STREET'S PHYSICAL GEOMETRY AND THE COOLING EFFECT OF WATERBODY OF URBAN MICRO-CLIMATE IN TROPICAL REGIONS

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STREET'S PHYSICAL GEOMETRY AND THE COOLING EFFECT OF WATERBODY OF URBAN MICRO-CLIMATE IN TROPICAL REGIONS

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To my mother who taught me love

And

To my father who taught me determination

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ABSTRACT

The thesis addresses the contributions of urban geometry under tropical climate in the Melaka city, Malaysia and their benefits toward optimum cooling effect of water body modification. The aim is to examine quantitatively the potential of the cooling effect from combination of water bodies and street geometries with the development of comfortable microclimate conditions at street level in the city environment. Main methodologies phases which is field measurement were conducted and computer simulations were developed in order to achieve the aim and objectives of study. Environmental Visual Image Microclimate software (ENVI-met Ver. 4.0) was used to predict the impact of modification according to the proposed hypothetical urban geometries were simulated with various street aspect ratio (building's height / street's width) where the ratio is equal to 1, more than 1, and less than 1, and river width equal to 18, 36, and 54 meters. The proposed urban settings in Melaka city that resulted from the combination of the various streets and river width were modelled on four different orientations, North-South, East-West, Northeast-Southwest and Northwest-Southeast, while a total of 36 different urban geometries were evaluated. The model was successfully validated through the correlation of measured experiments and computer simulation which reliable enough to present the actual urban microclimate condition of Melaka river area. The outdoor thermal comfort was assessed based on the Physiological Equivalent Temperature (PET) as reference to evaluate modification benefits towards outdoor comfort level. It is revealed that the existing variation in temperature between the different urban locations in the Melaka river area was due to the influence of their street geometrical characteristics. Overall, the improvements of thermal comfort via the addition of water bodies is very minimal when compared to the improvements brought by aspect ratios. The highly humid climate in Malaysia and the low wind speed conditions is the reason for this occurrence. The conclusions point out besides the necessity of street geometry, water body cooling effects can be implemented as additional guide lines in urban design to keep the external microclimate conditions in comfort range.

ABSTRAK

Tesis ini mengkaji sumbangan geometri bandar di Bandaraya Melaka, Malaysia yang beriklim tropika serta feadah-faedahnya terhadap kesan penyejukan optimum ke atas pengubahsuaian saiz sumber air. Tujuan utama adalah untuk mengkaji secara kuantitatif potensi gabungan kesan penyejukan sumber air dan geometri jalan serta pembangunan keadaan iklim yang selesa di jalan-jalan raya di persekitaran bandaraya. Fasa metodologi utama iaitu pengukuran di lapangan telah dijalankan dan simulasi komputer telah dibangunkan untuk mencapai matlamat dan objektif kajian. Perisian "Environmental Visual Image Microclimate" (ENVI-met Ver. 4.0) telah digunakan untuk meramal kesan pengubahsuaian saiz sungai mengikut hipotesis geometri bandar yang ditetapkan di mana simulasi computer telah dijalankan termasuk pelbagai nisbah aspek jalan (tinggi bangunan / lebar jalan) di mana nisbah aspek jalan yang bersamaan dengan 1, lebih dari 1, dan kurang dari 1, serta lebar sungai pula bersamaan dengan 18, 36, dan 54 meter. Cadangan model tetapan bandar di Bandaraya Melaka yang dihasilkan dari gabungan pelbagai arah jalan-jalan raya dan lebar sungai melalui empat orientasi yang berbeza iaitu Utara-Selatan, Timur-Barat, Timur Laut-Barat Daya dan Barat Laut-Tenggara, dan sebanyak 36 geometri bandar yang berbeza telah dikaji. Model ini telah berjaya disahkan melalui pengukuran korelasi dan simulasi komputer serta boleh dipercayai untuk membentangkan keadaan iklim-micro sebenar persekitaran sungai di Bandaraya Melaka. Keselesaan terma luar ("outdoor thermal comfort) telah dinilai berasaskan hasil kajian terhadap "Physiological equivalent temperature" (PET) tempatan sebagai rujukan untuk menilai faedah pengubahsuaian ke atas tahap keselesaan terma luar. Kajian ini telah mendedahkan bahawa perubahan yang sedia ada dalam suhu antara kawasan bandar yang berbeza di persekitaran sungai Melaka adalah disebabkan oleh pengaruh ciri-ciri geometri jalan-jalan raya. Secara keseluruhan, peningkatan keselesaan terma melalui penambahan sumber air adalah minima berbanding penambahan nisbah aspek. Keadan ini adalah disebabkan oleh iklim yang sangat lembab dan kelajuan angin yang rendah di Malaysia. Kesimpulan yang diperolehi telah menunjukkan selain keperluan geometri jalan, kesan penyejukan sumber air atau sungai juga boleh dilaksanakan sebagai garis panduan tambahan dalam reka bentuk bandar untuk mengekalkan keadaan iklim luar di dalam zon selesa.

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LIST OF ABBREVIATIONS

ABL	-	Atmospheric Boundary Layer
ASHRAE	-	American Society of Heating, Refrigerating and Air Conditioning Engineers
BLHI	-	The Boundary Layer Heat Island
CFD	-	Computational fluid dynamics
CLHI	-	Canopy Layer Heat Island
ET*	-	New Effective Temperature
E-W	-	East –West Street Orientation
GIS	-	Geographical Information System
H	-	Building Height
H/W	-	The ratio of building height (H) and street width (W)
H	-	Hour
ICUC	-	International Conference on Urban Climate
MTPV	-	Mean Thermal Perception Vote
MRT	-	Mean Radiant Temperature
N-S	-	North-South Street Orientation
NE-SW	-	Northeast-Southwest Street Orientation
NW-SE	-	Northwest-Southeast Street Orientation
P	-	Points of Measurements
PET	-	Physiological Equivalent Temperature Index
PMV	-	Predicted Mean Vote
OUT_SET*	-	Outdoor Standard Effective Temperature
RH	-	Relative Humidity
R/W	-	River Width
RS	-	River Side
SET	-	Standard Effective Temperature

SVF	-	Sky View Factor
∆ T	-	Temperature variations between two locations, i.e. urban – rural
Ta	-	Air Temperature
Tg	-	Globe Temperature
Tmrt	-	Mean Radiant Temperature
UBL	-	Urban Boundary Layer
UC	-	Urban Canyon
UCL	-	Urban Canopy Layer
UHI	-	Urban Heat Island
V	-	Wind Speed
W	-	Street Width
W/m^2	-	Direct, Diffuse, Global Solar Radiation Measuring Unit
Wd	-	Wind Direction
Zenith	-	Overhead sky view factor orientation

LIST OF SYMBOLS

%	-	Percentage
°C	-	Degree Celsius
°F	-	Degree Fahrenheit
K	-	Kelvin
3D	-	Three Dimension Building Database
2D	-	Two Dimensional
ΔT_{u-r}	-	Urban Heat Island Density
$K\downarrow$	-	Flux densities of downward shortwave radiation
$K\uparrow$	-	Flux densities of upward shortwave radiation
$L\downarrow$	-	Flux densities of downward longwave radiation
$L\uparrow$	-	Flux densities of upward longwave radiation
H	-	Sensible Heat
Q*	-	Net all radiation of building's exterior (net radiation)
Q_F	-	Total Anthropogenic Heat
Q_H	-	Sensible Heat flux
Q_E	-	Latent heat flux
ΔQ_S	-	Energy stored in the area structure
ΔQ_A	-	Net heat advection horizontal transfer of sensible heat
Q^*_W	-	Energy balance of the urban canyon wall
Q^*_g	-	Energy balance of the urban canyon floor
Z	-	Solar zenith angle
Oktas	-	Cloud cover measuring unit
°	-	Degree
kWh/m^2	-	Solar radiation measuring unit
m/s	-	Wind velocity measuring unit
X,Y and Z	-	Domain horizontal and vertical grid

