CONFIGURATION OF HORIZONTAL VOIDS AND LIGHTWELL TO IMPROVE NATURAL VENTILATION IN HIGH-RISE RESIDENTIAL BUILDINGS IN HOT HUMID CLIMATE

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To my beloved parents, wife, children and siblings

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ABSTRACT

Cross-flow ventilation is the most effective strategy for providing thermal comfort and ensuring air quality in buildings, while minimizing the required energy cost. In hot and humid climate, the high-rise building plan configuration incorporates different types of lightwell, either in the core or perimeter of the building, that allow for opening the windows in different directions and thus enables better cross-ventilation. The lightwell space is subjected to produce a suction effect along its space and thus adjoining indoor spaces. Lightwell at the core with opening at top trapped unwanted gases and thus reduce the fresh air flow in its space and reduce the cross flow ventilation in adjoining units. Nevertheless, having a lightwell may not be enough to provide adequate natural ventilation in high rise buildings. This study examines the internal lightwell connection to the outside through different horizontal voids as inlets. A Computational Fluid Dynamics (CFD) technique employing ANSYS Fluent code is used to predict airflow characteristics for eighteen (18) alternative ventilation configurations of a full-scale building model. The full-scale model was developed according to common configurations of high-rise residential (HRR) buildings in Kuala Lumpur, as well as referring to the minimum requirements of the Malaysian Uniform Building By-Law (1984). The results show that the existence of a direct connection of the internal lightwell through a horizontal void affects the air change per hour (ACH) and the thermal comfort in the lightwell space and adjoining units, respectively. Although the existence of double-level voids increases ACH by up to 67 % along the lightwell, it reduces the air velocity by 70 % in adjoining units compared to the lightwell without direct connection. In order to reduce such contrast and to optimize the cross-flow ventilation in the lightwell and its adjoining units, the study recommends giving more attention to the lightwell inlet design. This study provides proper guidelines to predict ventilation performance and to improve the design of naturally ventilated HRR buildings.

ABSTRAK

Pengudaraan aliran silang adalah strategi yang paling berkesan untuk memberikan keselesaan terma dan memastikan kualiti udara di dalam bangunan serta meminimumkan kos penggunaan tenaga yang diperlukan. Di negara beriklim panas dan lembap, konfigurasi pelan bangunan bertingkat tinggi menggabungkan pelbagai jenis telaga cahaya, sama ada pada teras atau sempadan bangunan, yang membolehkan bukaan tingkap dari arah yang berbeza dan seterusnya membolehkan pengudaraan silang yang lebih baik. Ruang telaga cahaya tersebut berfungsi menghasilkan kesan sedutan udara di sepanjang ruang tersebut dan seterusnya bersambung dengan ruang dalam bangunan. Telaga cahaya pada teras bangunan dengan bukaan di bahagian atas memerangkap gas yang tidak dikehendaki, oleh itu mengurangkan aliran udara segar ke dalam ruang telaga cahaya tersebut dan mengurangkan pengudaraan aliran silang di dalam unit-unit yang bersambung. Bagaimanapun, satu telaga cahaya mungkin tidak memadai untuk memberikan pengudaraan semula jadi yang mencukupi bagi bangunan bertingkat tinggi. Kajian ini menguji sambungan ruang dalaman dan luaran telaga cahaya melalui lowong mendatar yang berbeza sebagai salur masuknya. Satu teknik Perkomputeran Dinamik Bendalir (CFD) menggunakan kod aliran ANSYS telah digunakan untuk meramalkan ciri-ciri aliran udara untuk lapan belas (18) konfigurasi pengudaraan alternatif bagi sebuah model bangunan berskala penuh. Model berskala penuh tersebut telah dibangunkan mengikut konfigurasi umum bangunan-bangunan kediaman bertingkat tinggi di Kuala Lumpur dan juga merujuk kepada keperluan minimum Undang-undang Kecil Bangunan Seragam (1984). Keputusan menunjukkan bahawa kewujudan sambungan langsung antara ruang dalaman telaga cahaya dengan lowong mendatar memberi kesan kepada perubahan udara per jam dan keselesaan terma dalam ruang telaga cahaya dan unit-unit yang bersambung. Walaupun kewujudan lowong berganda meningkatkan perubahan udara per jam sehingga 67% di sepanjang ruang telaga cahaya, tetapi ia mengurangkan halaju udara sebanyak 70% dalam unit-unit yang bersambung, berbanding dengan ruang telaga cahaya tanpa sambungan langsung. Untuk mengurangkan perbezaan tersebut dan mengoptimumkan pengudaraan aliran silang di dalam ruang telaga cahaya dan unit-unit yang bersambung, kajian ini mencadangkan perhatian yang lebih perlu diberikan kepada rekabentuk salur masuk ruang telaga cahaya. Kajian ini menyediakan garis panduan yang tepat untuk meramal prestasi pengudaraan dan menambah baik rekabentuk pengudaraan semula jadi bagi bangunan-bangunan kediaman bertingkat tinggi.

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LIST OF ABBREVIATIONS

Q	-	flow rate (m^3/h)
T	-	temperature (^oC)
k	-	turbulent kinetic energy (m^2/s^2)
g	-	acceleration due to gravity (m/s^2)
Pr	-	Prandtl number
Re	-	Reynolds number
u	-	mean air velocity magnitude (m/s)
u'	-	velocity fluctuation component (m/s)
t	-	temperature fluctuation component (^oC)
S_{ij}	-	strain rate tensor (1/s)
$\overline{(\;)}$	-	time average
Γ	-	diffusion coefficient
Ω	-	magnitude of rotation tensor
κ	-	von Karman constant (= 0.4187)
θ	-	temperature fluctuation (^oC)
ε	-	dissipation of k (m^2/s^3)
β	-	coefficient of thermal expansion (K^{-1})
μ	-	dynamic viscosity (Pa.s)
ν	-	kinematic viscosity (m^2/s)
γ	-	intermittency
α^*	-	turbulent viscosity damping factor
ρ	-	mass density (kg/m^3)
ω	-	specific dissipation rate (s^{-1})
σ	-	turbulent Pr for k or ω
δ	-	Kronecker delta
U	-	local wind speed (m/s)
U_{ref}	-	reference wind speed (m/s)
U_{pot}	-	potential wind speed (at 10m height with y_0 = 0.03 m) (m/s)
NVB	-	Naturally ventilated building
HRR	-	High-rise residential
WTE	-	Wind-tunnel experiment
UBBL	-	Malaysian Uniform Building By-Law
CFD	-	Computational Fluid Dynamics
DSF	-	Double skin facade
KBES	-	Knowledge-based expert systems

