SHADE AND COOLING EFFECT OF COLONNADE IN LOW-RISE STREET CANYON IN TROPICAL CLIMATE

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To my beloved parents, brothers, sisters and friends
for their support and encouragement.

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ABSTRACT

The shophouse buildings in Malaysia, which flank commercial streets, are of low-rise planning. The building height is controlled according to council's plot ratio, but is always built on the development needs. Colonnade has been a part of the shophouse design regulations to provide overhead rain shelter and for sun shading. Provision of 7.5 feet (2.25 m) is the minimum depth. The main aim of this study is to investigate the potential of colonnade depth to lower the overall air temperature in the urban street microclimate. At the same time, fundamental climatic criteria of overhead shading elements and provision of enough space as a pedestrian thoroughfare in the urban must be fulfilled. *Ecotect* is used to run the shading analysis. Envelope Ratio and CTTC model are used for air temperature reduction simulations. In a H/W 0.25 street, adequate overhead shading from 1100 to 1600 can only be achieved with D_c/H_c 1.5 and above. This translates to 6 meters of colonnade depth. Colonnade in H/W 2 street with D_c/H_c 1 and above provides comfortable shades throughout the day. To lower the air temperature, the optimum colonnade depth to street width ratio is C/W 0.6. Deeper colonnade will give no significant microclimate improvement. It is found that the ideal colonnade ratio is C/W 0.2 to 0.6. Existing urban code requires D_c/H_c 0.75. In a north-south street, it is only able to offer adequate shade of 2 meter from 1230 to 1400. In a east-west street, it is only able to give 1 to 1.5 meter of shade, during the extreme case of summer and winter solstice. Existing colonnade depth of 2.25 meter and street width of 15 meter will give C/W 0.15. In both shallow and deep canyons, the effect in reducing the air temperature is limited.

ABSTRAK

Rumah kedai, bangunan yang biasa didapati di jalan-jalan komersial di Malaysia, dikategorikan dalam pembangunan bertingkat rendah. Ketinggian bangunan dikawal mengikut nisbah plot majlis, tetapi lebih biasa dibina mengikut keperluan. Ruang kaki lima telah menjadi sebahagian daripada rumah kedai untuk menyediakan tempat perlindungan hujan dan untuk teduhan matahari. Mengikut peraturan, kedalaman ruang ini sekurang-kurangnya 7.5 kaki (2.25 m). Tujuan utama kajian ini adalah untuk mengkaji potensi kedalaman ruang kaki lima dalam merendahkan suhu udara keseluruhan iklim mikro jalan bandar. Pada masa yang sama, asas tujuan reka bentuk teduhan atas kepala dan penyediaan ruang yang cukup sebagai ruang pejalan kaki perlu dipenuhi. Perisian *Ecotect* digunakan untuk menjalankan analisis teduhan. Model *Envelope Ratio* dan CTTC digunakan untuk menjalankan simulasi pengurangan suhu udara. Bagi jalan H/W 0.25, teduhan atas kepala yang mencukupi dari jam 11 hingga jam 16 jam hanya boleh dicapai dengan D_c/H_c 1.5 dan ke atas. Ini akan menterjemahkan ruang kaki lima sedalam 6 meter. Ruang kaki lima di jalan H/W 2 dengan D_c/H_c 1 ke atas menyediakan teduhan yang selesa sepanjang hari. Nisbah C/W 0.6 adalah nisbah optimum bagi pengurangan suhu. Kedalaman yang selebihnya tidak akan memberikan peningkatan yang ketara. Nisbah kaki lima yang optimum ialah C/W 0.2 hingga 0.6. Peraturan perancangan bandar sedia ada memerlukan D_c/H_c 0.75. Bagi jalan yang berorientasi utara-selatan, ia hanya mampu untuk menawarkan tempat teduh yang mencukupi (2 meter) dari 1230 hingga 1400. Bagi jalan yang berorientasi timur-barat, ia hanya dapat memberikan 1 hingga 1.5 meter tempat teduh, semasa solstis musim panas dan musim sejuk. Ruang kaki lima sedia ada yang sedalam 2.25 meter dan lebar jalan 15 meter akan memberikan C/W 0.15. Keupayaan nisbah ini dalam mengurangkan suhu udara adalah terhad.