Δx, Δy and Δz	-	Model horizontal and vertical grid cells
°N, °E	-	Longitude and Latitude
M	-	Measured data
S	-	Simulated data
R^2	-	Coefficient of determination
MBE	-	Mean bias error
RMSE	-	Root mean square error
$RMSE_S$	-	Systematic root mean square error
$RMSE_u$	-	Unsystematic root mean square error
<	-	Less than
>	-	More than
=	-	Equal

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Urban climate is of topical major concern for climatologists, as designers favour environmental influences upon buildings. Urban climatology is mostly focused on micro-scale UHI (Urban Heat Island). Urban geometry is regarded as one of the factors that can increase UHI (Ali-Toudert and Mayer, 2007a; Müller *et al.*, 2014; Oke, 2004).

Outdoor comfort issues are seen as an intertwining factor between urban climatology and design. The formers metaphorical and unproven approach complements the latters experimental and design-oriented results (Ali-Toudert and Mayer, 2007b). It is currently obvious that urban environmental quality is fast becoming a major problem for the aforementioned disciplines. Their respective prevalence have been discussed and detailed in scientific gatherings (e.g. ICUC, PLEA, and AMS conferences) and literature materials, mostly practice-oriented (Nikolopoulou and Steemers, 2003; Pugh *et al.*, 2012; Santamouris, 2013).

The form features of open spaces in cities vary considerably. Several parameters, such as water levels, urban geometry, properties of surfaces, and vegetation are very influential upon the microclimate of these spaces. The improper utilisation of the aforementioned parameters will result in increased environmental harshness and temperature compared to the suburbs, which is known as the urban heat island (UHI) (Oke, 2002). UHI are mostly caused by urban surfaces, man-made heat input, variations in vegetation cover, and heat trapping caused by urban geometries.

Urban areas are classic specimen that will allow for insightful climatic alterations, generally known as UCL (Urban Canopy Layer) (Ali-Toudert and Mayer, 2007a; Oke, 1988). It falls somewhere in between the ground (surface) all the way to the roof of the buildings. Urban structures are made up of inhomogeneous and tough "surface", both factors escalate turbulent activities and precipitate extended rates of variability in the amount of space of time for all meteorological measures towards a mixture of microclimates in an enclosed area (Ali-Toudert and Mayer, 2007a). The comprehension of urban outdoor microclimate and the implications of thermal comfort will precipitate the advancement of urban spaces. The quantification of outdoor thermal comfort is however, a relatively new area of inquiry.

The city of Melaka in this study is selected as a result of both deliberate choice and practical considerations. The aim was to find a city in a developing country located in the tropical zone. Another requirement was the population size of the city. A very large city such as a mega - city may have high levels of anthropogenic heat influencing the urban climate. Conversely, cities that are too small may present a limited variation in urban design and therefore limited intra-urban microclimatic differences. The choice is, however, also a result of local contacts and ongoing research cooperation which facilitated the implementation of the study. The city Melaka is representing the type of climate typical for many urban areas in developing countries. Since the study is carried out in the tropical climate of Melaka which has a larger scope of water area and the opportunity of the sea and the river, provided the possibility to study the temperature change under the influence of and distribution of water bodies within the urban streets. And this will be unfolded by perusing categorizing different street characters and proximities to the river and specific arrangement of them, perpendicular or parallel according to the river as the water body in the city of Melaka. In order to obviate the threat of effect of other variables and categories on measured parameters, streets for the study have been selected which may environmentally perform similarly under any weather conditions.

1.2 Background of the Study

It is almost impossible to look for a representative urban canyon if all the modifying parameters, such as orientation, aspect ratio, presence of vegetation, construction materials, are taken into account in this work (Oke, 1982). Nonetheless, these salient aspects of an urban canyon's microclimate have been rehashed through multiple works, and will be discussed in the proceeding subsections.

1.2.1 The Microclimate of an Urban Street Canyon

A designer, in the course of designing a street, will be facing obstacles in the form of seasonal, external, and internal needs, coverings that prevent direct sunlight during the summers, and sky access during winters, while designing urban streets. Based on the theory, these concepts convey the message of being compact with open access. Oke believes a "zone of compatibility", which guarantees an agreement between the visibly disagreeing objectives of street design, is indeed possible (Oke, 1988). For instance, Swaid proposed the concept of "intelligent buildings", which include a number of removable parts in the street in an attempt to gain control over shadings in different seasons, which is a theory that argues with conflicting issues (Swaid, 1993). Furthermore, contemporary and traditional architectures include a history of attempts and trials in designing streets vis-à-vis the climates (Ali-Toudert, 2005; Golany, 1983; Herzog and Kaiser, 1996; Santamouris and Asimakopoulos, 1996; Swaid, 1993), despite the fact that there is a huge requirement for quantitative data from scientific approaches that investigate the concept of optimal street design over climatic comforts.

For the sake of convenience, the term UC (Urban Canyon) has seen widespread usage within urban climatology community, replacing the primary structural unit in defining a common open space in an urban setting (Ali-Toudert and Mayer, 2007a; Arnfield, 1990a; Arnfield, 2003; Herbert *et al.*, 1998; Oke, 2004; Swaid, 1993), and namely got filtered from non-climatic relevant features. There are huge amounts of information that were collected about the microclimatic alterations within an urban street canyon. Literature mostly discussed the basic value of the *aspect ratio* or (H/W) *height-to-weight ratio*, on top of *street orientation*, as some of the most important urban features that are responsible for the aforementioned alterations. The influence of Sky View Factor (SVF) [1], (the extent of sky observed from a point as a proportion of the total possible sky hemisphere) of street design and H/W ratio was examined in the context of microclimates, particularly surface and air temperature. The results proved that SVF and the street geometry minimised air temperature fluctuations compared to surface temperatures. These two factors are regarded as vital vis-à-vis matter over energy balance in the framework of urban canyons (Ali-Toudert and Mayer, 2007a; Mills, 1993; Mills and Arnfield, 1993; Nunez and Oke, 1976). Daytime temperatures tend to be lower with increased H/W ratio in the hot and humid climate of Dhaka, Bangladesh, during summers (Johansson and Emmanuel, 2006).

Pearlmutter et al. (1999) studied the effect of orientation on the canyon air temperature in a dry hot desert climate. In their report, the North-South oriented street was somewhat cooler (<1 °C) by day, compared to the East-West oriented street. The canyons showed no significant temperature difference at night. Also, in a similar climate, the North-South oriented streets were 1 - 2 °C cooler than the East-West oriented streets during the day (Bourbia and Awbi, 2004; Pearlmutter *et al.*, 1999).

