The Development of New Generation of Manikin for Outdoor Thermal Comfort Evaluation – A Literature Review

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Abstract. Urban Heat Island (UHI) is a challenge to human in the following decade as a result of continuous urbanization without appropriate planning and design. The impacts of UHI will getting worse due to the increase of population density with improper urban development especially in dense metropolitan cities. In the point of view of outdoor thermal comfort, a prolonged exposure to the outdoor heat will significantly contribute to human discomfort and health problems. Therefore, various research efforts have been implemented for developing solutions the mitigation strategies. The development of thermal manikin is one of mitigation effort to investigate the occurrence of UHI and to evaluate thermal comfort in microclimate conditions as representative of human simulation model. Hence, the aim of this paper is focused on the consideration that are required to develop a thermal manikin for outdoor thermal comfort assessment which include outdoor thermal comfort index, development of thermal manikin and material for thermal manikin for outdoor thermal comfort assessment.

1.0 Introduction
Urbanization can drive the economic growth of a place and it is important specially to developing nation. However, without proper planning and carefully designed, it usually creates social problems that related to the environment [1]. For instance, rapid urbanization has changed the urban microclimate and caused the Urban Heat Island (UHI) problem. Recently, it is reported that the intensities of UHI is continuing to increase, especially, in big cities [2-3]. Due to UHI, air temperatures in urban areas are rising and causing an increase in heat-related deaths in recent years [4-5]. Moreover, this hot condition reduces the quality of outdoor thermal comfort and frequent exposure to this condition has increase the heat-related illness [6-8]. Therefore, frequent assessment to determine the level comfort of outdoor environments is important to ensure the health of individuals at outdoor environment is maintained.

Generally, the assessment of outdoor thermal comfort by subjective survey includes the exposure of respondents to the direct sunlight. However, this method is discouraged as it may exposed the respondent to uncomfortable situation and possibly will affect the health of the individual. Therefore, it is important to find a replacement of actual human body such as thermal manikin to assess thermal comfort under microclimate conditions [9-10]. It was reported that thermal manikin is able evaluate human thermal interaction with the surrounding environments [11]. A fairly accurate outdoor thermal comfort assessment by using thermal manikin can be obtained by considering the human factors such as physiological mechanism of thermoregulation by thermal manikin, thermal perception and assessment of thermal comfort indices based on meteorological data [12].
One of consideration in developing the thermal manikin for the assessment of thermal comfort is the ability of the manikin to simulate the human skin perspiration. Therefore, the application of porous material for developing the thermal manikin is seems to have potential for that purpose. This is due to the porous material has a capillary effect and the formation of a damp layer on the outer surface of porous material is almost similar to human skin [13]. In detail, a study by Mendes and Silva [13] highlighted that a porous material made of plaster, white clay and red clay has a potential to simulate evaporation in human sweating mechanism. However, there are still lack of documentation that reported the application of porous material on thermal manikin model for thermal comfort assessment. Hence, the aim of this paper is focused on the consideration that are required to develop a thermal manikin for outdoor thermal comfort assessment.

2.0 Literature Review

2.1 Outdoor Thermal Comfort and Assessment Parameter for Thermal Manikin

Thermal comfort is influenced by metabolic rate, clothing insulation, air temperature, relative humidity, wind speed and solar radiation to maintain thermal neutrality [14]. Thus, a person’s feeling of comfort is associated with the heat balance of the human body through metabolic processes and heat lost. Therefore, it is vital to enhance understanding of the heat exchange between the human body and the prevailing environmental through specific climate variables for thermal comfort studies [15]. Meanwhile, recent thermal comfort survey indicates that increasing comfort temperature will limits the response by the actual human respondent and the design requirements for outdoor spaces in hot and humid region [16].

