The Hong Kong Polytechnic University

Department of Building Services Engineering

The Study of Natural Ventilation in Residential Buildings

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A thesis submitted in partial fulfilment of the requirements for the Degree of Doctor of Philosophy

June 2011

CERTIFICATE OF ORIGINALITY

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ABSTRACT

Abstract of thesis entitled: The Study of Natural Ventilation in Residential Buildings

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Modern people spend 90% of their time indoor of which 65% are at home. Residential premises therefore demand a healthy and comfortable indoor environment. Natural ventilation is most preferred by people for cooling and for providing fresh air. However, for a densely populated city of subtropical climate like Hong Kong, air-conditioning is most often used. Energy statistics show that in a typical residential building in Hong Kong, air-conditioning accounts for 25% of the energy consumption. With increasingly crowded indoor environments and continuous growth in residential energy consumption, wider use of natural ventilation in residential premises is receiving greater attention.

However, the availability of adequate natural ventilation in dwellings to allow occupants to enjoy a healthy and comfortable environment is not simply by the provision of openable windows. There are other contributing factors including the window types, building orientations, openings configurations, surrounding buildings characteristics, and prevailing wind conditions. They all play very significant role in ensuring adequate natural ventilation in dwellings.

Taking all the above factors into account, this thesis presents a study of influence of openings configurations and window types on the natural ventilation performance of a hypothetical residential unit. In the study, CFD simulations and field measurements were used. Varying parameters were carefully determined.

Natural ventilation performance of eight openings configurations for the hypothetical residential unit was evaluated. The hypothetical unit was formulated with reference to findings of an extensive survey on the characteristics of dwellings in Hong Kong. The evaluation took into account four building orientations and three prevailing wind conditions. The results indicate that better natural ventilation performance can be achieved by locating two window groups (bedroom windows and living room windows) in opposite directions or in perpendicular to each other. As to the influence of different factors, it is noted that natural ventilation performance is most sensitive to changes in relative windows positions, followed by building orientations and door positions.

Based also on the hypothetical residential unit, natural ventilation performance of four commonly used window types was investigated. It was found that when dealing with cross configurations, better natural ventilation performance could be achieved by using full end-slider and side hung windows; while for single-sided configurations, side hung windows performed better than other types of windows to conclude that side hung windows were a better option.

The last part of this study is to take into account the complex influence of the surrounding building conditions on the results of the above studies. A large-scale private residential estate was chosen as a representative sample of typical residential environment in Hong Kong for the investigation of wind conditions around buildings. The local wind conditions were used to evaluate natural ventilation performance of different openings configurations and window types. The results indicate that when adding the influence of surroundings buildings, wind speed was reduced and wind direction was changed. Despite wind conditions were affected, the conclusions drawn on the influence of openings configurations and window types on natural ventilation performance were still valid.

Given adequate information on the influences of openings configurations, window types and surrounding buildings on natural ventilation performance in dwellings is not available in extant literature, the results of this study are expected to be useful to site planners and architects in Hong Kong while designing residential dwellings for better natural ventilation.

PUBLICATIONS

Journal papers based on the research project:

C. F. Gao, W. L. Lee, Evaluating the influence of openings configuration on natural ventilation performance of residential units in Hong Kong， Building and Environment, 46 (2011) 961-969

C. F. Gao, W.L. Lee, Evaluating the influence of window types on natural ventilation performance of residential buildings in Hong Kong, accepted by the International Journal of Ventilation

C. F. Gao, W.L. Lee, Evaluating the influence of surrounding buildings on natural ventilation of a residential unit, in preparation

Conference papers

C. F. Gao, W. L. Lee, Evaluating factors affecting wind ventilation performance inside pedestrian zone located within dense residential estates in Hong Kong, International Conference on Energy and Environment Technology 2009, Oct. 2009, Gui Lin, China

C. F. Gao, W. L. Lee, Influence of Window Types on Natural Ventilation of Residential Buildings in Hong Kong, International High Performance Buildings Conference at Purdue, Jul. 12-15, 2010. USA.

C. F. Gao, W. L. Lee, Measuring the influence of openings configurations on natural ventilation of residential buildings in Hong Kong. First International Conference on Sustainable Urbanization, Dec 15-17, 2010. Hong Kong

Others:

C. F. Gao, W.L. Lee, Optimized design of floor-based air-conditioners for residential use, Building and Environment: 2009(44): 2080–2088

C. F. Gao, W.L. Lee, Chen Hua, Locating room air-conditioners at floor level for energy saving in residential buildings, Energy Conversion and Management, 2009(50): 2009–2019

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NOMENCLATURE

Symbols	Description	Unit
A	Area	m^2
A_i	Mean age of air at the sample position	s
C	Concentration	ppm
C_D	Discharge coefficient	
$C_i\,(t)$	Contaminant concentration at time t	ppm
C_o	Initial contaminant concentration	ppm
ΔC_P	Pressure coefficient	
MAA	Mean age of air	s
$\dot{m}$	Injection rate	m^3/s
ΔP_{max}	Maximum differential pressure	N/m^2
$\overline{P}_{max}$	maximum mean pressure	N/m^2
$\overline{P}_{min}$	minimum mean pressure	N/m^2
q	Ventilation rate	m^3/s
Q_I	Instantaneous airflow volume	m^3/s
R	Integral proximity coefficient	

Sz	Sensitivity to a factor	
TWY	Typical weather year	
Γ	Diffusion coefficient	
U_R	Wind velocity at a reference point	m/s
U_{ref}	Mean velocity at reference height	m/s
V	Volume of the room	m^3
V_R	Velocity ratio	
Y_{ref}	Reference height	m
α	Power law exponent	
Φ	General variable	
SH	Side hung window	
TH	Top hung window	
ES	End-slider window	

CHAPTER 1 INTRODUCTION

1.1 Background information of utilizing natural ventilation

Ventilation can be categorized as forced or natural. Both can provide a healthy and comfortable environment through the supply of fresh air to remove dust, humidity, odor, and heat. Unlike forced ventilation which is realized by mechanical power, such as fan and air-conditioning system, natural ventilation is ensured by pressure difference caused by wind and/or stack effect. No energy is needed in this process. It is therefore a preferred option for energy saving especially in moderate seasons of subtropical cities like Hong Kong.

Hong Kong is famous over the world for the modern culture, highly developed economy, as well as the crowded living space. As one of the most densely populated cities in the world, Hong Kong has around seven million residents packed in 30 percent of the total land area (300 sq. km/116 sq. miles). To accommodate so many people in such a small place, most residential buildings in Hong Kong are tightly packed high-rise buildings. The functional rooms are exceptionally small. In result, the ventilation condition in indoor space and pedestrian area are generally opined stagnant and inadequate. The increasing number of people suffering from asthma and wheeze in recent years was also attributed to the stagnant and polluted indoor air conditions (Leung, 1998). Adding that Hong Kong was seriously hit by the severe acute respiratory syndrome (SARS) in 2003, the ventilation problem in Hong Kong since then has been receiving greater attention. The Hong Kong Government subsequently set up a Governmental Team Clean Committee to deal with the urban planning policies. The team led to the development of an air ventilation assessment (AVA) system which sets guidelines for all the major development projects to evaluate the natural ventilation performance in the pedestrian area (Ng, 2009). This is on the assumption that better ventilation performance in the pedestrian area will improve the indoor ventilation performance. However, the influence is not straight forward. Besides the wind conditions around buildings, indoor ventilation performance is influenced also by many other factors including building form, window design and locations, door positions etc. All these factors introduce impact on the indoor airflow pattern and thus the indoor ventilation performance. Investigations on the influence of all these factors for better indoor ventilation performance are valuable.

Energy statistics show that from 2007 to 2010, the total electricity consumption of the domestic sector has increased from 24.8% to 26.1%, mainly due to increasing use of air-conditioners (CSD, 2011). To take the leading role of combating global climate change and going toward the greenest city in the Pearl River Delta Region, the Hong Kong Government set a target of reducing carbon emission by 50% and 60% by 2020 when compared to 2005 and 2010. Reducing energy use for air-conditioning is considered as an effective measure for achieving the target (EB, 2010; EPD, 2010) in particular for the residential sector.

1.2 Research gaps

There are practical constraints in the utilization of natural ventilation. One constraint is the high outdoor air humidity, if utilizes, will introduce negative impact on the indoor environment. The wind velocity and direction are always changing such that uncertain availability of natural wind from outdoor is another constraint. Furthermore, the availability of adequate natural ventilation is affected by the building forms, openings configurations, as well as the surrounding environment. Hence, it is clear that the constraints can be introduced by external and internal factors. External factors include the urban form (e.g., density and site coverage), the building typology (e.g., building form and dimensions), and micro climatic conditions. They are often subject to constraints beyond the control of site planners and architects. Internal factors include the floor layout (e.g., internal partitioning and space utilizations) and the openings configuration (e.g., doors and windows characteristics). In respect of internal factors, little has been stipulated in local codes and regulations; site planners and architects are allowed to design internal space in terms of partitioning, doors and windows the way they deem proper (MCPRC, 2003a; Coceal, 2007). Obviously, influence of internal factors on natural ventilation performance is of particular importance to residential buildings in Hong Kong.

Although researchers devoted themselves to the investigation of natural ventilation have already contributed much in this area (detailed literature review will be seen in Chapter 2), and some of them used CFD simulation to assist building design for better usage of natural wind, the work done is still far from enough. There is still no suitable standard or reference to enable the design of openings configurations and the selection of window types for better ventilation performance. Hence, many questions which are of interests to site planners and architects are left unanswered. For example, how should the windows and doors be relatively positioned with different prevailing wind directions? Which type of window is more effective in delivering fresh air to complex indoor spaces?

1.3 Scope and purpose

This study focused on the investigation and evaluation of influences of opening configuration, and window types on the natural ventilation performance of residential dwellings under varying outdoor and surrounding buildings conditions.

As far as natural ventilation performance is concerned, it is worth to point out that in warm and humid months, maintaining thermal comfort by natural ventilation may consume more energy for air-conditioning. Accordingly, the use of natural ventilation in residential dwellings for maintaining thermal comfort should be under the premise that the heat content of the outdoor is acceptable to the occupants. Therefore, the purpose of this study is to enhance effective use of natural ventilation in and around high-rise residential buildings in Hong Kong.

1.4 Objectives of this study

Through the investigation and evaluation of the influences of openings configurations and window types on the natural ventilation performance of a hypothetical residential unit in Hong Kong by CFD simulations and field measurements, three objectives are expected to be achieved. First, the formulation of an optimum openings configuration of which is defined by the windows and door positions; and building orientations. Second, the identification of a better performed window type among those commonly used in high-rise residential buildings; and third, based on a representative residential estate, the evaluation of the influence of surrounding building conditions on the results achieved. In achieving the third objective, the wind conditions around buildings located at different zones of the residential estate was used as boundary conditions to ascertain the ventilation performance achieved by different openings configurations and window types. The results are helpful for the future design of green buildings that make full use of natural ventilation.

1.5 Structure of the thesis

This thesis is organized in 7 Chapters; Chapter 1 introduced the research background, gaps, scope and objectives.

Chapter 2 was a review of the relevant literature, and research work that had been done in openings configurations, window types and influence of surrounding building conditions. This forms the foundation of this study.

Chapter 3 reviewed and compared the methods commonly used for analyzing the influences of openings configurations and window types on the natural ventilation performance, under varying outdoor and surrounding building conditions. The methods adopted for this study was explained and presented.

Chapter 4 focused on the evaluation of influence of openings configurations parameters on natural ventilation performance. The parameters investigated included window combinations, door positions and building orientations. The sensitivity analysis and the results were presented.

Chapter 5 described the investigation on the natural ventilation performance of four commonly used window types. Their performance was synthetically compared under different building orientations and prevailing wind conditions.

Chapter 6 presented the study of influence of surrounding buildings on the wind conditions around buildings and thus the indoor ventilation performance. The mean age of air with and without the influence of surrounding buildings was compared and analyzed.

Chapter 7 provided the conclusions of this study.

CHAPTER 2 LITERATURE REVIEW

To appreciate the research work on related area and identify the research gap, relevant literature has been reviewed and key findings are summarized in this Chapter.

2.1 Guidelines for openings configurations and pedestrian area ventilation

Use of guidelines and codes for controlling building design is by far the most widely adopted means for enhancing building ventilation performance (Lee, 2002). According to the buildings ordinance of Hong Kong (Coceal, 2007), rooms for habitation should be provided with natural lighting and ventilation by one or more windows with an aggregate superficial area of not less than one-tenth of the floor area of the room. Among that window area, at least in the aggregate of one-sixteenth floor area should be openable in such a manner that the top of each window is at least 2 m above the level of the floor. A practice note issued to practitioners also under the building ordinance of Hong Kong adopts a performance based approach to specify a minimum requirement of 1.5 air change per hour (ACH) for habitable rooms to ensure adequate natural ventilation (Anonymous, 2005b).

In China, building designs are governed by mandatory codes enforced by the

Ministry of Construction. In the Design Code for Residential Buildings (MCPRC, 2003a), it is specified that the opening area of a habitable room ventilated by natural wind should not less than one- twentieth of the floor area of the room. Whilst in the Design Standard for Energy Efficiency of Residential Buildings in Hot Summer and Warm Winter Zone (MCPRC, 2003b) where Hong Kong belongs to, there are design criteria for windows. For living room, bathroom and bedroom, the minimum window area should be greater than 5% of the floor area. There are additional requirements for windows of different orientations. For windows facing North, East, West and South, they should have a size not bigger than 0.45, 0.3, 0.3, and 0.5 of the wall area. Furthermore, the aggregate openable window area should not be less than 8% of the room floor area and not less than 45% of the window area. These criteria were set to encourage more use of natural ventilation without compromising the energy performance due to the use of large windows.

It is worth to point out that the Hong Kong Government has been dealing with the ventilation problem in Hong Kong for years as a major part of work for promoting sustainable and balanced developments. The Planning Department has commenced a series of relative studies (PD, 2005a; PD, 2006; PD, 2009) with researchers since 2003. The key research outputs include a technical guide for air ventilation assessment (AVA) in surrounding area before new developments is built (PD, 2005b). The wind velocity ratio (VR) was introduced as an indicator to represent the availability of wind at a particular location surrounded by neighboring developments. VR is defined as V_p/V_∞ (V pedestrian /V infinity), and the higher the VR value, the better the ventilation performance. However, a minimum benchmark for VR is in absence in the technical guide to tell whether or not the ventilation performance of a development is satisfactory. Hence, the development of a benchmark for VR is needed. The Planning Department then commissioned the AVA system study team for a related study. The study includes the establishment of the urban climatic analysis map and the urban climatic planning recommendation map, as well as the development of optimum wind performance criteria that could be practically adopted for AVAs in Hong Kong and so on (PD, 2009).

Although many countries have codes and design guidelines to address gust and strong wind problems, few seem to have dealt with the issue of urban air stagnation and city air ventilation problems (Ng, 2009). Given Hong Kong is unique for the sub-tropical climate and high-density population characteristic, the primary expectation on ventilation is the higher the rate, the better the performance. Although the series studies initiated by the Government contributed to improve the ventilation around buildings, there is much room to work on for the establishment of quantitative guidelines, such as a performance criterion for ventilation effectiveness that correlate VR with local climate parameters.

2.2 Research on influence of openings configurations

Among internal factors, impact of openings configurations on natural ventilation performance is perhaps the most investigated. Openings configuration is commonly defined as the area, form and position of openings on wall surfaces (Lukkunaprasit, 2009). Hassan et al. (Hassan, 2007) conducted CFD simulations and wind-tunnel experiments to investigate the effects of window positions on ventilation characteristics of a simple single room. It was concluded that single-sided ventilation with two distant openings (one far left and one far right) performed better than two adjacent openings (center-located). Favarolo et al. (Favarolo, 2005) also adopted CFD simulations and laboratory experiments to analyze the influence of openings configurations on natural ventilation performance. It was concluded that when dealing with single-sided ventilation, ventilation performance was most affected by the vertical level and width of the openings. For cross ventilation, Tantasavasdi et al. (Tantasavasdi, 2001) found that ventilation performance is better with a larger inlet than with a larger outlet; and Yin et al. (Yin, 2010) reported that ventilation performance was most influenced by the relative level of the two window openings.

Another literature (El-Agouz, 2008) considered the effect of internal heat source and opening locations on natural ventilation performance. Three cases as shown in Figure 2.1, (a) to (d) were studied. Figure 2.1, (a) shows the physical configuration of the room and the location of a heat source (L_{hs}); Figure 2.1 (b) to (d) shows various locations of the openings (L_o) (case 1 to case 3). It was found that case 3 (dual openings with cross ventilation) performed better than the other two cases to indicate dual openings is better than single opening. Additionally, Evola and Popov (Evola, 2006) analyzed the wind driven natural ventilation in buildings by CFD-based programs. Again, three openings configurations were studied, they were single-sided ventilation with an opening on the windward wall, single-sided ventilation with an opening on the leeward wall, and cross ventilation. The study was based on a simple physical model as shown in Figure 2.2. It was found that the RNG turbulence model agreed well with the experimental data. For single-sided ventilation, positioning the only opening on the leeward side rather than on the windward side resulted in a larger indoor ventilation rate.

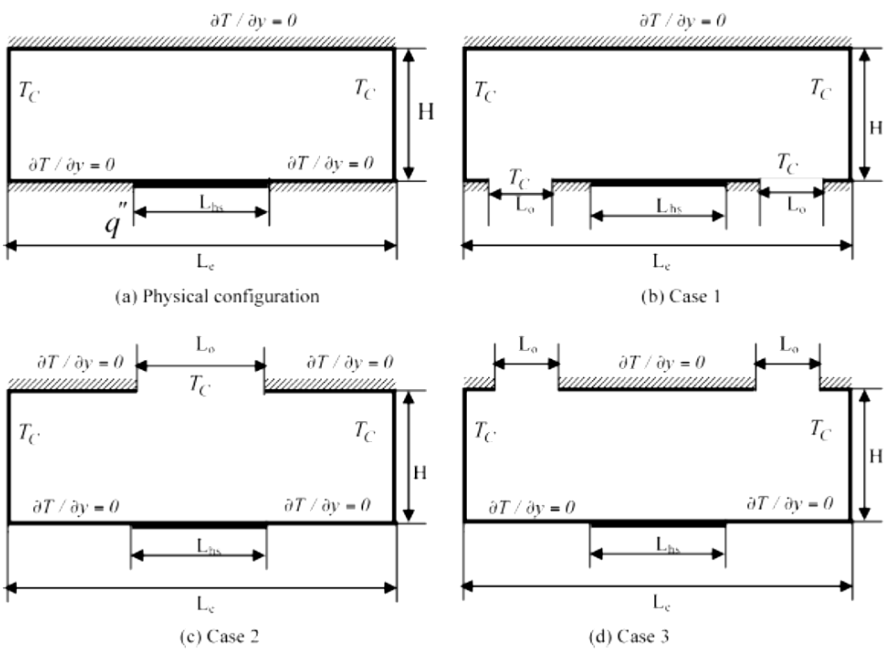


Figure 2.1 Physical configuration and considered cases (Lo and Lhs are the lengths of opening and heat source respectively) (El-Agouz, 2008)

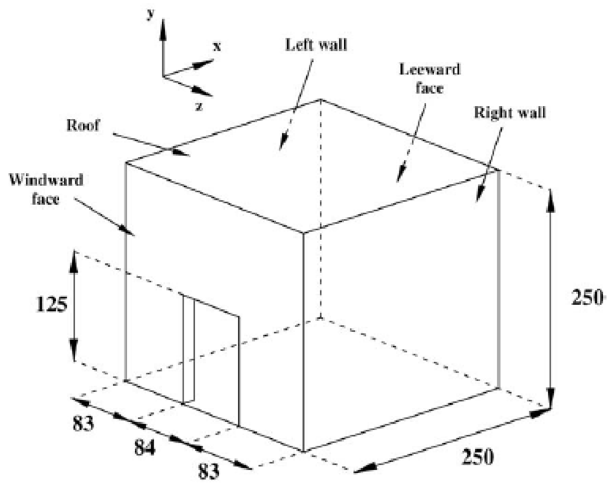


Figure 2.2 Building model in single-sided ventilation with an opening in the windward wall (Evola, 2006)

Recommendations on position and size of openings were found in a design book (Allard, 1998). It was recommended that outlet openings should be equal to or greater in size than inlet openings to avoid excessive air velocities with a limited airflow rate. Furthermore, it was suggested that more than one opening should be provided to a room with single-sided ventilation, while these openings should be located far apart from each other for better ventilation. Unfortunately, clear explanations for the recommendations were not provided.

Previous studies have identified the preferred openings positions and characteristics for better natural ventilation performance. However, it is noted that they were based on simple single room model. Factors such as the interactive effects of doors' positions, multi-room characteristics of residential units, building orientations and prevailing wind conditions seem not have been considered adequately. This study therefore addressed but not limited to the study of the influences of these factors on natural ventilation performance of residential units.

2.3 Research on influence of window type

A review article has presented a summary of existing and available information on the influence of different types of window openings on wind-driven cross-ventilation (Karava, 2004). It is noted from the surveyed information that most studies simply model a window as an opening for airflow. The influence of window sash has not been considered in the evaluations. Extant literature has little to offer on effects of window sash on natural ventilation.

There are no clear definitions of different types of windows. Classifications change from region to region and even country to country. There is classification by the location of the window, such that windows are classified as vertical, horizontal and inclined window if they are located correspondingly on a vertical wall, a horizontal roof, and an inclined roof (Li, 2000). However, windows are more often classified according to the way the sash and the frame are held together (Priyadarsini, 2004). Windows with hinges on one side of the sash to swing outward or inward are often classified as side hung windows. Top hung or bottom hung windows are those with hinges at the top or bottom side of the sash; while sliding windows bypass each other in separate tracks mounted on the header jamb and sill.