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CHAPTER 1

INTRODUCTION

1.1 Overview

Tropical cities in Southeast Asia are encountering the rapid growth of urban population, which has increased the demand for residential units. The increasing income level of people in most of these cities has led to an increasing demand level in both quantity and quality aspects of housing (Yuen and Yeh, 2011). In order to meet this growing demand, many countries in the region of Southeast Asia have adjusted their housing policies to include the construction of high-rise residential (HRR) buildings. This is particularly prevalent in capital cities such as Kuala Lumpur, Bangkok and densely populated cities with insufficient area of land such as Singapore and Hong Kong. For instance, in the last decade the number of high-rise buildings in Singapore has increased by three times and the number has doubled within the same period in Kuala Lumpur and Bangkok (Rimmer and Dick, 2009) according to updates by www.emporis.com. Most of these buildings are utilized for housing, particularly in Singapore due to the high population density (Yuen and Yeh, 2011). In Malaysia, for instance, census statistics for 2010 recorded a significant increase in the apartment housing numbers, which has increased by about 7.3% in the last decade. During this same period, only a rise of 3.8 % was recorded for terraced houses, whereas there was no increase in the number of detached and semi-attached houses (Population and Housing Census of Malaysia 2010).

The significant rise of housing projects, particularly apartment housing, demands more energy for lighting or cooling and running other utilities in houses. According to statistics reports in Malaysia (2011), the energy consumption in the building sector (residential and commercial) has doubled. About 67% of the total energy consumed in residential building is used only for cooling and refrigeration (CETDEM, 2006). The General Report of the Population and Housing Census in Malaysia, 1970, 1990 and 2000 shows that the number of households using air-conditioners dramatically increased from 13,000 in 1970 to 229,000 in 1990 and 775,000 in 2000. Kubota *et al.* (2009) found that the increase in using air-conditioners was mainly due to the increase in household income.

In order to cut down the energy consumption in the building sector, some Southeast Asian countries have established guidelines and codes, particularly those countries with high rates of energy consumption. In addition, these countries have developed criteria that adapt to the local environment when assessing energy consumption. In Malaysia, for instance, standards and checklists have been formulated to evaluate buildings' performances. The Green Building Index (GBI), Overall Thermal Transfer Value (OTTV) and Building Energy Indicator (BEI) are commonly used in Malaysia today (Rahman, 2010). In order to meet the criteria of these standards and checklists, minimizing energy consumption by applying bioclimatic principles and energy efficiency techniques in buildings is required.

Natural ventilation is considered one of the most fundamental low-cost passive cooling strategies in buildings (Jiang and Chen, 2002; Zhai, 2006). Thus, it could contribute to the reduction of energy consumption without compromising thermal comfort (Kubota *et al.*, 2009) and air quality inside the buildings. Many previous researchers recommended naturally ventilated buildings as being the preferred strategy in hot and humid climates (Aynsley, 1980; de Dear *et al.*, 1991; Feriadi and Wong, 2004; Givoni, 1994; Kubota *et al.*, 2009; Rahman *et al.*, 2011; Rajapaksha *et al.*, 2003). Therefore, the present research is directed towards naturally ventilated buildings, giving attention to high-rise residential (HRR) buildings in Malaysia. The result of the study will contribute to the knowledge related to this area, and is aimed at saving energy and thus reduction of household expenses as well as considering the environmental dimension.

1.2 Problem Background

Bioclimatic principles were first applied to large-scale buildings, e.g. high-rise buildings, in the last decade of the last century. These principles have been noted in some works of pioneering architects e.g., Yeang and Foster. Bioclimatic high-rise buildings could play an important role in reducing energy consumption, particularly the energy required for running air-conditioning. Based on a mixed mode of ventilation (hybrid ventilation), it can cut down 63% of the energy required for fully running air-conditioning in high-rise non-residential buildings in tropical climatic conditions (Wood and Salib, 2013). In Malaysia, the UMNO high-rise non-residential building is designed to be fully naturally ventilated (Wood and Salib, 2013). However, it cuts down on about 25% of the energy that is required for running air-conditioning as measured in post-occupancy evaluations of the building. The most famous international example is the high-rise building of Commerzbank, which relies on mixed mode ventilation and can be naturally ventilated 80% of the year, thus saving about 63% of energy compared to a fully air-conditioned building in Germany (Lambot, 1997; Wood and Salib, 2013). Table 1.1 clearly illustrates the dramatic increase of the number of naturally ventilated high-rise non-residential buildings during the last three decades.

In fact, the naturally ventilated high-rise non-residential building is not a new concept, but one that was introduced in the 19th century. Although the first high-rise air conditioned office building was built in 1928 (Milam in USA), many office buildings are still depend on natural ventilation, and thus the plans of such buildings are very limited in depth to induce cross-ventilation. The required energy to run such air conditioning systems was initially expensive and this also limits the depth of most high-rise office buildings' plans (Wood and Salib, 2013). The lightwell was integrated into the building in different configurations, e.g. internal and semi-enclosed (u-shaped). However, these configurations changed in the middle of the 20th century when the plan of the building became deeper. This is because these buildings started to rely on air-conditioned systems in office buildings once the energy became more affordable than before (Wood and Salib, 2013). In addition, operable windows disappeared and curtain walls were used in order to mechanically control the indoor environment i.e. totally using air-conditioned systems. As a result, bioclimatic design strategies found in old high-rise buildings gradually disappeared.