In outdoor extreme environments, the thermal comforts and sensations are complex in terms of the human body's physiological and psychological responses. Hoppe [17] mentioned that the physiological and psychological factors needed to be considered assessing indoor or outdoor thermal comfort. Moreover, a study by Thorsson et al. [18] conclude that relying only on physiological approach for outdoor thermal comfort assessment is inadequate to characterize the comfort conditions for outdoors. Additional considerations that include thermal adaptation, climatic conditions and thermal perceptions (psychological factors) should be included in the assessment of thermal environments [18]. Then, investigation should be made to correlate the physiological and psychological factors of the human body within the microclimate environment for further development and improvement of human thermal comfort evaluation [19]. Therefore, the human sweat loss and human perception have a potential to be considered physiology and psychology thermal comfort parameters, respectively. The human sweat loss is the parameter that can reflects the heat exchange occurring between the human body and its thermal environment [20] which can be related with the usage of porous material with surrounding environment.

2.2. Thermal Comfort Indices for Outdoor Comfort Evaluation

The impacts of climate change on global temperatures are discussed in several reports [21]. Serious health problems especially heat stress and heat stroke results from the exposure of extreme weather condition to children, adults, and the elderly. Climate change and higher heat stress in cities results from urbanization, has increased the interest in the research study assessing thermal comfort. A thermal comfort index is a single value that combines the effects of various parameters in each human thermal environment, and its value varies depending on the individual's thermal strain [22]. Therefore, human discomfort is measured by various quantitative thermal comfort indices [23].

Haldane was the first in suggesting in 1905, that the wet-bulb temperature is the most suitable method to measure heat stress [24]. Since 1950, numerous studies have explored human thermal comfort in both indoor and outdoor environments, resulting in a number of mathematical and schematic comparisons [25]. About 60 thermal comfort indexes have been proposed to measure high-temperature environments and estimate the likelihood of body heat strain [23]. These indices are classified into three categories: analytical/rational (based on human thermal exchange principles), experimental (based on human reaction to different environmental factors), and comfort-based (quantified by human experiments) [26].
Based on Potchter et al. [27], Universal Thermal Climate Index (UTCI), Wet Bulb Wet temperature (WBGT) and Heat Index (HI) is suitable for thermal comfort evaluation for all types of climates. Table 1 presents the main characteristics of these indices. However, previous research has reported that UTCI, WBGT and HI has been adopted as indices for thermal comfort evaluation in Malaysia. Hanipah [29] used UTCI index to evaluate heat stress in Malaysia [28]. WBGT index is another most widely used and accepted index for the assessment of heat stress in Malaysia. Estimation of heat stress based on the WBGT can be referred to ISO 7243 [29]. In 2017, Suparta and Yatim [30] investigate the heat stress trends in East Malaysia. The researcher used to choose the National Weather Services (NWS) method, which was developed by Rothfusz [31] based on the Steadman [32] for calculating Heat Index. The method was widely used in order to produce of weather warnings in real-life situations. NWS has modified this index for operational purposes such as specific ranges to health effects and extreme heat warnings when needed [30]. Hence this study intended, to adopt UTCI, WBGT and HI as thermal comfort evaluation based on confirmation from previous study in Malaysia.

### Table 1. The main characteristics of the most used indices in outdoor thermal perception studies.

| Index (unit) | Reference | Thermal sensation categories | Suitable climate | Thermal scale designation |
|-------------|-----------|-----------------------------|------------------|--------------------------|
| UTCI (°C)   | [28]      | 10 points scale             | All climates     | Intended for wide range of weather and climates [33] |
| WBGT (°C)   | [29]      | 5 points scale              | Hot climates     | Scaled for hot climates   |
| HI (°C)     | [30]      | 4 points scale              | All climates     | Intended for wide range of weather and climates [34] |

As the research of thermal manikins has gained more interest, it is now possible to use thermal comfort indices based on climatic parameters to assess human thermal comfort in an outdoor environment [12]. The knowledge gap is existing there, where not a single manikin used to evaluate human discomfort based on thermal comfort indices. However, the correlation between porous material and thermal comfort indices can be established in this preliminary to assess. This is to assess the effect of the human body in different conditions without exposing it to intense sunshine or the outdoor environment.

