IMPACT OF THERMAL BEHAVIOUR ON OUTDOOR HUMAN THERMAL COMFORT IN TROPICAL CLIMATE

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DEDICATION

Dedicated to my beloved family members and husband, *Yeong Huei*

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ABSTRACT

In recent years, the challenges of the urban environment have been identified as urban heat island phenomenon due to the impacts of thermal behaviour from the surrounding built-up environment, with a low surface albedo. Their impacts on individuals are getting worse due to improper urban building designs with albedo modification that changed thermal behaviour in cities which in turn affects the quality of thermal comfort, especially in tropical countries. Therefore, this research aims to evaluate human thermal comfort by developing a preferable range of Discomfort Index (DI) interpretation for tropical climate. Next, the study integrates the application of a Surrogate Human Sensor (SHS) with measurements of climatic variables. Following this, Heat Stress Index (HSI) and Thermal Comfort Index (TCI) are established, using the correlation of the thermal perception with SHS and climatic variables measurement for evaluating thermal comfort in outdoor spaces. In-situ field measurements were carried out to analyse the impacts of thermal behaviour and its relationship to human discomfort. Human discomfort levels were evaluated using Thom's DI and a new extended DI range of 20°C to 28.9°C for "partially comfortable". It was proposed in association with local climate as a result of thermal adaptability. Outdoor thermal sensations for the outdoor environment can be assessed using questionnaire surveys and a SHS model that was initially developed as a sensor to receive data on the impacts of thermal behaviour. SHS significantly reflects the impacts of thermal behaviour from the surrounding ambient environment towards human skin surface and found to be useful as a simple sensor, or indicator, for pre-assessing thermal conditions and comfort. In this study, two factors, i.e. climatic and psychological factors, are taken into consideration. Within this combination, SHS acts like a sensor to predict the thermal responses of people with respect to the influence from climatic variables. Thermal perception regression models, which represent the HSI, and SHS temperature regression models were developed based on the local microclimate environment. With this correlation, TCI was established where it enhances the understanding of the relationship between human psychologies and the climatic environment using SHS. Then, the SHS can be used to identify the perception level of the people as the SHS correlated with the thermal perception and surrounding climate measurements. All the regressions established were verified through execution in the real case scenarios by comparing the observed and predicted outputs. These verifications have shown that the regressions may be suitably applied in all tropical climate locations, especially in Malaysia, to evaluate correctly outdoor thermal comfort.

ABSTRAK

Sejak kebelakangan ini, persekitaran bandar telah mengalami cabaran besar yang dikenal pasti sebagai fenomena pulau haba bandar yang disebabkan oleh kesan haba daripada permukaan pembinaan yang mempunyai albedo rendah. Kesannya semakin teruk disebabkan oleh rekabentuk bangunan bandar yang tidak mesra dengan pengubahsuaian albedo yang akan mempengaruhi kesan haba di bandar, seterusnya akan menjejaskan kualiti keselesaan haba terutama di negara-negara tropika. Oleh itu, kajian ini bertujuan untuk menilai keselesaan haba dengan membangunkan satu julat baru yang lebih sesuai untuk penentuan Indeks Ketidakselesaan (DI) pada iklim tropika. Seterusnya, kajian ini mengintegrasikan penggunaan "*Surrogate Human Sensor*" (SHS) dengan mengunakan nilai pembolehubah iklim. Di samping itu, Indeks Haba Tekanan (HSI) dan Indeks Keselesaan Haba (TCI) juga dirangka dengan menggunakan korelasi di antara persepsi haba dengan pengukuran pembolehubah iklim dan SHS untuk menilai keselesaan haba di persekitaran luar. Pengukuran di tapak telah dijalankan untuk menganalisis kesan haba dan kaitannya dengan ketidakselesaan manusia. Tahap ketidakselesaan manusia dinilai menggunakan *Thom's* DI dan DI lanjutan baru dengan julat di antara 20°C hingga 28.9°C untuk "separa selesa". Ini adalah julat yang dicadangkan bagi iklim tempatan sebagai hasil penyesuaian haba. Selain itu, kepekaan haba untuk persekitaran luar boleh dinilai dengan menggunakan soal selidik dan SHS telah dibangunkan sebagai sensor untuk menerima data daripada kesan haba. SHS boleh mencerminkan kesan haba dari persekitaran ke permukaan kulit manusia dan didapati sangat relevan digunakan sebagai sensor mudah atau penunjuk untuk pra-penilaian keselesaan haba. Dalam kajian ini, dua faktor iaitu iklim dan psikologi juga diambil kira. Dengan gabungan ini, SHS bertindak sebagai sensor untuk meramalkan tindak balas haba terhadap pengaruh dari pembolehubah iklim. Regresi persepsi haba, yang juga diwakili oleh HSI, dan regresi SHS telah dibangunkan berdasarkan persekitaran kajicuaca tempatan. Menerusi korelasi ini, TCI akan dihasilkan serta ia dapat meningkatkan pemahaman antara hubungan psikologi manusia dengan persekitaran iklim menggunakan SHS. Dengan itu, SHS boleh digunakan untuk mengenalpasti tahap persepsi manusia kerana SHS menunjukkan korelasi yang nyata dengan persepsi dan pengukuran cuaca persekitaran. Semua regresi yang dijana disahkan melalui pelaksanaan senario kes sebenar dengan perbandingan output pemerhatian dan ramalan. Pengesahan ini telah menunjukkan regresi yang dijana boleh digunakan pada semua lokasi beriklim tropika, terutamanya di Malaysia, untuk penilaian keselesaan di persekitaran luar.

