 4(c) present the air temperature supply is 27 °C, and this result shows that the temperature slightly increases to the behind of the manikin from the supply level. As observed, the temperature around the manikin range between 34.0 to 37.0 °C. For this case study, the lower temperature was observed near the inlet, which is 27.9 °C. The gradient of the temperature increase with the distance from the inlet where the heat source (manikin) exist is strongly higher than the gradient in the space of the environmental chamber. It was also observed that the temperature near the wall behind the manikin was higher than the area near the inlets, which is 34.0 °C and 28.9 °C.

Figure 4(d) present the air temperature supply is 32 °C. The contour plot in the fluid domain is colour coded and related to the CFD colour map, ranging from 31.9 to 37.0 °C, and the result shows that the temperature increases slowly to the behind of the manikin from the supply level. As observed, the temperature around the manikin range between 36.0 to 37.0 °C. For this case study,

the lower temperature was observed near the inlet, which is 31.9 °C. The gradient of the temperature increase with the distance from the inlet where the heat source (manikin) exist is strongly higher than the gradient in the space of the environmental chamber. It was also observed that the temperature near the wall behind the manikin was higher than the area near the inlets, which is 35.0 °C and 32.9 °C.

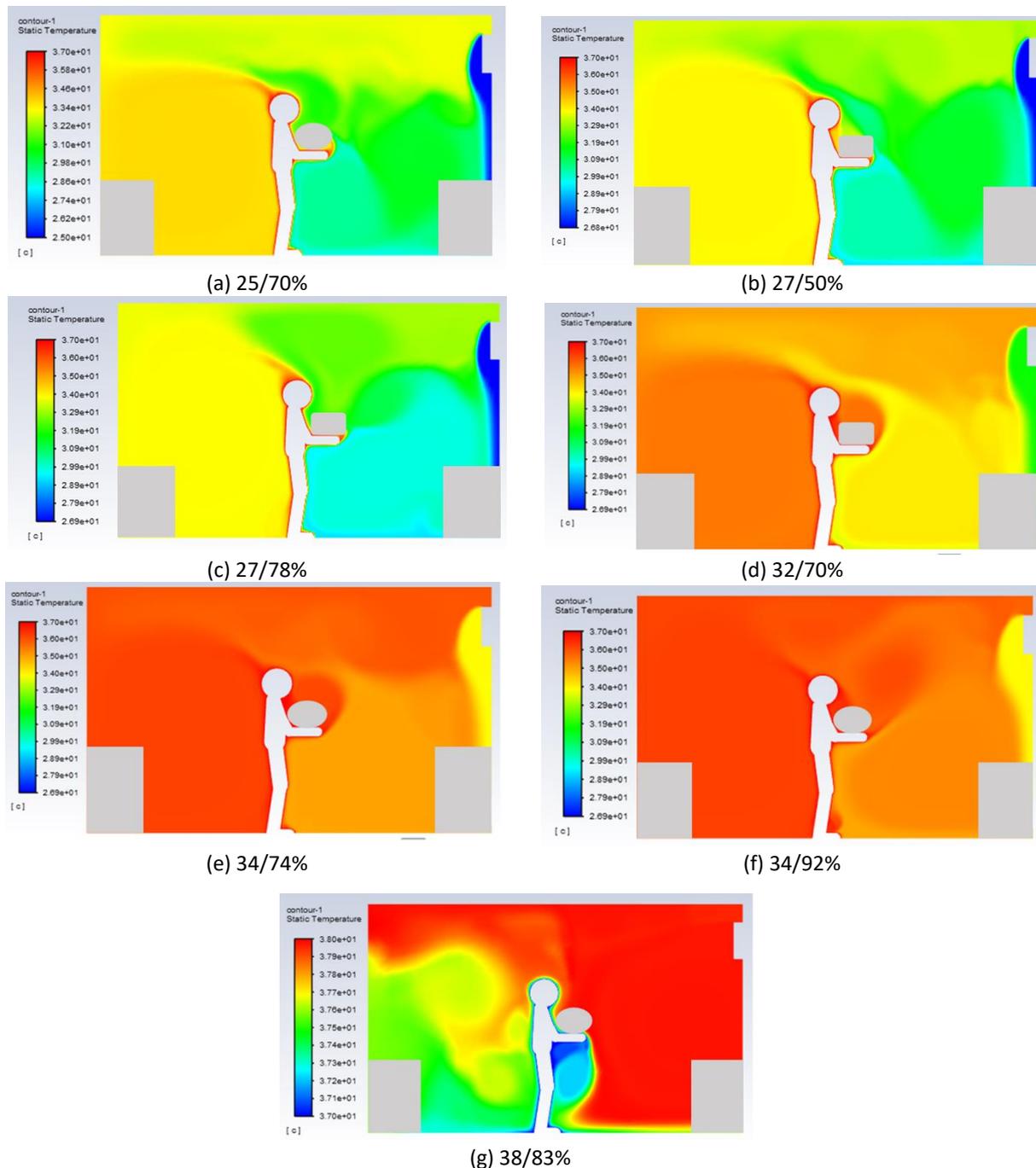


Fig. 4. The distribution of the temperature during work task

Figure 4(e) present the air temperature supply is 34 °C. The contour plot in the fluid domain is colour coded and related to the CFD colour map, ranging from 34.0 to 37.0 °C, and the result shows that the temperature increases to the behind of the manikin from the supply level. As observed, the temperature around the manikin range between 35.0 to 37.0 °C. For this case study, the lower

temperature was observed near the inlet, which is 34.0 °C. The gradient of the temperature increase with the distance from the inlet where the heat source (manikin) exist is strongly higher than the gradient in the space of the environmental chamber. It was also observed that the temperature near the wall behind the manikin was higher than the area near the inlets, which is 37.0 °C and 34.0 °C.