Table 1.1: High-rise non-residential buildings in different climatic regions that used natural ventilation (Source: after Wood and Salib (2013))

Building name	**Plan depth / floors number**	**Climate**	**Ventilation type / (%) of year natural vent. used**	**Natural ventilation Strategy**	**Design strategies**
Commerzbank Germany, 1997	11.5m (from the central atrium) / 56	Temp.	Mixed-mode / 80%	Cross & stack (connected spaces)	DSF, *full-height central atrium, void*
UMNO, Malaysia, 1998	14m / 21	Trop.	Mixed-mode / 0-100 % depends on users	Wind-driven cross (isolated spaces)	Vertical wing-wall wind, aerodynamic form
Liberty Tower, Japan, 1998	20 m / 23	Temp.	Mixed-mode / 29 %	Cross & stack (connected spaces)	*18-floors height atrium, void*
GSW Headquarters Germany, 1999	11 m / 22	Temp.	Mixed-mode / 70%	Cross & stack (connected spaces)	20-floors height DSF, Venturi, aerodynamic form
Post Tower, Germany, 2002	12m (from central atrium) / 41	Temp.	Mixed-mode / unpublished	Cross & stack (connected spaces)	DSF, *atrium, void*, wing-wall, aerodynamic
Torre Cube, Mexico, 2005	9-12m (from central atrium) / 16	Temp. & Trop.	Full natural ventilation (no mechanical)	Cross & stack (connected spaces)	*Lightwell, void*, wing-wall, aerodynamic form
Manitoba Hydro Place, Canada, 2008	11.5 (from central core) / 21	Cold	Mixed-mode / 35%	Cross & stack (connected spaces)	DSF, *atrium, void*, solar chimney
1 Bligh Streets, Australia, 2011	23.5(from atrium) / 30	Mild	Mixed- mode: zoned/lobby full natural vent.	Cross & stack (connected spaces)	DSF, *full-height atrium, void*, aerodynamic

Mixed-mode: switches between mechanical and natural ventilation daily or seasonally; DSF: double skin façade; Temp.: temperate climate; Trop.: tropical climate

Since the interest of the present study is the configuration of high-rise residential buildings, it is possible to rely on some developments trends in high-rise non-residential buildings, particularly the high-rise non-residential buildings that existed before HRR buildings. As a result, bioclimatic high-rise non-residential buildings have been the area of interest to many researchers (e.g. (Busch, 1992; Chang *et al.*, 2004; Daghigh *et al.*, 2009; Ismail, 1996; Ismail, 2007; Liu, 2012; Liu *et al.*, 2012; Wood and Salib, 2013)).

In Malaysia, house types were divided into four groups based on cost, these being low-cost, low-medium cost, medium-cost and high-cost (Ministry of Housing and Local Government, MHLG). Although most previous Malaysian Government plans have encouraged increasing the number of units for the first two groups to provide low-income household, the achievement is relatively low compared to the medium-cost and high-cost housing types (Shuid, 2004). Most of the low-cost HRR buildings were built by government e.g., Kuala Lumpur City Hall (DBKL). Since the housing policy in the present plans are directed towards achieving adequate, quality and affordable houses to all Malaysians, many passive design strategies are incorporated into this type of housing to provide quality. Sapian (2004) defined five configurations in low-cost HRR buildings of DBKL. These configurations are rectangular, rectangular with courtyard, compact rectangular, L-shape and U-shape plans. All of these configurations were built to promote daylight and cross-ventilation flow either using a single-loaded corridor, or providing lightwells. Figure 1.1 shows the plan configurations of non-lightwell HRR buildings utilizing a single-loaded corridor in a rectangular plan (a), internal-lightwell in rectangular plan with courtyard (b), semi-enclosed lightwell in double-loaded corridor, U-shape and L-shape, (c, d,& e, respectively). Therefore, the low-cost HRR buildings in Malaysia rely on different lightwell configurations as they are totally based on natural ventilation or low cost mechanical means such as fans.

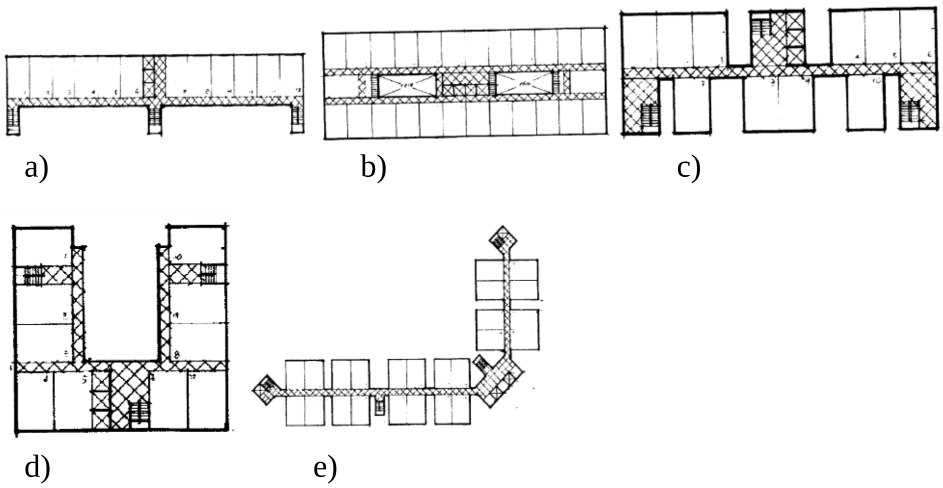


Figure 1.1 Plan configurations of low-income HRR buildings built by DBKL-Malaysia (Source: Sapian, 2004)

On the other hand, most of the medium-cost HRR buildings in Malaysia were built by the private sector (Shuid, 2004). This type of housing is more preferred by households and thus this encourages the private sector to build numerous units. For example, based on the Ninth Malaysian Plan (2006-2010), the achieved percentage of medium-cost units is 227.8 % of the targeted units in this plan.