Discharge coefficient is often used as a characteristic function for evaluating the airflow pattern and thermal performance of large openings (Heiselberg, 2002; Heiselberg, 2006). Heiselberg (2001) measured discharge coefficients of side hung and bottom hung windows by laboratory experiments. The results showed that discharge coefficient depended not only on window types, but also on opening area and pressure difference; using it for characterizing natural ventilation performance of different window types would not be appropriate.

Heiselberg (2001) concluded that for both single-sided and cross ventilation, bottom hung window was preferable in winter, while side hung window was preferable in summer. This conclusion was based on the longer (shorter) distance between the occupied zone and the bottom (side) hung window. Roetzel et al. (2010) compared properties of six different window types for different climatic conditions and concluded, based on opening percentages and angles, that during periods when heating was not required, side hung windows opening inward were preferred compared with sliding windows partially blocked by panes and top hung windows opening outward.

Unlike cold climate regions, Hong Kong has subtropical climate with hot summers and warm winters. Natural ventilation is the most preferred way of cooling interiors and for providing fresh air for better indoor environment and energy performance in almost all seasons (FoE, 2001). Understanding that window types can enhance natural ventilation is important. As one of the objectives of this study, the influence of window types on natural ventilation performance of residential units in Hong Kong were evaluated.

2.4 Research on influence of surrounding buildings

Much research on the influence of surrounding buildings on natural ventilation performance in pedestrian area has been conducted.

Stathopoulos's works (Stathopoulos, 1986; Stathopoulos, 1995; Stathopoulos, 1996; Stathopoulos, 2004; Stathopoulos, 2006) on investigating thermal comfort in pedestrian area around buildings can be found in past two decades. He proposed to establish an overall comfort index taking into account the combined effects of wind speed, temperature and relative humidity in the area. The AVA system (PD, 2005b) discussed in Chapter 1 also focused on the ventilation performance in pedestrian area within buildings groups. Similar studies can also be found focusing on the effect of street canyons (Vardoulakis, 2003), heat island (Giridharan, 2004), and urban morphology (Hang, 2009b) that caused by densely packed buildings.

There are also studies on the influence of surrounding buildings on natural ventilation performance of indoor environment (Chan, 2003; Coceal, 2007). However, the urban environments assumed for some of the studies were far from realistic, the building sites assumed were unreasonably large, and the building blocks within the site were assumed evenly distributed。 Furthermore, the interactive effects of outdoor and indoor environments on indoor natural ventilation performance were not discussed. For studies that were based on actual urban environments and have considered the interactive effect (Jiang, 2002; Yau, 2002; Yik, 2010), the impact of surrounding buildings were not specifically evaluated, and the wind conditions considered were limited.

To fill the gap, this study was based on a representative residential estate to represent actual urban environment, and took into account 85% of annual the prevailing wind conditions for evaluating the influence of surrounding buildings on the indoor natural ventilation performance.

CHAPTER 3 METHODOLOGY

The investigation of natural ventilation performance can be achieved by different methods including analytical solutions, experimental measurements, and airflow modeling solutions. Two main focuses for ventilation studies lie in calculating the air volume flow rate through openings and the prediction of the indoor air distribution patterns. This Chapter presented a review of methods commonly used for the investigation of natural ventilation, and the methods adopted in this study.

3.1 Commonly used methods

3.1.1 Analytical models for calculation of ventilation rate

Analytical models are derived from fundamentals of fluid dynamics and heat transfer, such as mass, momentum, energy, and chemical species conservation equations. Simplifications of the analytical models were used both in geometry and in thermo-fluid boundary conditions to obtain solutions. As a result, the equations obtained will have limitations which may not be applicable for other conditions without modifications (Chen, 2009).

A number of analytical models with conditions for applications were found in literature (Etheridge, 1996) as described below:

For a room with two identical openings like Figure 3.1(a), the equilibrium ventilation rate due to wind can be calculated by (Etheridge, 1996):

$$q = C_D A U_R \sqrt{\frac{\Delta C_P}{2}} \qquad (3.1)$$

where C_D is discharge coefficient (equal to 0.6 for the openings formed by doors and windows); A is the opening area; U_R is the wind velocity at a reference point well away from the influence of building; and ΔC_P is the pressure coefficient corresponding to a building exposed to the wind.

For a room with two identical openings on the same side but at different levels as (Figure 3.1(b)), the ventilation rate due to temperature difference can be calculated by Equation (3.2) (Etheridge, 1996):

$$q = C_D A \sqrt{\Delta T g \frac{h}{T_I}} \qquad (3.2)$$

Where g is the gravitational force per unit mass; ΔT is the temperature difference between indoor and outdoor; h is the vertical distance between the centers of the two openings; T_I is the internal air temperature.

For a room with two identical openings on different walls and at different levels, as shown in Figure 3.1(c), and under wind and buoyancy effect, the ventilation rate can be expressed as Equation (3.3) (Etheridge, 1996):

$$q_I = \sqrt{q_W{}^2 + q_B{}^2} \tag{3.3}$$

Where q_w denotes the ventilation rate due to wind alone, q_B denotes the ventilation rate due to buoyancy alone.

Based on previous research (Yin, 2009), Yin et al. developed a number of revised analytical models to estimate ventilation potential. The revised models took into account the percentage of window opening and the local climate, but there are still limitations with the models. It can be seen in Figure 3.2 that the windows considered were on two opposite walls. There were only vertical variation of window positions and wind was assumed blowing perpendicular to the building.

Although the analytical models seem to be simple and easy to use, the fact is, the actual conditions are far more complex and dynamic than assumptions made in developing the models. In actual conditions, there is typically more than one opening on different external walls and the prevailing wind directions are always changing. It is hard to tell if the opening(s) are serving as inlet or outlet. The parameters required to describe the characteristics of openings could not be just an empirical value as required in the analytical models. The wind pressure required to enter into the equations are either not readily available, or difficult to measure on site, resulting in large prediction errors. It was reported that the use of Equation (3.3) would have errors up to 50% (Walker, 1992a).

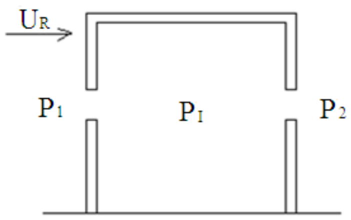
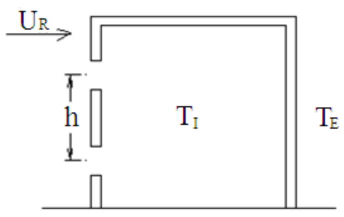
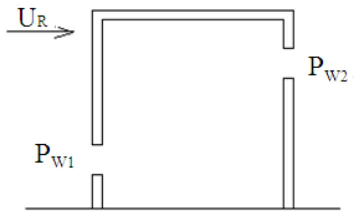
		
(a) Ventilation due to wind	(b) Ventilation due to buoyancy	(c) Ventilation due to the combined forces
Two openings at same level but on different walls	Two openings on same wall but at different levels	Two openings on different walls and at different levels

Figure 3.1 Physical models of the ventilated room (Etheridge, 1996)

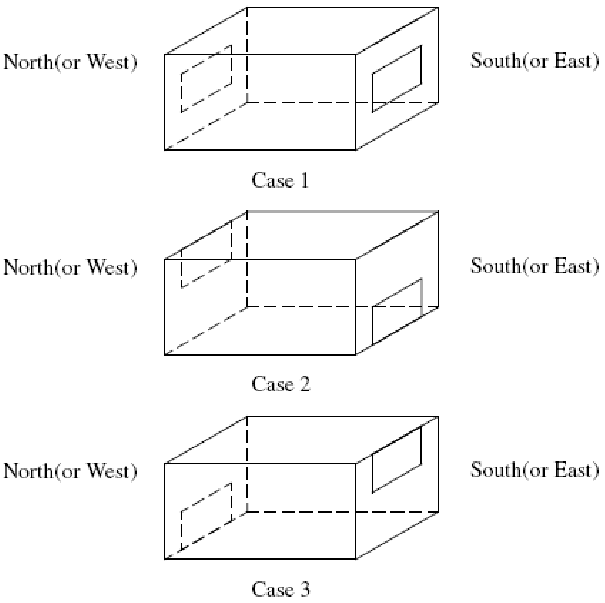


Figure 3.2 Conditions considered in the revised analytical models (Yin, 2009)

It is evident from the above that with the simplifications of the geometry and thermo-fluid boundary conditions in deducing the equations, the deduced equations can just be used in simple cases and under similar physical conditions.

Similar to analytical models, there are models developed based on empirical approximation, and are called empirical models. Given their similarity in the development process, they possess similar weakness as analytical models (Chen, 2009).

3.1.2 Experimental investigations of ventilation performance

Experimental method is one of the most recognized approaches that can be used to evaluate ventilation potential and to validate other predictive methods.

3.1.2.1 Full-scale experiments

Full-scale experiments are usually carried out to validate numerical simulation results, especially CFD simulations. It can be divided into two categories: laboratory experiments and field measurements.

(a) Laboratory experiments

Laboratory experiments often use chambers to mimic real rooms. By monitoring the parameters in the chamber, such as humidity, thermal conditions, tracer gas concentration etc., the airflow rate and distribution pattern as well as the thermal comfort indexes can be determined (Stavrakakis, 2008).

As experimental chamber is built for experimental purpose, the advantage is that the controlled parameters are more readily to be adjusted than the real situation. It is no doubt that changing of indoor and outdoor thermal environments, annual wind conditions, openings configurations to suit experimental requirements can easier be performed. However, field measurement is still most preferred because the ultimate objective of experiments in laboratory is to resemble real life situation.

(b) Field measurements

Field measurements of temperature and velocity for evaluating the indoor thermal comfort level, and for validating the results obtained from other methods are commonly used for natural ventilation studies (Fracastoro, 2002; Allocca, 2003; Georgakis, 2006; Mochida, 2006; Han, 2009; Lai, 2009). The measurement of air temperature and velocity are easy, but the accuracy is not always satisfactory; because wind conditions are highly variable and the apparatus may not be accurate. Another concern of field measurements is that the results may not be comprehensive enough because only limited sample points can be selected for measurements. These limitations exist both in the laboratory and in field measurements.

(c) Tracer-gas method

Tracer-gas technique is most widely used for laboratories and field measurements of natural ventilation rate through openings. During the measurements, a readily detectable tracer gas is injected into a space and the concentration history in the building is recorded. The inflow rate of fresh air can then be determined by the variation in tracer gas concentration. The principle of tracer-gas technique will be introduced in Chapter 4 on methodology.

3.1.2.2 Small-scale experiments

When full-scale experiments are difficult or not feasible to be conducted, scaled models built in laboratory can be used as an alternative. In order to simulate the real life situation, some dimensionless flow parameters in the small scale models, such as Reynolds number, Grashof number, Prandtl number and so on, must be same as the actual condition.

One of the commonly used small-scale experiments is wind-tunnel experiments for estimating ventilation performance in buildings (Murakami, 1991; Chang, 2003; Priyadarsini, 2004; Ahmad, 2005; Yoshie, 2007; Zhang, 2008). More often, the experiments are combined with other methods such as CFD simulations, and the results are used to validate numerical models.

It is undoubtedly that the experiments, conducted either by field or laboratory measurements, can provide the most reliable information for ventilation studies. However, they are defective in some aspects. First, experiments are usually very expensive and time-consuming. Second, the results are generally not informative enough since equipments and human resource are limited, especially for monitoring temperature or velocity field in ventilation. Last, experimental measurements are not free from errors (Melikov, 2007) of which can be resulted from human factor or the equipments themselves.

3.1.3 Airflow modeling of natural ventilation

The modeling methods to predict airflow in buildings can be classified into two categories: macroscopic methods and microscopic methods (Axley, 2008).

3.1.3.1 Macroscopic modeling

Macroscopic methods are based on modeling buildings and their supporting heating, ventilating and air-conditioning (HVAC) systems as collections of finite-sized control volumes within which mass, momentum or energy transport is described by straightforward algebraic and/or ordinary differential conservation equations. They provide means to predict bulk airflows moving into, out of and within whole building/HVAC systems, and give results like spatially averaged temperature, species concentration and mass flow rate (Axley, 2007). Basically, macroscopic methods include single zone and multi-zone modeling according to the number of target zones. Two popular multi-zone programs COTAM (Walton, 2006) and COMIS (Feustel, 1999) are often used by researchers, but they do not have a user-friendly interface for data input and the display of the results are not attractive (Chen, 2009). As a result, the application is not as wide as that of the commercial CFD software. Another weakness of macroscopic methods is that air is assumed well mixed and the air temperatures and velocities in each zone are assumed uniform. As such, it is impossible to obtain air distribution information within a zone, which is inadequate for large indoor space or a room with stratified ventilation system. Therefore, some researchers (Tan, 2005; Wang, 2007) combined the use of multi-zone modeling and CFD modeling to obtain more comprehensive information of natural ventilation in buildings.

3.1.3.2 Microscopic modeling

Microscopic methods are based on continuum descriptions of mass, momentum, and energy transport that defined in terms of partial differential conservation equations.

(a) Zonal modeling

Zonal model (Megri, 2007) was developed as a remedy for single and multi-zone models. It divides a room into a limited number of cells, usually less than 1000 for a three dimensional space. Air parameters can be calculated for each cell to indicate their non-uniform distribution in the space. It is a method similar to the CFD modeling but can save much computing capacity. However, the deficiency is that zonal models are not applicable for airflow with strong momentum, because they do not solve momentum equations for reducing the computing capacity. It is considered not superior to a coarse-grid CFD simulations in accuracy and computing time (Chen, 2009).

(b) CFD simulation

CFD simulation is the most popular technique for prediction of airflow conditions. It can provide detailed field distributions of air pressure, air velocity, air temperature, relative humidity and contaminants concentrations by solving a set of partial differential equations, including equations of mass, momentum, energy, and chemical species concentration conservations. The theoretical principle of CFD technique will be introduced in a later section.

3.2 The methodology used in this study

CFD simulations and field measurements were used in this study. Field measurements were conducted in a carefully selected building. The indoor ventilation parameters were monitored by tracer gas decay method and the outdoor wind conditions were recorded by a portable meteorological station. The collected data were used to validate the CFD simulations. Based upon the validated model, further CFD simulations were carried out to investigate the influence of openings configurations, window types, and surrounding building conditions on the natural ventilation performance of a hypothetical residential unit.

3.2.1 CFD simulation

CFD simulation is a practical and powerful tool which has been employed for pure or applied research and industry applications. The reason CFD simulation is used in this study is that CFD simulation can: i) effectively simulate actual fluid flow;

ii) predict flow conditions that cannot be measured in experiments, such as space that are too remote or too large; and iii) provide detailed, visualized, and comprehensive airflow information.

3.2.1.1 Theoretical principles of CFD

The basic principles of CFD are derived from conservation laws of physics and expressed by governing equations mathematically. The fundamental governing equations of a compressible Newtonian fluid include(Verteeg, 2007):

(1) Continuity equation (Equation (3.4)) which means the mass of a fluid is conserved.

$$\frac{\partial \rho}{\partial t} + \mathrm{div}(\rho U) = 0 \tag{3.4}$$

(2) Momentum conservation equations (Navier-Stokes equation). They are obtained by the application of Newton's second law to fluid motion. The equations (Equations (3.5a, 3.5b and 3.5c)) indicate the rate of change of momentum equals the sum of the forces on a small fluid element.

$$\frac{\partial(\rho u)}{\partial t} + \mathrm{div}\left(\rho u U\right) = -\frac{\partial p}{\partial x} + \mathrm{div}\left(\mu \,\mathrm{grad} u\right) + S_{Mx} \tag{3.5 a}$$

$$\frac{\partial(\rho v)}{\partial t} + \mathrm{div}\left(\rho v U\right) = -\frac{\partial p}{\partial y} + \mathrm{div}\left(\mu \,\mathrm{grad} v\right) + S_{My} \tag{3.5 b}$$

$$\frac{\partial(\rho w)}{\partial t}+\operatorname{div}(\rho wU)=-\frac{\partial p}{\partial z}+\operatorname{div}(\mu\operatorname{grad}w)+S_{Mz} \tag{3.5 c}$$

And (3) Energy conservation equation (Equation (3.6)). It is developed based on the first law of thermal dynamics. The equation indicates the rate of change of energy is equal to the sum of the rate of heat addition to and the rate of work done on a small fluid element.

$$\frac{\partial(\rho i)}{\partial t}+\operatorname{div}(\rho iU)=-p\operatorname{div}U+\operatorname{div}(k\operatorname{grad}T)+\Phi+S_i \tag{3.6}$$

Where vectors U = U(x, y, z, t), ρ =ρ(x, y, z, t), p = p(x, y, z, t), and T = T(x, y, z, t). $\operatorname{div}U=\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}$, i is the internal energy of a fluid element, S_{Mx}, S_{My}, S_{Mz} are the momentum sources. S_i is the internal heat source of the fluid, and the dissipation function is:

$$\Phi=\mu\left\{2\left[\left(\frac{\partial u}{\partial x}\right)^2+\left(\frac{\partial v}{\partial y}\right)^2+\left(\frac{\partial w}{\partial z}\right)^2\right]+\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2+\left(\frac{\partial u}{\partial z}+\frac{\partial w}{\partial x}\right)^2\right.$$

$$\left.+\left(\frac{\partial v}{\partial z}+\frac{\partial w}{\partial y}\right)^2\right\}+\lambda\operatorname{div}U \tag{3.7}$$

In addition, the state of a substance in thermodynamic equilibrium can be described by means of state variables as summarized in Equations (3.8a, 3.8b, 3.9a, and 3.9b).

$$p = p(\rho, T) \tag{3.8a}$$

and

$$i = i(\rho, T) \tag{3.9a}$$

For a perfect gas,

$$p = \rho R T \tag{3.8b}$$

and

$$i = C_v T \tag{3.9b}$$

Equations (3.4) to (3.9), consisting of five flow equations and two algebraic equations with seven unknowns, can be mathematically solved, and a general form of governing equations can be formulated as Equation (3.10):

$$\frac{\partial(\rho\phi)}{\partial t} + \mathrm{div}(\rho\phi U) = \mathrm{div}(\Gamma \mathrm{grad}\phi) + S_\phi \tag{3.10}$$

Where ϕ is a general variable, and Γ is the diffusion coefficient.

Equation (3.10) is generally known as the transport equation for property ϕ which can equal to 1, *u*, *v*, *w*, and *i* (or *T*) to represent different equations. It clearly highlights the various transport processes: on the left is the rate of change term and the convective term of the property ϕ, while on the right are the diffusive term and the source term respectively.

3.2.1.2 Turbulent models

Equation (3.10) can be solved by numerical methods on a control volume basis. When the flow is in the laminar regime, it can be described completely by the equations. However, in many cases, the flows of engineering significance are turbulent, and thus, more complex methods are needed to analyze the flow details.

Generally, the Reynolds decomposition defines instantaneous value of flow property ϕ at a point equals the sum of a steady mean component $\bar{\phi}$ and a time varying fluctuating component ϕ' with zero mean value:

$$\phi = \bar{\phi} + \phi' \tag{3.11}$$

Where $\bar{\phi} = \frac{1}{\Delta t}\int_{t}^{t+\Delta t} \phi(t)dt$, and this method considering the turbulence fluctuation in flow is also known as the Reynolds averaging method.

Substitute Equation (3.11) to the general form Equation (3.10), we can get Reynolds-averaged Navier-Stokes (RANS) equations:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{x_i}(\rho u_i) = 0 \tag{3.12}$$

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{x_i}+\frac{\partial}{\partial x_j}\left(\mu\frac{\partial u_i}{\partial x_j}-\rho\overline{u_i'u_j'}\right)+S_i \quad (3.13)$$

Where i and j are number valued from 1 to 3. The overbars indicating time-averaged variables were omitted for convenience except the one called Reynolds stresses item $-\rho\overline{u_i'u_j'}$. This item is an additional one for the time-averaged fluid equations in comparison with the original instantaneous Navier-Stokes (NS) equations, and leads to 6 more unknowns. Therefore new turbulence models are to be introduced to make the RANS equations be closed.

According to the methods used to tackle the Reynolds stresses, different models have been developed by researchers. The models include the Spalart-Allmaras model, the standard, RNG, and Realizable k-ε models, and the standard and shear-stress transport k-ω models etc.. They are options in Fluent (Anonymous, 2005a). The k-ε series of models are most often used, and among them, the standard and the RNG k-ε models are proved very stable during computations, but the standard k-ε model's prediction of the various airflow is less accurate than that of the RNG k-ε model (Chen, 1995). The RNG model is therefore recommended for simulations of indoor airflow. In addition, RNG k-ε turbulence model is widely acknowledged superior to other models, such as enhanced accuracy for rapidly strained flows and swirling flows. As a result, the RNG k-ε model was used for simulating the airflow in this study.

3.2.2 Field measurement

Wind velocity and indoor mean age of air (explained in later section of this Chapter) were obtained by field measurements. Some of the results were used as boundary conditions for the CFD simulations and others were used to validate the simulation results.

3.2.2.1 Airflow volume

Tracer-gas technique was used to measure the air exchange rates of different openings configurations, of which is one of the most widely used and practical methods to obtain natural ventilation through openings on an enclosure.

Depending on the type of control and injection approach, tracer-gas method can be further classified as (Etheridge, 1996):

Decay method: a short burst of gas is injected into the space to establish a uniform concentration within the space and the concentration decay process is recorded.

Constant injection: gas is injected at a constant rate and the concentration response is recorded.

Pulse technique: a short duration gas pulse is injected into the space and the response is recorded.

Constant concentration method: gas is injected into the space under control in order to keep a constant concentration.

The first three methods give the total airflow rate of a space while the constant concentration method provides also the airflows to individual rooms. Theoretically, the constant injection method and the pulse technique are the same methods, but the latter begins measurements before a known volume of tracer gas is injected and then wait until the concentration decays (Sherman, 1990).