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LIST OF ABBREVIATIONS

2D	-	Two-dimensional
3D	-	Three-dimensional
CBD	-	Central business district
CFD	-	Computational fluid dynamic
CTTC	-	Cluster Thermal Time Constant
DEM	-	Digital elevation model
E	-	East
GIS	-	Geographic information system
H/W	-	Aspect ratio
HSA	-	Horizontal shading angle
N	-	North
NE	-	North-east
NLWR		Net long-wave radiation loss
NW	-	North-west
PET	-	Physiological Equivalent Temperature
RH	-	Relative humidity
RMT	-	Radiant mean temperature
S	-	South
SE	-	South-east
SVF	-	Sky view factor
SW	-	South-west
UCL	-	Urban canopy layer
UHI	-	Urban heat island
VSA	-	Vertical shading angle
W	-	West

LIST OF SYMBOLS

$\propto$	-	Reflectivity of short-wave radiation
α	-	Albedo
β_t	-	Sun altitude angle (°) at time t
Br	-	Brunt number
C	-	Heat capacity (J m^{-3} K^{-1} x 10^6)
C/W	-	Colonnade depth to street width ratio
D	-	Diffuse-beam radiation (W/m^2)
D	-	Depth of building (m)
D_c/H_c	-	Colonnade depth to colonnade height ratio
dx	-	Offset from the shading point
dy	-	The depth of the shade
e_t	-	Solar azimuth angle (°) measured from the south, at time t
ε	-	Emissivity for long-wave radiation at the surface
FA	-	Plan area of building roofs in cluster (m^2)
GA	-	Ground area (m^2)
h	-	Overall heat transfer coefficient at surface (W/m^2 K)
H	-	Building height
h_{roof}	-	Overall heat transfer coefficient at roof surface (W/m^2 K)
$I_{canyon\ top}(t)$	-	Solar radiation intensity on rooftop (W/m^2)
I_{g}	-	Solar radiation intensity on the ground (W/m^2)
I_{pen}	-	The total absorbed solar irradiation on surface (W/m^2)
I_{NLWR}	-	Net long wave radiation loss from an unobstructed

		black surface
Iv_i	-	Solar radiation intensity on the sunny part of the *i*th wall (W/m^2)
K	-	Temperature degree Kelvin
k	-	Thermal conductivity (W m^{-1} K^{-1})
$K*$	-	Incoming short-wave radiation (W/m^2)
$K\uparrow$	-	Reflected radiation (W/m^2)
$K\downarrow$	-	Incoming global radiation (W/m^2)
$L*$	-	Incoming long-wave radiation (W/m^2)
$L\uparrow$	-	Outgoing long-wave radiation (W/m^2)
$L\downarrow$	-	Incoming long-wave radiation (W/m^2)
m	-	Surface solar radiation absorptivity
m_g	-	Ground surface solar radiation absorptivity
m_H	-	Wall surface solar radiation absorptivity
σ	-	Stefan-Boltzmann constant
PSA_g	-	Walls' partial shaded areas on the ground
PSA	-	Partial shaded area
ρ	-	Density (in kg m^{-3} x 10^3)
ΔQ_A	-	Net advection through the sides of the volume
ΔQ_S	-	Net heat storage
Q_E	-	Latent heat
Q_F	-	Anthropogenic heat
Q_H	-	Sensible heat
S	-	Direct-beam radiation (W/m^2)
S	-	Total investigated area (m^2)
SVF_{roof}	-	Sky view factor of the roof surfaces
t	-	Time (h)
t_{min}	-	Minimum value a time *t*
T_0	-	Base temperature (°C)
T_a	-	Air temperature variation (K)
T_{air}	-	Ambient air temperature (K)
T_{NLWR}	-	Contribution of net long-wave radiation exchange to air temperature (K)

T_{solar}	-	Contribution of solar radiation absorption to air temperature (K)
T_s	-	Temperature of the surface
u	-	mean wind speed (m/s)
μ	-	Thermal admittance (J m^{-2} $S^{-1/2}$ K^{-1})
V	-	Envelope ratio
V	-	Envelope ratio
WA	-	Wall area (m^2)
X_t	-	Shaded strip width (m) at time t
λ	-	Time (h) of indexing

CHAPTER 1

GENERAL INTRODUCTION

1.1 Introduction

Optimization can be done in our existing urban design to unleash the fullest potential. Evaluation on the current urban planning regulations and a profound understanding on climate-sensitive design theories will lead to a revisit on the common practices of urban planning and design.