The high-cost housing type considered the highest percentage in terms of implementation in Malaysia for the last three plans (MHLG). This type of housing is not affordable for Malaysian households as it is high-cost and thus it is only used by a limited section of the population. Although naturally ventilated high-rise buildings are implemented for low-income households as stated above, there are good examples of high-cost HRR buildings built in Kuala Lumpur. They are incorporated with architectural and aerodynamic elements to provide natural ventilation. For example, Hamzah and Yeang, who began to design naturally ventilated high-rise non-residential buildings (e.g. the UMNO building) at the end of the last century, introduced naturally ventilated HRR buildings at the beginning of this century. Well-known HRR building projects in Kuala Lumpur are the Idman Residence (2008), The Plaza (2006) and The Residences (2006) (Figs., 1.4 -1.6). These buildings incorporated architectural and aerodynamic elements such as wing-wall wings, and internal, attached and semi-enclosed lightwells (Richards, 2007). Some of these design strategies played an important role in avoiding deep plan and thus encourage cross-ventilation flow for most units (Hart and Littlefield, 2011; Richards, 2007).

These architectural and aerodynamic elements implemented in pioneering high-rise buildings (residential and non-residential) in hot and humid region are presented in Table 1.2. It is noted from the table that the high-rise non-residential buildings are integrated with several aerodynamic elements more than those in high-cost HRR buildings. In addition, the table shows that these architectural and aerodynamic elements of HRR buildings were started to be implemented in the last decade (at least in tropical cities) and was limited to luxury or high-cost housing as extra cost was required. However, some of these architectural elements could be used to improve airflow characteristics due to their multi-functions.

Those multi-function elements could be found in other types of HRR buildings i.e. low-cost and medium-cost HRR buildings. Some of these design elements such as corridors, balcony, void, lightwell and staircase could be feasible in terms of adaptation to provide indoor natural ventilation (Ismail, 1996). For example, the void can be used as car parks, entrance to the lifts hall and at the same time provide shadow and so it can be employed to induce the airflow into the units of the building (Sapian, 2004). In addition, lightwell can be used to induce ventilation and admit daylight into the units or rooms, which are far from the perimeter of the building and at the same time it can be used for some vertical installations. These architectural elements usually have a large space that could be adapted as thermal buffer zones to control the indoor thermal performance of HRR buildings (Ismail, 1996).

Table 1.2 : Vertical and horizontal architectural elements and aerodynamics elements in some pioneering naturally ventilated high-rise residential and non-residential buildings and highlighted elements of the present study

		Vertical elements				Horizontal elements			Aerodynamic elements and forms				
		Lightwell	Atrium	S. chimney	DSF	Void	Corridor	Balcony	Wing-wall	Narrow plan	3D Building form	Venturi-effect	Innovative windows
High-rise Non-Residential Building	Commerzbank Germany, 1997		●		●	●							●
	UMNO, Malaysia, 1998							●	●	●	●		●
	Liberty Tower Japan, 1998		●			●							
	GSW Germany, 1999				●						●	●	
	Post Tower Germany 2002		●		●	●			●		●		
	Torre Cube Mexico 2005	●							●		●		
	Manitoba Hydro Canada, 2008		●	●	●	●							
	1 Bligh Streets, Australia, 2011		●		●	●					●		
High-rise Residential Buildings	Idman Residence Malaysia, 2008	●					●				●		
	The Plaza Malaysia, 2006	●					●		●			●	
	The Residences Malaysia, 2006	●					●		●				
	The Troika, Malaysia, 2012								●				
	D'Leedon, Singapore, 2014	●				●			●		●		
	Moulmein, Singapore, 2003				●					●			●
	The Met, Thailand, 2013	●								●			

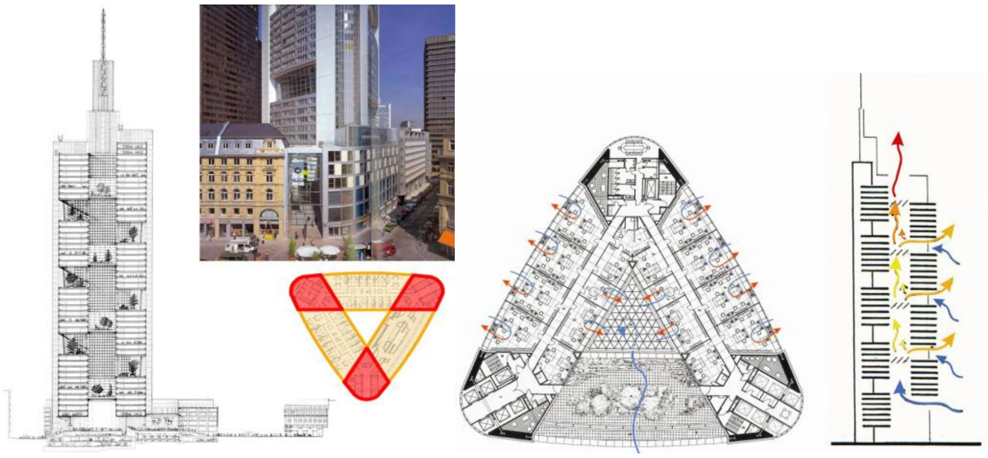


Figure 1.2 Commerzbank - Frankfurt, 1997, shows aerodynamic configuration, open-able segmented atrium and sky gardens (Source: Lambot (1997), 1997 and PC. Liu, 2012)