Djenane (2008) investigated the microclimatic conduct of urban forms in the dry hot city of Béni-Isguen, Algeria. The study aimed to evaluate the relations between the climatic limitations and the adapted solutions in the context of occupational modes of the urban morphology and ground in the streets. During the summer, practical microclimatic measurements were taken from four locations. The morphological areas varied between low and high urban densities, with plot coverage of 10 % and 87 %, as well as H/W ratios of 1.6 - 9.7 (Djenane M., 2008).

[1] The extent of sky observed from a point as a proportion of the total possible sky hemisphere.

Bourbia and Boucheriba (2010) assessed the influence of geometry on microclimate in Constantine, Algeria, during the summer. Site measurements (surface and air temperatures) were taken from 7 sites, with SVFs of 0.076 - 0.58, varied between H/W ratios of 1 - 4.8. There was about 3 - 6 °C of air temperature difference between the city and the nearby rural environment. It was argued that SVF is directly proportional to air temperatures. Also, higher H/W ratio results in lower surface air and temperatures (Bourbia and Boucheriba, 2010).

Getting exposed to shadow patterns has a strong influence on the temperature of the canyon’s surface, later, the heat gravitate towards the air in the form of a sensible flux, affecting the temperature of the air (Ali-Toudert and Mayer, 2007b; Nakamura and Oke, 1988; Santamouris and Asimakopoulos, 1996; Santamouris *et al.*, 2001). Experiencing wind flow on the streets are also reliant upon the aforementioned parameters (Ali-Toudert, 2005; Mills and Arnfield, 1993; Santamouris *et al.*, 2001). The building substances for the surfaces of the canyon were also regarded as being important to the storage rate of diurnal heat for a street canyon (Ali-Toudert, 2005; Herbert *et al.*, 1998; Mills and Arnfield, 1993; Oke, 2002), in addition to the cooling rate of the night (Mills, 1993; Mills and Arnfield, 1993). The chances of getting solar access indoors, and by inference, the layout for the site and the urban density, are matters that are directly linked to the orientation and vertical profile of the street itself (Knowles, 1982; Pereira *et al.*, 2001).

1.2.2 Water Bodies and their Effects on their Surrounding Microclimate

For controlling urban temperatures, architects, and by extension, urban planners, utilised water bodies shaped like tools (Coutts *et al.*, 2013). The logic behind this is explained via its heightened evaporation during daytime. Considering a consistent net radiation, this water evaporation results in similar costs when compared to sensible heat, which helps maintain the temperature of the air at levels that are more workable in the absence of other water bodies. Sun and Chen understood that an extensive lowered daily temperature for land surface adjacent to Beijing lakes (China) (Sun and Chen, 2012). According to Hathway and Sharples

(2012), rivers also helped reduce the air temperature in the U.K. They also highlighted the cooling effect of the rivers is at its strongest in the beginning of spring and beginning to decline in June (Hathway and Sharples, 2012).

Water, on top of its evaporative properties, also demonstrated increased affinity for heat retention. Therefore, water's diurnal temperature range is believed to be smaller within similar range for a rural landscape, i.e. the suppression of maximum temperatures, and limitations to nocturnal cooling. There direct path between the air temperature and the surface decodes the aforementioned signal towards the screen level temperature (Heusinkveld *et al.*, 2010). There are quite a number of studies involving the role of lakes within urban microclimates (Givoni *et al.*, 2003; Oláh, 2012), most of them focusing on thermal human comfort and daytime UHI. The wetlands are also believed to have a downwind cooling effect, which is a phenomenon called the lake effect (Coutts *et al.*, 2013).

Water bodies are an unending supply of moisture: this is especially useful in maintaining the oasis effect during the day for areas that it is in, or surrounded by, drier climates (Coutts *et al.*, 2013; Oke, 1988) of urban environments. Even water parameters (e.g. fountains) possess features that help relieve the high temperatures of urban areas via improved evaporation (Coutts *et al.*, 2013; Norton *et al.*, 2015; Smith and Levermore, 2008). An increasing number of research has been done on the influences of open water bodies (pond, retreatment wetland, river, or other water features) on an urban area`s climate. Generally, analyses showed that temperatures close to the downwind of the water bodies are 1-2 ^{o}C lower than the adjacent areas, while the maximum temperatures drop during the day (Coutts *et al.*, 2012; Coutts *et al.*, 2013; Nishimura *et al.*, 1998). Saaroni and Ziv (2003), who researched a 100 m pond within an urban park in Tel Aviv, Israel, pointed out that at the daytime downwind of the pond, the levels of heat stress was lower, while the levels of humidity was higher (Coutts *et al.*, 2012; Coutts *et al.*, 2013; Saaroni *et al.*, 2000; Saaroni and Ziv, 2003). At the latter stages of the day, as the cover of the grass' temperature was lower than the surface temperature of the pond, which was due to evaporative cooling, this helps improve the humidity rate and heat stress (Coutts *et al.*, 2013; Saaroni and Ziv, 2003). In Hiroshima, Japan, Murakawa et al. (1991)

discussed the downwind cooling influence from the River of Ota that was effective for at least a few hundred metres. Temperatures of the surrounding air adjacent to the 270 m wide river were 3-5 ^{o}C lower (between 12:00-17:00) compared to the nearby surrounding area on normal days, while the local cooling, which was getting extended by the river, was more widespread over the interval where the building density was not very high, and the streets were a bit wider (Coutts *et al.*, 2012; Murakawa *et al.*, 1991).

It is quite apparent from these studies that the design of the nearby urban landscape that surrounds a specific area is vital in the context of taking full advantage of the influence of downwind cooling, although evaporative cooling may not be as helpful in humid and hot tropical climates where humidity is pretty high. Evaporation from open water bodies may be helpful in lowering the temperature, but it might also increase the humidity. Subsequently, one can deduce that higher levels of humidity lower the levels of comfort, which means that there are lesser improvements in human thermal comfort than what is suggested by the sole influences of the temperature. Additionally, in cases where the water`s temperature exceeds the air temperature (such as situations in fall or at nights), the body of water demonstrate the opposite effect, where the water body will finally heat the urban area. This information might be helpful to urban designers in implementing water bodies for the urban areas in both aesthetic and practical aspects.

The influence of water bodies on the temperatures of urban areas has not been fully explored (Steeneveld *et al.*, 2014). There are quite a few studies that have been done on the viability of water in reducing heat. However, only a few have hypothesised the role of bodies of water as the strongest cooling factor in urban areas over the hot summer days (Oláh, 2012; Rinner and Hussain, 2011). The majority of these studies' measure field observations or remote sensing data pertaining to daytime. Therefore, it is vital that future studies focuses on the effect of open water on both day and night times.

Since the study is carried out in a tropical Town of Melaka, which incidentally has a river, we used this possibility to study the temperature change under the influence and distribution of water body within an urban area. From the aforementioned review, it is hypothesised that the city will be affected by the created microclimate, while the urban geometry of the surrounding area will have a decisive effect when receiving the benefit of the presence of water. This hypothesis needs to be unfolded by perusing the different street characters and proximities to the river and their respective specific arrangement according to the water in the tropical Town of Melaka. Examples of climate-conscious urban planning and design in developing countries in tropical water body climates are rather scarce. In this study, the focus is on the aspects of microclimate that can be successfully implemented in an urban design in the tropical Town of Melaka, which can encourage the cooling effect of the water in entering the urban area.

Therefore, it is vital that this study specifically addresses the combined modifications of urban street canyon and water body microclimate, which will help induce an optimum cooling effect at the street level, aiming to effectively mitigate the thermal stress in the tropical region.