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LIST OF EQUATIONS

LIST OF SYMBOLS

clo	-	Clothing Insulation Unit
mtoe	-	Million Tons of Oil Equivalent
RH	-	Relative humidity
v	-	Wind speed
β	-	Slope (hypothesis test)
s	-	Standard error
H_A	-	Alternative hypothesis
T_a	-	Ambient temperature
$SHS_{average}$	-	Average temperature at Surrogate Human Sensor
H_o	-	Null hypothesis
R_0	-	Solar radiation intensity
ΔT_{u-r}	-	Temperature difference between urban and rural
T_h	-	Temperature of human skin surface
T_{SHS}	-	Temperature of Surrogate Human Sensor

LIST OF ABBREVIATIONS

ASHRAE	-	American Society of Heating, Refrigerating and Air-Conditioning Engineers
UHI	-	Urban Heat Island
SPSS	-	Statistical Package for the Social Sciences
DI	-	Thom's Discomfort Index
PET	-	Physiological Equivalent Temperature
PMV	-	Predicted Mean Vote
PPT	-	Predicted Percentage of Dissatisfied
CFD	-	Computational Fluid Dynamics
H/W	-	Height to Width ratio
W/L	-	Width to Length ratio
G	-	Green area
CS	-	City street at crowed town area
FB	-	In front of buildings
IB	-	Buildings located inward from the main road
BB	-	Between the buildings
SB	-	Surrounded by buildings
OSG	-	Open space with vegetation ground
OSC	-	Open space with concrete ground
BO1S	-	Building orientations with building at one side
BO2SO	-	Building orientations with buildings at two sides
BO3SU	-	Building orientations with buildings surrounded but open at the front of the measurement equipment
BO4SS	-	Building orientations with buildings surrounded at all sides
QSOS	-	Location questionnaire survey at open space
QSPW	-	Location questionnaire survey at pedestrian walk nearby roadside between the buildings

QSRA	-	Location questionnaire survey at student resting area
QSSB	-	Location questionnaire survey at parking lot with buildings surrounded and trees at the left side
QSPL	-	Location questionnaire survey at parking lot
UTM	-	Universiti Teknologi Malaysia
SET	-	Standard Effective Temperature
ET	-	Effective Temperature
SHS	-	Surrogate Human Sensor
BS EN ISO 7730	-	British Standard EN ISO 7730 (2005)
HSI	-	Heat Stress Index
TCI	-	Thermal Comfort Index
TP	-	Thermal Perception regression
TP - SHS	-	Perception - Manikin regression

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CHAPTER 1

INTRODUCTION

1.1 Background of the Study

The world is experiencing high rates of urbanisation and it has slowly become an alarming social process, especially in developing countries. Many cities are gradually transformed into urban metropolitans. The outdoor thermal environment of urban spaces plays a great role on the quality of life in a city. It directly affects people's comfort and/ or behaviour and usage of outdoor spaces. In the path of investigation, the thermal behaviour of urban environments has been documented by various researchers, in anthropogenic factors (Sailor, 2011; Shahmohamadi *et al.*, 2011; Zhou *et al.*, 2011) and 'albedo' effects of surface material (Bougiatioti *et al*., 2009; MD Din *et al*., 2012; Shashua-Bar *et al.*, 2011) as well as the urban arrangement (Amirtham *et al*., 2014 Sharmin *et al*., 2012). According to Kolokotroni and Giridharan (2008), the most critical variables during the day time and nocturnal air temperature is the surface thermal behaviour that influences the absorption and reflection of the incoming solar radiation. This effect highly contributes to the increasing temperature in urban environments. Hence, the thermal behaviour of surface material with high surface albedo and the albedo modification of construction materials are recommended for implementation in the urban built environment as it reduces the urban heat island (UHI) effects (Susca, 2011; Taha, 1988).