The basis of tracer-gas technique is the mass balance equation of a specific gas in air. With assumptions of complete mixing and no temperature difference between indoor air and outdoor air (explained in a later section), the mass balance equation can be described as (Etheridge, 1996):

$$V\frac{dC}{dt} = \dot{m} - QC \tag{3.14}$$

Where V is the volume of the room, C is the concentration of tracer gas, $\dot{m}$ is the injection rate, Q is the airflow rate.

Rewriting Equation (3.14) becomes:

$$Q = \left(\dot{m} - V\frac{dC}{dt}\right)\frac{1}{C} \tag{3.15}$$

By integration over a time period T gives:

$$\int_0^{T} Q dt = \int_0^{T} \frac{\dot{m}}{C} dt + V\left(\ln C(0) - \ln C(T)\right) \qquad (3.16)$$

Dividing both sides of Equation (3.14) with T gives:

$$\overline{Q} = \frac{\overline{\dot{m}}}{C} + \frac{V}{T}\left(\ln C(0) - \ln C(T)\right) \qquad (3.17)$$

Where the overbar denotes a time average.

When the injection rate is constant, Equation (3.17) becomes

$$\overline{Q} = \dot{m}\overline{\frac{1}{C}} + \frac{V}{T}\left(\ln C(0) - \ln C(T)\right) \qquad (3.18)$$

Where the average of the inverse concentration ($\overline{1/C}$) differs from the inverse of the average concentration $1/\overline{C}$.

It is evident that based on the tracer-gas technique, different methods can be adopted to determine the airflow rate.

For decay method, $\dot{m}$=0 during the measurement period. According to Equation (3.18), the average airflow rate between t_1 and t_2 can be calculated by

$$\overline{Q} = V \frac{\ln \frac{C(t_1)}{C(t_2)}}{(t_2 - t_1)} \qquad (3.19)$$

The decay method is most commonly used in the measurement of airflow rate (Sherman, 1990). However, the limitations are that the space being investigated need be definable as a single zone and the decay must begin with a uniform tracer gas concentration throughout the space (Chao, 2004).

For the constant injection method, the steady-state equation is

$$Q_I = \frac{\dot{m}}{\overline{C}} \tag{3.20}$$

Where Q_I is the instantaneous airflow volume. This method can provide accurate mean flow rates or instantaneous flow rate, it depends on the length of the flow variation period and the measurement period.

And for the constant concentration method, the airflow rate (Q_I) of the Ith room can be calculated by

$$Q_I = \frac{\dot{m}_I}{C_t} \tag{3.21}$$

Where $\dot{m}_I$ is the release rate of tracer gas into room I, C_t denotes the target concentration. The key advantage of this method is that it can be used to determine the ventilation parameters for individual room, and multiple zones, as well as particular sample positions. However, the additional equipment required is an automated and networked sampling and dosing system to adjust continuously the gas injection rate on the basis of negative feedback control principle (Chao, 2004).

3.2.2.2 Ambient conditions

The local climate parameters including temperature, relative humidity, wind velocity and direction were recorded by appropriate apparatus. Thermal-couples, data logger, and anemometers were used. The results were used as boundary conditions where applicable in simulation and to validate simulation results.

3.2.3 CFD model validation

Field measurements were conducted in a carefully selected site for model validation, and the following parameters were measured

(1) Wind condition

(2) Indoor mean age of air at sample positions

3.2.3.1 The site

To facilitate the investigation of openings configurations on the ventilation performance of residential premises, a residential unit was carefully selected for field measurements. The considerations for selection were: i) the studied area (highlighted in red in Figure 3.3) fits the area range (between $40m^2$ and 69.9 m^2 as explained in Chapter 4) desired for this study; ii) as shown in Figure 3.4, the studied area consists of four identical windows, enabling study of the influence of opening positions on natural ventilation performance; and iii) the residential estate (Figure 3.5) where the unit is located is a rather isolated site with few external obstructions, thus the influence of surrounding buildings can be ignored.

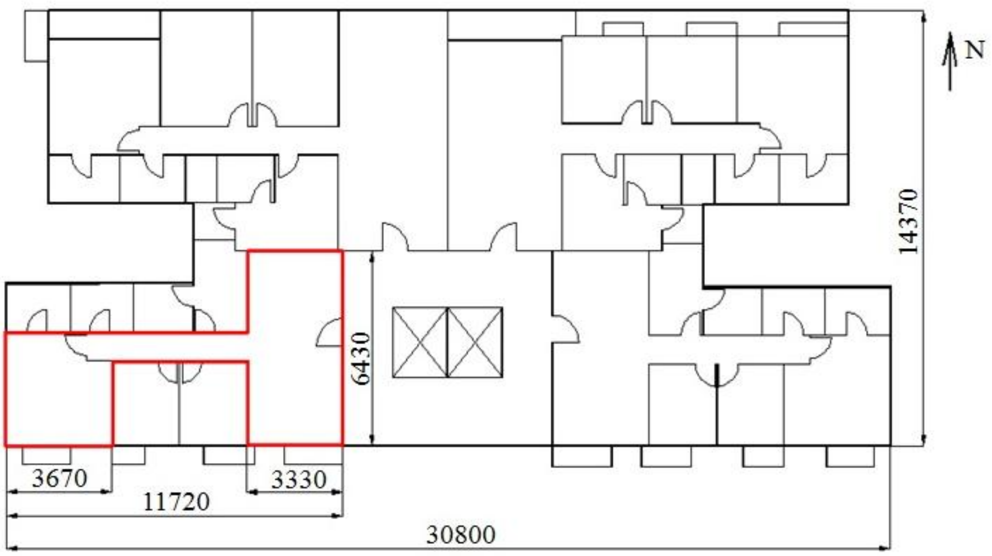


Figure 3.3 Floor layout of the unit chosen for case study

3.2.3.2 The measurements

The tracer-gas technique, used widely in similar studies in the past (Sherman, 1990), was adopted for measuring ventilation performance in this study. CO_2 was chosen as the tracer-gas as it is safe, does not cost much, and satisfies accuracy requirements (Roulet, 2000). The concentration decay method was used to compute mean age of air (refer to explanation in Equation (3.22)) at various sample positions.

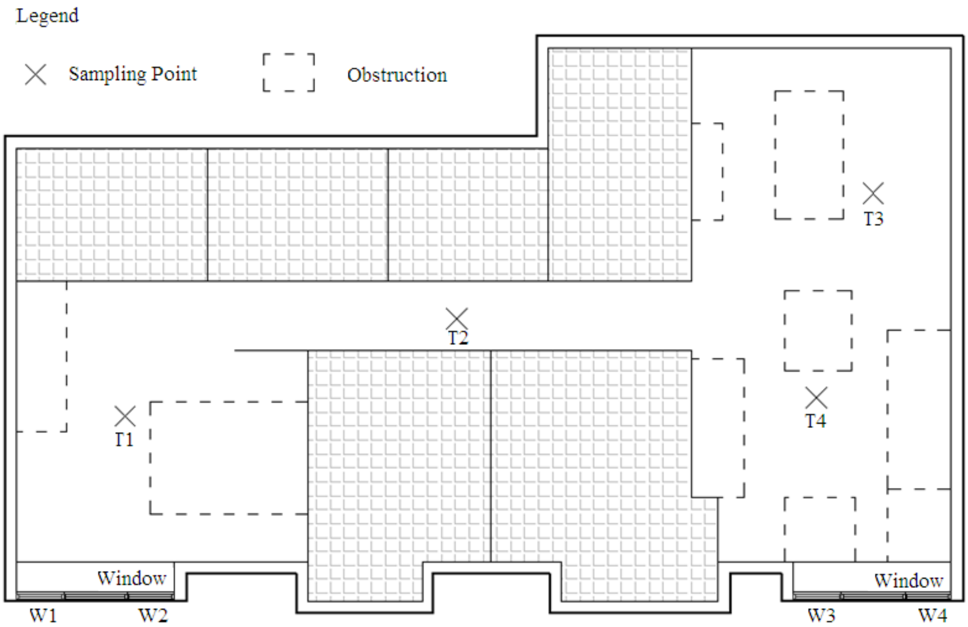


Figure 3.4 Windows locations and sample positions for MAA data collection

Figure 3.5 Site layout of the studied residential building

To simulate different window opening positions, different combinations of open and close positions of windows (W1 to W4 in Figure 3.4) were used. For each window open-close combination, CO_2 concentrations at 1.1 m level at the four sample positions (T1 through T4) (Figure 3.4) were recorded at 30s intervals. Telaire 7001 CO_2 monitors were employed for monitoring CO_2 levels. CO_2 monitors were calibrated according to the user manual, to an accuracy of ±50 ppm.

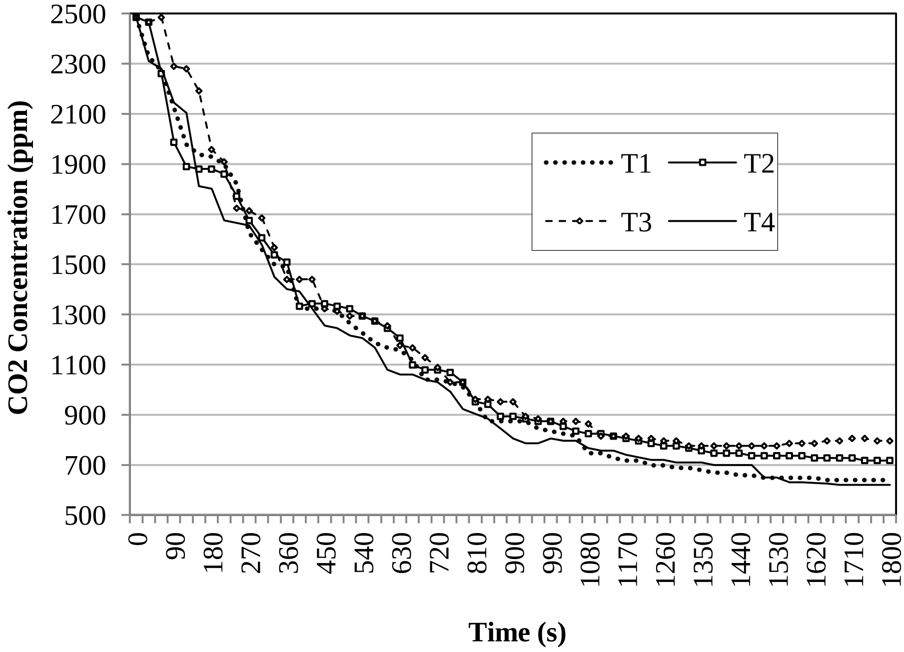


Figure 3.6 CO_2 concentration decay curves at the four sampling points

As can be seen in Figure 3.4, the two parts of the studied area are quite distant. To ensure proper tracer-gas measurements, other areas in the studied unit were properly sealed to avoid leakage of CO_2. Windows were opened simultaneously, according to the pre-determined window combinations, only after CO_2 concentration of the entire studied area was in equilibrium. Figure 3.6 indicates that CO_2

concentration decay curves at the four sample positions differ only slightly from each other, confirming that tracer-gas measurements were properly conducted.

Meteorological conditions were measured according to ASTM standards (ASTM, 2009). A portable meteorological station was set up at the least obstructed location of the estate. Gill UVW Anemometer model 08274 was used to record outdoor wind direction and velocity, while temperature and humidity sensors were used to record air temperature and humidity. The sensors were placed at 11m above the ground floor. They were calibrated to ±1% (wind velocity), ±0.3 ^{o}C (temperature), and ±1.8% (humidity).

Background CO_2 concentrations were recorded during the field measurements and were used to determine the absolute increase in indoor CO_2 concentrations for calculation of MAA.

Two sets of field measurements each on 17 and 18 November 2009 were recorded for comparison. The data collected on 18 November 2009 was used in the analysis because of the relatively stable wind movements on that day.

During the measurement period, wind speed fluctuated within a narrow range and the mean value was 2.3 m/s. Wind directions were mostly at 0 degree to indicate that the prevailing wind was from the north, Figure 3.7, which is typical for winter seasons in Hong Kong.

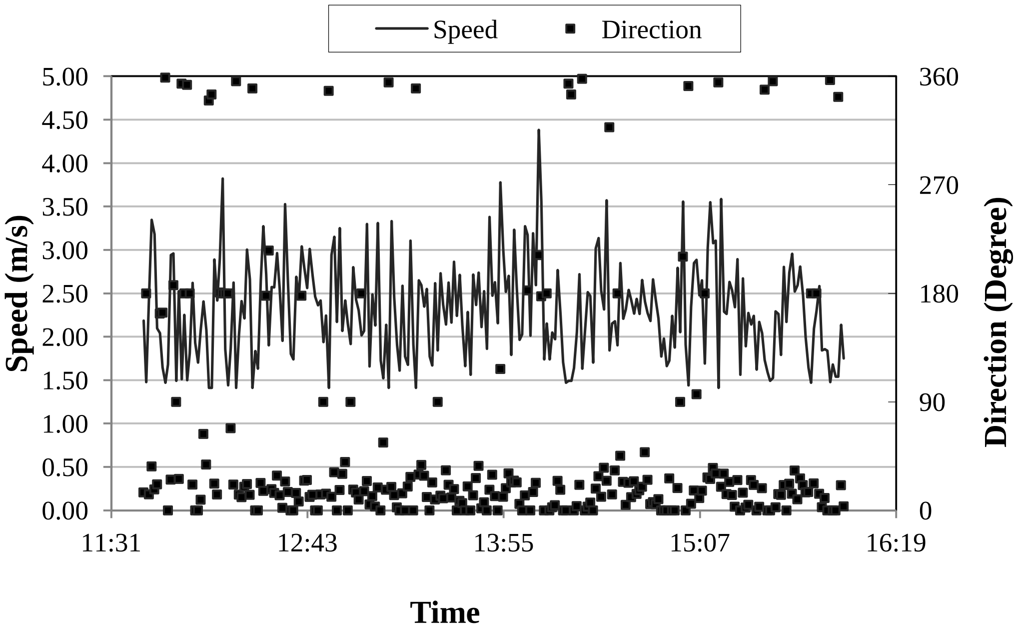


Figure 3.7 Outdoor wind speeds and directions

(Note: 0 and 360 degree refer to north, and others are measured clockwise)

The recorded meteorological data were used where applicable to set the boundary conditions for CFD model validation.

The concept of mean age of air (MAA) was adopted to represent natural ventilation performance in both field measurements and CFD simulations since this concept has been widely applied in similar studies (Walker, 1992b; Gan, 2000; Sherman, 2008). MAA at a sample position is represented as (ASHRAE, 2002):

$$A_i = \frac{1}{C_o} \int_0^\infty C_i(t)\, dt \qquad (3.22)$$

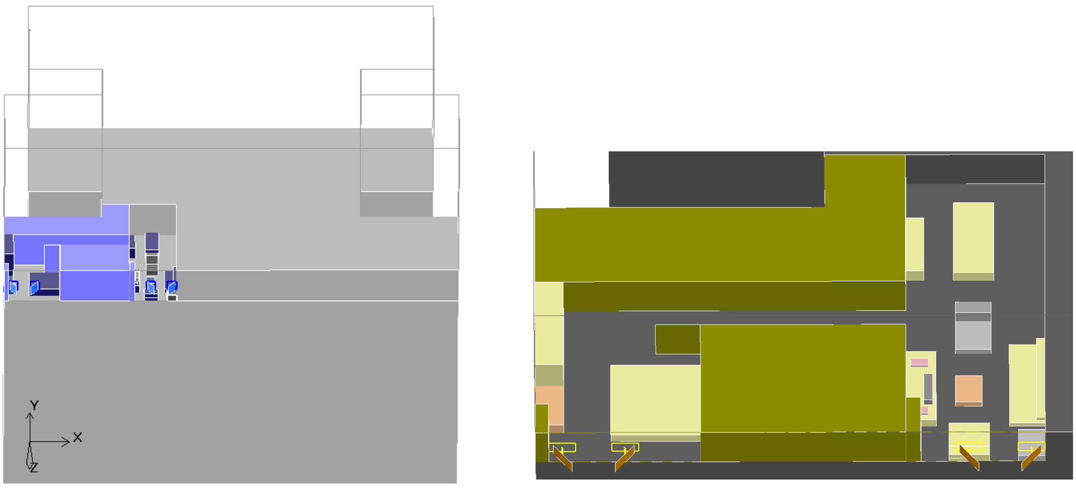
Where A_i is the mean age of air at the sample position; C_o is the initial contaminant concentration at the sample position; and C_i *(t)* is contaminant concentration at sample position as a function of time, obtained by regression of measured values over the decay period.

Representative CO_2 concentration decay curves at the four sample positions (Figure 3.6) differ only slightly from each other, confirming that tracer-gas measurements were properly conducted. The decay process was also used to calculate the mean age of air, which can be compared with the simulated results.

3.2.3.3 The validation

CFD software AIRPAK (Anonymous, 2008) was used to simulate airflow distributions of the studied residential unit. Three dimensional (3D) actual size physical models of the building where the study unit is located were established (Figure 3.8). The upper part of the building was set to be transparent to better demonstrate the location of the unit. In determining the optimal dimensions of the calculation domain, the length behind the built area were gradually increased in multiples of the height of the building (H). Trial simulations indicated that despite the tremendous increase in computing time and effort for changing the domain length from 1H to 5H and to15H, the simulations results differed only by 5% and 7% correspondingly. Considering this study involved 96 case studies (explained in later section), dimensions of the calculation domain were eventually set as 5L×5W×3H (L = 30.8m; W = 14.37m, and H = 30.25m). This was determined such that computing capacity and accuracy of results could be balanced. To reflect the geometric shapes of the objects in the building, the unstructured hexahedral mesher was used to create the mesh; grid refinement was adopted at the openings to account for the large gradient that might occur. This follows the grid generation results of the first case and a grid independence test.

Grid generation in the first case was based on an initial grid size of 0.008 m near crucial walls; and a maximum expansion ratio in grid size of 2. Grid independence test was performed by creating grid using coarse mesh and normal mesh (with grid refinement) methods; which were 47,927 and 902,657 respectively. Simulation results based on the two grid numbers showed that air distribution and MAA values at positions T1 and T4 were below 5%, this indicated the grid independence was satisfactory.



Residential Building Residential unit

Figure 3.8 3D model of the studied residential building and residential unit

The renormalization group (RNG) $k-\varepsilon$ turbulence model was used to simulate the steady state natural ventilation. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) pressure-velocity coupling algorithm was used to discretize the controlling equations in AIRPAK. The solution was considered converged when residual flow were less than or equal to their specified convergence criteria 10^{-3}.

Boundary conditions were set on the basis of field measurement results; and wind power law as shown in Equation (3.23) was used to calculate the inflow velocity profile.

$$\frac{U_Y}{U_{ref}} = \left(\frac{Y}{Y_{ref}} \right)^{\alpha} \tag{3.23}$$

Where U_{ref} is the mean velocity at reference height (= 2.3 m/s), Y_{ref} is the reference height (= 11m), and α is the power law exponent; taken as 0.2 by reference to a study with similar geographic characteristics in same terrain (Liu, 2010).

Ventilation was taken as isothermal because temperature difference between indoor and outdoor environments is small during transition seasons in Hong Kong. As observed from the measurement results, this was particularly prominent when the natural ventilation rate was stable. Accordingly, the energy conservation equation was not checked in the simulations to reduce requirements of computing time and capacity, and to improve the efficiency of solving other equations.

A mathematical module is embedded in AIRPAK for calculation of MAA. It relates the local air age spectrum to properties of the airflow pattern in the domain. Under steady state condition, the local air age at any position depends only on the flow characteristics. Upon checking the IAQ/thermal comfort item in the basic parameter settings dialog box prior to run the solver, MAA at any position in the domain can be determined when the solution is converged.

To validate the selected turbulence model and the input boundary conditions, MAA at the four sample positions (T1 through T4) were extracted from the simulation results. They were compared with the measurement results in Figure 3.9. MAA in the living room (T3 and T4) was found to be consistently smaller than that in the bedroom (T1), and the range of the difference was 4.8% to 25.4%, which was considered marginally acceptable since another study used the same turbulence model reported differences of up to 20% (Liu, 2008).

To explain the difference between MAA in the living room and the bedroom, MAA and the velocity vector at 1.1 m level (y = 1.1m above floor) of the studied area are shown in Figure 3.10. It can be seen that the outdoor air enters the unit through the living room windows, and leaves through the bedroom windows. Consequently, MAA of the living room was smaller than that of the bedroom.

Given the acceptable range of the difference and the fundamental consistency in the two sets of data, validations were regarded as acceptable to conclude that it would be reasonable to adopt the turbulence model and the associated parameter settings for further investigations.