1.3 Problem Statement

In many parts of the world, urban development occurs over a long period, thus allowing urban policy-makers time to respond to any further changes that could induce adverse impacts on the environment and the well-being of inhabitants. In some countries, however, urbanisation is very rapid and occurs within a relatively short period of time creating a range of environmental and energy challenges. One such country is Malaysia.

In a relatively short time-span, the country has experienced several significant urban changes that have transformed the urban fabric in major cities from the vernacular urban form into a modern one, which was introduced at the beginning of the last century by the major foreign companies and planning expertise who were working in the country during that period.

Due to the growth of an urban-based economy and the associated large local and foreign labour migrations to the Melaka City, there was an emergence to adopt a new urban design approach to accommodate the increasing demand for new residential units and the ever-increasing number of automobiles in the city. The urban reclaimed development scenario took place in the south part of the city, which signalled a departure from the traditional urban pattern of Melaka, to accommodate the modern urban pattern (Melaka historic city council, 2014)

The modest efforts of adopting climatic considerations and human dimension during the design process has exacerbated the severity of the microclimate conditions in such tropical water body region. Indeed, this increases the reliance on the active cooling systems in outdoor spaces to overcome such degradation in the environmental quality of indoor spaces.

A field study, by Remaz (2009), investigated the existence, intensity, and magnitude of the urban heat islands in the Melaka has shown that such climatic phenomenon does exist in the city and is more evident during the night time. It is concluded that more attention should be given to minimise the severity of urban microclimate conditions in the Melaka City by proposing various urban design strategies including maintaining low building density in order to reduce heat emissions that are usually associated with highly populated urban areas, increasing the distance between high-rise buildings to accelerate the process of heat loss, increasing the surface albedo for solar radiation by using lighter colours, and increasing the vegetated and green cover areas in the city or the most important issue in this study water cooling effects (Kubota and Ossen, 2009).

In a temperate climate, the maximum UHI effect can be noted only during the summer season (Santamouris, 2001; Swaid, 1993). However, in the tropics it can be experienced during hot dry seasons and year round due to the constant high exposure to solar radiation in these areas (Azhari *et al.*, 2008). This phenomenon has become serious in the tropics where lack of shading and green spaces has led to a failure to balance the heat from direct solar gains. This leads to air temperature increases and negatively influences thermal comfort and increases building energy consumption in the tropics.

Numerous studies on heat island intensity in tropical cities around the globe, have been presented widely, and contributed to the understanding of the phenomenon's behaviour (Emmanuel, 2005; Givoni, 1998; Monteiro and Alucci, 2006; Nichol, 1996). However; in the case of Malaysia specifically, research in this field was initiated by Sani (1973, 1986, 1987, and 1990/91) who investigated UHI intensity in selected cities in Malaysia finding heat island intensity ranges from 2 to 7°C. In a Kuala Lumpur heat island intensity study, he found about a 6°C difference on clear days. Since then various studies have been undertaken to assess the UHI in other urban centres in Malaysia (Elsayed, 2006; Siraj, 1980). However, there is a lack of studies on those newer city areas that have been developed over recent years. This information is crucial to an understanding of the effect of UHI behaviours when designing and planning contemporary urban developments.

For this reason Melaka is considered here, as it have a new reclaimed area. The city was established recently and it is still undergoing minor development. Deterioration of the outdoor environment from a result of heat island effects and similar phenomena has become a serious problem. This aggravation of the thermal environment threatens urban sustainability. Rapid development and the lack of trees are turning these cities into urban heat islands (UHI) that are warm even at night. It also reported that scientifically, Melaka and the other cities are termed as UHIs, a phenomenon where concrete surfaces trap heat during the day and release it during the night.

With respect to the previous statements, the present demand for a sustainable built environment in Melaka city is coupled with the need to minimise the effect of the severe microclimate conditions during the year on users of outdoor spaces, as well as to reduce the reliance on the use of active cooling among urban dwellers. The configuration of urban geometry, quantified by the river width, street aspect ratio and street orientations, is utilised in the present study as a means of microclimate urban design to investigate the influence of different urban configurations on the thermal comfort in urban spaces among urban dwellers in a hot-humid region.

Water bodies based studies have been lacking in tropical regions, either based on field measurement or modelling approaches. Variation in cooling effects from water needs to be determined in order to understand the absolute cooling effect on the urban environment. In the enhancement of cooling effect from water into urban environment, additional strategy promoting aspect ratios have a significant effort on maximizing impact. Therefore, it is important for this study to focus on both combination modifications in order to create an optimum cooling effect at street level aiming to effectively mitigate the temperature and improving microclimate in tropical region. Two critical issues for further explanation of problem statements are explain in details below.

1.3.1 Poor Outdoor Thermal Comfort and its Consequences

Although people are capable of adapting to difficult climatic conditions, this is likely to be a hidden problem, especially for the urban poor, who are exposed to the outdoors more often than others, and whose dwellings are not designed to mitigate the influence of the climate, making them susceptible to urban warming. The lack of outdoor thermal comfort is also likely to have negative social and economic consequences. If the climate is too unpleasant, people will tend to spend time outdoors only when it is necessary, that is, in performing essential tasks, such as travelling to work and shopping. Optional and social activities, such as taking a walk, meeting people in public spaces, children's play, and so forth, will duly diminish (Gehl, 2011; Givoni *et al.*, 2003; Ng and Cheng, 2012; Nikolopoulou *et al.*, 2001). As a consequence of this, there is also a risk that outdoor commercial activities, such as cafés and restaurants, streets and open-air markets, and cultural events, will suffer (Ng and Cheng, 2012).

Poor urban microclimatic conditions will also, indirectly, lead to deteriorating indoor comfort. This will have a negative impact on both performance and health, and extended usage of air conditioning and the increase of energy costs for people living in urban areas. The consequences of greater energy use include increased air pollution through the consumption of fossil fuels, and higher pressure on the energy supply, which may cause frequent power outages. In warm countries, there is also a risk that a feedback loop will arise: Air conditioning units cool the interior of buildings, but emit sensible heat to the exterior, further worsening outdoor conditions and creating a vicious cycle (Baker *et al.*, 2002; de Schiller and Evans, 1998; Ng and Cheng, 2012; Nikolopoulou *et al.*, 2001).

Additionally, outdoor urban spaces, such as streets, are the major outdoor spaces for people to walk on or engage in recreation and social activities. An environment that is comfortable is crucial vis-à-vis enjoyment of the outdoors. In countries like Malaysia, where tourism is an important source of income and outdoor activity is expected in most places of attractions, thermal comfort within urban dwellings is imperative (Yang *et al.*, 2015). Therefore, it is important for outdoor spaces to be properly designed.

1.3.2 Lack of Climate-Conscious Urban Planning and Design

Despite the fact that urban areas can be designed to offer a favourable microclimate at a level that is more pleasant than that of its surroundings, (Givoni *et al.*, 2003), this is not usually the case. One of the major causes of urban discomfort is the fact that urban microclimate and outdoor thermal comfort is simply not accounted for in urban planning and design processes (de Schiller and Evans, 1998; Eliasson, 2000; Upmanis *et al.*, 1998). Many studies from warm countries reported that climate issues are generally not taken into account in contemporary urban design, and current urban designs had led to undesirable microclimates around the buildings.