The efforts of reducing UHI are becoming significantly important as it negatively effects human thermal comfort. Hence, any approach to assess the consequences of surface thermal behaviour on human comfort should be incorporated into the climatic variables such as ambient temperature, relative humidity, solar radiation and wind velocity. Ann environmentally conscious urban design solution should give high priority to the impacts on outdoor thermal comfort from urban microclimate.

In fact, the increasing of thermal heat, especially in urban areas, could cause discomfort and heat stress. Discomfort and inconvenience that arise from the urban population due to higher temperatures will place the urban population at a greater risk in terms of increased morbidity and mortality rates (Shahmohamadi *et al.*, 2011). The conceptual requisites for the determination of one's thermal comfort are the average body core temperature of 36.5 - 37°C, skin temperature of 30°C at the extremities and 35°C at the body stem and head. At core temperatures beyond 38 − 39°C, there is an increased risk of heat stress and beyond these temperatures, heat stroke can occur with an eventual failure of the central nervous thermoregulatory system (Lundgren *et al*., 2013). There are six main factors that affect human thermal comfort, namely ambient temperature, relative humidity, mean radiant heat, wind velocity, personal activity level and clothing. Thermal comfort indices are indicators that assess the relationship between the climatic variables that could affect human health and activities. In response to the consequences of heat stress, thermal manikins were developed to enhance the understanding of the relationship between the human body and surrounding environment (Gao and Niu, 2005).

As a city grows, the developed area will expand and the natural ground surface is slowly being replaced by an artificial surface. As a consequence, this increases the amount of heat accumulation during sunny days. This hot city phenomenon is far-reaching the consequences for environmental sustainability and is believed to have significant impacts on human health. The high urban city temperatures, as compared to surrounding rural or suburban areas (green area), is recognized as Urban Heat Island (UHI) phenomenon (Che-Ani *et al.*, 2009; Livingstone, 2006; Voogt, 2004). The significant difference in heat concentration created between cities and neighbouring areas is caused by the anthropogenic modifications of land surfaces, urban expansion, population growth, lack of green spaces, thermal admittance of building fabric and its consequent generation of waste heat that causes alarming effects in many metropolitan areas (Ghazanfari *et al.*, 2009; Kololotsa *et al.*, 2009; Kolokotroni and Giridharan, 2008; Shahmohamadi *et al.*, 2011). Since high UHI indicates the increment of heat stress, worse air quality, and higher energy usage especially during hotter days (Kolokotroni and Giridharan, 2008) awareness of this situation has risen in many cities. Additionally, its impact on the cooling load of buildings, as well as the peak electricity demand for cooling, is also becoming an issue for sustainability.

In the 10th Malaysia plan (2011-2015), two major national policies: National Green Technology Policy 2009 and National Climate Change Policy 2009, were outlined on environmental protection and conservation. These policies place emphasis on sustainable development and the application of green technologies, as well as help stream line and coordinate the policy and legislation to facilitate implementation (Ho *et al.*, 2013). Hence, it is essential for the evaluation of thermal comfort, especially in urban cities in parallel with developmental activities, to achieve sustainability. The UHI effect is one of the main factors that contribute to the rise in temperature and eventually induces climate change and thermal discomfort. By introducing this research in Malaysia, it will support a sustainable environment for better living and become one of the solutions for the National Climate Change Policy 2009.

In tandem with the Malaysia Plan and other national policies, the Ministry of Housing and Local Government of Malaysia, through its Department of Town and Country Planning, had translated these into spatial form through the National Physical Plan and the National Urbanisation Policy. Green urbanism has been introduced in the Malaysia's National Urbanisation Policy (NUP) and approved by the Cabinet on August 8th, 2006. The NUP guides and coordinates the planning and urban development in Malaysia where it encourages development that reduces the impact of UHI by proper land use planning and integrates the development of green areas in urban centres (Rosly *et al.*, 2010). The UHI factors that contribute higher heat impacts on the environment and its effects toward human thermal comfort have been reported (Rosly *et al.*, 2010). This encourages the implementation of mitigation strategies for UHI and heat stress reduction that the NUP must fulfil. Furthermore, this study is important in benefiting the consumer by reducing their electricity consumption, for example, the usage of an air-conditioner can be reduced in order to meet the sustainable low-energy building. By reducing the temperature and energy usage, this can also reduce the effect of global warming which has a major impact on human life and the built environment, according to governmental policies.