One of the possible potential in Malaysian context, is the use of colonnade (commonly known as five-foot-way locally) to reduce the thermal heat stress in the urban canopy layer. Colonnade has been a part of the shophouse design regulations to provide overhead rain shelter and for sun shading in the commercial street since 1822, by Sir Stamford Raffles (Governor of Singapore). It was set to be 7.5 feet (2.25 m) minimum in depth.

The street's size and geometry are governed by a set of urban planning codes (refer chapter 2.5.1 for detailed descriptions). Among all these constraints, colonnade depth has the potential to be explored to achieve urban cooling effect.

There are a few infant theories explaining this phenomenon and they point to a promising environmental advantage of such design element to the canyon street microclimate. Hanna Swaid (1993) confirmed the use of colonnade would offer reduced heat stress round the clock. Johansson (2006) found out that colonnades provide more efficient shading than trees. Ali-Toudert's (2007) research observed shorter period of high streets in the street which was caused by the colonnade. B Taylor (2008) explained the role of colonnade in minimizing diffuse as well as direct solar gain. It was further affirmed that the colonnade makes maximum use of shaded thermal mass which is able to reduce the radiant temperature field to below the air temperature.

In another finding, Shashua-bar (2006) suggested that the cooling effect is proportionate to the envelope ratio (ratio of ground area to total surface area in the site, ($\frac{\text{Ground Area}}{\text{Ground Area+Wall Area}}$) (refer figure 3.16 for illustration). The depth of the five-foot-way will add the total wall area in the envelope. Therefore, as a rule of thumb, in the street envelope area, the more wall area added, the more cooling effect it will bring to the urban canopy layer.

Malaysia, an under developing nation, is experiencing rapid urbanization as well. In accommodating the growth, the solution is by increasing row houses or structures to accommodate the growth. Developments of new dwelling areas are always accompanied by paved surfaces, parking lots, roofs and wall surfaces and etc. Construction materials like tarmac, concrete and steel are large heat storage in the urban, which absorb heat in the morning and radiate into the surrounding at night. It is predicted to cause 10^{o}C or more temperature rise in city centers than suburban green areas (Ahmed, 2003).

Drainage and Irrigation Department (2000) carried out the rainfall analysis for Kuala Lumpur after the CBD was observed and reported to be too hot in the daytime hours. It was found that the increasing trend in flash floods was related to the increased frequencies of extreme rainfall events and increased total annual rainfalls.

Most developing nations and cities are located in the tropical region. These nations are experiencing unprecedented rate of growth. There are influxes of population into the urban areas in seeking of opportunities. In year 2000, the proportion of the world's population living in the tropical climate zone was estimated at about 40% (Landsberg, 1984). World Bank (2002) projected the urban population in the developing world is expected to increase by about 25–45% except in Latin America and the Caribbean where the urban population already exceeds 70%) from 1990 to 2020. By 2020, the urban population is expected to be greater than the rural population in all parts of the world.

Construction is unavoidable in solving the constant increase of population. In the world most populated nation, China, the housing sector accounted for 40% of global new building volume in year 2007 (Fernandez, 2007).

Urban areas act as climate modifiers. Climate elements, such as solar radiation, air temperature, humidity and wind are affected by the urban fabric. These caused the nocturnal urban-rural temperature differences of 6°C or more in the centres of major cities (Oke, 1987). The average diurnal temperature rise due to urbanization is projected to be greater than the estimated 1–3.5°C rise in temperature due to global climate change over the next 100 years (IPCC, 2001).

Physical environmental issues are also reported as the results of rapid urbanization. These include air (air pollution), water (floods and storms) and climate quality (heat waves) (Campbell-Lendrum and Corvalan, 2007).

