Implication of human skin temperature under high humidity to the construction workers’ by using computational thermal simulation

Ahmad Rasdan Ismail1,2*, Norfadzilah Jusoh1, Nor Kamilah Makhtar3, Raemy Md Zein4, Ismail Abdul Rahman4, Nor Kamaliana Khamis5 and Darliana Mohamad1

1Faculty of Creative Technology & Heritage, Universiti Malaysia Kelantan, 16300 Bachok, Kelantan, Malaysia.
2Centre for Management of Environment, Occupational Safety and Health (CMeOSH), Universiti Malaysia Kelantan, 16300 Bachok, Kelantan, Malaysia.
3Department of Educational Planning and Research, Institute of Teacher Education, Campus Kota Bharu, Kota Bharu, Kelantan, Malaysia
4National Institute of Occupational Safety and Health (NIOSH), 43650 Bandar Baru Bangi, Selangor, Malaysia.
5Department of Mechanical & Materials Engineering, Faculty of Engineering and Built Environment, Universiti Kebangsaan Malaysia, 43600 Bangi Selangor Malaysia.

*Corresponding author, e-mail: rasdan@umk.edu.my

Abstract. Workers in construction are the most in danger to the poor health effects of heat exposure every day. A simulated lifting task based on computational thermal model of the workers in the construction is designed and utilized to study the distribution of skin temperature under two different temperatures (32°C and 25°C) and static relative humidity at 70%. The thermal distribution and simulation for the temperature towards human/manikin body was designed by utilising ANSYS Simulation software. The Computational Fluid Dynamics (CFD) simulation revealed the detailed analysis of the thermal distribution around the body/manikin while conducting lifting activities. The CFD also indicated that case study (32 °C/70%) provided the significant physiological effect to the workers in the construction. The mean skin temperature in this case study is 34.7 °C. The heat index shows that when the human working in a hot climate, they had received significantly heat as high as the heat generated from their surrounding. This experiment concluded that skin temperature was influenced significantly by the tropical climate. This particular study provided potential exploration of the environment heat to the construction workers in Malaysia through the prediction of skin temperature.

1. Introduction

There have been established the impact of high temperature to human performance especially to those human that have to work under tropical climate [1,2]. Malaysia is located in a tropical region, which is exposed to high air temperature, relative humidity, and radiation. In Malaysia, the mean air temperature is 27 °C as yearly, the mean maximum temperatures monthly fluctuated from 33.5 °C in
March/April to 31.9 °C in December. Besides that, the monthly mean minimum temperatures varies from 23.1 °C in January to 24.3 °C in May. Generally, the relative humidity achieves a maximum above 90%, and the mean of relative humidity 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]. Therefore, the high air temperature and relative humidity, intensified solar radiation, and generally over cast sky coverage as well as insignificant air velocity besides heavy rainfalls distinguish the microclimate of this tropical region.

With the rapid development of construction in Malaysia, the action has to take to adjust the environment have played an increasingly important role to make sure 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.

In part of the thermoregulatory process, the human body skin is continually 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].

Assessment of thermal conditions in industry can be done in one of the following; by using human subjects, by direct measurement of microclimate physical activities or by human shaped or called thermal manikins. Apart from experimental methods, there are usually used 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, we study the effect of hot environment in the construction workers. The objective of the study to examined distribution of skin temperature under two different temperatures (32 and 25 °C) and maintained relative humidity at 70%. The main idea is to focus on workers, how skin will react to different climatic situations.

2. Methodology
Climate chamber, as shown in Figure 1 with sizing of 4.1 m (L) × 4.1 m (W) × 2.5 (H) was used as the simulated working environments. In this study, we adopted two temperature levels with a combination similar relative humidity. The designed conditions of simulation for the study are 32 °C/70% and 25 °C/70%.

This experiment 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 [23].
There are four steps of the task done by the subject. This operation is repeated again and again manually for 15 minutes. Total time for completing one single round is 30 s. Additionally, the sand bag had to be lifted and placed at the height of 1 m from the table to another table to minimize repetitive bending, which could assist to body discomfort.