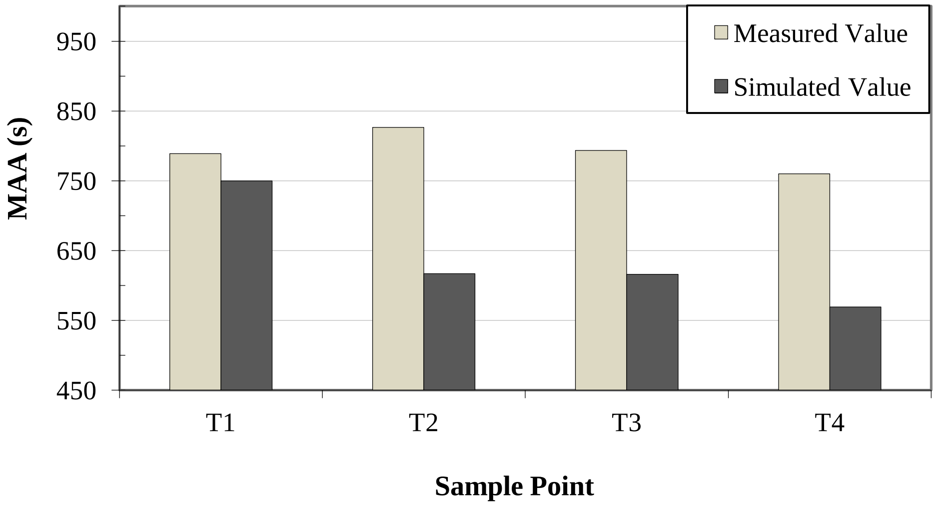


Figure 3.9 Comparison of simulated and measured results

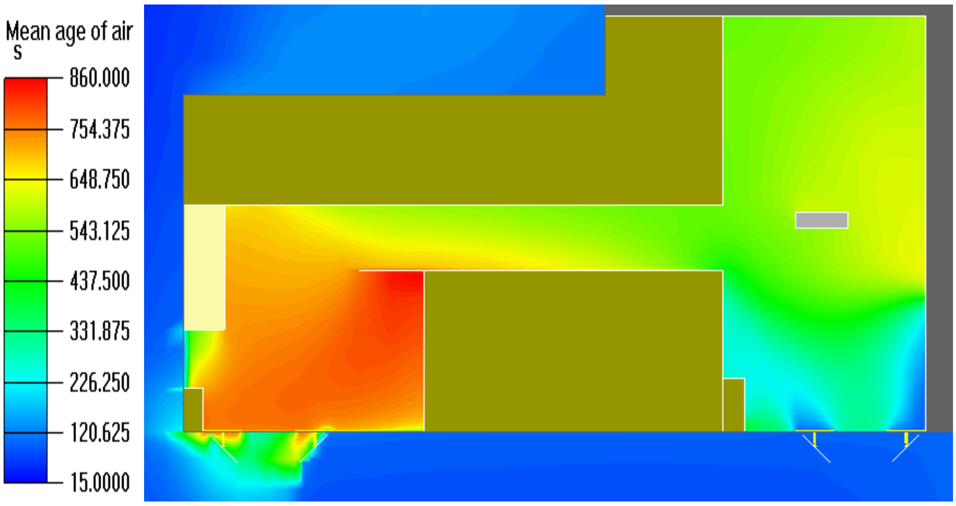


Figure 3.10 Mean age of air distribution at 1.1m level

CHAPTER 4 INFLUENCE OF OPENINGS CONFIGURATIONS

Given the Hong Kong Building Regulations have already stipulated the minimum window to floor area ratio (MCPRC, 2003a; Coceal, 2007), the configuration parameters investigated in this study were the relative positions of window opening groups (i.e. bedroom windows and living room windows), building orientations and the doors positions. A representative floor layout was formulated and scenarios of different openings configurations were generated based on the parameters to be investigated. CFD simulations of the MAA of different scenarios were performed by AIRPAK for comparing their ventilation performance.

AIRPAK (Anonymous, 2008) is one of the CFD software packages that can accurately and easily model airflow, heat transfer, contaminant transport and thermal comfort in ventilation system. It is developed specifically for the use of engineers and researchers in heating, ventilation and air-conditioning (HVAC) field. It uses the Fluent solver but combines the preprocessor and postprocessor together making it more easily be applied.

4.1 Hypothetical residential unit

A hypothetical residential unit was established to represent characteristic of typical residential units in Hong Kong to facilitate the evaluations. It was formulated after an extensive survey of physical characteristics of residential buildings in Hong Kong, including the unit area, floor layout, window design, and aspect ratio (ratio of width to length).

(a) Unit area

According to the statistics of the HKSAR Government (CSD, 2008; CSD, 2010), (Figure 4.1), 42% to 69% of the newly constructed private residential units are of areas between 40 m^2 and 69.9 m^2. Accordingly it is appropriate to assume a similar floor area for the hypothetical unit.

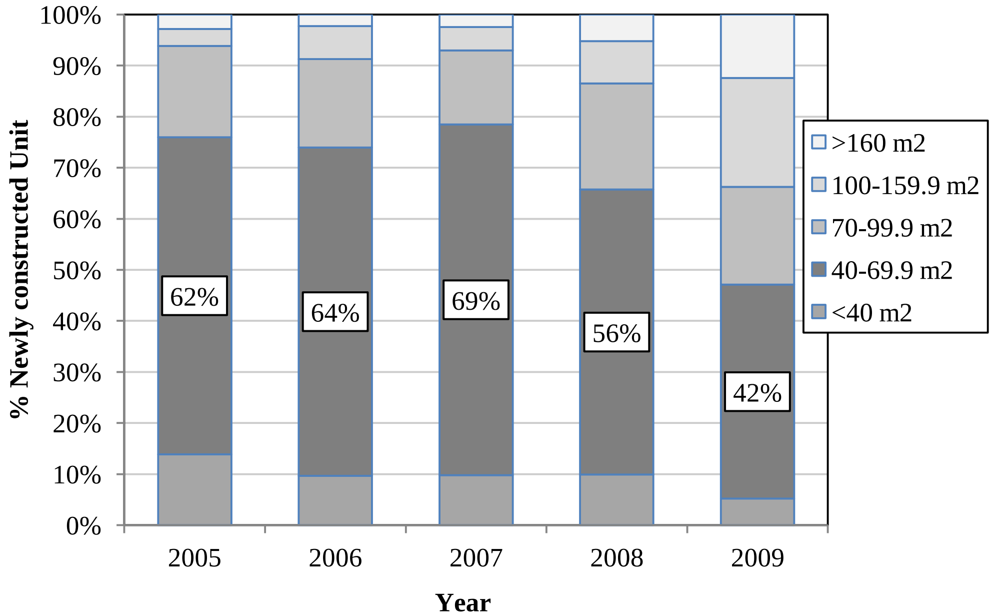


Figure 4.1 Floor area of new private residential units

(b) Floor layout

Although Hong Kong is a small place, the number of domestic households was 2.05 million in 2001. It is almost impossible to review the floor layout of all residential units in Hong Kong to formulate the floor layout for the hypothetical unit. Reference is, therefore, made to floor layout of residential units in Phases 1 and 2 of Mei Foo Sun Chuen (MF). MF was selected because it is the largest private housing estate in Hong Kong. The housing estate consists of 13,500 residential units accommodating approximately 60,000 people. The 99 blocks in MF were developed in 8 phases. Phases 1 and 2 comprise of 28 blocks of 3766 residential units accommodating approximately 17,000 people in total. The households distribution by floor area matches perfectly with that of Hong Kong in 2008, i.e. 60% of units in Phases 1 and 2 of MF are of floor area ranging between 40 m^2 and 69.9 m^2, and the mean area is 60 m^2. The floor layout of building blocks in Phase 1 and 2 of MF was therefore referenced in establishing the layout of the hypothetical unit (Figure 4.2).

One of the units (highlighted in Figure 4.2), with floor area ranged between 50 m^2 and 70 m^2 fits the area range desired for this study, and thus was selected as the sample layout for the hypothetical unit (Figure 4.3). Considering there are variations in room dimensions, window design, etc, for units located at different blocks, such details for the hypothetical unit are yet to be determined.

(c) Room dimensions

To set room dimensions for the hypothetical unit, a survey of detailed room dimensions of the 3766 residential units in Phases 1 and 2 of MF was conducted. Based on the collected data, aspect ratios (ratio of width to length) of bedrooms and living rooms were computed. It was found that the aspect ratio of bedrooms was between 0.65 and 1, with a mean of 0.81, while that of living rooms was between 0.39 and 1, with a mean of 0.69. Considering the collected data are of equal importance and should be given equal weight, mean values (i.e. 0.81 and 0.69) were used to set aspect ratios of the hypothetical residential unit. Consequently, the physical dimensions and the floor layout of the hypothetical unit were set as shown in Figure 4.3.

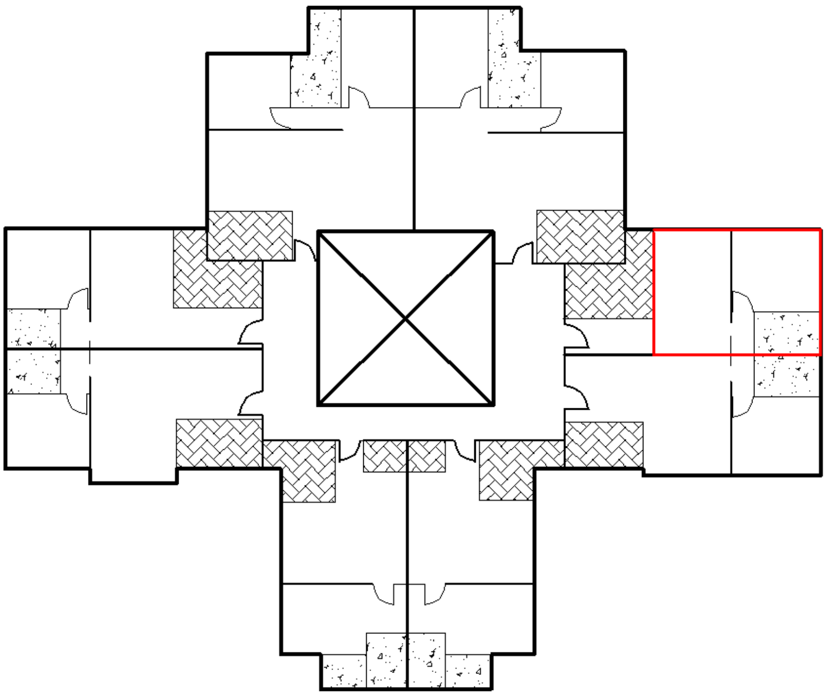


Figure 4.2 Typical floor layout of Phrase 1 and 2 of MF

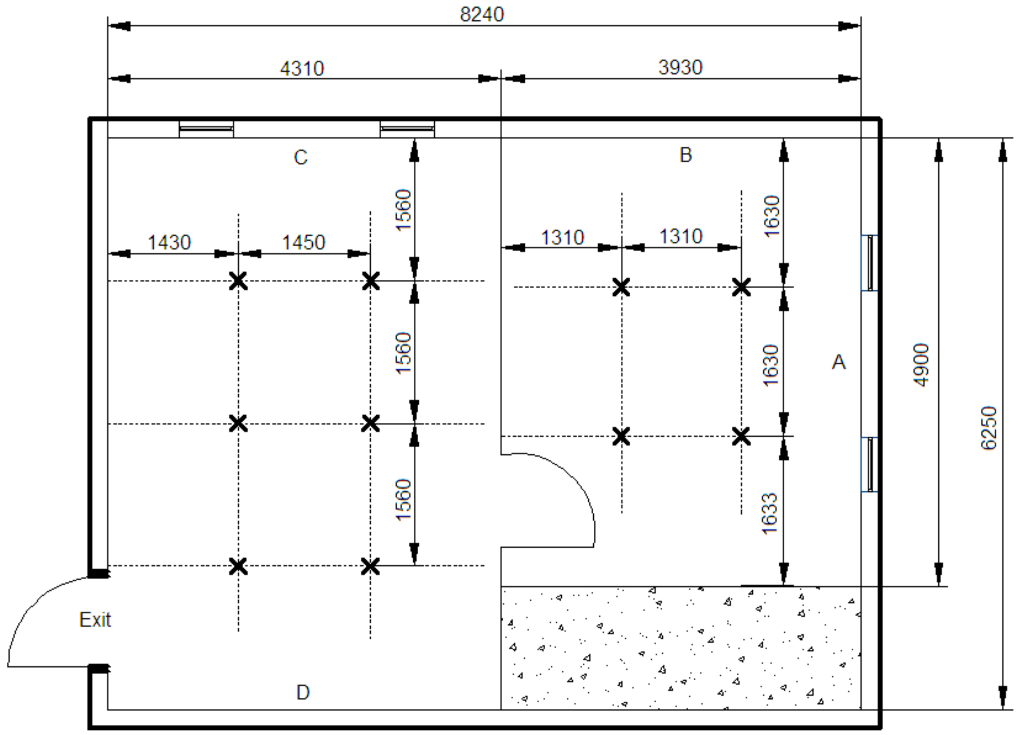


Figure 4.3 The hypothetical residential unit

(d) Window design

A survey of the types of window design used in MF was also conducted. It was found that three types of window design (Figure 4.4) are most commonly used. According to the definition of different window types as given in Chapter 2, Design A with full-height sliding door can be classified as sliding window, while Designs B and C can be classified as side hung window. Designs B and C differ only in the presence of a fixed pane between two openable panes. Given that the studied unit adopts window of Design C, it was also assumed for the hypothetical residential unit. Window area was assumed in compliance with the Building Regulations of Hong Kong, i.e. at least 1/16 of the floor area (Coceal, 2007), i.e. windows dimensions in the hypothetical unit were set at 0.6m height and 0.78m width.

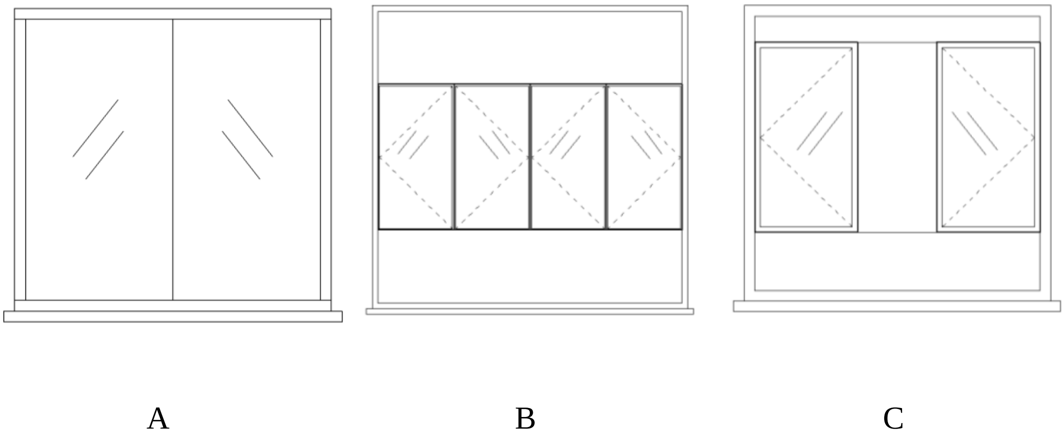


Figure 4.4 Types of window design in MF

4.2 Openings configurations

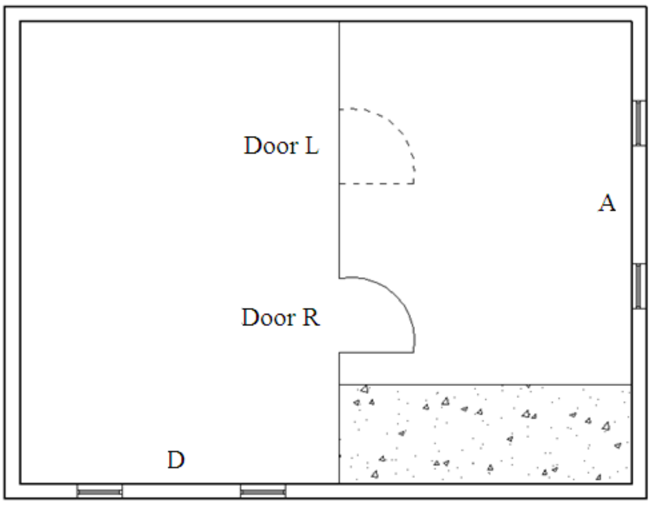
Openings configuration is defined by many spatial parameters, including orientation of the building, windows' and doors' positions, and the prevailing wind directions and conditions. For evaluation of the influence of various parameters on natural ventilation performance, each parameter needs to be carefully defined for CFD simulations. In simulations, the influence of each parameter and the combined effect of all parameters, were evaluated. Consequently, different combinations of parameters were studied. While the studied parameter(s) were varied, all other parameters were assumed constant.

(a) Building orientation

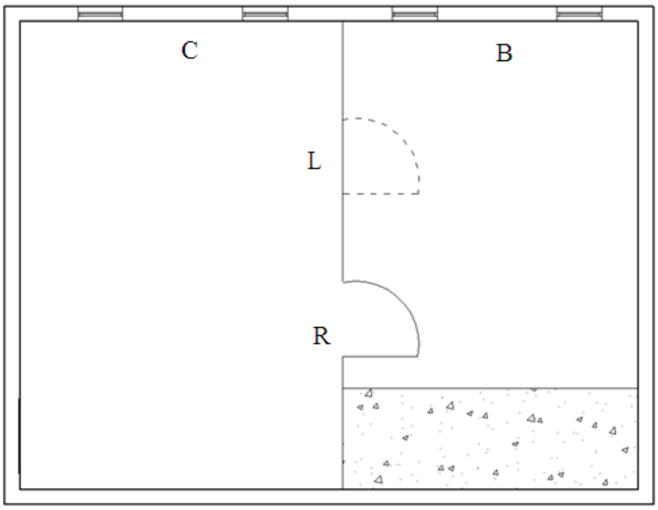
Building orientation is a key factor affecting natural ventilation performance of a residential unit. In this study, four basic orientations were assumed for the hypothetical unit; namely, north (N), west (W), south (S) and east (E). While there are two external façades in the unit, façade A (where window A is located in Figure 4.5) was taken as the principal orientation of the unit.

(b) Window and door positions

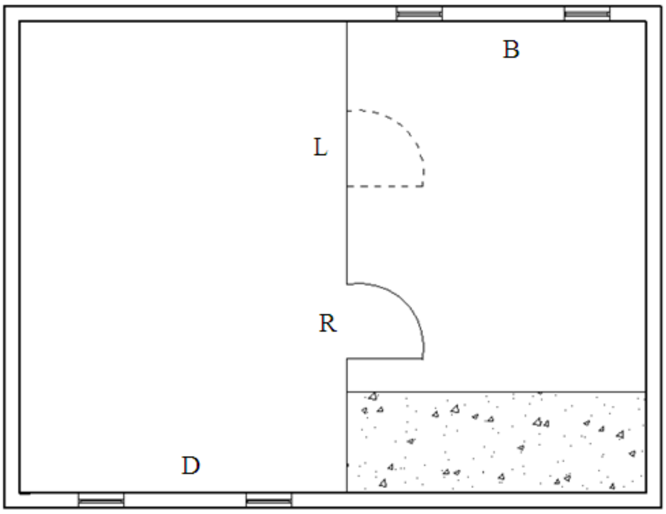
Bedroom windows could be located at façade A or B, while living room windows can be at façade C or D, as shown in Figure 4.5. As a result, there were four different combinations of windows positions, depending upon where bedroom room and living room windows are located (according to the façade). These are denoted as AC, AD, BC, and BD. Furthermore, there are two possible doors positions (left (L) and right (R) in Figure 4.5).



(a) Configuration AD-L or –R



(b) Configuration BC-L or –R



(c) Configuration BD-L or -R

Figure 4.5 Combinations of windows and doors openings

(c) Prevailing wind conditions

The meteorological data of the typical weather year (TWY) of Hong Kong (i.e. 1989) were analyzed and are summarized in Table 4.1. It can be seen that in Hong

Kong, the prevailing wind directions were at 30° (North = 0°) for 13.9% of the time (W1), at 90° (W2) for 57.4% (W3) of the time, and at 270° for 13.8% of the time. The rest of the time was at various directions. Considering that these three prevailing wind directions are most frequently occurred (> 85%) throughout a year, they were adopted in the CFD simulations.

Table 4.1 Summary of prevailing wind conditions in TWY

Wind direction (60 Deg. Intervals)	*Mean wind direction (Deg.)	Frequency of occurrence (%)	Mean speed (m/s)
0-60	30	13.9	2.42
70-120	90	57.4	3.70
130-180	150	5.1	1.86
190-240	210	6.2	2.13
250-300	270	13.8	1.97
310-360	330	2.2	1.65

Remarks: (*)0° = North; 90° =East; 180°= South and 270° = West

The above indicated that there were altogether eight window-door positioning combinations, together with four orientations, a total of 32 (4×8=32) openings configurations were generated. For ease of reference, each configuration was abbreviated as XY-I-J; where X denotes the façade where the bedroom window is located; Y denotes the façade where the living room window is located; I denotes the position of the door; and J denotes the orientation of the unit. Considering also the three most likely wind conditions, there were 96 possible combinations to be simulated.

4.3 Simulation

Based on the layout of the representative residential unit (hypothetical unit), the physical models for the eight window openings configurations were built. One of them (configuration AC-L-N) is shown in Figure 4.6.

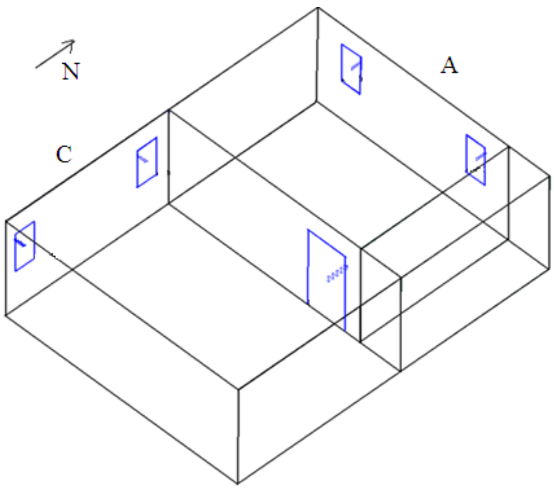


Figure 4.6 Physical model (Configuration AC-L-N)

Physical models of the hypothetical unit based on the 8 window-door positions combinations were built. The renormalization group (RNG) $k\text{-}\varepsilon$ turbulence model and the associated settings, which were the same as the validated model (domain dimensions of 5W, 5L, and 3H with different input parameters), were used for simulating the 96 different combinations of building orientation, windows and doors positioning and wind conditions.