Eliasson (2000) interpreted the lack of climate consciousness in urban planning and design as follows: “Urban climate is often a largely unplanned outcome of the interaction of a number of urban planning activities, an outcome for which no authority and no profession take responsibility”. Studies have shown that knowledge about climate issues among climatologists, planners, and urban designers are often lacking, and that there is a lack of suitable design tools for urban planners and designers on designing a particular area (Eliasson, 2000; Givoni, 1994; Givoni *et al.*, 2003).

De Schiller and Evans (1998) emphasise that incorrect decisions at town planning levels are normally impossible to correct at a later stage. Eliasson (2000) argued that outdoor thermal comfort should be a routine aspect of urban development, and that climatic aspects should be included in urban codes at different planning levels. In developing countries, rapid urbanisation often implies uncontrolled growth of cities through the formation of substantial informal settlements. In these settlements, climatic aspects are often disregarded. One of the reasons that planned settlements also become uncomfortable is that regulations determining urban design are often inspired by planning ideas from temperate climates, and are consequently poorly suited to local conditions (Ng and Cheng, 2012; Nikolopoulou *et al.*, 2001).

1.4 Research Gap (Significance of the Research)

The urban climate has been studied broadly in moderate regions, primarily in cities with mid-latitude in developed countries. There have not been many studies regarding low latitude climates (Ali-Toudert, 2005). The majority of tropical studies have addressed the urban rural differences, while the other few studied the difference of microclimates within cities. Furthermore, a limited number of studies dealt with intra-urban microclimate variances relative to city designs (Andreou, 2013).

The majority of field studies on intra-urban variations showed that urban geometry has a significant influence on air temperature and that daytime maximum temperatures are inversely proportional to H/W ratios. However, the effect of street orientation on air temperature has been proven to be limited, and only a few studies have been conducted in hot humid climates. To some extent, the existing guidelines are vague, since, with a few exceptions, they do not define or quantify design aspects, such as the space between buildings, building heights, and H/W ratios. In part, this is probably due to the fact that these guidelines are more general for a larger region. De Schiller and Evans (1998) pointed out that their guidelines must be adjusted to local climatic factors and other local conditions, such as topography, existing urban forms, and building traditions. However, the "vagueness" of the guidelines may also be the result of the lack of research on the actual effects of urban design on the microclimate.

The studies being reviewed showed that climate is rarely considered in urban planning and design, while also indicating that the codes and regulations are poorly adapted to local climatic conditions, often acting as obstacles to climate-conscious urban designs. However, there are a few studies from hot humid climates; most stressing the importance of increasing knowledge on climate aspects among urban planners and designers, and of increasing the cooperation between planners and urban climatologists during the entire planning process. For hot humid climates, the majority of the guidelines being reviewed urged for an open and dispersed city plan. This comes into conflict with the need of many tropical countries in increasing population densities in their respective cities.

Urban design guidelines in hot humid climates are often general and not based on systematic research. They need to be improved via specific guidance on design parameters, such as H/W ratio, orientation, surface properties, distance to the sea, and the spacing of the buildings. Although these topics have gained increased attention in tropical climates in recent years, the number of studies remains scarce, especially with regards to hot and humid climates, and rarely in tropical water body zones.

Water bodies' zones have not received much attention compared to other zones in tropical areas, due to the fact that the evaporative effect of water is seen as an alternative for mitigating the ambient temperature of the environment (Manteghi and Remaz, 2015). Past studies have found that in sub-tropical areas, water bodies can provide a significant cooling effect by lowering the ambient temperature by 4 °C as opposed to areas lacking one (Sun and Chen, 2012). Additionally, water ponds favouring evaporative cooling were identified as one of the potential mitigation points for UHI (Givoni and La Roche, 2000; Nishimura *et al.*, 1998; Robitu *et al.*, 2006). Yet Ken-Ichi (1991) and Givoni (1991) pointed out that evaporative cooling is arguably one of the most efficient ways of reducing temperature for buildings and urban spaces in hot regions (Givoni, 1969; Murakawa *et al.*, 1991; Robitu *et al.*, 2006). Based on literature, the water bodies' positive effect works better at lower temperatures and humidity, which is coincidentally analogous to tropical climates.

Some researchers have only studied the cooling effect of the water feature, showing a significant temperature reduction near water facility areas. This might suggest that, in a country like Malaysia, water can be one of the potential cooling factors to its surrounding. However, this might not be the case, due to the humidity that is inherent in the Malaysian climate, which reduces the water evaporation rate, or in some cases, prevent it altogether. This is not the case in hot and arid climates, where increased humidity has raised the comfort levels via the water bodies' cooling effect.

Few studies have focused on outdoor thermal comfort in Malaysia. There is a significant lack of information on data for evaluation of thermal comfort conditions in outdoor spaces in Malaysia and the quantitative assessment of the effect of urban design on outdoor human thermal comfort is lacking. The literature indicate that UHI mitigation has been studied. It has been the most widely applied mitigation measure for achieving extensive energy savings through the temperature reduction of an area (Akbari and Konopacki, 2004).

Water features have not received much attention compared to vegetation in tropical areas whereas the evaporative effect of water is seen as an alternative for cooling the environment. Some researchers have argued the need to aid in the cooling of the water bodies more than in the cooling effect produced by the greenery. Past studies have found that, in sub-tropical areas, water bodies can provide a significant cooling effect by lowering the ambient temperature by 4oC compared to areas without water bodies. In addition, water ponds favoring the evaporative cooling were identified as one of the potential mitigations for UHI (Nishimura *et al.*, 1998). Yet Ken-Ichi (1991) and Givoni (1991) mentioned that evaporative cooling is arguably one of the most efficient ways of passive cooling for buildings and urban spaces in hot regions. Based on the literature review, water bodies' cooling effect might work better at a low temperature and in low humidity, as in the sub-tropical climate.

In Malaysia, some researchers have only studied the cooling effect of the water feature, showing a significant temperature reduction near water facility areas. This might suggest that, in Malaysia, water can be one of the potential cooling factors on its surrounding environment. However, Malaysia might not find the same result due to its humid conditions. In a very humid environment, the water does not evaporate very fast at all. In hot and arid climates, raising the humidity of the air has brought welcome relief through water bodies' water cooling effect.

Hence, the aim of the thesis is to first establish a relationship between water bodies' cooling effect on a larger scale—namely, rivers, reservoirs, and bays—with the surrounding air temperature on a hot sunny day. Second, it evaluates the effectiveness of the different types of surrounding areas in helping the water bodies reduce heat from the thermal environment around it. Whilst evaporative cooling has been one of the most effective ways of passive cooling for architecture and urban spaces in hot regions since ancient times, it is more effective in hot and dry regions in terms of total amount of cooling, as the increase in humidity gives additional comfort. However, it can be equally effective in hot and humid regions in terms of the enhanced level in a thermal environment compared to severe summer conditions (Nishimura *et al.*, 1998).

Therefore, due to lack of detailed evidence and studies, this study seeks to bridge the aforementioned gaps by deepening the knowledge on how urban geometry influence urban microclimate via the analysis of the water body area of the Melaka Town. This study attempts to link the measurements and simulations of the urban microclimate by determining the role of climate aspects in the urban planning and design processes, and analyse the effects of existing urban regulations on urban microclimates. This is the first study in Malaysia in the field of microclimate in outdoor urban spaces at the street level that investigates the relationship between canyon geometry and microclimate created by the water and the subsequent influence of urban planning regulations on the aforementioned microclimate.