### 2.3. Thermal Manikin

Thermal manikins were developed at least half a century ago to improve the understanding of the relationship between the human body and the surrounding environment in order to distinguish the thermal behaviour of different construction materials [15]. They are widely used to analyse the human body and its environment’s thermal interface. The direct method of exposing the human body to outdoor environment, however, is discouraged due to the induction of health issues. As a result, thermal manikins were created to help researchers better understand the relationship between the human body and its surroundings [11,15]. Similarly, the manikins will determine how much perspiration is transmitted from the skin to the environment in a specific ambient condition. The number of sweating thermal manikins has gradually increased as modern technology has advanced, and many modern thermal manikins are built with a sweating capability [35].

Recent advancements in sweating manikins have made it possible to simulate the human thermal interaction with the environment even more realistically [11,20]. This manikin can be used to measure the effect of the human body as well as simulate human responses in thermal environments [11]. As for the sweating manikin, the measurement is only done in indoor with the goal of creating a better and...
more realistic simulation of the human body [19]. This is because the manikins in operation can simulate human sweating, provide valuable information on heat exchange for evaporation and predict human thermal responses to hot and cold environments for later use in practical applications [19]. There are few manikins have been developed to simulate human responses towards thermal environments. Thus, Table 2 summarizes the using of sweating manikin by previous researcher.

Table 2. Previous researchers used a sweating manikin to assess the effect of the human body responses in thermal environments.

| Sweating Manikin                        | Material                        | Features                                                                 | Year/Reference |
|----------------------------------------|---------------------------------|--------------------------------------------------------------------------|----------------|
| Japanese sweating thermal manikin “Taro” | Porous bronze                  | The material of this manikin is in bronze which simulate the human body’s perspiration. The manikin tested is under control chamber which is indoor. | 1992 [36]     |
| Finnish sweating thermal manikin “Coppelius”: | Nonwoven inner layer and microporous outer layer | The manikin tested is under control chamber which is indoor. | 1999 [37]     |
| Hong Kong sweating thermal manikin “Walter” | Polytetrafluoroethylene Gortex membrane | Walter manikin can simulate the real life perspiration of human beings. The manikin is using computer control under control chamber. | 2002 [38]     |
| Japanese sweating thermal manikin “KEM” | Porous material that is used in “Coppelius” | The manikin tested is under control chamber which is indoor. | 2004 [39]     |
| United States sweating thermal manikin “ADAM” | Porous metal | The manikin is using computer control under control chamber. | 2004 [40]     |
| Swiss sweating thermal manikin “SAM” | Plastic | The manikin can simulate realistic human motion and perspiration. This manikin can move through various curves under computer control. | 2001 [41]; 2006 [42] |
| United States sweating thermal manikin “Newton” | Carbon-epoxy composite | The manikin is using computer control under control chamber. | 2008 [43]     |

There is few sweating manikins has been used worldwide with different material [35]. To date, there hasn't been a sweating manikin that made of red clay, white clay, or plaster. However, in 2004, Mendes and Silva had used the porous material of plaster, white clay and red clay to simulate human perspiration and they stated that the porous material has the capillary effect and formation of a humid layer on the external surface of the porous material which is almost similar to human skin [13]. Based on theory, porous materials have shown the ability to simulate evaporation in the human sweating mechanism. However, due to their study limitations, the researchers never compared actual human sweat loss to the porous material. The knowledge gap is existing there.

By the same time, current sweating manikins are mostly used in indoor environments, where they are installed in a climatic chamber and connected to a power supply through a computer-controlled system to investigate the necessary parameters. These parameters are mostly used to investigate human thermal comfort by simulating human parameters such as sweat rates in a controlled condition rather than investigate it on outdoor thermal comfort. Based on Lee et al. [1], the application of sweating manikin is mainly focused to the indoor environment despite of outdoor environment. However, the
assessment of thermal comfort not only depending climatic variables but is also depending on the physiology and psychology factor. In order to obtain a better assessment of human thermal comfort, adequate data with these three aspects must be established along with a set of indices.