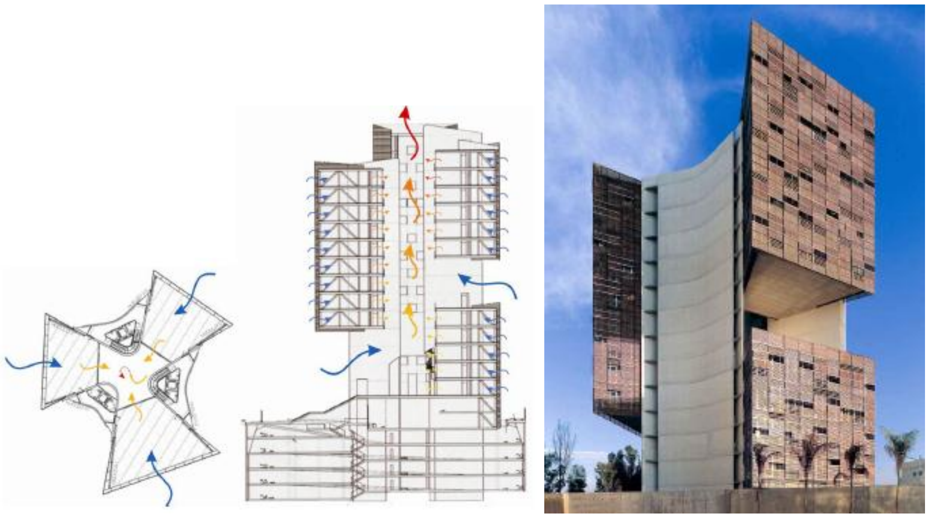


Figure 1.3 Torre Cube, Mexico, 2005, 100 % naturally ventilated throughout the year (Source: Wood and Salib, 2013)

Figure 1.4 The Residence - Kuala Lumpur by T. R. Hamzah & Yeang (2006), attached lightwell, wind corridor and wing-wind wall (Source: http://www.propwall.my)

Figure 1.5 The Idaman Residence - Kuala Lumpur by T. R. Hamzah & Yeang (2008), using semi-enclosed lightwells as funnels to capture wind, wind corridor and attached lightwells (Source: http://www.skyscrapercity.com)

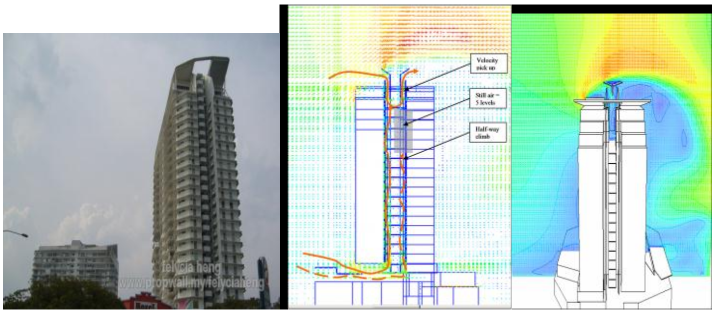


Figure 1.6 The Plaza - Kuala Lumpur by T. R. Hamzah & Yeang (2006), using attached lightwells for upward flow, wind corridor and wing-wind wall (Source: EAG website http://eag.my/)

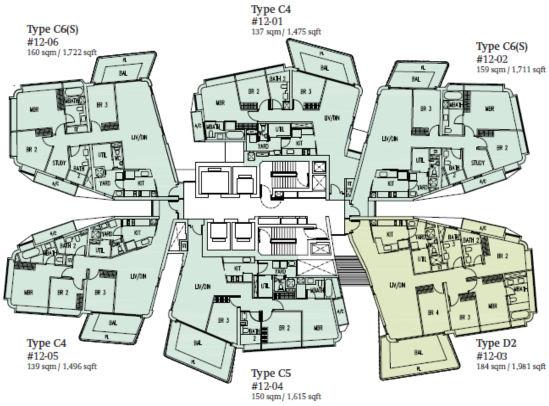


Figure 1.7 D'Leedon – Singapore by Zaha Hadid, (under construction), semi-enclosed lightwell as funnel to capture wind (Source: Feng (2012))

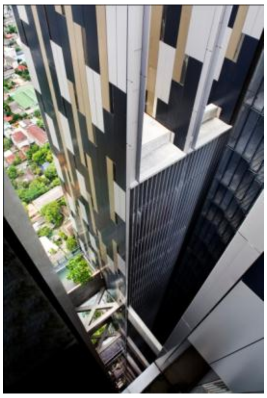


Figure 1.8 The Met – Bangkok by WOHA (2013), view looking down through the semi-enclosed lightwell between the towers, (Source: Feng (2012))

1.3 Problem Statement

From the environmental design point of view, the building configuration in hot and humid climate incorporating different types of lightwell either in the core or perimeter of the building (Givoni, 1998; Nutalaya, 1999) affords large external facades and thus allows the opening of windows in different orientations, which provides cross-ventilation for most indoor spaces. The internal lightwell is commonly implemented in the core of high-rise building to maintain daylight and natural ventilation. Physically, the position of the internal lightwell means that it is totally separated from the surrounding outdoor environment. However, it connects directly to outside through sky openings at the top which act as outlets and horizontal spaces such as corridors and voids acts as inlets. It also connects indirectly to the outdoor through its adjoining spaces, i.e. rooms have external and adjoining window (Fig. 1.9).

The internal lightwell is subjected under the Malaysian building code (UBBL) to improve its performance in terms of providing natural ventilation and daylight. However, the code determines the minimum area for the outlet (sky opening) of the lightwell space and links with its height. In order to guarantee better performance of the lightwell in terms of providing natural ventilation to adjoining rooms, the code also stipulates the minimum area of the adjoining windows, as later presented in Section 3.1.5. Based on the results of a survey conducted in Kuala Lumpur (Farea *et al*., 2012), the stipulated minimum area of the lightwell outlet by UBBL is achieved in most surveyed HRR buildings (see Table B.1 in Appendix B). However, the survey results found that the lightwell connected to outdoors through several methods, which are categorized into four groups (see Table B. 2 in Appendix B). This indicates that the inlet of the lightwell space was left for the designer to select the method of the connection. Thus, the provision of the regulations may not be enough to guarantee indoor natural ventilation into adjoining units through only stipulating criteria for the outlet and adjoining windows areas.