2.1. Boundary conditions
Figure 1 represent the climate chamber 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 [24], 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. [25,26]. 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, [27]). The air was evacuated through two circular openings on the wall.

Figure 2. Boundary condition.

Figure 2. The layout of the environmental chamber: (a) Environmental chamber with empty, (b) Environmental chamber with occupied and (c) Environmental chamber in side view.
2.2. Numerical methodologies
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 [28];

\[
\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0 \tag{1}
\]

\[
\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = \frac{\partial \tau_{ji}}{\partial x_j} + \rho f_i \tag{2}
\]

\[
\frac{\partial t}{\partial t} + \frac{\partial \rho t}{\partial x_i} = \frac{\partial}{\partial x_i} \left( (k + k_i) \frac{\partial t}{\partial x_i} + S_h \right) \tag{3}
\]

\[
\frac{\partial \rho m_l}{\partial t} + \frac{\partial \rho u_i m_l}{\partial x} = \frac{\partial}{\partial x} \left( D_l \frac{\partial m_l}{\partial x} \right) + S_l \tag{4}
\]

where \( \rho \) is air density, \( u_i \) is the velocity, \( f_i \) is unit mass force, \( \tau_{ji} \) is air Viscous stress, \( k \) is heat conductivity coefficient, \( k_i \) 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.

![Figure 3. Solution convergence.](image)

3. Results and Discussion
Figure 4 presents the air temperature supply is 32 °C and the contour plot in colour coded on left side is related to the CFD colour map, ranging from 31.9 to 37.0 °C. 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 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.
Figure 4. The distribution of the temperature during work task under condition at 32 °C/70 %.

Figure 5 present the air temperature supply is 25 °C and the contour plot in colour coded on left side is related to the CFD colour map, ranging from 25.0 to 37.0 °C., and this 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 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.

This study agrees with Luo et al. [29] 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. This is because of the different flow fields. The flow field around the human body is highly based on the detailed side view 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 skin temperature within one segment was observed quite a bit. According to Kong et al. [30], 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 [31].
CFD can provide detailed information about the thermal environment near a human computational manikin, which is difficult and expensive to obtain from the experiments [32,33]. The thermal balance between the human body and the surrounding is strongly dependent upon the boundary conditions [34]. These include the surface skin temperature of the human body, air velocity, relative humidity and radiation temperature of the surrounding.

The normal human body temperature is variable, and the widely accepted average core body temperature is 37.0 °C. Some measure typically defined extreme temperature, for instance, an ambient temperature, the heat index (a combination of temperature and humidity), or wind chill (a combination of temperature and wind speed), exceeding predefined thresholds over several days [35-37]. Table 1 presents the manikin temperature phenomena occurred to the subject during the lifting task. According to NWS [38], in this study, the higher heat index (a combination of temperature and humidity) is 32 °C/70% in category danger. In this level, the subject feel heat cramps, or heat exhaustion and heatstroke.

| No | Case study | Skin temperature (°C) |
|----|------------|-----------------------|
| 1  | 25 °C/70%  | 31.7                  |
| 2  | 32 °C/70%  | 34.7                  |

4. Conclusions
This study examined air temperature around the workers during lifting task in the construction. The air temperature distribution around the human body is examined with the manikin temperature, and lifting and carry the bag. The CFD results reveal that case study 1 gives (32 °C/70%) effect on 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 experiment showed that skin temperature was influenced significantly by the tropical climate. Based on the results, the author concludes that the CFD models can predict the temperature field of the whole climate chamber in the skin temperature tests. Besides that, this study could be explored for future in research on modelling heat transfer to the construction workers in Malaysia and the accurate prediction of hot skin temperature.
Acknowledgment
Authors would like to acknowledge the assistance or encouragement from National Institute of Occupational Safety and Health, Malaysia (NIOSH) by providing technical and financial support to Universiti Malaysia Kelantan (UMK) in conducting this research.