Plagued by financial resources, political will and professional input, rapid urbanization in developing countries is often negative. It causes poor housing conditions, poverty, environmental problems, health problems and social issues.

Thus, there is an urge for the urban built-environment planning approaches which ameliorate the urban climate change. Researchers and urban planners should therefore take up the challenge to offer their expertise, to help ensure the life quality of the urban dwellers.

According to Emmanuel (2006), the current trend of emphasis for urban heat island mitigation has been on ventilation. In his suggestion, the basis for possible mitigatory approach in tropical cities lies in the provision of urban shade by utilizing buit-up areas. Not only shade offers further enhancement to the ventilation mitigation approach, the happy by-product of shade by utilizing urban geometry approach is the possibility of accommodating very hight density urban living.

1.2 The Problem Statement

The current urban street geometry is mostly governed by various urban design and planning codes, manuals and standards. The shophouse buildings, which flank a commercial street, are of low-rise planning. Often, they are not more than 4 stories high. There is no front set back. The building height is controlled according to council's plot ratio, but is always built on the development needs. The street width is planned to accommodate the driveway, parking lots and sometimes landscape features, which made it between 15 m to 25m. The backlane, if built in minimum distance, is only 6 m apart (refer table 2.7 for the regulations and codes).

When translated to the urban climatic design terms, the current urban design and planning codes will give a shallow canyon to the entire fabric. There is also no street orientation consideration as well.

Thus, despite a set of constrained planning rules on the street width and building height, the most possible variable to be adjusted and utilized is the colonnade depth. Hence, the focus of this study is to find out the influence of colonnade depth to the overall microclimate of the urban canopy layer.

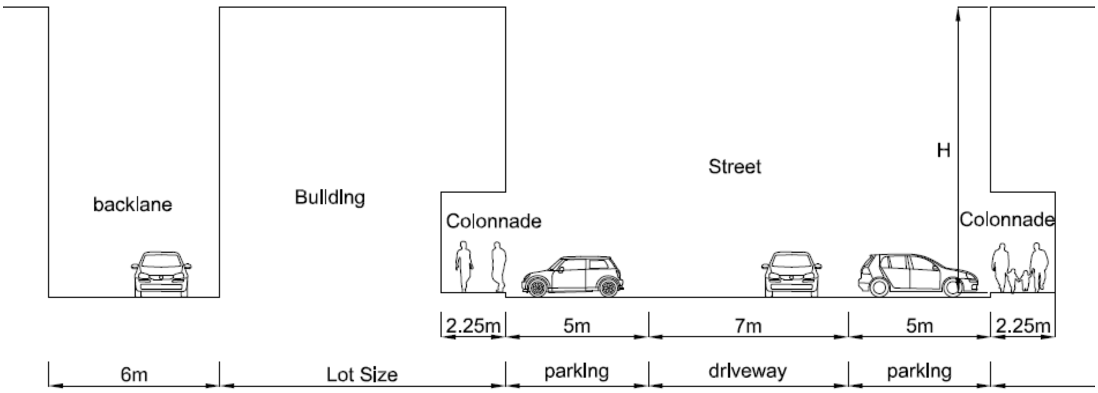

Figure 1.1 : Sectional diagram of a typical commercial street in Malaysia

1.3 Research Hypothesis

The hypothesis of this study is that an optimum depth of a colonnade will achieve the following:

i. Provide adequate shade as an overhead shading shelter.
ii. Reduction of the thermal heat stress of the street.
iii. Thus, creating cooling effect to the street canopy layer.

1.4 Research Questions

The following questions will be addressed in this thesis:-

i. What is the depth of the colonnade to provide adequate overhead shading in different street aspect ratio and orientation?

ii. What is the influence of colonnade depth to the envelope ratio?

iii. What is the influence of envelope ratio in reducing solar radiation absorption?

iv. What is the influence of colonnade depth in SVF and heat release?

v. Does existing colonnade requirement favour or hinder climate-conscious urban design?

1.5 Research Gap

Previous reseaches on street design and colonnade were reviewed in order to get a clear understanding of the shading and thermal heat stress reduction knowledge and identify the areas which had not been covered in the past. It reviewed that research on tropical urban street design had been focusing mainly on: solar shading strategies on urban canopy street, thermal balance and microclimate in urban canopy layer, and human comfort and perception.