A literature survey demonstrates that the lightwell space is subjected to produce a suction effect along the lightwell by either upward or downward cross-flow (Chiang and Anh, 2012; Etheridge, 2012; Ghiaus and Roulet, 2005; Ismail, 1996). Thus, the method used to connect the lightwell to outside through different locations of the inlet certainly affects the suction force along the lightwell. If the lightwell does not connect to the outdoor appropriately, unwanted gases may become trapped in the lightwell and thus reduce the fresh air flow in its space and reduce the cross flow ventilation in adjoining units. In other words, lightwell outlet and windows size (as stated above) may not be adequate to achieve the target of providing natural ventilation. This leads to use of mechanical ventilation to extract the unwanted gases from the lightwell space (e.g. exhaust fans) and to provide thermal comfort to the adjoining room. Although the direct inlet of the internal lightwell space is an important parameter that affects the airflow pattern along its space and adjoining indoor spaces, there is lack of exploration on the ventilation configuration between lightwell and horizontal void and its performance. Consequently, it is important to understand the aerodynamics characteristics in the internal lightwell connected, whether directly or indirectly, to the outdoor in HRR buildings for improving natural ventilation.

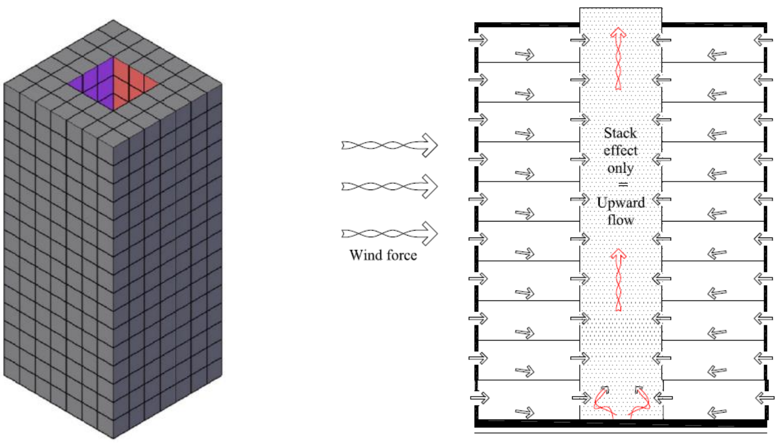


Figure 1.9 Ventilation configuration of the internal lightwell connected indirectly to the outdoor through its adjoining units

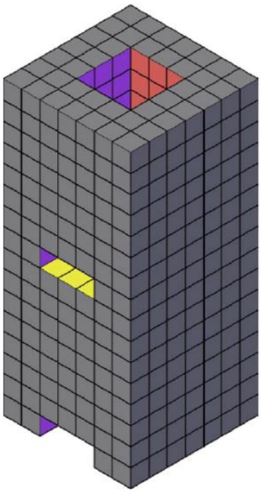
1.4 Research Hypothesis

This research hypothesises that connecting the internal lightwell to the outdoor through horizontal voids (Fig. 1.10) in an appropriate ventilation configuration will achieve the following;

a) Improve air quality through increased air changes per hour (ACH) and thus supply fresh air which is important to discharge the CO_2 and other contaminants from the lightwell space,

b) Improve the cross- flow ventilation in the adjoining units and thus provide the required indoor thermal comfort without total dependence on mechanical means.

This is applicable to climatic conditions of Kuala Lumpur, and to satisfy the minimum dimensions of the lightwell ratio and adjoining windows as subjected by UBBL. It should be noted that the term “ventilation configuration” refers to the configuration of the connection between the lightwell and the outdoor through the void or no-connection i.e. no void.



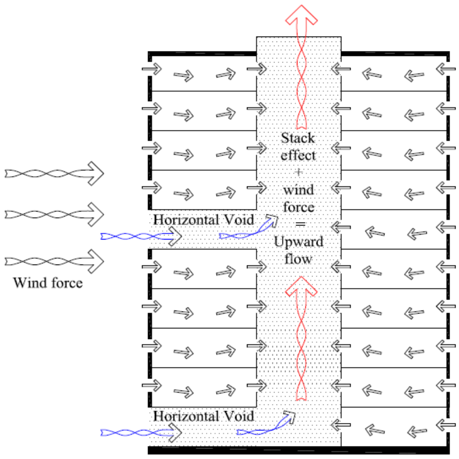


Figure 1.10 Ventilation configuration of the lightwell connected to the outdoor through horizontal voids, which may affect upward flow and indoor air velocity

1.5 Research Questions

This thesis addresses the following questions:

1) Does the connection of the lightwell to the outdoor environment through horizontal void affect the cross-flow ventilation in the lightwell space and thus the adjoining units?

2) What is the most effective ventilation configuration of the lightwell and void to increase air velocity and reduce temperature in order to obtain adequate indoor thermal comfort?
3) What is the optimum ventilation configuration for providing adequate fresh air in the lightwell, while at the same time providing adequate thermal comfort to the adjoining units?
4) Are the level and position of the adjoining unit significant parameters in increasing air velocity and thus reducing indoor air temperature?
5) Is the CFD model acceptable and reliable as a tool to predict the air velocity and temperature in high-rise buildings with an internal integrated lightwell?

1.6 Research Aim and Objectives

The primary goal of this research is to investigate the effect of the horizontal void existence and its position on the cross-flow ventilation in the lightwell and thus adjoining units in HRR buildings. The investigation includes a wide range of alternative ventilation configurations of the lightwell connected to the outdoor environment through different void positions and directions. The objectives are as follows:

a) To identify alternative physical configurations of the lightwell connection to the outdoor with special reference of the HRR buildings in Kuala Lumpur.
b) To validate the performance of CFD in terms of predicting the temperature gradient and the upward airflow velocity driven by combined wind and buoyancy forces in the lightwell.
c) To evaluate the ventilation configurations of the lightwell in terms of providing adequate indoor thermal comfort of adjoining units and adequate fresh air in the lightwell space. This is achieved by following the sub objectives:
    - To examine the effect of proposed ventilation configurations on the air velocity and temperature in the lightwell space and adjoining units.
    - To examine and compare the adjoining unit position (lower and upper) effect on the indoor air velocity and airflow pattern.