References
[1] Ahmed, K.S., Comfort in urban spaces: Defining the boundaries of outdoor thermal comfort for the tropical urban environments, Energy Building, 35 (2003), 1, pp. 103-110
[2] Niu, J., Liu, J., Lee, T., Lin, Z., Mak, C., Tse K. T., Tang, B., & Kwok, K. C. S. A new method to assess spatial variations of outdoor thermal comfort: On site monitoring results and implications for precinct planning, Building Environment, 91 (2015), pp. 263-270
[3] Makaremi, N., Salleh, E., Jaafar, M. Z., & Hoseini A. H. G., Thermal comfort conditions of shaded outdoor spaces in hot and humid climate of Malaysia, Building Environment, 48 (2012), pp. 7-14
[4] Ghaffarianhoseini, A., Berardi, U., & Ghaffarianhoseini, A, Thermal performance characteristics of unshaded courtyards in hot and humid climates, Building Environment, 87 (2015), pp. 154-168
[5] Ismail, A. R., Mat Daud, K. A., Khidzir, N. Z., Mohd Anwar, M. F., & Mahamad Ali, M. F. Application of visual computer simulation in industrial ergonomics, International Journal of Creative Futures and Heritage, 2 (2014), 1, pp. 1-13
[6] Sun, P. Y., Zhu, N., Study on assessment of high temperature and humidity in working environment on human health, Advanced Material Res., 610 (2013), pp. 739-742
[7] Kielblock, A. J., The functional performance of formal gold mine and colliery refuge bays with special reference to air supply failure, Journal Mine Vent. Soc. S. Afr., 51 (1998), pp. 58-69
[8] O’Neal, E. K., Bishop, P., Effects of work in a hot environment on repeated performances of multiple types of simple mental tasks, International Journal Industrial Ergonomics, 40 (2010), 1, pp. 77-81
[9] Psikuta, A., Allegrini, J., Koeltlen, B., Bogdan, A., Annaheim, S., Martinez, N., Derome, D., Carmeliet, J., & Rossi, R. M. Thermal manikins controlled by human thermoregulation models for energy efficiency and thermal comfort research – A review, Renewable and Sustainable Energy Reviews, 78 (2017), pp. 1315-1330
[10] Holmer, I., Thermal manikin history and applications, Eur Journal Applied Physiology, 92 (2004), 6, pp. 614–618
[11] Wyon, D. P., Use of thermal manikins in environmental ergonomics, Scand J Work Environ Health, 15 (1989), pp. 84-94
[12] Psikuta, A., Bogdan, A., Kuklane, K., & Havenith, G. Opportunities and constraints of presently used thermal manikins for thermo-physiological simulation of the human body, International Journal Biometeorol, 60 (2016), 3, pp. 435-446
[13] Fan, J., Chen, Y. S., Measurement of clothing thermal insulation and moisture vapour resistance using a novel perspiring fabric thermal manikin, Measurement Science Technology, 13 (2002), pp. 1115-1123
[14] Xing, H., Hatton, A., & Awbi, H. B., A study of the air quality in the breathing zone in a room with displacement ventilation, Building Environment, 36 (2001), 7, pp. 809-820
[15] Melikov, A., Kaczmarczyk, J., Measurement and prediction of indoor air quality using a breathing thermal manikin, Indoor Air, 17 (2007), 1, pp. 50-59
[16] Brohus, H., Nielsen, P. V., Personal exposure in displacement ventilated rooms, Indoor Air, 6 (1996), 3, pp. 157-167
[17] Brohus, H., Measurement of indoor air quality by means of a breathing thermal manikin, Dept. of Building Technology and Structural Engineering. Aalborg University, 2000
[18] Shi, S. Li, Y., & Zhao, B., Deposition velocity of fine and ultrafine particles on to manikin surfaces in indoor environment of different facial air speeds, Building Environment, 81 (2014), pp. 388-395

[19] de Dear, R. J. Arens, E., Hui, Z., & Oguro M. Convective and radiative heat transfer coefficients for individual human body segments, International Journal Biometeorol, 40 (1997), 3, pp. 141-156