Some researches were done in temperate climate and were in the summer period. They covered both shallow and deep canyon street strategies. Thus, literature materials can be extracted to review the microclimate on low-rise street canyon.

There are research on the influence and impact of colonnade, but they are limited to only conventional depth / width. Hence, exploration into various depths can be carried out.

Table 1.1 : Summary of previous research related to tropical urban street design, colonnade and urban canopy layer microclimate

Research	Methodology	Climate	Design Variables							Performance Variables				
			H/W – Shallow Canyon	H/W – Deep Canyon	Orientation	SVF	Envelope Ratio	Colonnade Depth	Projection Ratio*	Shade	Direct Solar Radiation	Diffuse Solar Radiation	Temperature	Human Comfort (PET)
Morad (1979)	S	T	√	√	√				√	√	√			
H Swaid (1992)	S	T	√	√	√	√			√				√	
H Swaid (1993)	S	T	√	√	√	√		L					√	
E Johansson (2006)	S	HH	√	√	√			L				√		√
Shashua Bar (2006)	S	T	√	√		√	√	L					√	
R Emannuel (2007)	S	HH	√	√	√							√	√	√
Ali Toudert (2007)	S	HA	√	√	√			L				√	√	
B. Taylor (2008)	S	T						L					√	
Present Study (2011)	***S***	***HH***	√		√	√	√	√		√	√		√	

* Projection ratio of shading device, adjustable louvers or any kind of overhang

HA Hot Arid — HH Hot Humid — L Limited depth
S Simulation — T Temperate

1.6 Research Objectives

The main purpose of this study is to study the potential use of colonnade depth in current shophouse design to lower the overall air temperature in the urban street microclimate. Other fundamental climatic criterions of the colonnade design must be fulfilled for hot and humid climate context: overhead shading and provide enough space as a pedestrian thoroughfare in the urban. It is envisioned that the next generations of shophouse façade design will be revolutionized. It not just merely fulfils the basic urban planning and design codes, but incorporates climate-sensitive principles.

In achieving the above goals, a few objectives are derived.

i. To define the colonnade and street design in Malaysia urban by looking into the urban planning codes.

ii. To evaluate the climatic impacts of colonnade in current shophouse and street design in terms of the shade percentage in the colonnade and contribution to the urban street air temperature.

iii. To determine the depth of the colonnade based on the performance of shading and street cooling effect.

iv. To determine the influence of aspect ratio (building height to street width ratio) on the shade and cooling performance of the colonnade.

1.7 Scope and Limitations

The study and analysis of the research are limited by the microclimate evaluation model used. The overall microclimate evaluation concept is built upon the Cluster Thermal Time Constant model. It is a simple evaluation calculation model to calculate the air temperature in the urban canopy layer. Envelope Ratio concept is a further development of CTTC model, which quantifies that the ratio of the ground surfaces to the overall street envelope surfaces main influence to the heat gain of the canopy layer. It is, however, limited to the calculation of a symmetrical street. Further, *Ecotect* building simulation software is used to run the shading analysis and solar insolation on facades.

This research concentrates on how colonnade depth impacts the thermal heat stress in the urban microclimate. The scopes of the research are discussed as follows:-

(i) The configurations of the colonnade and street will be formulated to represent the low rise aspect ratio found in Malaysia cities. The street canyons are made up with aspect ratio of 0.25, 0.50, 1, 2, for both north-south and east-west oriented street. Street canyons are treated as terraced building in infinity length. Back lane is not considered. Only street front with colonnade is considered.

(ii) The study is limited to hot humid climate. Johor Bahru climate data is selected as input such as base temperature and solar radiation. Data were obtained from Senai Airport station.

(iii) Dry or wet season is not important in this research. Ground cover and wall materials are set constant throughout the simulations.

(iv) Shading analyses are done on the colonnade facing cardinal directions. For east and west facing facades, solar angles of 21 June are used. Whereas for north and south facing facades, solar angles of extreme cases during summer and winter solstices.

(v) The thermal heat reduction analysis is limited to the microclimate at street level, i.e. the urban canopy layer, roughly the space between the ground and the roof tops.