1.5 Research Questions

In order to better understand the aforementioned research review, this study will also answer the following research questions:

1. How can street geometries vis-à-vis the river be modified and combined to optimise the cooling effect of the water body?
2. How much does the microclimate environment differ in terms of air temperature and other microclimate variables after combined modifications have been made?
3. How much outdoor thermal comfort is influenced after the outdoor combination modifications has been made?
4. How can new urban areas be designed to improve the microclimate and modified to promote a significant cooling effect and mitigate the temperature at street level in urban water bodies?

This study will address these questions via a case study of the Melaka Town river body area.

1.6 Research Aim

The aim of this study is to quantitatively examine the potential of the cooling effect from water bodies, in combination with street geometries at the street level in mitigating heat stress in a city environment. It will assess the potential and predict the optimal cooling measures for outdoor urban spaces, based principally on the physical properties of streets and water body. It will also include the measurement of how much the combination modifications would reduce the urban air temperature and improve outdoor thermal comfort. This study will highlight the tropical climate environment by using, as a case study, the water body area of Melaka Town, Malaysia. To realise this, the following objectives are devised:

1.6.1 Research Objectives

Objective 1: To assess the currently created microclimate conditions in the context of the benefits of water bodies to the surrounding urban geometry.

Objective 2: To investigate the impact of multiple existing urban street geometries on ambient temperatures and how the air temperatures vary and interact with the water bodies during hot sunny days.

Objective 3: To propose different hypothetical urban geometries, represented by the canyon's aspect ratio, solar orientations, and river width in order to evaluate their respective impacts on the water body's microclimate.

Objective 4: To evaluate the outcomes of the simulated configurations and assess the optimal model based on their respective impact on comfort levels.

1.7 Scope and Limitation of the Research

This work concentrates on how urban design affects microclimate, and how it leads to the development of a comfortable microclimate. The research focused on the combined effect of street ratio, orientation, and distances with water body modification at the street level on the improvement to the outdoor environment via air temperature reduction and thermal comfort improvement in the Melaka river body, Malaysia.

Urban geometries and buildings' typologies: The study limits itself to street level microclimates, i.e. the urban canopy layer, roughly the space between the ground and the rooftops. This work explicitly excludes rooftops, which allows for a better understanding of the horizontal impact and the behaviours of cooling from river with the streets on the surrounding outdoor environment. Therefore, the investigations incorporated the influence of the cooling impact from the water body on temperature mitigation and microclimate outdoor thermal comfort (Ng and Cheng, 2012).

As the study is limited to a town and the water body of a hot and humid climate, some of the findings will seem very general, which makes the conclusion valid, but only for a certain hot humid climate groups, due to the fact that there are climatic variations between different cities in terms of size, planning principles, proximities to the water body, and topography (Ng and Cheng, 2012).

The main focus of the work would be on business and mixed-use areas, and to a lesser extent, on other land use areas. The study concentrates on urban design and detailed planning levels, rather than on comprehensive planning aspects, such as the location of urban areas within a city. Therefore, detailed street design and vegetation, alongside public spaces such as squares and parks, are not included in this work.

Outdoor thermal comfort: Thermal comfort is estimated by calculating a comfort index based on the environmental parameters that are measured, calculated, or simulated. The study does not include field studies on subjective thermal comfort, as perceived by pedestrians (Ng and Cheng, 2012).

Melaka's climate characteristics: In order to identify locations with multiple urban geometries, the variation in air temperature and microclimatic conditions are analysed at street levels. However, the amount of air pollution and the influence of vegetation and anthropogenic heat on climatic have not been accounted for. Therefore, the microclimatic condition is evaluated strictly with regards to the effects of the characteristics of the geometries of the chosen areas. Moreover, the effect of air pollution on thermal conditions in cities was proven to be small, at least in moderately polluted cities, such as the ones included in this work. Energy use in buildings is not treated, mainly to limit the study, but also because the use of space conditioning is, to date, limited to the city being studied. Although indirectly affected by the urban climate, indoor thermal comfort is not treated.

Urban microclimate studies: In-situ microclimatic measurements were carried out for ten days in June due to time constrains, cost issues, and equipment limitations. However, the prevailing climatic condition in this month is considered representative of typical hot sunny days. This will not influence the results, due to the fact that the weather condition in the tropical climate of Malaysia remains similar throughout the year, while parameters such as temperature and humidity shows little monthly fluctuations.

Numerical modelling: The numerical models that are going to be generated will agree with the building regulations of Melaka Town in terms of local street width, maximum ratio of opening allowed in building façades, Melaka River width, and the common building materials used in Melaka.

Briefly, the scopes of this research are:

- The effect of water body microclimate on the performance in terms of ratios and orientations in several street canyons in Melaka city based on meteorological parameters performance; and
- The use of field measurement methods and ENVI-met simulations to study the effect of water bodies of the surrounding area covering the climatic performance on a hot sunny day.

Limitations are listed according to the individual investigations in the following order:

In the field measurement investigation, there were a limited number of data loggers and a handheld climate meter for data collection. Both were needed for data collection, which intends to be more representative of the different outdoor landscape environments across the area being studied. Therefore, 18 significant location points on different streets were located and selected to represent the environment of the water body study area.

ENVI-met simulation was limited to 36 proposed scenarios due to time and hardware constraints.

There were limited numbers and types of instruments for field measurement. Thus, the measurement was taken according to instrumentation limitations and availabilities.

Thermal investigation consisted of measuring air temperature, globe temperature, the relative humidity, and wind speeds.

1.8 Research Design

The research in this study is multidisciplinary in nature. The main objective is to understand how the microclimate created by water will affect the urban area and how the physical characteristics of the built environment will influence the microclimate within similar areas. However, the study also examines how climate-related issues are accounted for in the urban design and planning processes. To respond to the research questions presented, it is necessary that the design of the research process combine two research methodologies. The overall design could be classified as experimental, although it includes a combination of experiments and simulations research methodologies.

Within each methodology, different methods or techniques were used. The aim of the experimental part of this study is to map the variations of microclimates within the city. This entailed field measurements in areas with significantly different characteristics, including variations in urban street orientation and ratios, and their respective locations vis-à-vis the river. However, microclimatic variations in the city are large, and representing all of these variations will require very involved and extensive measurements. Therefore, the study is restricted to the current existing conditions in the city. The aim of numerical simulations is to cover a wider range of urban designs. Moreover, the usage of simulations will allow us to pinpoint the independent variables, which will help in determining their individual impacts upon microclimates. This will also help in anticipating the influence of new urban designs upon microclimates and optimise it from the perspective of microclimatic and thermal comforts. Prior to that, a comprehensive review on current knowledge was done to illuminate the size of the problems under investigation within a global context and the local microclimatic conditions of Melaka Town.

The two methodologies combine multiple ways to optimise the research results. For example, the physical and atmospheric processes governing urban climate are rather complex. This makes them difficult to simulate, and the accuracy of existing models is sometimes questioned. Consequently, the experimental study is important in validating and calibrating the results of the simulation study. The mixed methodology also helps identify the strengths and weaknesses of existing urban codes in the context of climate-conscious urban designs.