2.4 Porous Materials in Simulating Sweat Rate Evaporation

Ancient civilizations were aware of and used the unique properties of porous materials when wet, such as the cooling effect near the surface caused by heat extraction during water evaporation. During sweat evaporation of the sweat which had formed on the human body’s external surface, the amount of the energy that being utilized to change the sweat molecules from liquid to gas form induces a cooling effect. The same cooling effect takes place in a hollow vessel with porous material. When the hollow vessel is being filled with water and the permeability of the vessel’s wall in it’s a suitable range, it is possible to create a uniform of humidified layer on the external surface. The necessary heat for sweat evaporation is produced by the cutaneous surface during human perspiration, which causes a temperature drop similar to that observed in a wet porous material. This method creates a decent potential for simulating the human sweat mechanism and also quantifying the impact of latent heat losses on the human thermal balance for the given surrounding [13].

The porous material's cooling effect and evaporation rate are based on air temperature and they are nearly identical to that of human skin. This is because the porous material has the capillary effect and formation of a humid layer on the external surface of the porous material which is almost similar to human skin [13]. Therefore, porous material is suitable to simulate human sweat evaporation rate. This represents a step forward in simulation of the sweating mechanism. Furthermore, the researcher found that all three porous materials tested had good sensitivity in terms of evaporation rate response to environmental variables [13]. Therefore, porous material such as red clay, white clay and plaster can be used as the material to fabricate new generation of thermal manikin in future.

3. Conclusion

This paper presents the related literatures in developing the thermal manikin for outdoor thermal comfort assessment. Evaluation of thermal comfort is crucial as the process of urbanization is continuing and the effect of UHI becomes more significant. People at outdoor are more prone to thermal discomfort such as heat stress since the increasing of the air temperature due to effect of UHI. The increase in outdoor temperature will influence the indoor temperature, in which return can lead to thermal discomfort. As for developing thermal manikin for outdoor thermal comfort assessment, it was found the human sweat loss and human perception is the most important parameters to be considered that covers the aspect of physiology and psychology of thermal comfort, respectively. Meanwhile, the suitable thermal comfort index to be used in hot humid climate was identified to be the Universal Thermal Climate Index (UTCI), Wet bulb Globe Temperature (WBGT) and Heat Index (HI). Finally, the suitable porous material that can be considered to develop the thermal manikin are the red clay, white clay, and plaster. These materials have the potential to simulate human sweat evaporation rate for thermal comfort evaluation in future. These findings have significant implication, particularly to researchers in developing a better prediction of outdoor thermal comfort in future work.

4. References

[1] Lee Y Y, Din M F M, Noor Z Z, Iwao K, Taib S M, Singh L, Khalid N H A, Anting N and Aminudin, E 2018 Surrogate human sensor for human skin surface temperature measurement in evaluating the impacts of thermal behaviour at outdoor environment, Measurement 118 61-72

[2] Dos Santos A R, De Oliveira F S, da Silva A G, Gleriani J M, Gonçalves W, Moreira G L, Silva F G, Branco E R F, Moura M M, da Silva R G and Juvanhol R S 2017 Spatial and temporal distribution of urban heat islands, Science of the Total Environment 605 946-956

[3] Yao R, Wang L, Huang X, Niu Z, Liu F and Wang Q 2017 Temporal trends of surface urban heat islands and associated determinants in major Chinese cities, Science of the Total Environment 609 742-754
[4] Shahmohamadi P, Che-Ani A I, Maulud K N A, Tawil N M and Abdullah N A G 2011 The Impact of Anthropogenic Heat on Formation of Urban Heat Island and Energy Consumption Balance, Urban Studies Research 2011 1-9