1.2 Problem Background

Due to the increasing rate of urbanisation and population, the consequences resulting from heat impacts should be vital in order to obtain sustainable living. Climate change on outdoor thermal environment and UHI dominantly effect human health and well-being in a city. The increment in outdoor air temperatures also creates economic consequence, where UHI has clearly exemplified the environmental and economic impacts associated with a rise of ambient temperature. Apart from that, climate effects are negatively impacted by the UHI phenomenon, especially for people working outdoors. The outdoor environment is the most extreme and critical condition in investigating human thermal comfort as it is exposed to the "double sun" phenomena, exposure from both direct sunlight and heat reflecting off the surrounding buildings. These issues can lead to social impacts if there is still lack of awareness and attention given to the thermal condition. The current study focused on the determination of thermal comfort in selected areas, with several urban environmental parameters, i.e. street geometry, orientation, surface albedo and vegetation, and concentrated on using conventional methods for accessing heat stress. However, a knowledge gap still exists, which can be related to the impacts of thermal behaviour on outdoor human thermal comfort and heat stress in tropical climate, in terms of the effect of the built environment, land use and artificial construction materials. Little research can be found on the relationship between the impact of urban surface thermal behaviour and outdoor thermal comfort in Johor Bahru a city in Malaysia.

The interest shown in thermal manikin studies has gradually increased. However, previous thermal manikin studies are mainly focused on indoor environments, where it is installed in a climatic chamber and connected to a power supply with a computer-controlled system or using computational fluid dynamic methods (CFD) to investigate the necessary parameters. Among the parameters investigated, there is thermal radiation, resistance and evaporative resistance of the clothing; distribution of local and overall body segment's surface temperature; heat transfer coefficient, sweating mechanism, etc. These parameters are mostly used to investigate the thermal radiation or comfort and simulate human parameters in a controlled environmental condition rather than for predicting the impacts of thermal behaviour of outdoor space or hard surfaces on thermal comfort. Previous manikin using complex mechanism and set up tools in computer or numerical based system for simulation. Besides that, there is a lack of exposure on the prediction of the impacts of thermal behaviour by using a thermal manikin in an outdoor environment.

There are a series of thermal comfort indices for evaluating thermal comfort. Among the thermal comfort indices, Discomfort Index (DI) has been used in this study where a combination of ambient temperature and relative humidity are involved in a simple and quick evaluation of thermal comfort. With regards to this, Thom (1959) proposed a series of range for the classification of DI. However, when compared to a seasonal climate, people in tropical climates like Malaysia may have a wider range of thermal perception (Makaremi et al., 2012). With this in mind, Thom's DI may exhibit inadequacies in the classification of DI when adopted into a tropical climate. Outdoor thermal comfort is directly affected by thermal environment, especially due to the climatic data of ambient temperature, relative humidity, wind speed and solar radiation (Lin, et al, 2010). In hot and humid tropical climates, a state of discomfort is often caused by ambient atmosphere that is too hot and very humid, with greater solar radiation intensity. Wind speed, on the other hand, plays an important role in increasing comfort through evaporative cooling (Sangkertadi, 2012). Each of these parameters provides various impacts on human psychology. It is clearly stated that climatic data is inter-related with thermal comfort, as people are directly exposed and influenced by different meteorological conditions. Traditional studies using thermal indices try to take all climatic variables into account and consequently provide a comprehensive picture of the thermal environment. However, the subjective thermal sensation is difficult to explain with conventional methods. In addition, there are no indicators suitable for evaluating thermal perception in Malaysia, a location with climatic data of ambient temperature, relative humidity, wind speed and solar radiation.