Figure 4(f) present the air temperature supply is 34 °C. The contour plot in the fluid domain is colour coded and related to the CFD colour map, ranging from 34.0 to 37.0 °C and the result shows that the temperature increases to the behind of the manikin from the supply level. As observed, the temperature around the manikin range between 36.0 to 37.0 °C. For this case study, the lower temperature was observed near the inlet, which is 34.0 °C. The gradient of the temperature increase with the distance from the inlet where the heat source (manikin) exist is strongly higher than the gradient in the space of the environmental chamber. It was also observed that the temperature near the wall behind the manikin was higher than the area near the inlets, which is 37.0 °C and 34.5 °C.

Figure 4(g) present the air temperature supply is 38 °C. The contour plot in the fluid domain is colour coded and related to the CFD colour map, ranging from 37.0 to 38.0 °C., and the result shows that the temperature decreases to the behind of the manikin from the supply level. As observed, the temperature around the manikin range between 37.3 to 37.7 °C. For this case study, the lower temperature was observed near the wall behind of the manikin, which is 37.4 °C. The gradient of the temperature increase with the distance from the inlet where the heat source (manikin) exist is strongly higher than the gradient in the space of the environmental chamber. It was also observed that the temperature near the wall behind the manikin was lower than the area near the inlets, which is 37.4 °C and 38.0 °C. The skin temperature in this thermal condition was higher than other thermal conditions. It is thought that the skin temperature is influenced by the high temperature.

4. Discussion

Comparing with other parts, the skin temperatures of the hand and foot changed greater, while the skin temperatures of the chest, back, waist and abdomen changed less. A similar observation was made by Liu *et al.*, [29] that because of a relationship with the distribution of vessels and blood flow. When the ambient temperature is higher than skin temperature, the human body absorbs heat from its ambient environment and evaporation is the sole avenue of heat dissipation from the skin. This study agrees with Luo *et al.*, [30] stated that it is supposed that for the higher climate set points, the temperature differences between the skin. The manikin temperature for hand and feet are lower than in other parts. The reason may be due to the different flow fields. The flow field around the human body is highly dependent on the detailed profile of the body, for instance, the manikin temperature around the arms and feet can be lower than manikin temperature around the back part due to the block of the inlet to the flowing air. The surface temperature within one segment was found quite a bit. According to Kong *et al.*, [31], the non-uniform surface temperature distribution was confirmed, and at least a 1.0 °C surface temperature difference was found on almost all the segments. Each segment always had a higher temperature in the central part and the lower temperature at the edge. This study showed a significant with the previous study stated that the body feature difference of thermal manikins could directly affect the airflow field in the vicinity of the Computational Thermal Manikins (CTMs) and its impact would be enlarged in the upper regions due to the development of the buoyancy-driven thermal plume [32].

Table 2 presents the skin temperature phenomena occurred during the seven thermal conditions setting. As seen, increasing the temperature from 25 to 38 °C, linearly increased the average skin temperature from 31.7 to 37.8 °C. Both temperature and relative humidity had a significant impact on skin temperature. The skin temperature slightly increases with increasing relative humidity; when

temperature was 27 °C, the skin temperature changed significantly when relative humidity increased from 50% to 78%. Also, when temperature was 34 °C, the skin temperature changed significantly when relative humidity (RH) increased from 74% to 92%. These results were similar with Jin *et al.*, [33] that indicated that the greater the increase of the skin temperature caused by an increase in RH. Atmaca and Yigit [34] investigated skin temperature and operative temperature was 26, 30 and 34 °C. Therefore, the author compared the skin temperature in this study with the experimental data obtained by Atmaca and Yigit. When the temperature was 34 °C, in this study skin temperature was 35.6 °C, meanwhile study by Atmaca and Yigit was 35.1 °C. According to NWS [35], the higher heat index (a combination of temperature/relative humidity) is 34 °C/92% and 38 °C/83% in category extreme danger. In this level, the workers feel heat/sunstroke highly likely with continued exposure. Based on simulation data under high temperature and high relative humidity as a tropical climate is a concern. The heat transfer reveals that the skin experiencing high temperature and high relative humidity at the skin temperature of 35.7 °C and 37.8 °C. Meanwhile, the second higher heat index (a combination of temperature and humidity) is 34 °C/74% in category danger at the skin temperature of 35.6 °C.

Table 2
The summary of results skin temperature

No.	Temperature, °C	Relative Humidity, %	Skin temperature, °C
1	25	70	31.7
2	27	50	31.9
3	27	78	32.2
4	32	70	34.7
5	34	74	35.6
6	34	92	35.7
7	38	83	37.8

5. Conclusions

In this study, skin temperature in a simulated heat-exposure experiment in a well-controlled climate chamber were compared with different conditions. The CFD results reveal that all seven conditions provide an effect to the workers in the construction. The heat index shows that when the human working in a hot climate, they feel heat/sunstroke highly or feel heat cramps, or heat exhaustion and heatstroke. This study has shown that skin temperature was influenced significantly by the hot and humid environment.

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