4.4 Results

Indoor airflow distributions of the 96 cases were simulated by the use of AIRPAK. For each case, the MAA at four levels, namely, 0.1m, 0.6m, 1.1m and 1.7m, and at ten different sample points (Figure 4.3) of the hypothetical unit were computed. Given the vast number of data generated from the simulations, the weighted average MAA ($\overline{\text{MAA}}$) was adopted for evaluating the influence of each configuration parameter (i.e. XY, I and J) on the natural ventilation performance of the hypothetical unit. Sensitivity analysis was conducted for evaluating the combined effect of different parameters.

4.4.1 Weighted average MAA

$\overline{\text{MAA}}$ for each configuration parameter was obtained by weighting the MAA for the three prevalent wind directions on the basis of the frequency of their occurrence as shown in Equation (4.1). The results are shown in Figure 4.7.

$$\overline{\text{MAA}}_{(\text{XY-I-J})} = \frac{\Sigma f_n \text{MAA}_{(\text{XY-I-J}),n}}{\Sigma f_n} \tag{4.1}$$

Where

$\overline{\text{MAA}}_{(\text{XY-I-J})}$ = the weighted average MAA for configuration XY-I-J (second)

$\text{MAA}_{(\text{XY-I-J}),n}$ = the simulated MAA for configuration XY-I-J under wind condition N (second)

f_n = the frequency of occurrence of wind condition n

n = the wind conditions; from 1 to 3

Figure 4.7 compares the computed $\overline{MAA}$ of the 32 openings configurations. It was noted that among the 32 configurations, when the following conditions were fulfilled, $\overline{MAA}$ were smaller (~50 seconds), indicating better natural ventilation performance:

XY = BD; I = R or L; J = N and S

Given the two options for I were acceptable, it could be concluded that I (i.e. door position) did not have much influence on $\overline{MAA}$.

To further evaluate the influence of XY on $\overline{MAA}$, $\overline{MAA}$ (XY-I-J) were further averaged to deduce $\overline{MAA}$ (XY) (i.e. XY = BD, AD, AC, and BC) (Figure 4.7). It could be seen that $\overline{MAA}$ (BD) had the smallest value, indicating that the BD configuration had the best overall performance, followed by AD and AC, while BC was the worst. The results indicated that for achieving better natural ventilation performance ($\overline{MAA}$<140 seconds), it was preferable to have the two groups of window openings in opposite directions (i.e. BD) or perpendicular to each other (i.e. AC and AD), to ensure cross ventilation. However, when the two windows groups were on the same side (i.e. BC), offering only single-sided ventilation, the natural ventilation performance was less than desirable ($\overline{MAA}$= 233 seconds).

Positioning the two window groups on the same side is sometimes unavoidable. Accordingly, focused evaluations of $\overline{MAA}$ for such configurations were conducted. It was found that under easterly wind conditions, $\overline{MAA}$ of configuration BC-L-N (west-facing windows) was consistently smaller than BC-L-S (east-facing windows), and vice versa, for westerly wind conditions. Given the two configurations differ only in orientation of the openings groups, the results indicate that under single-sided ventilation condition, it is advisable to position the openings on the leeward side rather than the windward side. This result is consistent with the conclusion reached by Evola and Popov (Evola, 2006).

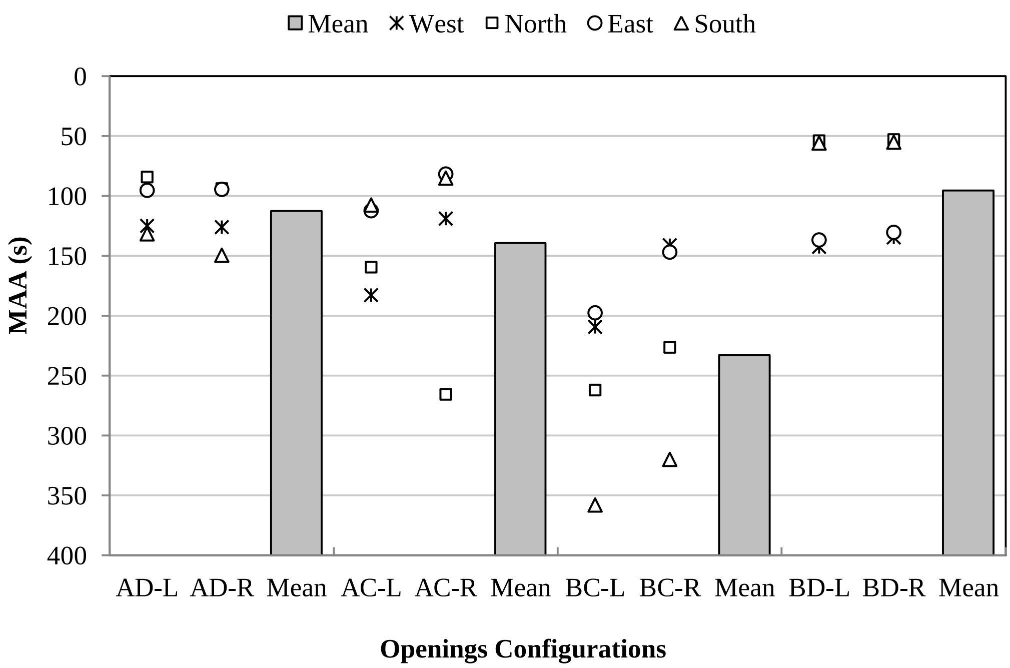
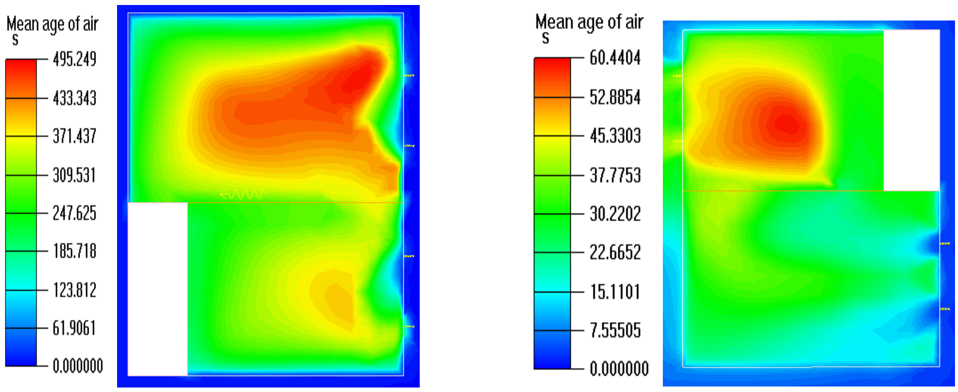


Figure 4.7 $\overline{MAA}$ of various openings configurations

To better understand the influence of openings configurations on natural ventilation performance of a residential unit, MAA distribution of the best openings configuration (BD-R-N) and that of the worst configuration (BC-L-S), both at 1.1 m level, and with wind coming from east, were compared (Figure 4.8). It can be seen in Figure 4.8 that the high MAA (red) region for configuration BC-L-S is much larger than for configuration BD-R-N, indicating a higher MAA. A review of $\overline{\text{MAA}}$ also indicated that there was a profound difference (358s vs. 53s) between the two configurations.



(a) Worst Configuration (BC-L-S) (b) Best Configuration (BD-R-N)

Figure 4.8 MAA distribution at 1.1m level (y = 1.1m)

4.4.2 Sensitivity analysis

To evaluate the combined effect of different configuration parameters on natural ventilation performance of the hypothetical residential unit, the worst configuration, i.e. BC-L-S was assumed to be the baseline case, and additional simulations were conducted for sensitivity analysis. The sensitivity (S) was quantified by the percent reduction in $\overline{\text{MAA}}$ of various openings configurations (XY-I-J) relative to $\overline{\text{MAA}}$ of the baseline configuration, as shown mathematically in Equation (4.2).

$$S_Z = \frac{\left|\overline{\text{MAA}}_{(Z)} - \overline{\text{MAA}}_{(BC\text{-}L\text{-}S)}\right|}{\overline{\text{MAA}}_{(BC\text{-}L\text{-}S)}} \tag{4.2}$$

Where S_z is sensitivity of configuration Z; $\Delta\overline{\text{MAA}}_{(Z)}$ is the absolute change in MAA of configuration Z; and $\overline{\text{MAA}}_{(BC-L-S)}$ was MAA of the baseline case.

Given $\overline{\text{MAA}}_{(BC-L-S)}$ has the highest value among all configurations, taking $\Delta\overline{\text{MAA}}_{(Z)}$ as an absolute value, S_z becomes positive. Accordingly, a higher S_z indicates $\overline{\text{MAA}}$ is more sensitive to change of the parameter(s).

In additional simulations, instead of just varying one parameter (i.e. XY, I, J), two (XY+I, XY+J, I+J) or three (XY+I+J) parameters were varied, while all other parameters of the baseline configuration were retained. The varied configuration(s) are denoted by Z. The results are summarized in Figure 4.9.

It can be seen in Figure 4.9 that $\overline{\text{MAA}}$ was most sensitive to varying windows positions (i.e. XY), where S_z was 72.5%, followed by building orientation (i.e. J) and door position (i.e. I), with S_z of 37.7% and 7.8%, respectively. Obvious improvements in $\overline{\text{MAA}}$ could be obtained when two parameters (windows positions and building orientation) were varied. Among openings configurations with these two parameters varied, S_z values (in descending order) were XY+I, XY+J and

I+J. This indicates that $\overline{MAA}$ was most sensitive to the changing of XY (i.e. window positions). It is also proved by the small difference between S_z of XY (=72.5%) and XY+I (=73%). Furthermore, it is noted that S_z (= 65.9%) was not particularly high when all the three parameters were varied. The results indicate that there was a counter-effect on $\overline{MAA}$ when orientations and the doors positioning were changed simultaneously. This again pointed to the fact that door position incurred very little influence on the overall natural ventilation performance.

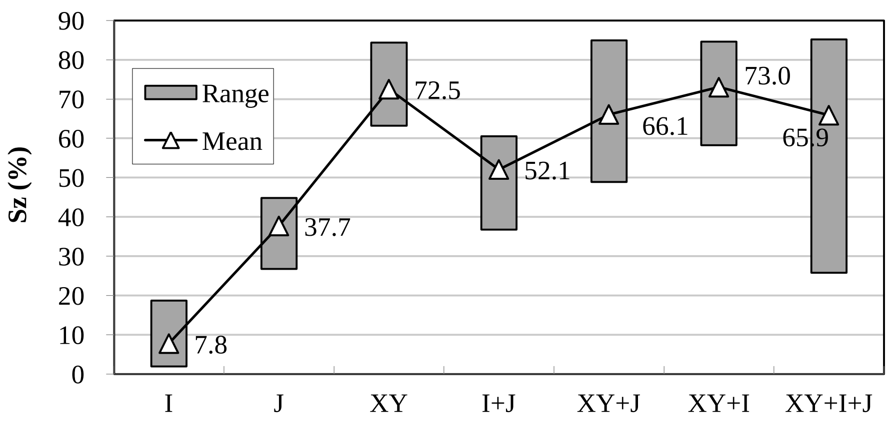


Figure 4.9 Sensitivity of various openings configurations

(Note: I = door position; J = building orientation; and XY = window position)

4.5 Conclusions

Field measurements were conducted as part of the study, at a carefully selected unit. The measured data were used for CFD model validation and settings of the boundary conditions. CFD simulations using AIRPAK were conducted to evaluate the influence of various openings configuration parameters on natural ventilation performance of a hypothetical residential unit. The hypothetical residential unit was formulated on the basis of an extensive survey of window designs, floor layouts, and floor areas of residential units in Hong Kong, such that it represents characteristics of typical residential units in Hong Kong. Openings configuration consists of many parameters. Cases studies were generated by changing the configuration parameters including eight windows positions, two doors positions, four building orientations, and three wind conditions. It was found that better natural ventilation performance, as represented by the mean age of air (MAA), can be achieved by locating two window groups (bedroom windows and living room windows) in opposite directions or in perpendicular to each other.

Sensitivity analysis revealed that natural ventilation performance was most sensitive to change of window positions, followed by building orientations and door positions. In terms of the combined effect of different parameters, it was found that varying two parameters (windows positions and building orientation) would have a positive influence on natural ventilation performance, but changing all the three input parameters does not yield improvement because of counter effects of changes in doors' positions.

CHAPTER 5 INFLUENCE OF WINDOW TYPES

Extant literature has little to offer on the performance of different window types for ensuring natural ventilation in residential buildings. Accordingly, the study of their influence on natural ventilation performance will be useful for site planners and architects in choosing the appropriate window type for better use of natural ventilation

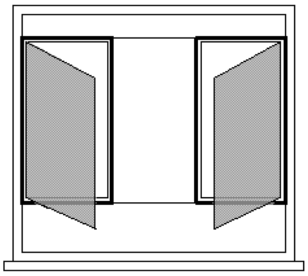
The hypothetical residential unit described in Chapter 4 (Figure 4.3) was again adopted for investigation of the ventilation performance associated with the use of different window types. CFD simulation was conducted based on the validated model.

5.1 Window types

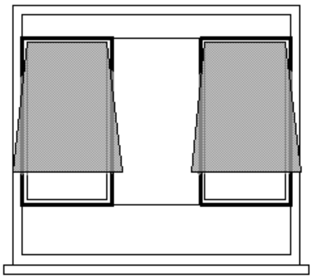
According to the Buildings Department of Hong Kong (Anonymous, 2005c)**,** three types of windows are commonly used in Hong Kong: side hung, top hung and end-slider types, as described in Chapter 2 and shown in Figure 5.1 (a), (b) and (c). Side hung windows are popular because of large operable area, while end-slider type is simple and space saving, and top hung windows are rain proof.

The opening area assumed was 0.6m height and 0.78m width as explained in Chapter 4. Opening angles of side hung and top hung window sashes were assumed 45 degree and 30 degree respectively.

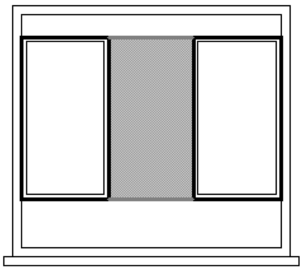
Since end-slider windows depend on the construction, the operable area can be the same or half of the other two types of windows. They are, therefore, further classified as full (Figure 5.1(c)) and half end-slider windows (Figure 5.1 (d)). Thus there are altogether four window types.



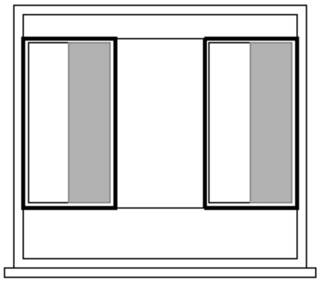
(a) Side hung



(b) Top hung



(c) Full end-slider



(d) Half end-slider

Figure 5.1 Window types

5.2 Openings configurations & orientations

Windows can be located at different positions in the hypothetical unit. According to the study on openings configurations (Chapter 4), configuration BD-R (Figure 4.5 (b)) (i.e. bedroom windows at façade B, living room window at façade D and door on the right) was the best to ensure cross ventilation, while configuration BC-L (Figure 4.5 (c)) (i.e. bedroom windows at façade B, living room windows at façade C and door on the left) with single-sided ventilation was the worst in ventilation performance (Gao, 2011). Thus these two configurations were selected for evaluation of influence of window types on natural ventilation performance.

Keeping the consistency of different parts in this study, four basic orientations were assumed for the hypothetical unit, namely, north (N), east (E), south (S) and west (W). While there are four external façades in the unit, façade A (Figure 4.3) was taken as the principal orientation of the unit.

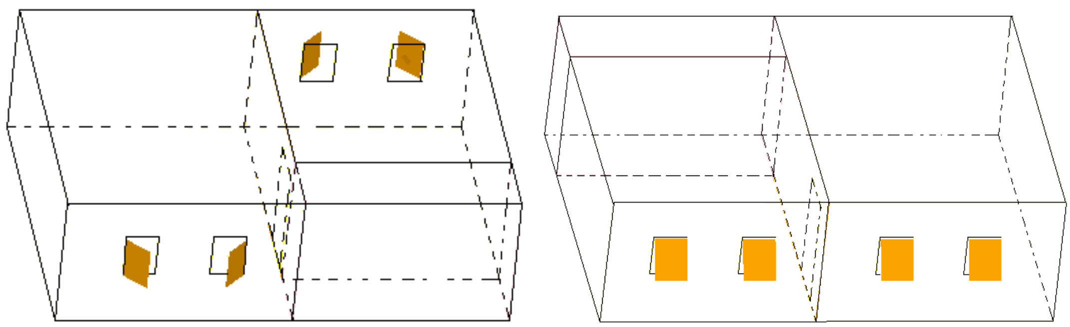
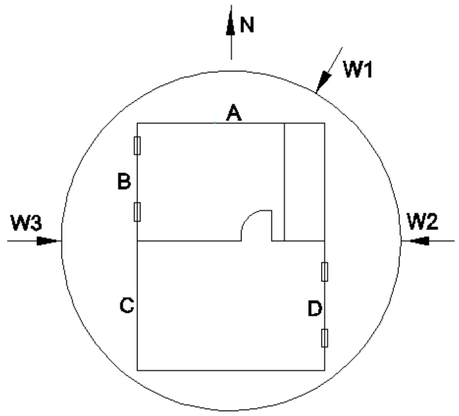


Figure 5.2 Models of configurations BD-R-E and BC-L-W

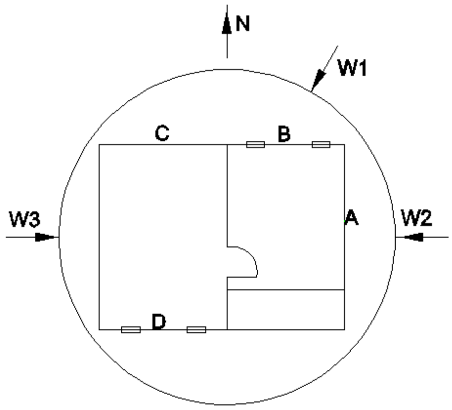
Models were built based on configuration BD-R and BC-L, both with four window types, and two of them are shown in Figure 5.2.

5.3 Prevailing wind conditions

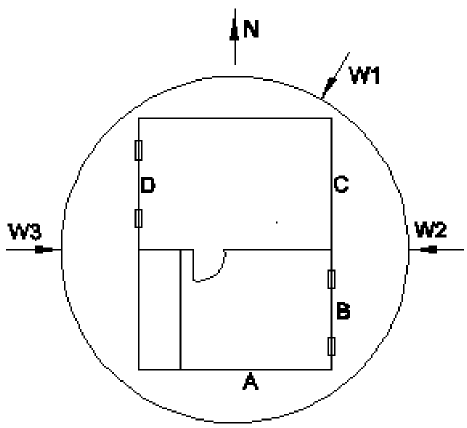
The three wind conditions, derived from the typical weather year of Hong Kong (explained in Chapter 4) were again used as the prevailing wind conditions. Configuration BD-R (best scenario) under four orientations and three wind conditions is illustrated in Figure 5.3 (a) through (d).



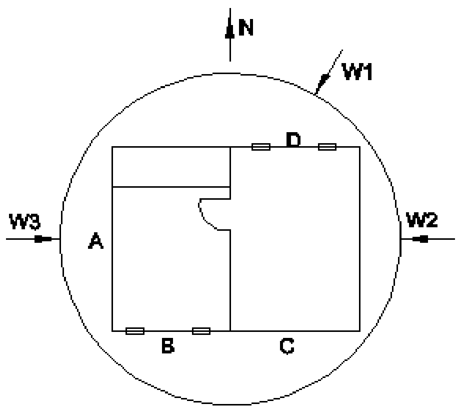
(a) A to North



(b) A to East



(c) A to South



(d) A to West

Figure 5.3 Configuration BD-R under various wind conditions

Using four building orientations, three prevailing wind conditions, two openings configurations and four window types, a total of 96 ($4\times3\times2\times4=96$) combinations were generated for further investigations.

5.4 Results

Indoor airflow distributions of the 96 cases were simulated by the use of AIRPAK. For each case, MAA was computed at four levels, 0.1m, 0.6m, 1.1m and 1.7m at ten different sample points (Figure 4.3) of the hypothetical unit. This is according to ASHRAE's spacing recommendations (ASHRAE, 2005). When summing up the 40 MAA values for each case, it was assumed that the figures were independent, and of equal importance, because they were evenly distributed in the hypothetical unit. It is, therefore, acceptable to use simple arithmetic mean of the figures to derive the average MAA ($\overline{\text{MAA}}$). Given there are altogether 96 cases, influence of each window type (top hung (TH), side hung (SH), full end-slider (ES) and half end-slider (½ES)) on natural ventilation performance of the hypothetical unit was evaluated in terms of weighted average $\overline{\text{MAA}}$ of each window type.