1.8.1 Experimental Methods

The experimental part of the study comprises of measuring climatic parameters in urban environments. The measurements will be performed within an urban canopy layer. The periods during which the experimental studies will be conducted will cover the seasons exhibiting the worst thermal stress. In the case of Melaka, where the annual climate variations are small, the climate measurements was conducted during the most thermally uncomfortable period.

1.8.1.1 Climate Measurements in Urban Street Canyons

The testing environment consists of a set of urban street canyons in the town of Melaka. The selected canyons represented their respective neighbourhoods. The canyons are completely different in terms of urban geometry (H/W ratio), orientations, and locations to the river.

The parameters that would be measured are:

- Air temperature (Ta)
- Relative humidity (RH)
- Wind speed (W)
- Wind direction (Wd)
- Globe temperature (Tg)

In an attempt to assess the temperature of the air over urban street, multiple locations were measured from the river, which was then selected based on their respective of H/W ratios and orientations. In this work, air temperature urban street canyons are independent variables, while physical and climatological parameters are dependent variables. At the urban site, the temperature and humidity of the air was measured continuously using miniature data loggers, which was shielded against radiation. The loggers were placed at least 2 m above ground, due to pedestrian traffic and the risk of theft, and at least 1 m from the nearest façade. The measurements are assumed to be representative of the conditions at the pedestrian level, since the temperature and humidity variations within urban canyons have proven to be small, except near the urban surfaces (Ng and Cheng, 2012; Oke, 2004). Wind speed, globe temperature, and global radiation will only measure instantaneously and on a limited number of occasions.

1.8.2 Simulation Methods

The simulation part of the study included computer simulations of the urban microclimate.

1.8.2.1 Choice of Model and Calibration

Among the numerical models being reviewed, 3D model ENVI-met (Bruse, 1999) version 4.0 is regarded as the most suitable for the simulation, since it simulates the microclimatic conditions within urban environments in a high spatial and temporal resolution, and it will be used in this case due to its fastness and low-cost (Ali-Toudert *et al.*, 2005; Arnfield, 1990b; Arnfield, 2003). The measurement site in the city will be modelled in the ENVI-met model, and the simulated microclimate was compared to the measured results.

1.8.2.2 Parametric Study

The simulation is performed as a parametric study, where different parametric characteristics of the urban canyons are subjected to adjustment. The effect of the following design parameters on microclimate will analyse:

- Street geometry (H/W ratio)
- Street orientation
- River width

The H/W ratio is selected to reflect the measurement sites. The street orientations for each H/W ratio: East-West and North-South will be analysed for all simulations. The real width of the Melaka River, which is twice or thrice wider than the original, will be simulated as well. The final step will involve the combination of the changes to the microclimate at the street level and the "Best Case" scenario.

1.9 Anticipated Findings and Contribution of the Study

The main aim of this research is to realise the principles and fundamentals for the promotion of the quality of urban street canyons via changing physical characteristics and extend the microclimate created by the river to the surrounding areas, intending to promote the local microclimatic comfort in the water body tropical climates. Additionally, via simulation and experimental measurements, the findings could be used to determine how the surrounding street canyons near the water affect the performance of microclimates. The qualitative information about optimal street forms, which helps regulate the climatic comfort in the urban canyons in tropical water body cities, will contribute to this as well (Krüger *et al.*, 2010). Due to the fact that there are no comprehensive framework, evaluation, and strategic model for promoting of tropical water body microclimate of urban open spaces in street canyons being presented in this case, the main achievement of this research will be to empower architectural specialists in identifying the effective parameters of local microclimates in tropical water body and its relation to street geometry parameters. In fact, the aforementioned evaluation model provides the designers with certain criteria and methods that utilises similar parameters, which will lead to the promotion of space street canyons. Consequently, the main users are landscape architects, and on a micro scale, urban planners and designers. They shall benefit from the results of this research in terms of the establishment, designation of dimensions, scale, and the main utilisation of the streets.

Other predictions of this research involve the designation of a limit for microclimate comfort and its predictive equations. This can be utilised by urban planners and designers, and support researchers involved in natural geography works. Other achievements of this research include the possibility of using statistical results of environmental achievements by researchers and geographical and climatic sciences. Statistical achievements of individual, social, and physical characteristics and microclimatic models may be utilised by researchers of social sciences and psychology on thermal comfort research as well.

1.10 Organisation of the Thesis

This study is made up of six chapters, and is organised under five key phases. The first phase covers Chapters 1 - 2, both of which sets out the background for the problem being investigated, and reviews the relevant literatures. Chapter 3 discusses the methodology associated with the research. Chapter 4, which is part of the third phase, will discuss the empirical studies, including the preliminary studies and microclimate measurements, which were designed to address the majority of the research questions. The fourth phase, which includes Chapter 5, will detail the numerical modelling, including the urban setting used in the present study, and the results of the microclimates of a number of proposed configurations. Finally, the fifth phase, which comprise of Chapter 6, highlights the findings of the research, conclude the work, and make some recommendations for future works pertaining to this subject (Fig.1.1).

1.10.1 Phase One: Research Background, Methodologies, and Literatures

1.10.1.1 Introduction

Chapter One: Presents a comprehensive background on the problem under investigation and the current knowledge in the field, followed by the research problems and the justifications for the present study. The aim, questions, and objectives of the research will be presented in this chapter, along with the methodology, research scope, and limitations.

Chapter Two: Sets out the theoretical background for the problem under investigation by covering various aspects related to the impact of urban and canyon geometries on the outdoor microclimate, and its relation to thermal comfort in outdoor spaces. The scope of literature review will include urban microclimate, urban heat islands, and the causative factors of the UHI, and the methods used to estimate the intensity and the magnitude of such urban climate phenomena. The urban energy balance and the thermal structure of the urban canyon, such as surface and air temperature, and the wind flow over the urban areas and within the urban canyon outdoor thermal comfort, and the literature review will be dedicated to investigating the influence of urban and canyon geometry and the resulting microclimatic condition on outdoor thermal comfort and energy consumption in urban dwellings, the effect of water bodies in moderating microclimates, and finally, the model and tools for predicting urban microclimates.

1.10.2 Phase Two: Methodology Studies

Chapter Three: Presents the preliminary studies, including a brief description of the geographical characteristics and climatic features of Melaka Town. The City will be detailed within the urban context, selected study zones, old heritages, and new modern zone in the water body of Melaka town and the selected measured points. The methodology and the instrumentations used in the continuous and instantaneous measurements of the microclimate condition will be presented here as well. The computer based design aid tools will be used; including the microclimate model (ENIVI-met), and the Ray-Man model to calculate the PET index will be presented and discussed.

1.10.3 Phase Three: Preliminary and Measurement Studies

Chapter Four: Preliminary studies with the microclimatic measurements, which were carried out in two zones of Melaka town, along with the results, are presented. After that, the computer simulation results and the validation of the ENI-met model will be discussed, and at the end of this chapter, the approach used in presenting the outdoor thermal comfort will be presented.

1.10.4 Phase Four: Numerical Modelling

Chapter Five: Presents the methodology used in generating the hypothetical urban geometries. This will be followed by the discussion of the results of the microclimate the proposed configurations. The outcomes of the simulated numerical models are categorised into three groups and will be evaluated according to their micro-meteorological data and outdoor comfort at the end of this chapter, where a comprehensive study over the average outdoor comfort of all numerical models will be presented.