(vi) The main variable in the colonnade is the colonnade depth, which will influence also the envelope ratio of the street.

(vii) Thermal heat stress reduction will be analysed through absorbed solar irradiation and net long-wave release on the envelope surfaces. Only direct beam solar radiation is considered. Anthropogenic heat and all other types of heat are not considered.

(viii) Solar radiation absorption simulation is based on data on 18 August, which represents a typical fine and clear day which shows high and consistent solar radiation through the day. Time period of simulation is based on the local standard time. Simulated hours will start from 07:00 to 23:00. Diurnal effect applies from 07:00 to 20:00 when the canyon receives solar radiation. Nocturnal effect applies from 21:00 to 23:00.

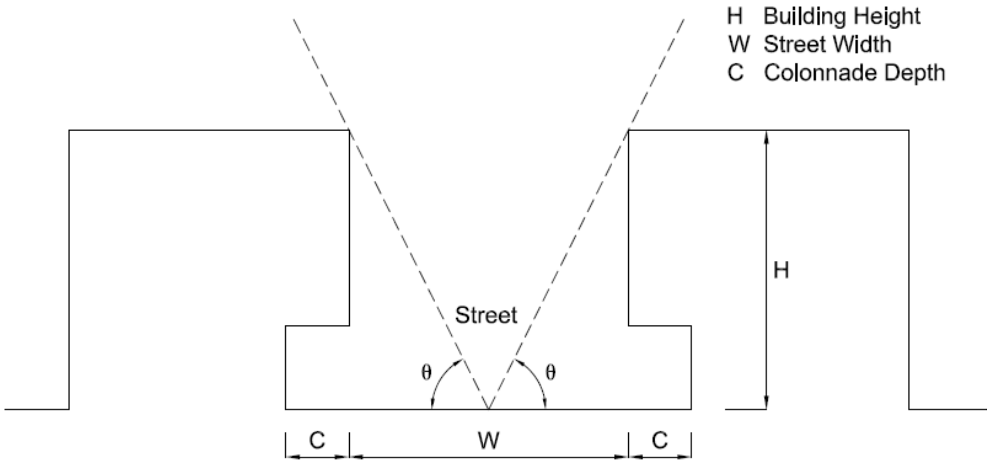

Figure 1.2 : Main variables for heat stress reduction analysis – Street aspect ratio (H/W) and Colonnade depth to street width ratio (C/W)

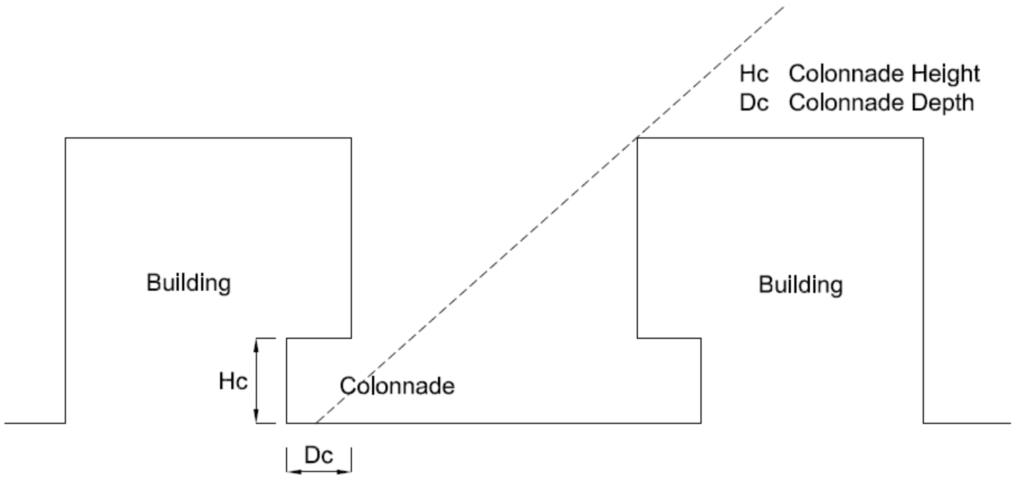

Figure 1.3 : Main variables for shading analysis – Colonnade depth to colonnade height ratio (D_c/H_c)

1.8 Importance of The Research

This research aims to study a possible optimization of existing colonnade to reduce heat stress in the street canyon. The outcome will be helpful in reducing the heat island effect and to enhance the usability of the urban outdoor spaces.