5.4.1 Weighted average MAA

Weighted average MAA for each window type at different orientations were obtained by weighting $\overline{\text{MAA}}$ for the three prevalent wind directions on the basis of frequency of occurrence, as shown in Equation (5.1).

$$\overline{\text{MAA}}_{(i,j)} = \frac{\sum f_n \overline{\text{MAA}}_{(i,j),n}}{\sum f_\text{n}} \qquad (5.1)$$

Where

$\overline{\text{MAA}}_{(i,j)}$ = the weighted average $\overline{\text{MAA}}$ for window type i (TH, SH, ES and ½ES) at orientation j (N, E, S or W) in second;

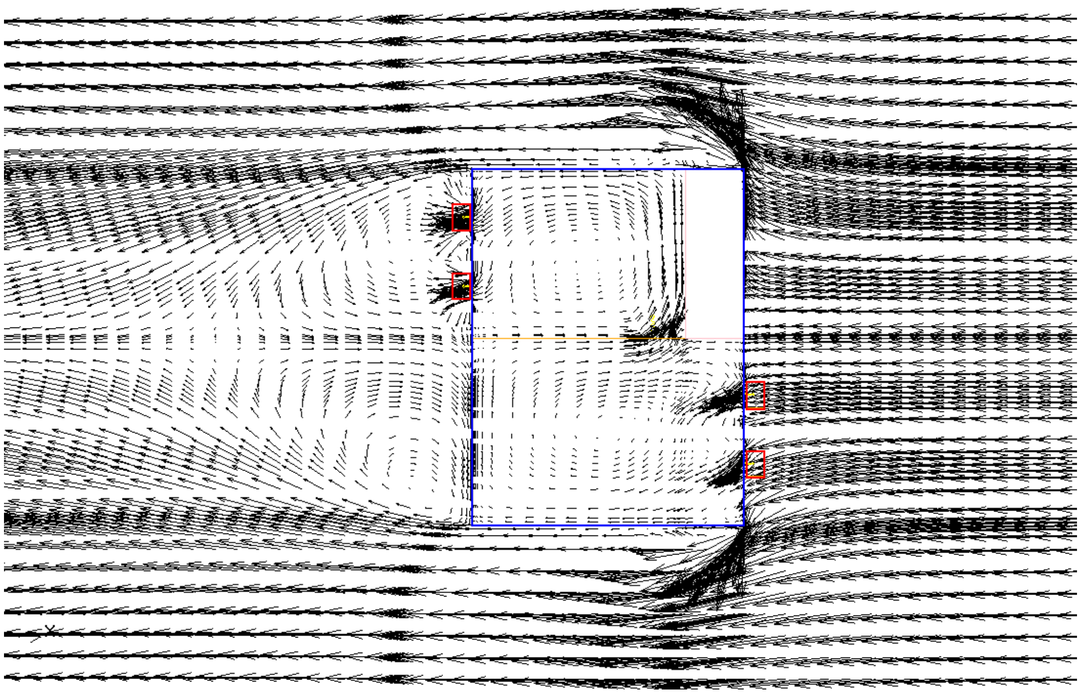
f_n = the frequency of occurrence of wind condition n; and

n = the number of wind conditions (from W1 to 3).

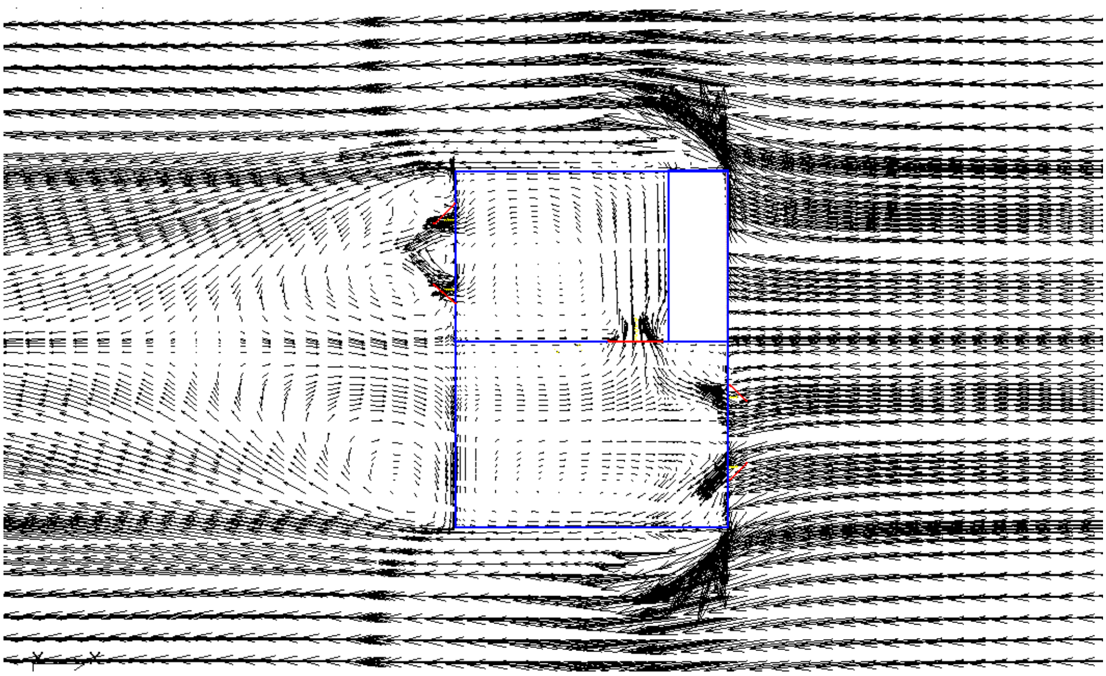
$\overline{\text{MAA}}_{(i,j)}$ for the two openings configurations are separately discussed.

5.4.2 Configuration BD-R (cross ventilation)

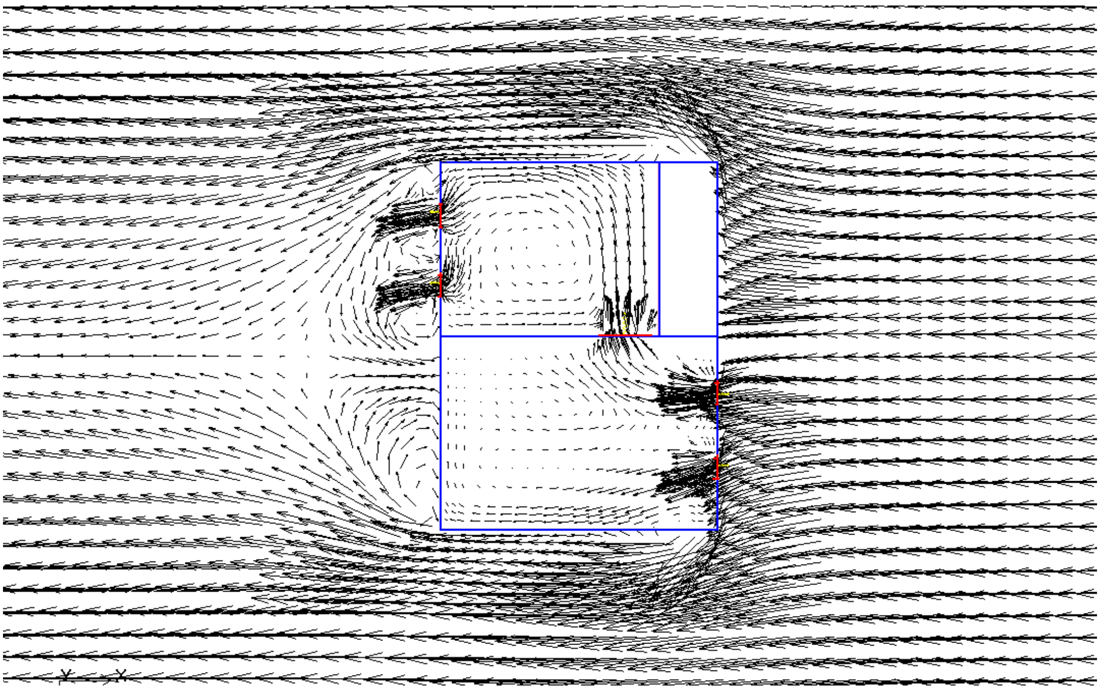
The airflow patterns of configuration BD-R-N by window types, under the strongest wind condition (W2), are shown in Figure 5.4 (a) to (d). It can be seen in Figure 5.4 (b) and (c), that the subtended angle of the entering air to the window and door openings, and the strengths of the corresponding airflow paths, are larger and stronger than that of half end-slider window type (Figure 5.4 (d)) to indicate that better natural ventilation performance can be achieved by full end-slider and side hung window types. In Figure 5.4 (a) (top-hung window), although the passing airflow through the door seems not weak, the entering air subtended a very small angle to the walls to result in higher resistance for entering air to be circulated to the occupied zones.



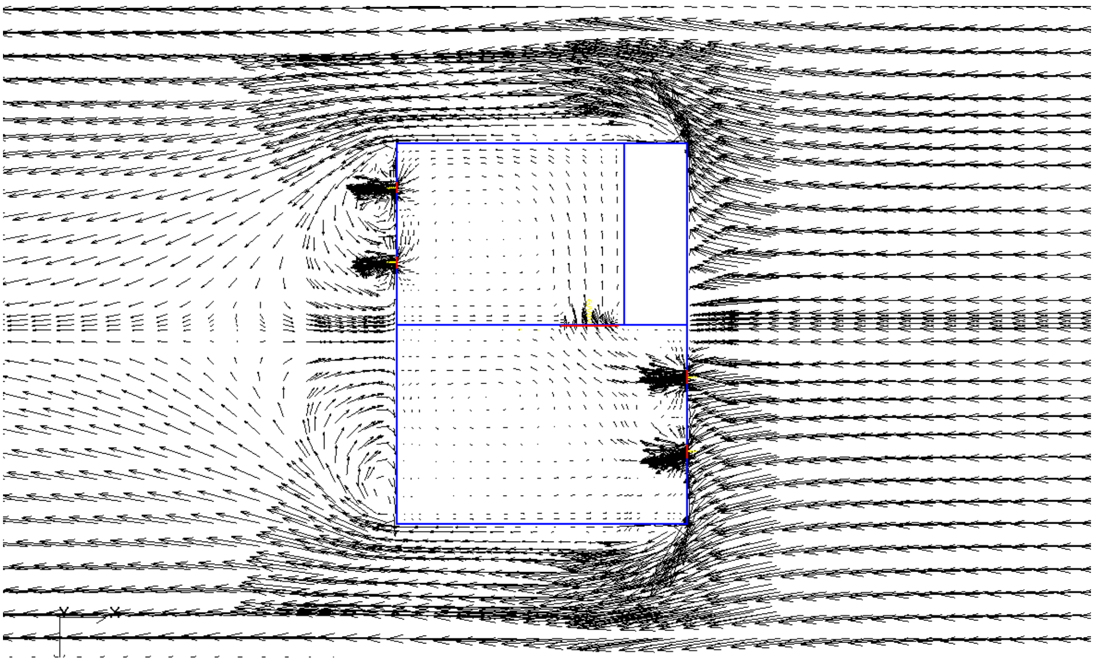
(a) Airflow pattern of top hung window



(b) Airflow pattern of side hung window



(c) Airflow pattern of full end-slider window



(d) Airflow pattern of half end-slider window

Figure 5.4 Airflow patterns associated with four window types

To quantify their natural ventilation performance, $\overline{\text{MAA}}_{(i,j)}$ are shown in Figure 5.5. It can be seen that average (of four orientations) $\overline{\text{MAA}}_{(i,j)}$ values of side hung windows (*i* = SH), half end-slider windows (*i* = ½ES) and top hung windows (*i* = TH) were higher than the full end-slider windows (*i* = ES) by 1.4%, 56.1% and 64.4%, respectively. The results indicate that natural ventilation performance of full end-slider windows and side hung windows are better and comparable. Furthermore, it is noted that when the following conditions are fulfilled, weighted average $\overline{\text{MAA}}$ are smaller (~50 seconds), indicating better natural ventilation performance:

i = SH or ES; and j = N and S

The difference in $\overline{\text{MAA}}$ values associated with the use of different window types can be explained by the impact of window sash on natural ventilation performance of a window opening. Similar to wing walls, window sash can promote or suppress natural ventilation at various wind speeds and wind directions (Mak et al., 2007). Consequently, full end-slider windows which are free from window sashes, and side-hung windows with window sashes to promote natural ventilation, performed better than the other window types to result in smaller indoor $\overline{\text{MAA}}$ values.

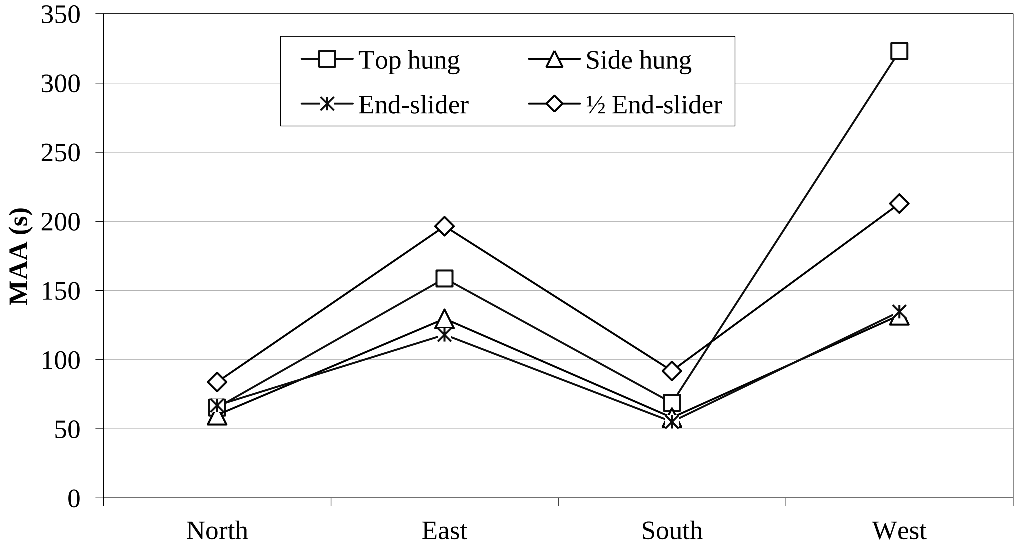


Figure 5.5 $\overline{\text{MAA}}_{i,j}$ of configuration BD-R

Besides the above observations, Figure 5.5 indicates that better natural ventilation performance was obtained when façade A was facing either North or South, for all window types. This can be explained by the differential pressure between the two window groups (bedroom windows and living room windows) under these two orientations (Figure 5.3 (a) and (c)), irrespective of window types. Figure 5.6 shows the pressure distribution under wind condition W2 for the case with the highest overall pressure differential (*i* = SH, *j* = N). It can be seen in Figure 5.6 that between the two window groups, outside pressure of one window group was positive, serving as inlet, while the other was negative, serving as outlet, to ensure cross ventilation.

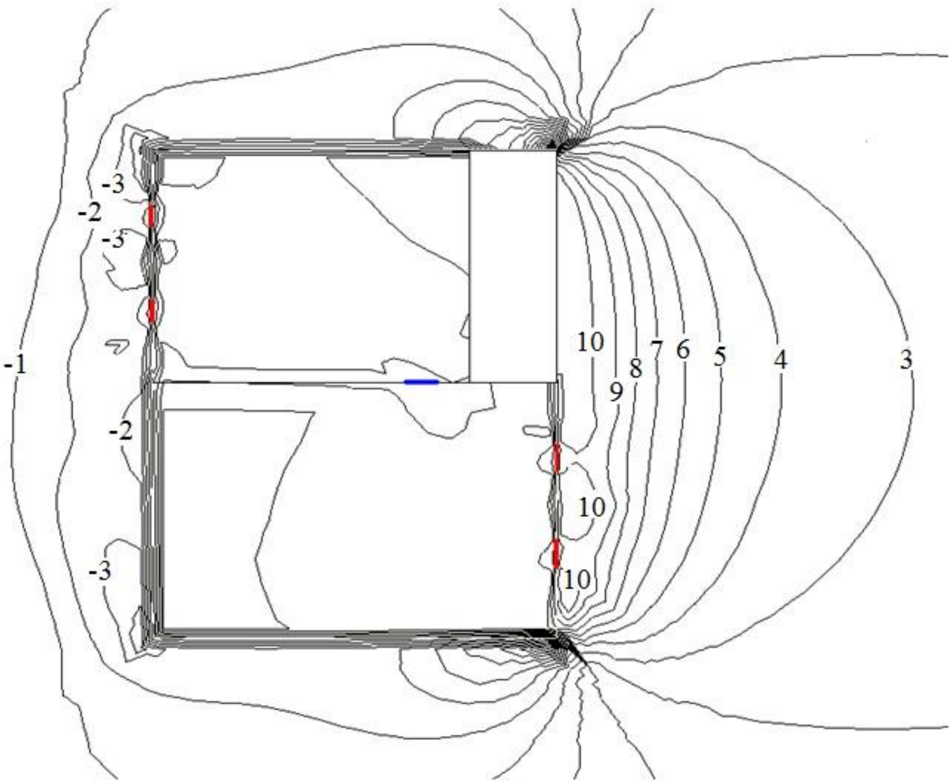


Figure 5.6 Pressure distribution of configuration BD-R (i = ES; j = N)

To further explain the simulation results, maximum differential pressure (ΔP_{max}) between the two window groups under the four orientations are compared in Figure 5.7. It can be seen that ΔP_{max} was higher when façade A was facing North or South. ΔP_{max} was obtained by Equation (5.2):

$$\Delta P_{max} = \overline{P}_{\max} - \overline{P}_{\min} \tag{5.2}$$

Where $\overline{P}_{max}$ and $\overline{P}_{min}$ are the maximum and minimum mean pressure; and $\overline{P}$ is the mean pressure at each of the four window openings.

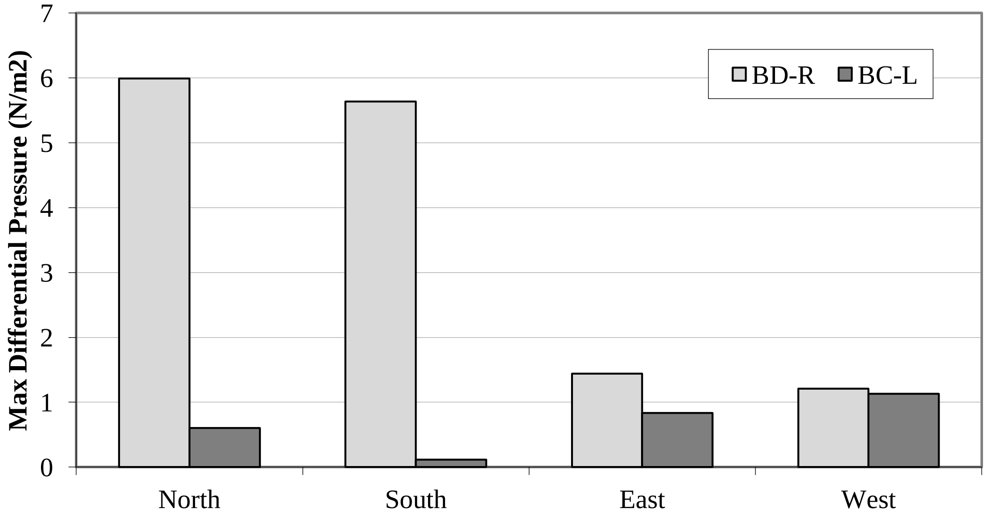


Figure 5.7 $\Delta P_{\max}$ between windows groups for four orientations

5.4.3 Configuration BC-L (single-sided ventilation)

$\overline{\text{MAA}}_{(i,j)}$ values are shown in Figure 5.8. It can be seen that $\overline{\text{MAA}}$ values smaller than 200 seconds were obtained when the hypothetical unit was provided with side hung windows (i = SH) and façade A was facing either East or West.

Besides, better natural ventilation performance was obtained when façade A was facing either East or West, for all window types. This again can be explained by the higher differential pressure (ΔP_{max}) under these two orientations (Figure 5.7). Higher ΔP_{max} under these two orientations was because most of the times wind blows in parallel to the two window groups (similar to Figure 5.3 (b) and (d)), creating a differential pressure. Consequently, one window group serves as air inlets and the other as outlets to complete the ventilation circuit. In contrast, for the other two orientations (North and South), wind was blowing perpendicular to the two window groups. Owing to their symmetrical characteristics, little differential pressure was created, i.e. the ventilation circuit was not formed. This phenomenon was shown to occur in one of the cases (*i*=ES, *j*= S, wind condition = W2) (Figure 5.9). It can be seen that pressure values between the two window groups were nearly the same.

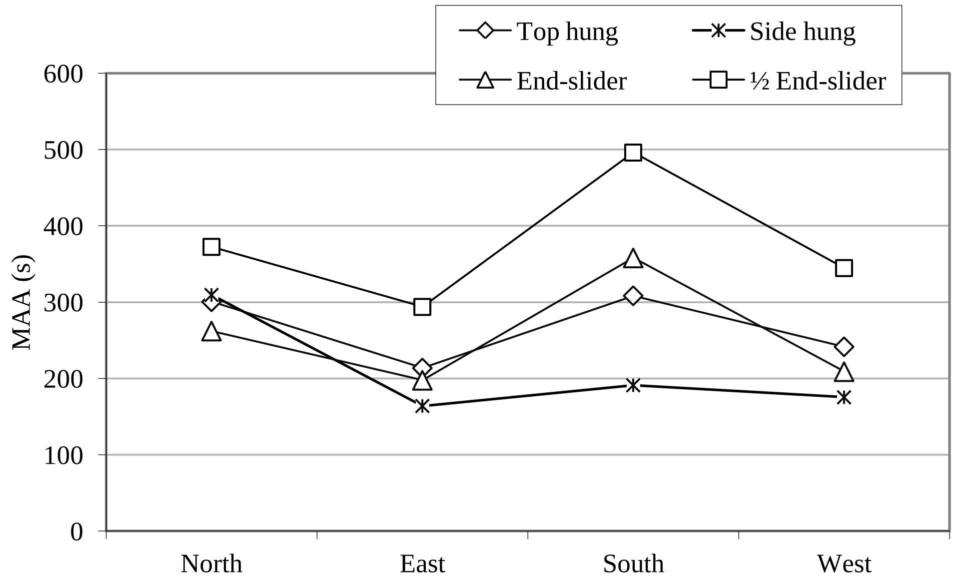


Figure 5.8 $\overline{\text{MAA}}_{i,j}$ of configuration BC-L

Figure 5.8 also shows that $\overline{\text{MAA}}_{(i,j)}$ of side hung windows (*i* = SH) was the smallest (regardless of orientations). Average (of four orientations) $\overline{\text{MAA}}_{(i,j)}$ values of full end-slider windows (ES), top hung windows (*i* = TH), and half end-slider windows (*i* = ½ES), were higher than side hung windows by 22.2%, 26.7% and 79.4%, respectively.