Based on previous research, there were a large number of theoretical and empirical indices used to assess human thermal comfort. Most of these indices were originally developed for enclosed indoor spaces and their validity under outdoor conditions has been increasingly questioned. These indices might face a number of methodological problems such as variability of meteorological parameter measurement, and difficult interpretation, with respect to actual human perceptual and physiological factors in achieving human thermal balance (Tseliou *et al.*, 2010). There is flaw in the existing indices for describing thermal comfort with a combination of parameters of psychological (thermal perception) and meteorological variables, with the assistance of Surrogate Human Sensor (SHS) usage. Less attention is given to the evaluation of outdoor thermal comfort with the use of a sensor or indicator, also known as a "SHS", which is used to evaluate behavioural or psychological aspects based on local climate conditions. In order to obtain a better assessment of human thermal comfort, sufficient data with these three aspects are needed to be developed with a series of indices to accurately evaluate thermal comfort, especially in a tropical climate. It is expected to facilitate better planning exercises for a more sustainable and comfortable environment.

1.3 Objectives of the Study

In order to answer the problems statements, this research aims:

i. To evaluate human thermal comfort by developing a new range of DI in tropical climate based on the impacts of thermal behaviour.
ii. To integrate the application of SHS with climatic variables for establishing a correlation and predicting the impacts of thermal behaviour.
iii. To establish a Heat Stress Index using the correlation of thermal perception and climatic variables in evaluating thermal comfort.
iv. To identify the human thermal perception using SHS with newly established thermal comfort index in outdoor spaces of tropical climate.

1.4 Scope of Study

This study covers in-situ measurements in outdoor spaces at the Universiti Teknologi Malaysia (UTM) and several other locations within the town centre of Johor Bahru. The impacts of artificial urban structure, albedo effect, surface materials and building orientation toward human thermal comfort are investigated. The selected locations for the in-situ measurements are proposed at the urban city of Johor Bahru town centre and suburban area of UTM.

In-situ measurements consist of analytical parameters of ambient temperature, solar radiation, relative humidity and wind velocity in order to observe the thermal condition due to the impact of thermal behaviour between the hard and soft surfaces at the selected built-up areas. The criteria for the locations selection of in-situ measurements include consideration of urban-rural environment based on different albedo effects, building orientation, open spaces and different land use environment. The built-up areas are qualitatively different from non-urban terrains in terms of their surface geometry and materials. These physical characteristics can decisively influence the absorption and reflection of solar radiation, the capacity for heat storage as well as the absorption and emission of long-wave radiation. In addition, anthropogenic heat from traffic and the heating and cooling of buildings also affects the urban climate, though such effects are beyond the scope of the present study.

Thermal manikins can act as human simulating devices or indicators. In this study, a Surrogate Human Sensor (SHS) is a more suitable term that is developed at the starting point and preliminary stage of the study for establishing a link between human skin surface and devise. It was fabricated to examine the impact of thermal behaviour on human thermal comfort by simulating only the sensible heat process. The SHS used in this study is considered as a simplified model of manikin that uses simple, low cost and easily handled materials for fabrication. SHS is placed in outdoor spaces; areas surrounded by buildings, pedestrian footpaths, carparks and recreational parks, where there is a high risk of exposure to heated environments. This sensor does not consists of a complete physiological model of the human body as it is only limited to human skin surface, but it is used to serve as a useful tool for an evaluation of thermal load due to the impact of thermal behaviour at the surrounding environment. An experiment was designed to determine a linkage between the SHS and the human skin surface and then further expand to establish correlation between SHS and climatic variables

Subjective measurements using questionnaire surveys were carried out to identify the thermal response of occupants in a real thermal environment with at least 10 selected respondents in UTM. Ten healthy female university students were selected and the subjects were, on average, 1.6m in height. The experiment took placed at all daytime where the thermal responses on the environment was recorded at every 1 hour for each of the respondents. A pilot test on the questionnaire survey was carried out on these 10 selected respondents for the pre-screening process on the questionnaire. This was to ensure the reliability of the questionnaire and make sure the respondents understood the questions about certain critical aspects, i.e. temperature and humidity sense, perception and their opinions about the selected heat areas. The respondents were placed at the investigated locations 5 minutes prior to the survey. ASHRAE thermal sensation scale was selected and used to evaluate the thermal response of occupants within the selected environments (ASHRAE Standard 55P, 2004). The obtained data collected from the in-situ measurement such as climatic data, temperature variation from SHS as well as thermal perception from questionnaire survey were correlated to establish a heat stress and thermal comfort index that was incorporated with local microclimate. Both meteorological and psychological, were taken into consideration in this index to then be adapted in the Malaysian tropical climate for the evaluation of human thermal comfort. The results were analysed using Statistical Package for the Social Sciences (SPSS) version 16.0. Appropriate tests such as multiple linear regressions, assumption test, significant test, correlation and two sample hypothesis tests were conducted to establish an equation and determine the relationship, significance, reliability and consistency.