The basic function of a colonnade, which is as an overhead shading shelter (shading between 11:00 to 16:00), will be evaluated. Further, the depth of the colonnade and its climatic influence will be studied. To the occupants, reduce in thermal heat stress would mean reduce in cooling load of buildings. So, improvements on urban microclimate would lead to energy savings. To the developers and architects, this study opens up new possibilities in architectural facade design and colonnade design with consideration of climatic design principles.

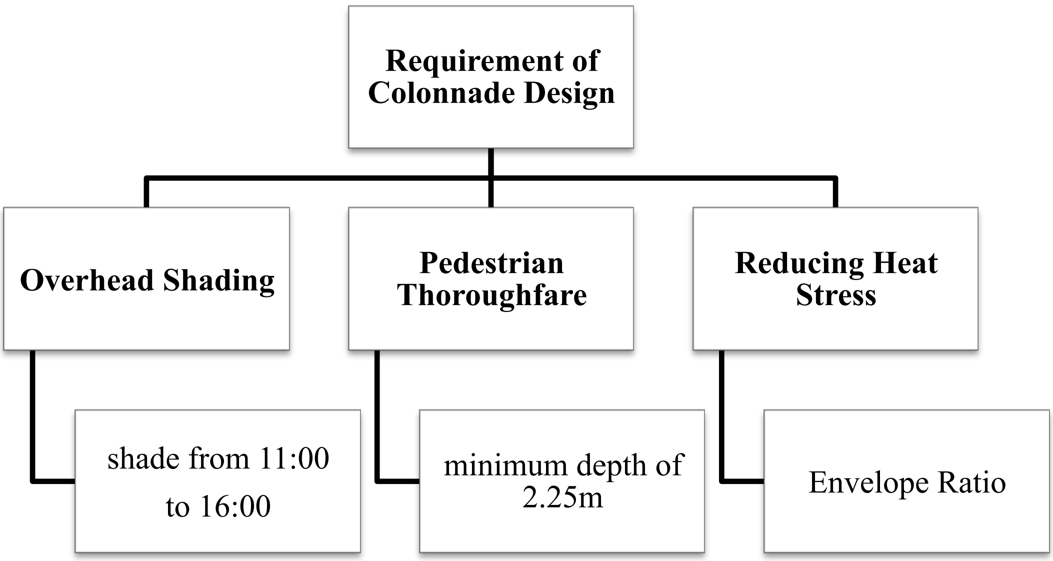

Figure 1.4 : Requirement of colonnade design chart

1.9 Thesis Organization

This thesis report is structured into five chapters as summarized below.

Chapter one is the introductory of this thesis. It tells the background of this research, the main issues, proposed hypothesis of the study, research questions and the objectives of the research. Further, research gap, scope and limitations of the study are further highlighted. The overall thesis structure is presented at the end of the chapter.

Chapter two reviews the energy balance within the urban canopy layer and especially the low-rise street canyon. Strategies in improving the urban microclimate are discussed. The rationale of colonnade design is presented. Johor Bahru is taken as the study area for this research. A few shophouse developments are chosen as samples to evaluate the street aspect ratios (as results of existing planning rules) and colonnades.

Chapter three discusses the methodology implemented in this research. Available urban canopy layer microclimate evaluation models are reviewed Experimental needs are determined and appropriate model is then formulated, which are based on the CTTC (Cluster Thermal Time Constant) mathematical calculation and Envelope Ratio concept. Further, the mathematical simulation procedure, assumptions and limitations are described. Validation is done by using Ecotect simulation software. Finally, the data analysis criterions are discussed, which is used to analyse the results of the experiment.

Chapter four presents the results and analysis of shading, absorbed solar radiation, net long-wave radiation loss and cooling effect for the simulated models.