1.7 Research Scope

The study focuses on common configurations of the lightwell high-rise residential building with special reference to the hot and humid climate of Kuala Lumpur in Malaysia. The lightwell in HRR buildings can be divided into three types based on its location in the plan and the configuration of the building, namely internal, semi-enclosed and attached (Farea et al., 2012; Ismail, 1996). The present study only focuses on the internal lightwell as representative of the worst case in terms of driving external wind flow into the building. The internal lightwell is also totally separated from the outdoor surrounding environment.

The connection of the lightwell to the outdoor environment through the void does not only affect the air quality in the lightwell and thermal comfort in the units but it also plays an important role in cooling the building fabric and outdoor environment (Givoni, 1998). However, the effect of cooling down the building construction and outdoor flow are not included in the output of the present study.

Since the study focuses on air quality in lightwell and thermal comfort in adjoining units, the air change per hour (ACH) and air temperature in the lightwell and the air velocity and air temperature in the units are the output of this study. Thermal comfort data applicable to tropical cities in general, and specifically to Kuala Lumpur, were used in order to evaluate the acceptable thermal comfort for different ventilation configurations of the lightwell. Thermal comfort is determined based on neutral temperature, which was derived by two approaches, namely field studies and the adaptive approach. The neutral temperature method is based on the previous field work in several tropical cities, while the adaptive approach is based on the outdoor average air temperature of Kuala Lumpur. Since neutral temperature estimations considered only those studies based on operative temperature (the combination between average air temperature and mean radiant temperature), the humidity variables are not considered in the output of the thermal comfort estimation (see Section 2.3.2.).

1.8 Research Limitations

The limitations of the research are discussed in three main categories as follows:

a) Building model configuration:

From the perspective of building design, it is difficult to involve all possible configurations in one study. Therefore, a systematic method is used in order to develop the building model, which is based on a survey for selected HRR buildings in Kuala Lumpur in addition to the data obtained from the literature. In the process of developing the building model and the parameters of the ventilation configurations (combination between the lightwell and void), the functional approach rather than aesthetic is employed. For example, the horizontal void is usually used on the ground floor as a car park or used on the middle level for building services or a refuge floor.

In order to reduce the number of variables in the numerical proposed building model that represents the common configurations of the lightwell high-rise residential building, an isolated and generic building model is used in this study. This is because the nature of the wind is varied with time (wind direction and magnitude variable per second) and thus it is difficult to predict its characteristics with complex configurations and more architectural details of the building model.

b) Methods:

There are many methods available to predict the airflow characteristics based on theoretical, experimental and numerical models. The numerical model is the primary method used in this study, which is based on CFD simulations. However, the small-scale building model in wind tunnel experiments available in the literature is used to validate the CFD. Similarly, the validation study was used in order to examine the performance of the CFD code for predicting the non-isothermal airflow (combination between wind and stack forces) in high-rise buildings. The results of CFD simulation of the small-scale model are compared with wind tunnel experimental data for validation. In addition, the small-scale model simulation is used to examine different wind direction, and further discussion on this issue is provided below.

Full-scale building model simulations are conducted in an atmospheric boundary layer (ABL), closer to the realistic environment than possible in small-scale model simulations. However, simulation results of the full-scale building model still need further realistic conditions because the effects of the existing surrounding buildings are neglected. Since HRR buildings are usually surrounded by lower buildings rather than high-rise buildings (Ismail, 1997), the absence of the surrounding environment in simulation could not have a significant effect on the results of CFD simulations, particularly at upper stories where the wind is free flow (Burnett *et al.*, 2005). The present study examines the natural ventilation in the lightwell and higher floor units so the effect of surrounding buildings will be less significant. Therefore, the study concentrates only on isolated and generic buildings, which helps to reduce the time of calculations.

The objective of the parametric study is to examine and compare the performance of different ventilation configurations in terms of providing thermal comfort and air quality in the units and lightwell. Therefore, reproducing the actual transient conditions (i.e. for specific days) is out of the scope of this study. This is because reproducing the actual transient of the thermal behavior of the building under realistic transient conditions (i.e. Kuala Lumpur boundary condition) is difficult in CFD (van Hooff and Blocken, 2010). However, the realistic building and climatic conditions complexity can be reproduced either by using transient simulation which is very costly and time consuming or by coupling the CFD with building energy simulation software e.g., (Wang and Wong, 2009).

Based on CFD applications, modelling airflow in the built environment can be distinguished under two categories; coupled and de-coupled simulation (Etheridge, 2012; Ramponi and Blocken, 2012a). Coupled simulations are between external wind flow and internal airflow and have a single computational domain, while the de-coupled simulation involves either outdoor wind flow or indoor airflow and thus includes two computational domains. Since the cross-flow ventilation is the main objective of this study, the interaction between the external wind flow and internal airflow in units and the lightwell are considered a coupled simulation, as is selected in this study.

As is commonly known in CFD simulation studies, there is a lack of high computational performance for modelling large-scale environments. Therefore, the performance of computer sources available in the market is considerably the greatest limitation of the present study. For example, in order to decrease the computational time, all simulations are isolated and the building model is simplified with only two units representing lower and upper levels.

The wind direction is an important parameter to determine the airflow characteristics in the lightwell and its adjoining units. However, different wind directions require large sizes of computational domain and thus increase the computational time. This problem increases with full-scale model simulation when it exceeded the maximum length of the CFD pre-processing software. As a result, three different wind directions of 0^{o}, 45^{o} and 90^{o} are examined in small-scale models.

c) The output of the study (Ventilation Functions)

The acceptable air velocity range for providing indoor thermal comfort is based on previous field studies in Kuala Lumpur. The estimations of the most appropriate air velocity in naturally ventilated HRR buildings applicable to Kuala Lumpur still lack real field studies. In general, the output of the study is applicable to hot and humid climate conditions.