The indoor $\overline{MAA}$ values associated with the use of different window types again revealed that window sash has an impact on the natural ventilation performance of an indoor environment. Under single-sided ventilation where natural ventilation performance is relatively poor (in comparison to cross-ventilation), the influence of window sash becomes more prominent. It functions as a wing wall to help promote natural ventilation. This explains why the ventilation performance of end-slider windows is worse than side hung windows, and is only comparable to top hung windows.

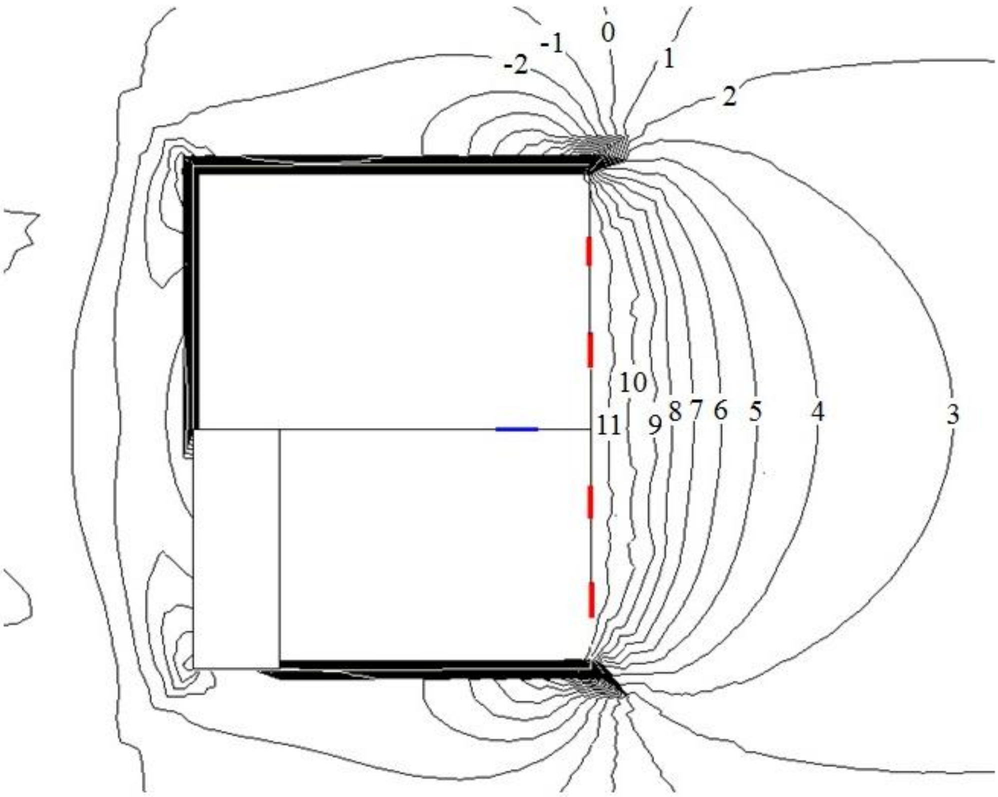


Figure 5.9 Pressure distribution of configuration BC-L (i = ES; j = S)

The above differential pressure analysis indicates that simulation results are reasonable, and combining results of the two openings configurations, it is apparent that side hung window performs better than other window types, followed (in descending order) by full end-slider, top hung and half end-slider windows.

5.5 Conclusions

CFD simulations using AIRPAK were used to evaluate the influence of window types on natural ventilation performance of a hypothetical residential unit under cross and single-sided openings configurations, four building orientations, and three wind conditions. It was found that when dealing with cross configurations, better natural ventilation performance could be achieved by using full end-slider and side hung windows; MAA values of these two window types were comparable (1.4% difference). For single-sided configurations, $\overline{\text{MAA}}$ values of the other window types were 22.2% to 79.4% higher than side hung windows, indicating that side hung windows were a better option. The results lead to the conclusion that side hung window is preferred for enhancing natural ventilation performance of residential units in subtropical climates, followed (in descending order) by full end-slider, top hung and half end-slider windows.

CHAPTER 6 INFLUENCE OF SURROUNDING BUILDINGS

Tightly packed high-rise buildings form obstructions to natural ventilation. They affect the wind availability among buildings, the diffusion of pollutant, as well as the thermal comfort in pedestrian areas (Stathopoulos, 1995). Considering their complex influence, in Chapters 4 and 5, the surrounding buildings influence was ignored in the investigations of influences of openings configurations and window types on natural ventilation performance. This was achieved by purposely selecting a residential unit at an isolated location for field measurements to facilitate the model validation exercise and the subsequent CFD simulations. The objective is to enable easy establishment of exemplary cases for further analysis.

Further analysis focus on investigating how the surrounding buildings affect the natural ventilation performance of tightly packed high-rise building environment and whether or not the conclusions drawn in Chapters 4 and 5 are still valid. A representative residential estate was identified to facilitate subsequent investigations and evaluations.

6.1 Typical residential estate

In Hong Kong, there are two major residential building developers: the

Government and the private developers. Building developments are correspondingly known as public and private housing. According to the statistics released by the Census and Statistics Department of Hong Kong in 2006 (CSD, 2006), more than 48% of the Hong Kong people lived in public housing estates, where site layouts and building plans are relatively standard. Over 55% of the building blocks are of corners recessed shape (Table 6.1). The building plans adopt New Harmony 1 (Figure 6.1) (CSD, 2006) or new cruciform, Figure 6. 2 (PD, 2008), design. They are well known for the high efficiency in land use and feasible in floor layout design. The wings of the new cruciform blocks are even more flexible in accommodating combinations of residential units with different dimensions (Anonymous), while for site layouts, the building blocks (sometimes building groups) are obviously dispersed arranged (Table 6.1).

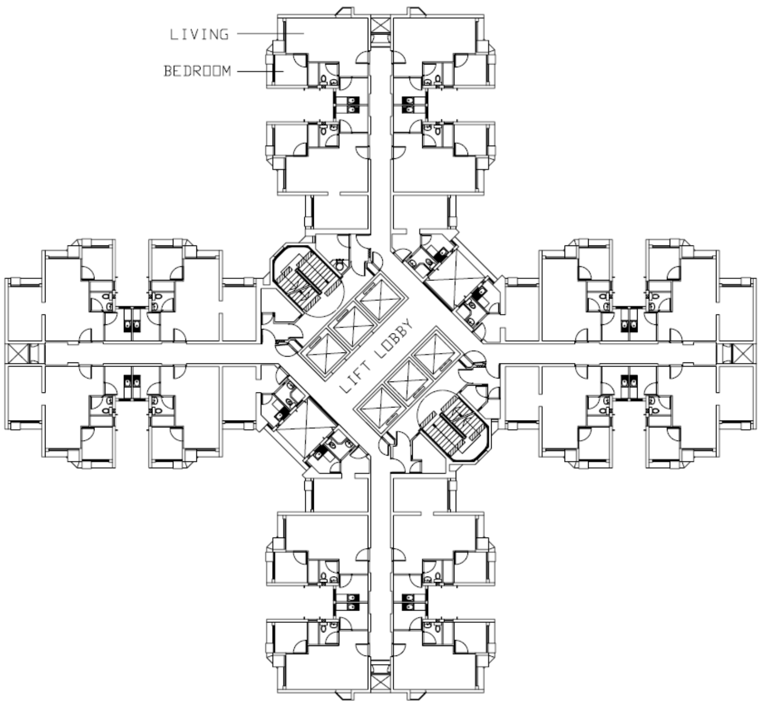


Figure 6.1 Building plan of a New Harmony One block

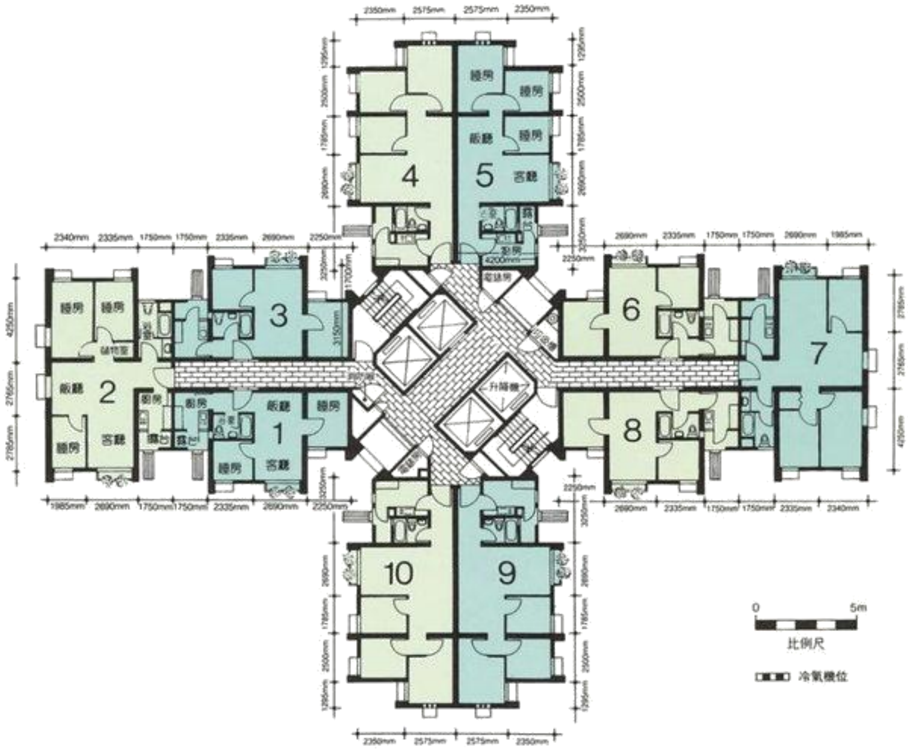
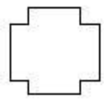
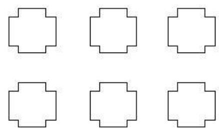
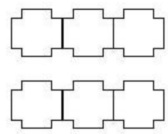


Figure 6. 2 Building plan of a new cruciform block

One of the top 10 housing estates, City One, located at Shatin Hong Kong, was identified as the representative residential estate for further investigations owing to three key features: i) it consists of 52 blocks which is one of the largest residential estates (Wikipedia), ii) the 52 blocks are of corners recessed shape which is typical for public and private housing estates in Hong Kong, and iii) the building blocks are dispersed arranged (Table 6.1), which again is typical for public and private housing estates in Hong Kong. According to studies, this is the layout pattern that can enhance urban ventilation (Xing, 2008).

Table 6.1 Characteristics of the surveyed developments and the site layouts

Development	Building shape	Site layout	
			
	Corners Recessed	Dispersed Arranged - building blocks are obviously separated positioned	Connected - more than 3 blocks are obviously connected
Harmony 1Design	✓		
Cruciform Design	✓		
Heng Fa Chuen	✓	✓	
Kornhill	✓		✓
South Horizons	✓	✓	
Tai Koo Shing	✓	✓	
Leguna City	✓		✓
Mei Foo Sun Chuen	✓		✓
City One	✓	✓	
Metro City	✓	✓	
Whampoa Garden	✓		✓
Kingswood Villas	✓	✓	

6.2 Local wind conditions

Due to the influence of surrounding buildings, local wind conditions are different from the prevailing wind conditions. To determine the local wind conditions, a 3D model consisting of the 52 blocks of City One was built by AIRPAK as shown in

Figure 6.3 for simulation studies. The simulations are to identify boundary conditions for further studies. Given the flow conditions adjacent to walls are not of interest and the building blocks are of recessed corners shape, to avoid generating too many tiny meshes to overload the computing processes, the building blocks were simplified as rectangular blocks in the modelings. This practice is in fact widely used in similar investigations (Stathopoulos, 1995; Stathopoulos, 2006; Hang, 2009a). The calculation domain was set as 1000 m length (L), 300 m height (H), and 1000 m width (W) which is around three times the dimensions of the whole building development. The dimensions were set by reference to the optimal domain dimensions determined based on a balance of computing capacity and accuracy of results as reported in Chapter 3.

The renormalization group (RNG) $k-\varepsilon$ turbulence model was used to simulate the steady state natural ventilation. The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) pressure-velocity coupling algorithm was used to discretize the controlling equations in AIRPAK. The solution was considered converged when residual flow were less than or equal to their specified convergence criteria 10^{-3}.

Wind speed increases with height and is lower towards the ground due to frictional drag. Wind power law Equation (3.23) was again used to calculate the inflow velocity profile. But α was taken as 0.5 for the city center and high rise buildings environment (PD, 2005a).

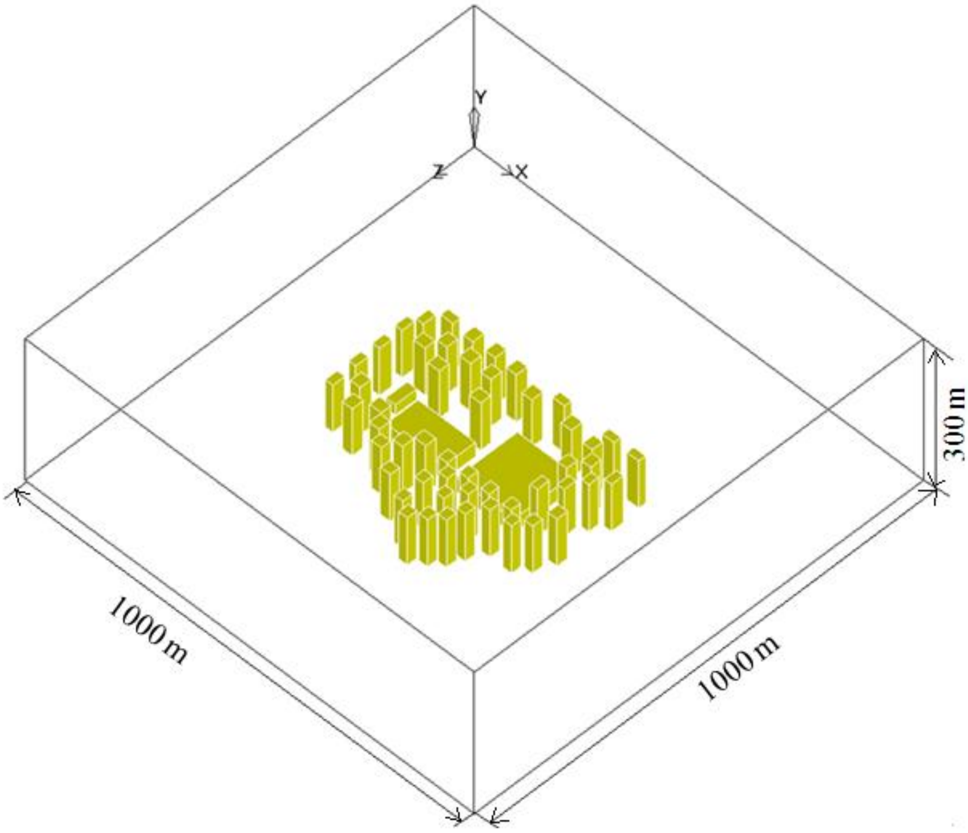


Figure 6.3 Model of City One

The three prevailing wind conditions obtained from the typical weather year of Hong Kong were again used in the simulations (i.e. W1, W2 and W3 in Chapter 4). Because the geometrical orientations of the building blocks in City One are not parallel to the city axis, the wind directions relative to the buildings were adjusted accordingly (Figure 6.4). It can be seen in Figure 6.4 that wind directions of W1 (30^o, 2.42m/s), W2 (90^o, 3.7m/s), and W3 (270^o, 1.97m/s) were adjusted to become W1a (346^o, 2.42m/s), W2a (46^o, 3.7m/s), and W3a (226^o, 1.97m/s). The frequency of occurrence is still 13.9%, 57.4%, and 13.8% respectively.

In the simulation of local wind conditions based upon the adjusted prevailing wind conditions, ventilation was taken as isothermal because the wind driven force is predominant and temperature difference between indoor and outdoor environments is small during transition seasons in Hong Kong (as explained in Chapter 4). Accordingly, the energy conservation equation was not checked in the simulations to reduce requirements of computing time and capacity, and to improve the efficiency of solving other equations.

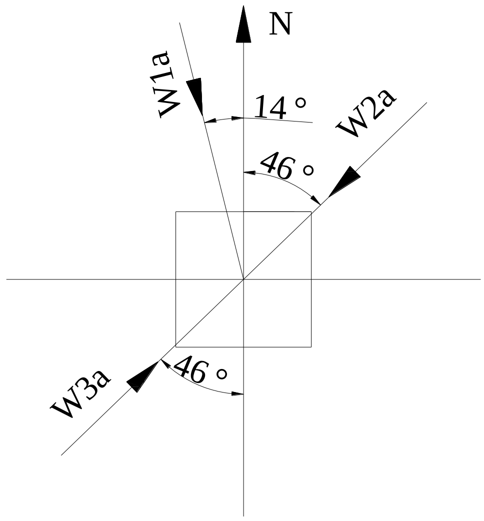


Figure 6.4 Adjusted prevailing wind conditions (the square box represents the building block)

Local wind conditions were taken as wind velocities 5 m away from building blocks of which is half the distance between most buildings. While for vertical level, local wind velocities at 20 m intervals of the buildings were considered, i.e. 10m, 30m, 50m, 70m, and 90m levels. Accordingly, wind velocities on the windward side of the building blocks at the five pre-determined building levels were extracted from the simulation results. Given for each building block there were vast number of velocity values, the bi-variate correlations procedure was used to compute the proximity correlation coefficients (r) of the five velocity value groups (i.e. the velocity values at the five building levels), which helped unveil the similarity among velocity value groups. The results are summarized in Table 6.2. Taking the generally stated significance level of 0.05 as being statistically significant, the absolute value of the proximity correlation (R) of each velocity value group was calculated by Equation (6.1), and results are summarized also in Table 6.2.

$$\overline{R_X^2} = \sum \frac{r^2}{(m-1)} \tag{6.1}$$

Where R is the integral proximity coefficient of one group to all other groups, r is the proximity coefficient of one group, X is the building levels, and m is the number of groups.

Table 6.2 Proximity coefficient (r) matrix

Case	Proximity correlation coefficients (r)					Absolute Proximity Coefficient (R)
	90m	70m	50m	10m	30m	
90m	1.000	0.994	0.984	0.946	0.970	0.948
70m	0.994	1.000	0.995	0.950	0.981	0.961
50m	0.984	0.995	1.000	0.939	0.990	0.955
30m	0.970	0.981	0.990	0.957	1.000	0.898
10m	0.946	0.950	0.939	1.000	0.957	0.950

It can be seen that velocity values at the 70m level group correlate significantly with the other four groups to indicate they are typical among the vast number of velocity values.

The above analysis provides the typical building level for considerations of local wind conditions. However, under each of the three adjusted prevailing wind conditions, depending if a particular building block is in the windward or leeward side, the local wind conditions can differ significantly from each other. As a result, each building block will have a different set of local wind conditions, and thus there will be 52 sets for City One. To enable formulation of representative local wind conditions, K-means cluster analysis was conducted to group building blocks into leeward and windward side under each adjusted prevailing wind condition. Cluster analysis results are shown in Table 6.3. Velocity distributions of the two cluster groups under the three prevailing wind conditions are shown in Figure 6.5, Figure 6.6, and Figure 6.7. It can be seen that the local wind speeds, as compared to the prevailing wind speeds, were reduced by 2.5% to 86.8%. Furthermore, with two cluster groups for each prevailing wind conditions, the local wind conditions of the 52 building blocks can further be classified into eight different wind conditions groups (= $2 \times 2 \times 2$). The frequency of occurrence of the 52 blocks in each of the wind conditions group is summarized in Table 6.2. It can be seen that there are actually seven wind conditions groups, and the first three local wind groups (A1B1C1, A1B2C1, and A1B1C2) are most probable wind conditions which exceed 69.2% (= 26.9%+25%+17.3%) in a year.

Table 6.3 The original wind conditions and the clustering results

Description		W1a		W2a		W3a	
Adjusted prevailing wind conditions	speed	2.42m/s		3.7m/s		1.97m/s	
	direction	346°		46°		226°	
Cluster Group		A1	A2	B1	B2	C1	C2
Local wind conditions	speed	1.14m/s (-52.8%)	2.36m/s (-2.5%)	1.98m/s (-46.5%)	0.85m/s (-77.0%)	0.76m/s (-60.0%)	0.25m/s (-86.8%)
	direction	11.8°	-49.0°	64.3°	-22.2°	-94.5°	121.4°

Table 6.4 Frequency of occurrence of eight local wind condition groups

Wind condition group	A1B1C1	A1B2C1	A1B1C2	A2B2C1	A2B1C1	A2B1C2	A1B2C2	A2B2C2
Frequency of occurrence	26.9%	25%	17.3%	15.4%	5.8%	5.8%	3.8%	0

To investigate how the surrounding buildings affect the ventilation performance of a studied building, the hypothetical representative residential unit was again employed and was assumed located to receive wind from different wind condition groups for the evaluation and investigation of the influences of openings configurations and window types on natural ventilation performance.