The role of urban planning codes is also discussed. The results of the simulations are analysed based on the following principles:

a. Colonnade depth and shade.
b. Influence of colonnade depth on envelope ratio.
c. Impact of sky view factor on shading on radiation loss.
d. Impact of envelope ratio on canyon cooling effect.
e. Assess the relationship between aspect ratio, orientation and envelope ratio.

Chapter five sums up the overall thesis, through reviews of the thesis objectives and research questions. It is followed by the conclusion remarks of the major findings of the experiment. Envelope Ratio concept and CTTC are reviewed as well. Finally, other possible areas to be further studied are suggested.

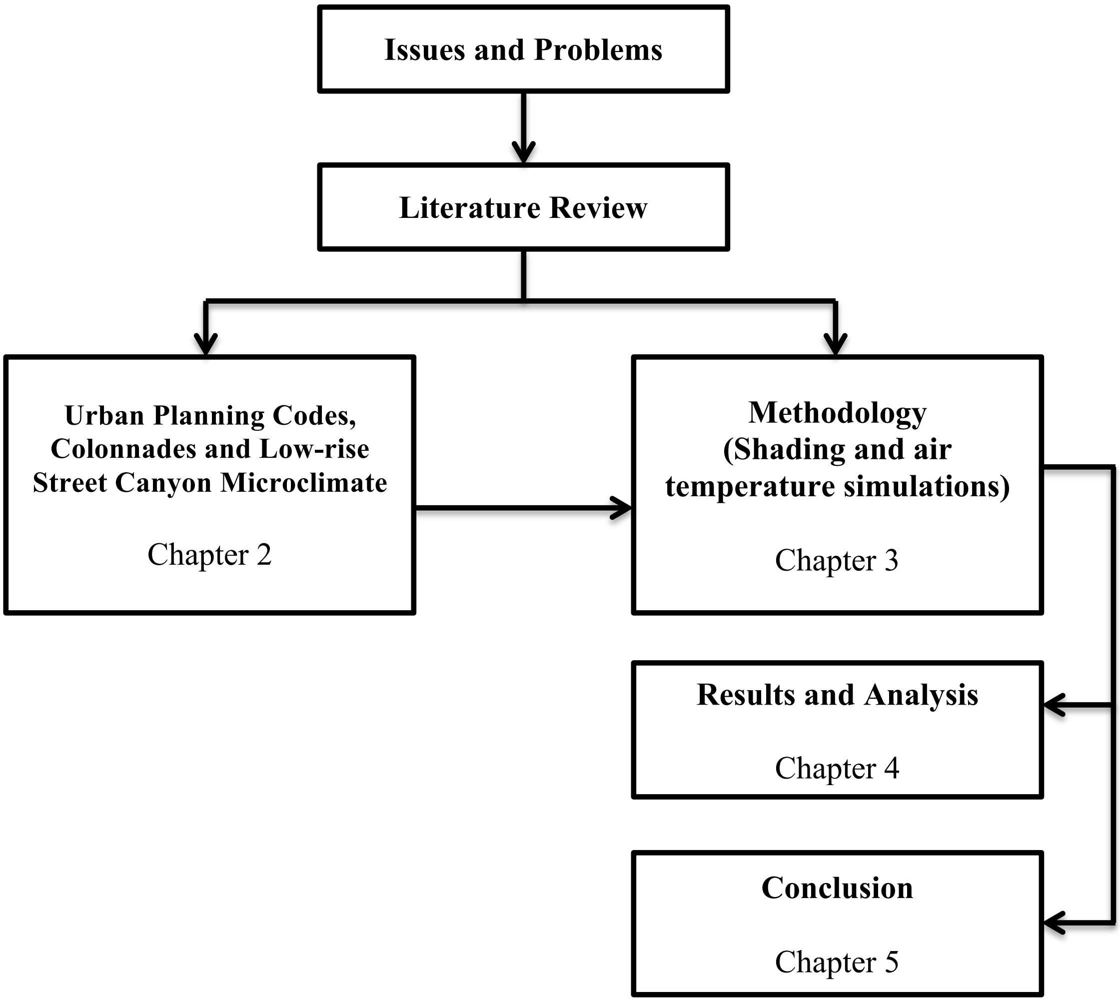

Figure 1.5 : The flow of research process and thesis structure

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