1.9 Research Significance

Assessing airflow in the lightwell as a semi-open space, which is common in HRR buildings, is important in order to improve the upward flow in the core of the building and thus:

a) Removing the heat from the core of the building and providing better air quality and thermal comfort which are important for human health and occupants' activities;
b) Providing cross-flow ventilation for the adjoining units may contribute to reducing indoor thermal discomfort time, which leads to saving the household extra expenditure on electrical appliances, cost of running, maintenance and electricity bills.
c) Contributing towards the development of design guidelines for naturally ventilated HRR buildings. This guideline could be also used by policy makers to improve the building code in Malaysia (UBBL).

1.10 Thesis Outline

This thesis contains seven chapters, including the present chapter which covers the introduction, background, problems and the objective of the study while the rest is organized as follows (Fig. 1.11):

Chapter 2 covers the natural ventilation principles in buildings and wind environment in hot and humid region. Benefits of natural ventilation and models which are used to predict both air quality and acceptable thermal comfort are also presented in this chapter. The overview of methods used to predict ventilation performances in buildings are also outlined.

Chapter 3 reviews transitional spaces in buildings with further detail on semi-open spaces in high-rise buildings. Most of the studies conducted for natural ventilation through the lightwell and horizontal void in high-rise buildings are presented here. This chapter concludes by presenting the research gap in the study.

The most appropriate models that are used to achieve the objective of the present study are discussed in detail in Chapter 4. The settings and sensitivity analysis results of the CFD validation for small-scale model are presented in this chapter. The procedures used to collect data for several HRR buildings in Kuala Lumpur are also presented here. The important aspects relating to Kuala Lumpur boundary conditions e.g. acceptable thermal comfort and main wind reference speed are determined. The chapter concludes with the presentation of the full scale model CFD simulation settings.

Chapter 5 presents the results of the air temperature, airflow velocity and airflow pattern in the lightwell and hypothetical units in each configuration. The averages of temperature and air velocity in the units and ACH for all configurations are compared in terms of air quality in the lightwell and thermal comfort levels in hypothetical units according to Kuala Lumpur boundary conditions. This chapter is concluded with the important findings of the study.

The summary of the study and conclusions are presented in Chapter 6. Further research and recommendations in design of naturally ventilated high-rise buildings are outlined in this chapter.

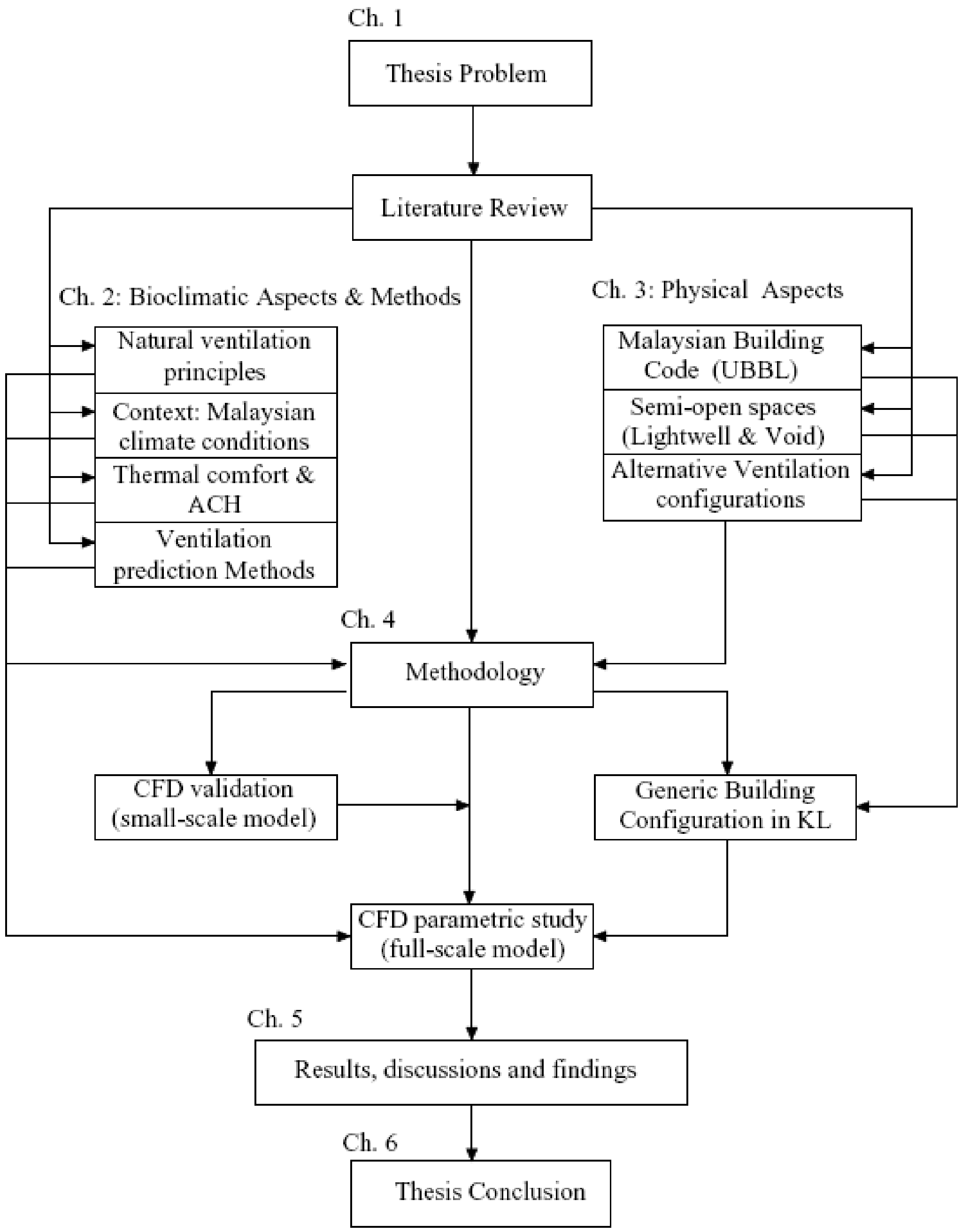


Figure 1.11 The flow of the research process and thesis chapters

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