1.10.5 Phase Five: Discussion and Final Conclusion

Chapter Six: Concludes and discusses the findings from the research, including those obtained from the in-situ microclimate measurements, and highlights the intra-urban air temperature variations found in Melaka town from the outdoor thermal comfort study. This will also include the discussion of the modelling effect of different canyon geometries and orientations on microclimatic conditions and outdoor thermal comfort from the urban buildings in the Melaka town. Finally, the considerations for climate in urban design in Melaka town and recommendations for climate-conscious urban design are presented, along with suggestions for future studies.

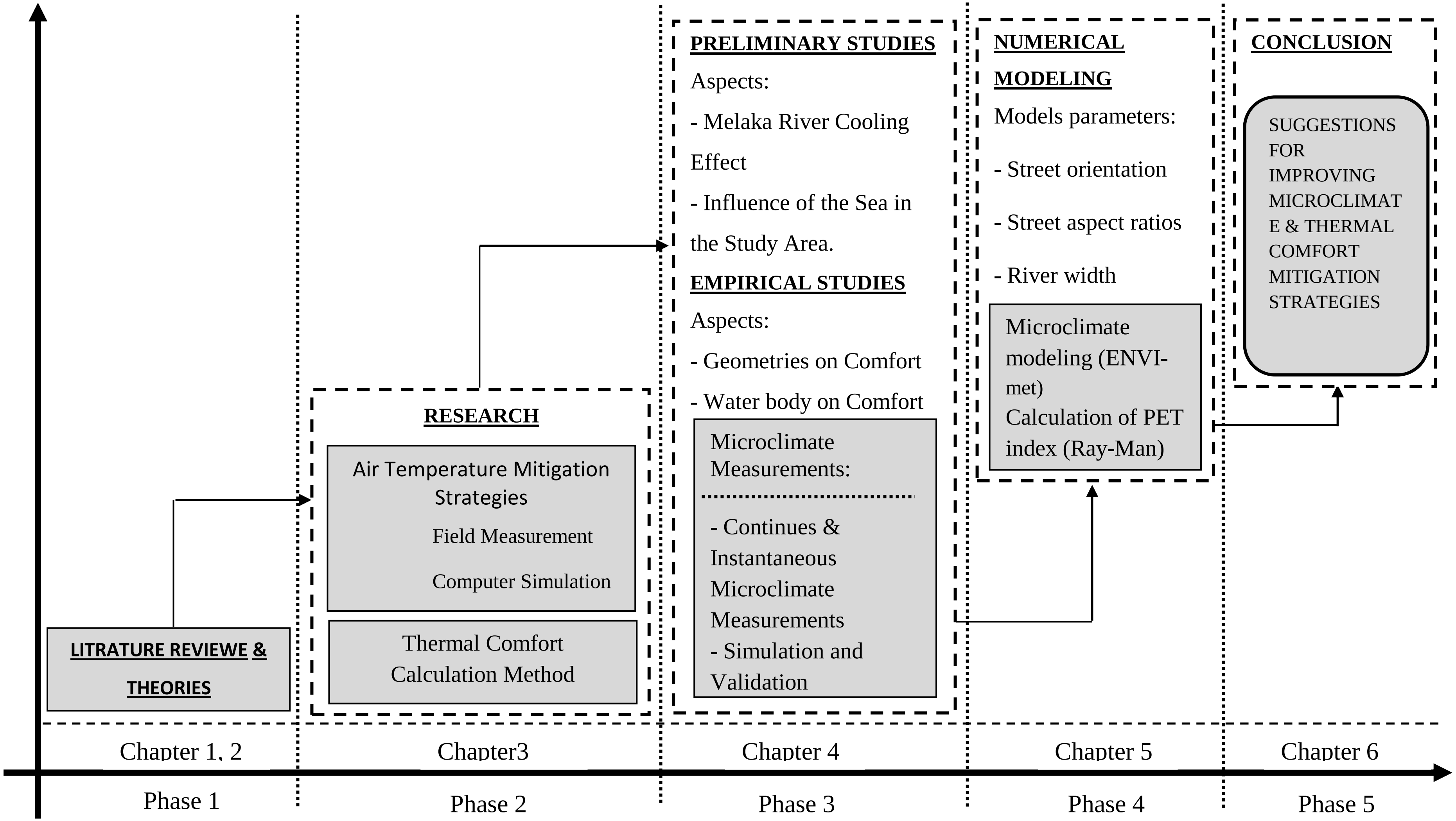

Figure 1.1 The research frame work

1.11 Summary

This chapter highlights the need of this study to improve the water body's microclimatic conditions via heat stress mitigation strategies to improve thermal comfort in the tropical country of Malaysia. The Melaka river body area was focused on in the heritage and modern zones. In order to further understand the current scenario related to the research, literature supporting the research scope and theory would be reviewed in Chapter 2.

6.11 Future Studies

In this study, thermal comfort was calculated theoretically and comfort limits were estimated on the basis of other studies. The effects of climate adaptation were not considered in this work. Therefore, there is a great need to conduct field surveys in hot humid climates in order to determine actual comfort zones. Such field surveys should include simultaneous microclimate measurements at street level and subjective comfort votes by pedestrians.

This study examined the impact of the urban geometries and the spatial arrangement between buildings on the microclimate conditions and, consequently, on the outdoor thermal comfort. Future studies should include in-situ measurements to develop more detailed knowledge on the effect of the thermal mass of the canyons facets (walls and ground) on its microclimatic conditions and outdoor thermal comfort. This factor can be now investigated using the updated version of the 3D microclimate model (ENVI-met), which now takes into account the buildings' thermal mass in the calculation of the external microclimate conditions.

Wind speeds need to be promoted in hot humid climates, especially where they are low. The design of urban areas to promote air flow needs to be studied thoroughly, for example via detailed CFD analysis.

Apart from the obstacles that hinder the usage of vegetation as design options in such climates, future studies may examine the effect of selected trees that are typically found in the humid regions, i.e. Maleleuca leucadendron, on the external microclimate condition and outdoor thermal comfort. Some of the common species that have proven efficiencies and are used for environmental management are Filicium decipiens, Mesua ferrea, and Ficus benjamina (Shahidan *et al.*, 2012)

Future studies may examine the influence of a number of urban geometries on the indoor energy consumption from air condition buildings, and predict the cooling loads needed to maintain a consistent indoor temperature and investigate the influence of urban geometries on thermal comfort in naturally ventilated buildings using the adaptive comfort approach.

6.12 Summary

It can be surmised that the design strategies, despite resulting in lower air temperatures, might not increase outdoor comfort levels. The simultaneous increase of mean radiant temperature and relative humidity, and the decrease of wind speeds would be detrimental to outdoor thermal comfort. This effect can be mitigated via superior design that lowers both the air temperature and mean radiant temperature, which would result in increased thermal comfort levels. If the positive influence of air temperature and the reduction of the mean radiant temperature could mitigate the negative influence of relative humidity increase and wind speed reduction, the levels of outdoor comfort can be greatly enhanced. The aforementioned points implies that shading as representing one of the key strategies that help enhance outdoor thermal comfort in Malaysia, due to the fact that it decreases the air temperature, resulting in cooler thermal sensations. Shading that is realised via high aspect ratios can substantially increase thermal comfort for people on the street. Maintaining increased aspect ratios is confirmed as an effective technique that helps decrease the exposure to solar energy and absorbed short-wave irradiance. The effect of water cooling was also proven to be effective in enhancing thermal comfort, which results in improved outdoor comfort levels.

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