[5] Kodera S, Nishimura T, Rashed E A, Hasegawa K, Takeuchi I, Egawa R and Hirata A 2019 Estimation of heat-related morbidity from weather data: A computational study in three prefectures of Japan over 2013–2018, Environment International 130 104907

[6] Na W, Jang J Y, Lee K E, Kim H, Jun B, Kwon J W and Jo S N 2013 The effects of temperature on heat-related illness according to the characteristics of patients during the summer of 2012 in the Republic of Korea, Journal of Preventive Medicine and Public Health 46 19-27

[7] Gu S, Huang C, Bai L, Chu C and Liu Q 2016 Heat-related illness in China summer of 2013, International journal of biometeorology 60 131-137

[8] Ministry of Health Malaysia MOH 2016 Planning division Health Informatics Centre (Malaysia: Kementerian Kesihatan Malaysia)

[9] Cheong K W D, Yu W J, Kosonen R, Tham K W and Sekhar S C 2006 Assessment of thermal environment using a thermal manikin in a field environment chamber served by displacement ventilation system, Building and environment 41 1661-1670

[10] Nilsson H O 2007 Thermal comfort evaluation with virtual manikin methods, Building and Environment 42 4000 - 4005

[11] Holmer I 2004 Thermal manikin history and applications, European Journal of Applied Physiology 92 614–618

[12] Djongyang N, Tchinda R and Njomo D 2010 Thermal comfort: A review paper, Renewable and Sustainable Energy Reviews 14(9) pp 2626–2640

[13] Mendes J C A F and Silva M C G 2004 On the use of porous materials to simulate evaporation in the human sweating process, European Journal of Applied Physiology 92 654–657.

[14] Taleghani M, Tenpierik M, Kurvers S and van den Dobbelsteen A 2013 A review into thermal comfort in buildings, Renewable and Sustainable Energy Reviews 26 201-215.

[15] Gao N P and Niu J L 2005 CFD study of the thermal environment around a human body a review, Indoor and built environment 14 5-16

[16] Wijewardane S and Jayasinghe M T R 2008 Thermal comfort temperature range for factory workers in warm humid tropical climates, Renewable Energy 33 2057-2063.

[17] Hoppe P 2002 Different aspects of assessing indoor and outdoor thermal comfort, Energy and Buildings 34 661–665

[18] Thorsson S, Lindqvist M and Lindqvist S 2004 Thermal bioclimatic conditions and patterns of behaviour in an urban park in Goteborg Sweden, International Journal of Biometeorology 48 149–156

[19] Lee Y Y, Md Din M F, Ponraj M, Noor Z Z, Iwao K and Chelliapan S 2017 Overview of Urban Heat Island UHI phenomenon towards human thermal comfort, Environmental Engineering and Management Journal 16 2097–2112

[20] Yang J, Weng W and Fu M 2014 Coupling of a thermal sweating manikin and a thermal model for simulating human thermal response, Procedia Engineering 84 893–897

[21] Diffenbaugh N S and Ashfaq M 2010 Intensification of hot extremes in the United States, Geophysical Research Letters 37 1-5

[22] Parsons K C 2003 Human thermal environments the effect of hot moderate and cold environments on human health comfort and performance (New York: Taylor and Francis)

[23] Burton I, Ebi K L and McGregor G 2009 Biometeorology for adaptation to climate variability and change In Biometeorology for Adaptation to Climate Variability and Change eds K L Ebi, Burton I and McGregor G (Netherlands: Springer Netherlands) chapter 1 pp 1-5

[24] Haldane J S 1905 The influence of high air temperatures No I, Epidemiology and Infection 5 494-513

[25] Abdel-Ghany A M, Al-Helal I M and Shady M R 2013 Human thermal comfort and heat stress in an outdoor urban arid environment a case study, Advances in Meteorology 2013 1-7
[26] Pantavou K and Lykoudis S 2014 Modeling thermal sensation in a Mediterranean climate-a comparison of linear and ordinal models, *International Journal of Biometeorology* 58 1355-1368