[20] Quintela, D. Gaspar, A., & Borges, C. Analysis of sensible heat exchanges from a thermal manikin, Eur Journal Applied Physiology, 92 (2004), 6, pp. 663-668

[21] Zukowska, D. Popiolek, Z., & Melikov, A. Impact of personal factors and furniture arrangement on the thermal plume above a human body, in: Proceedings of the 10th International Conference on Air Distribution in Rooms e Roomvent 2007, 2007, pp. 137-144. Helsinki, Finland

[22] Golbabaei, F. Heidari, H., Shamsipour, A., Forushani, A. R. & Gaeni, A., A new Outdoor Environmental Heat Index (OEHI) as a simple and applicable heat stress index for evaluation of outdoor workers, Urban Climate, 29 (2019), pp. 100479

[23] Department of Occupational Safety and Health (DOSH), Guidelines for Manual Handling at Workplace, 2018

[24] Chen, Q., Comparison of different k-ε models for indoor air flow computations, Numerical Heat Transfer Part B Fundamental, 28 (1995), pp. 353-369

[25] Nilsson, H. et al., CFD modeling of thermal manikin heat loss in a comfort evaluation benchmark test, Proceedings Roomvent 2007: 10th International Conference on Air Distribution in Buildings, Helsinki, Finland, 2007

[26] Nilsson, H. O. Brohus, H., & Nielsen, P. V., Benchmark test for a computer simulated person – Manikin heat loss for thermal comfort evaluation, Aalborg University Denmark and Gävle University, Aalborg, Sweden, 2007

[27] Luo, N. Weng, W. G., Fu, M., Yang, J., & Han, Z. Y. Experimental study of the effects of human movement on the convective heat transfer coefficient, Experimental Thermal and Fluid Science, 57 (2014), pp. 40-56

[28] Versteeg, H K and Malalasekera W. 2007. An Introduction to Computational Fluid Dynamics: The finite method (2nd Edition). Pearson Education Limited: Edinburgh Gate

[29] Luo N, Weng WG, Fu M, Yang J, Han ZY. 2014. Experimental study of the effects of human movement on the convective heat transfer coefficient. Experimental Thermal and Fluid Science. 57: 40-56.

[30] Kong M, Dang TQ, Zhang J, and Khalifa HE. 2017. Micro-environmental control for efficient local cooling. Building and Environment. 118: 300-312

[31] Yan Y, Li X, Yang L, Tu J. 2016. Evaluation of manikin simplification methods for CFD simulations in occupied indoor environments. Energy and Buildings. 127: 611-626.

[32] Gao N and Niu J, CFD Study of the Thermal Environment around a Human Body: A Review, Indoor and Built Environment, pp. 5-16 (2005)

[33] Kilic M and Sevilgen G, Modelling airflow, heat transfer and moisture transport around a standing human body by computational fluid dynamics, International Communications in Heat and Mass Transfer 35, pp. 1159-1164 (2008)

[34] Teixeira S, C P. Leão, M Neves, P Arezes, A Cunha, J C Teixeira. 2010. Thermal comfort evaluation using a cfd study and a transient thermal model of the human body. V European Conference on Computational Fluid Dynamics ECCOMAS CFD 2010, Portugal. 1-13.

[35] Barnett, A.G., S. Hajat, A. Gasparrini, and J. Rocklöv, 2012: Cold and heat waves in the United States. Environmental Research, 112, 218-224.

[36] Lavigne, E., A. Gasparrini, X. Wang, H. Chen, A. Yagouti, M.D. Fleury, and S. Cakmak, 2014: Extreme ambient temperatures and cardiorespiratory emergency room visits: Assessing risk by comorbid health conditions in a time series study. Environmental Health, 13, 5.
[37] Lippmann, S.J., C.M. Fuhrmann, A.E. Waller, and D.B. Richardson, 2013: Ambient temperature and emergency department visits for heat-related illness in North Carolina, 2007-2008. Environmental Research, 124, 35-42.

[38] National Weather Services (NWS). 2014. Beat the heat weather ready nation campaign. National Oceanic and Atmospheric Administration