1.5 Significance of the Study

Several thermal environment factors such as the albedo effect, land use, surface materials and building orientations that lead to the occurrence of UHI phenomenon were investigated to discover the most uncomfortable outdoor spaces or urban designs in the cities. This investigation can be enhanced by combining human thermal sensation study in order to obtain true responses in different environmental conditions. The investigation on the impacts of thermal behaviour based on different built up areas is relevant, especially in urban environments, to place stress on the thermal environmental conditions that contribute to the higher heat impact so that people can avoid the thermal condition and stay in healthy and comfortable conditions. Nonetheless, it can also be used by relevant authorities in order to strive towards the best precautionary practice in public health and mitigation for heat stress reduction.

In this study, the Discomfort Index (DI) used to determine the human discomfort level was modified by incorporating psychological factors (thermal sensation) in order to precisely evaluate thermal comfort, especially in the tropical climate of Malaysia. This modified DI that replaced the existing DI classification can be very useful as an indicator for identifying human thermal comfort, which is also correlated to heat related illnesses and health.

Nevertheless, thermal perception of the occupants can be identified by using the established Heat Stress Index (HSI) due to its relation with the climatic variables. Thus, the relationship between thermal perception with the climatic variables and SHS can be developed to establish an index readily useable by practicing engineers or public health. This index is simple when compared to previous heat stress indices and is an informative interpretation of thermal comfort by taken into account the two important factors: climatic and psychological (perception) with the assistance of developed SHS. In addition, the SHS can also act as the sensor or indicator to investigate the impact of the thermal behaviour from the surrounding built-up environment conditions as well as thermal perception or the heat stress of people by integrating the established indices. In the future, the SHS can be used and improved for planning and managing township in order to achieve better human thermal comfort.

1.6 Thesis Outline

This thesis is divided into seven chapters, Chapter 1 presents the introduction; Chapter 2 consists of the literature review; Chapter 3 contains the research methodology on experimental sampling and analytical procedure; Chapter 4 discusses the analysis on climatic measurement and outdoor thermal comfort; Chapter 5 presents the analysis on Surrogate Human Sensor (SHS) measurement; Chapter 6 consists of the analysis of outdoor thermal sensation, with respect to the SHS; and Chapter 7 presents the conclusion and recommendation. Throughout Chapter 1, the background of thermal behaviour and thermal comfort, problem statement, objectives of the study, significance and scope of the study are included in this section. Introduction to the urban environment is presented in the initial part of Chapter 2 where the thermal behaviour of the built environment, and its effect towards human thermal comfort, are reviewed. Human thermal comfort due to heat environment and its relation to heat related illnesses and the assessment of thermal comfort using thermal comfort indices are also included in this chapter. It is then followed by a critical review on the history and related research on SHS as a simplified version of thermal manikins to demonstrate their relevance to the thermal comfort analysis. In addition, a detailed and comprehensive literature review of previous research is carried out to identify the lack of investigation in the field. Lastly, UHI phenomenon was reviewed and it was demonstrated that the impact of the thermal behaviour from the surrounding built-up environment should be discussed instead of elaborating on the concept or the UHI phenomenon. Chapter 3 discusses the research methodology and framework of this research. The procedure, method and experiment design for fabrication of SHS are discussed. Analytical parameters and instrumentations that provide great response to the environment are studied. Experiments, samplings and analytical procedures are discussed in this chapter. For Chapter 4, analysis on climatic measurement and its relation to human discomfort level is discussed. In-situ field measurements had been carried out based on several criteria i.e., green and open space versus urban building, building orientations are also included in this chapter. Also, evaluation of human discomfort level by using Thom's Discomfort Index (DI) and modification of DI based on tropical climate criteria is also analysed in Chapter 4. In Chapter 5, analysis on SHS measurement and its advantage on the investigation of thermal conditions due to the impact of thermal behaviour are discussed. An equation has been determined to measure the temperature at SHS based on climatic variables. In Chapter 6, outdoor thermal sensation based on the questionnaire and its relationship to the climatic variables and SHS are highlighted. A regression model has been developed to integrate the relationship between thermal perception and climatic variables. The advantages of SHS as a sensor and indicator for evaluating thermal perception are discussed and analysed in this chapter. The verification of the regression models established on the four selected field studies are also examined. Lastly, the conclusions and recommendations for future works are highlighted in Chapter 7.

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