[27] Potchter O, Cohen P, Lin T P and Matzarakis A 2018 Outdoor human thermal perception in various climates: A comprehensive review of approaches, methods and quantification, *Science of the Total Environment* 631 390–406

[28] Hanipah M H, Abdullah A H, Sidik N A C, Yunus R, Yasin M N A and Yazid M N W M 2016 Assessment of outdoor thermal comfort and wind characteristics at three different locations in Peninsular Malaysia, *MATEC Web of Conferences* 47 04005

[29] DOSH 2016 *Guidelines on Heat Stress Management at Workplace* (Malaysia: Ministry of Human Resources Malaysia)

[30] Suparta W and Yatim A N M 2017 An analysis of heat wave trends using heat index in East Malaysia, *Journal of Physics: Conference Series* 852 012005

[31] Rothfusz L P and Headquarters N S R 1990 The heat index equation (or, more than you ever wanted to know about heat index) Retrieved on March 22, 2021 from https://wonder.cdc.gov/wonder/help/Climate/ta_htindex.PDF

[32] Steadman R 1979 The assessment of sultriness. Part I: a temperature-humidity index based on human physiology and clothing science, *Journal of Applied Meteorology* 18 861–873

[33] Blažejczyk K, Broede P, Fiala D, Havenith G, Holmér I, Jendritzky G, Kampmann B and Kunert A 2010 Principles of the new Universal Thermal Climate Index (UTCI) and its application to bioclimatic research in European scale, *Miscellanea Geographica* 14 91-102

[34] Delworth T L, Mahlman J D and Knutson T R 1999 Changes in heat index associated with CO2-induced global warming, *Climatic Change* 43 369-386

[35] Nayak R and Padhye R 2017 *Manikins for Textile Evaluation* (Duxford: Woodhead Publishing)

[36] Dozen Y, Aratani Y, Saitoh T, Tsuchida K, Harada K and Takenishi S 1992 Modeling of sweating manikin, *Journal of Textile Machinery Society of Japan* 38 101–112.

[37] Meinander H 1999 Extraction of data from sweating manikin test *Proceedings of the Third International Meeting on Thermal Manikin Testing (3IMM)* (Stockholm)

[38] Fan J T and Chen Y S 2002 Measurement of clothing thermal insulation and moisture vapor resistance using a novel perspiring fabric thermal manikin, *Measurement Science and Technology* 13 1115–1123

[39] Fukazawa T, Lee G, Matsuoka T, Kano K and Tochihara Y 2004 Heat and water vapor transfer of protective clothing system in a cold environment measured with a newly developed sweating manikin, *European Journal of Applied Physiology* 92 645–648

[40] Rugh J P, & Bharathan D 2005 Predicting Human Thermal Comfort in Automobiles Retrieved on March 22, 2014 from https://www.researchgate.net/publication/228625768_Predicting_Human_Thermal_Comfort_in_Automobiles

[41] Richards M G and Mattle N G 2001 Development of a sweating agile thermal manikin SAM *4th International Meeting on Thermal Manikins* (St Gallen, Switzerland)

[42] Richards M G, Psikuta A and Fiala D 2006 Current development of thermal sweating manikins at Empa, *Thermal Manikins and Modelling* 173–179

[43] Wang F 2008 A comparative introduction on sweating thermal manikin Newton and Walter *Proceedings of the 7th International Meeting on Thermal Manikin and Modeling* (University of Coimbra)

**Acknowledgements**

The authors would like to express gratitude to the Malaysian Ministry of Higher Education and Research Management Centre of Universiti Tun Hussein Onn Malaysia for financially support under Postgraduates Research Grants (GPPS) Vote No. U944 and TIER 1 grant under Vote No. H079. The support of Faculty of Built Environment, Universiti Teknologi Malaysia is also appreciated.