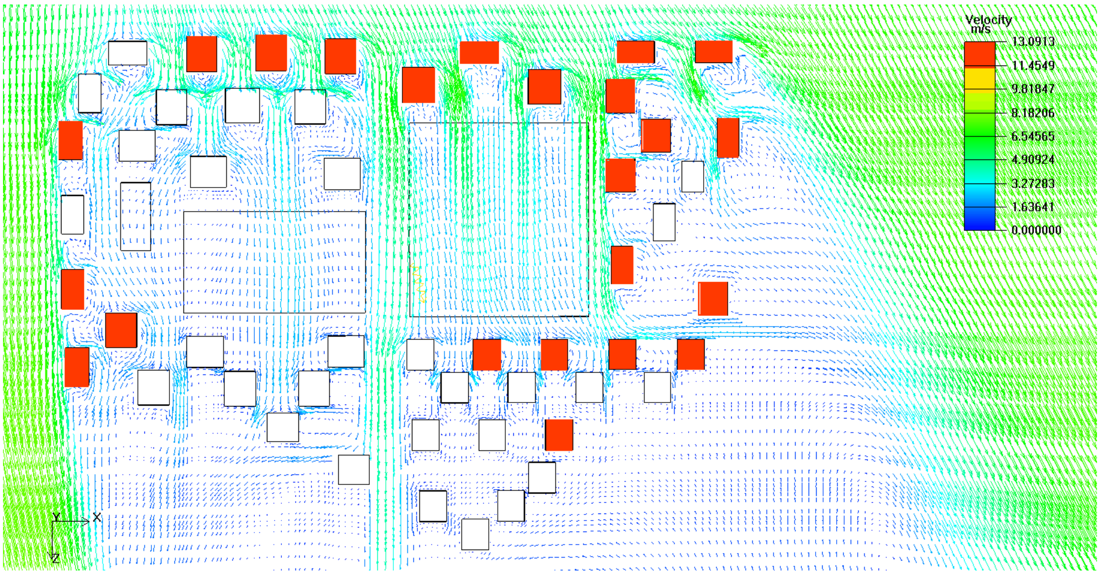


Figure 6.5 Velocity distribution at 70m under wind condition W1a with A2 highlighted

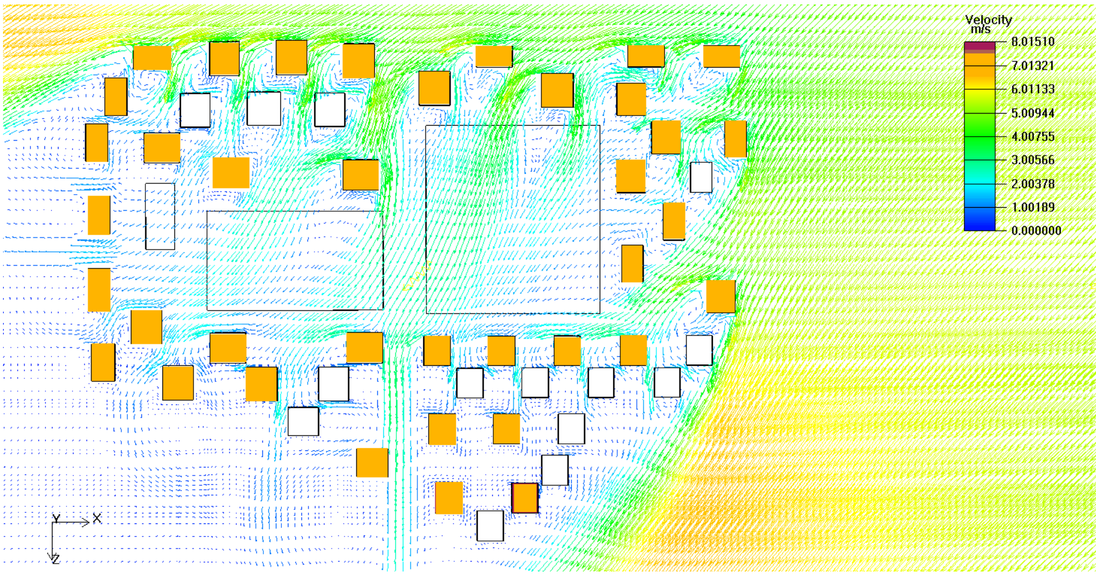


Figure 6.6 Velocity distribution at 70m under wind condition W2a with B1 highlighted

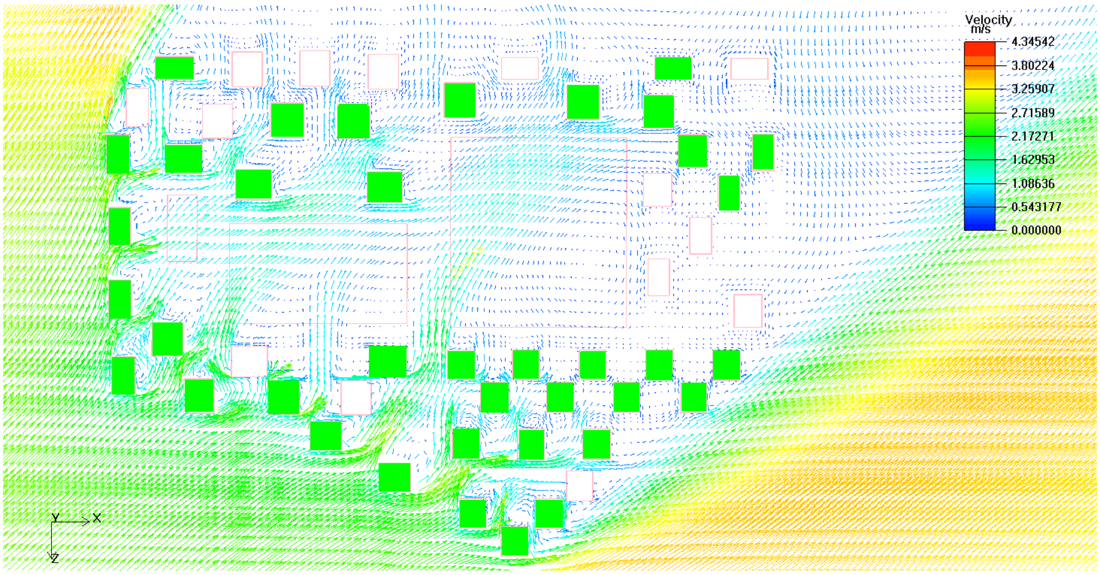


Figure 6.7 Velocity distribution at 70m under wind condition W3a with C1 highlighted

6.3 Influence of configuration parameters

To take into account the influence of surrounding buildings, MAA values of the hypothetical residential unit with four building orientations, three prevailing wind conditions, and eight openings configurations were again simulated, and $\overline{\text{MAA}}$, determined according to Equation (4.1) were computed for evaluations. In the simulations, the same models as those reported in Chapter 4 were used, but the local wind conditions were taken as boundary conditions. The three most probable wind conditions groups which exceed 69.2% of all possible conditions were taken as local wind conditions for modeling.

Accordingly, 288 (4×3×8×3) cases were generated for simulations. The

$\overline{\text{MAA}}$ associated with the use of different openings configurations and the sensitivity of $\overline{\text{MAA}}$ to change of each configuration parameters (i.e. window positions, building orientations and doors position) are compared in Figure 6.8 and Figure 6.9. The results obtained previously in Chapter 4 ((i.e. Figure 4.7)**,** influence of surrounding buildings ignored), named as the original case, are also shown in the figures for easy comparison. Note that the term “original case” with the definition explained above will be used in this Chapter.

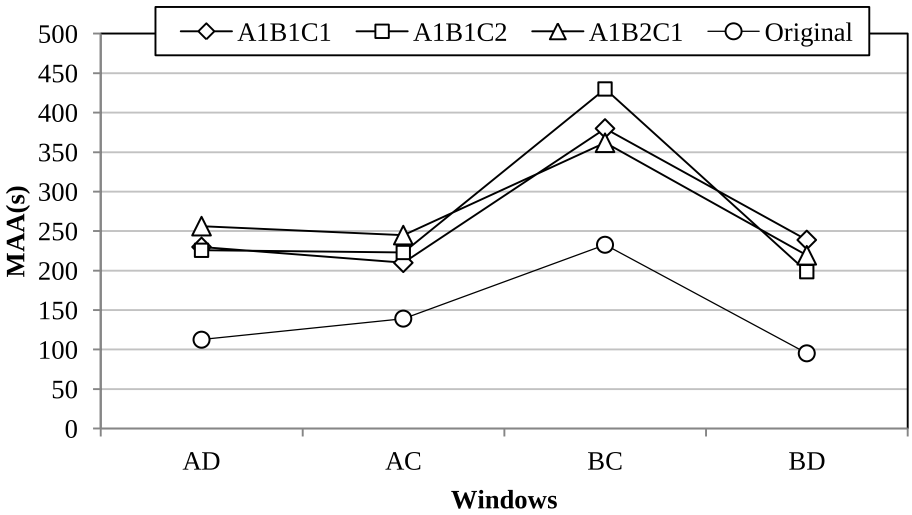


Figure 6.8 MAA of the various windows positions under local wind conditions

It can be seen in Figure 6.8 that the order of natural ventilation performance of the hypothetical residential unit, represented by $\overline{\text{MAA}}$, by windows positions under different wind conditions are consistent. The performance, in descending order is: BD, AC or AD, and BC.

It is worth to note that with the surrounding buildings' influence taking into account, $\overline{MAA}$s of the hypothetical residential were 0.6 to 1.6 times higher than the original case, indicating the indoor ventilation performance was weakened by the surrounding buildings.

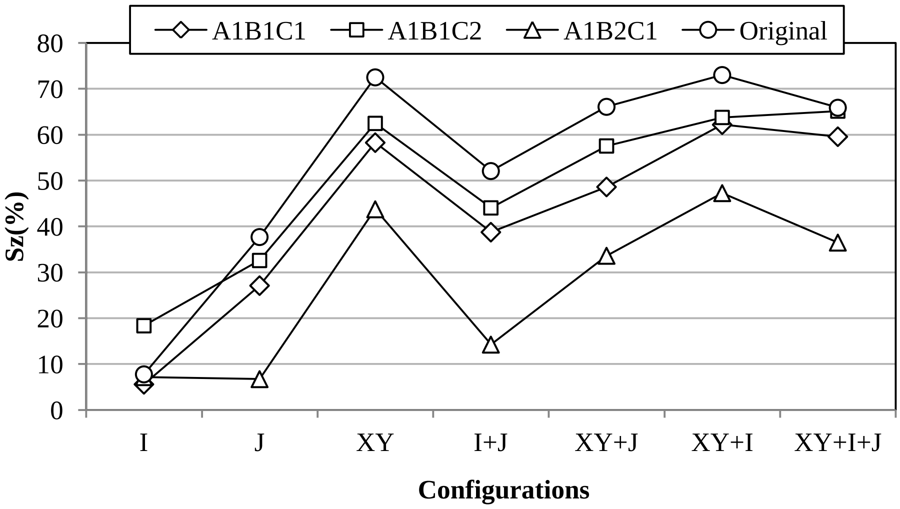


Figure 6.9 Sensitivity of various configurations parameters under local wind conditions (Note:I = door position; J = building orientation; and XY = window position)

The sensitivity of $\overline{MAA}$ to change of configurations parameters, together with the original case, are summarized in Figure 6.9. It can be seen that results for all local wind conditions were consistent with that of the original case. Figure 6.9 also showed that MAA was most sensitive to change of window position (XY), and was the least sensitive to the change of door position. In terms of the combined effect of different parameters, it was found that varying any two or three parameters, I+J, XY+J, XY+I or XY+I+J, would have a positive influence on natural ventilation performance, but changing all the three input parameters does not always yield much more improvement than changing one or two, because some changes may have counter effect to each other.

6.4 Influence of window types

To be consistent with the studies in Chapter 5, in investigating the influence of surrounding buildings on the hypothetical residential unit with different window types, the best (BD-R) and the worst (BC-L) configurations were considered. The four window types were again studied. They were top hung, side hung, full end-slider, and half end-slider windows (Figure 5.1). Similar models (Figure 5.2) were built for simulation studies.

The wind conditions groups, A1B1C1, A1B2C1, and A1B1C2 were used as boundary conditions. Accordingly, 288 cases were generated, which include two configurations, four buildings orientations, four window types, and three local wind conditions groups.

MAA values of the hypothetical residential unit for the 288 cases were determined by simulations. $\overline{\text{MAA}}$ for different window types under different local wind conditions were calculated according to Equation (5.1) (Chapter 5.4). The results, together with the original case, are compared in Figure 6.10 and Figure 6.11.

Figure 6.10 showed that the order of natural ventilation performance (represented by $\overline{\text{MAA}}$) of configuration BD-R by window types under different wind conditions (including the original case) were consistent. The smallest $\overline{\text{MAA}}$ was achieved by the use of side hung window, followed by the full end slider window. Calculation results revealed that $\overline{\text{MAA}}$s of other window types were 21.2% to 57.2% larger than that of the side hung windows.

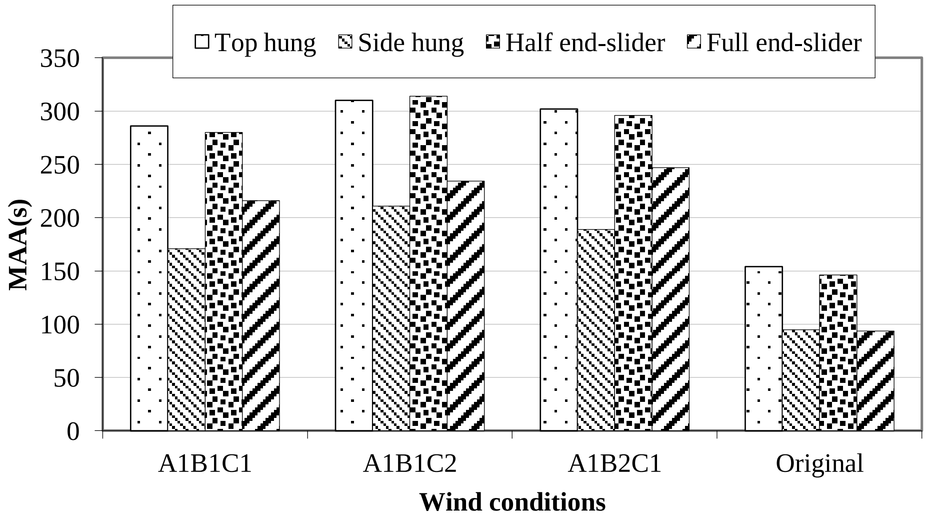


Figure 6.10 $\overline{\text{MAA}}$ of configuration BD-R under local wind conditions

Similar to Figure 6.10, Figure 6.11 showed that the order of natural ventilation performance (represented by $\overline{\text{MAA}}$) of configuration BC-L. Again, consistent result by window types under different wind conditions (including the original case) was obtained. It can be seen in Figure 6.11 that better natural ventilation performance was obtained by side hung window, followed by full end-slider, top hung and half end-slider. $\overline{MAAs}$ of others was 32.3% to 79.7% larger than that of the side hung window.

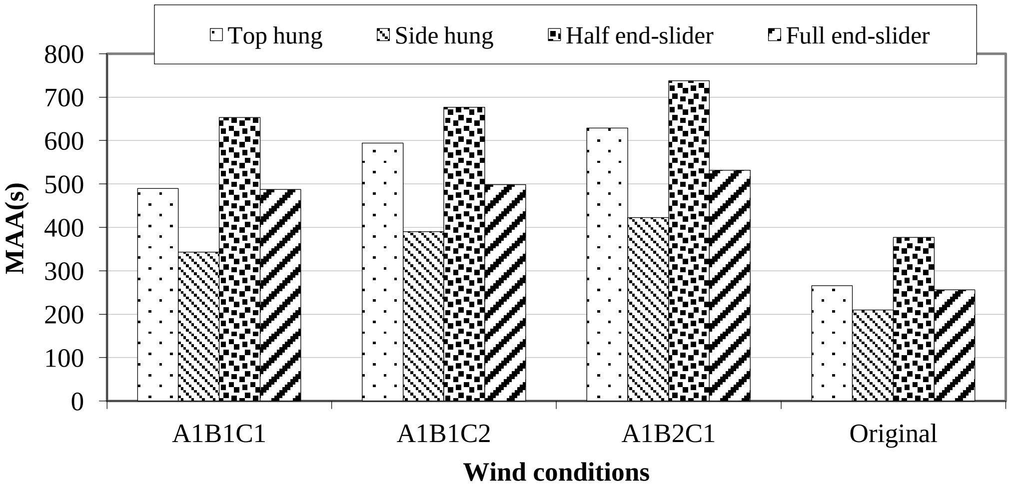


Figure 6.11 $\overline{MAA}$ of configuration BC-L under local wind conditions

It is evident from the above analysis that consistent results were obtained for cases with and without taking into account the influence of surrounding buildings. The results revealed that surrounding buildings did not introduce any impact on the conclusions drawn in Chapters 4 and 5 on openings configurations, and window types.

6.5 Conclusions

The influence of surrounding buildings on the conclusions drawn in Chapters 4 and 5 about openings configurations and window types were evaluated in this Chapter. The evaluations started with identifying a residential estate to represent typical characteristics of surrounding environments in Hong Kong. Based on the representative residential estate and the prevailing wind conditions, wind conditions around buildings at different levels were determined by simulations. With the use of bi-variation correlation and cluster analyses, the vast number of wind data set was evaluated for establishing the representative local wind conditions. The representative local wind conditions were used as boundary conditions for further simulations. CFD models and simulations were similar to what have been done in Chapters 4 and 5, but the analyses were focused on how the surrounding buildings influenced the natural ventilation performance of the hypothetical units with the use of different openings configurations and window types.

The results showed that the surrounding buildings did reduce the available wind around buildings and affect the natural ventilation performance of the studied unit. However, surrounding buildings did not introduce any impact on the conclusions drawn in Chapters 4 and 5. This can be explained by the fact the prevailing wind conditions from different directions and of various speeds were considered in coming up a conclusive result. In other words, conclusions drawn on the influence of openings configurations and window types are valid in real urban environment.

The priority order for openings configurations for better ventilation performance was still, BD, AC or AD, and BC, while the performance was most sensitive to window opening positions. As for the window type, the priority order was still side hung, full end-slider, and top hung or half end-slider.

CHAPTER 7 SUMMARY AND CONCLUSIONS

A review of relevant literatures showed that a lot of studies have been done on natural ventilation of residential premises. However, the interactive effects of outdoor and indoor environments and the multi-room characteristics of residential units were not adequately considered. The review concluded that studies on the influences of these factors on natural ventilation performance of dwellings are needed.

This study investigated the interactive effects of outdoor and indoor environment on natural ventilation performance of residential buildings in Hong Kong. For indoor environment, emphasizes were on openings configurations and window types, while for outdoor environment, the influence of building orientations, prevailing wind conditions, and surrounding buildings were investigated.

Field measurements at a carefully selected residential unit were conducted. CO_2 tracer gas decay method was adopted to obtain the Mean Age of Air (MAA) at sample positions. A portable meteorological station was set-up at an appropriate location to measure the outdoor wind conditions. The measurements results were used for CFD model validations and as boundary conditions for the CFD simulations.

A model validation exercise was performed. Three dimensional (3D) actual size physical models of the study unit and the building where the study unit is located were built by CFD software AIRPAK. A proper calculation domain (5W, 5L, 3H), RNG turbulence model were used in the simulations. The simulated and measured MAA values were compared. It was found that they matched well with each other to confirm that the simulation results were reliable and the settings were appropriate. The validated settings were used in the subsequent simulations.

A multi-room hypothetical residential unit was designed to represent typical characteristics of residential units in Hong Kong. The unit was formulated by analyzing the characteristics of residential buildings in Hong Kong, including the mean floor area, aspect ratio, layout, and openings configurations.

Based on the hypothetical residential unit, simulation studies on the influence of indoor environment were conducted. In the simulations, natural ventilation performance of the hypothetical unit with eight openings configurations and four window types were evaluated. The eight openings configurations were formed by four possible window groups combinations, and two door positions.

For outdoor environment, because of the complex influence of surrounding buildings, the preliminary study focused on three prevailing wind conditions derived from the typical weather year of Hong Kong, and four possible building orientations were considered.

Upon identifying the influences of configurations parameters and window types on natural ventilation performance of residential dwellings, the surrounding buildings' effect was taken into consideration. Further studies were done based upon a typical residential estate – City One. The available wind around building blocks of City One was obtained by simulations. Given wind conditions around buildings differed by locations of building blocks and the building levels in considerations, a large amount of wind conditions data were generated. In obtaining meaningful and representative local wind conditions for subsequent studies, the wind data were evaluated by bi-variate correlation and cluster analyses. It was identified that the typical wind conditions was at 70m level, and the local wind conditions could be further classified into seven local wind condition groups. The most probable wind condition groups (= 69.2%) in a year were used as boundary conditions to assess the impact of surrounding buildings on the conclusions drawn in the earlier part of the study.

The main findings of this study are summarized in the following paragraphs.

Among the eight openings configurations, it was found that better natural ventilation performance could be achieved by locating two window groups (bedroom windows and living room windows) in opposite directions or in perpendicular to each other. As to the sensitivity of natural ventilation performance to change of the configurations parameters, window positions (combinations) was the most significant, followed by building orientation and door positions. In considering the combined influence of the studied parameters, it was found that varying one or two parameters would have a positive influence on natural ventilation performance, but changing all the three configuration parameters did not yield much improvement.

The study on the influence of window types indicated that when dealing with cross configurations, better natural ventilation performance could be achieved by using full end-slider and side hung windows; while for single-sided configurations, side hung windows were a better option. It was concluded that side hung windows were a better option for all openings configurations.

When taking into account the impact of surrounding buildings, the wind speed around buildings, in comparison to the prevailing wind speeds, were lowered by 2.5% to 86.8%, and the wind directions were also changed. Due to a lower wind speed, the mean age of air (MAA) of the hypothetical residential unit was found increased by 0.6 to 1.6 times for various openings configurations, and was increased by 0.2 to 0.8 times for various window types. However, the order of influence of different openings configurations and window types remained unchanged.

In this study, the extent of influence of different openings configurations and window types on natural ventilation performance of residential dwellings under varying outdoor and surrounding buildings conditions was concluded. The results will be useful to enhance effective use of natural ventilation in and around high-rise residential buildings in Hong Kong.

However, the results of this study, concluded based on the use of the hypothetical residential unit with rectangular floor layout, is restricted in applications to buildings with similar characteristics. As a result, the conclusions drawn may be not applicable to buildings with irregular floor layouts, such as hexagon, triangular or other shapes that differ greatly to the hypothetical unit. Moreover, the conclusions drawn in this study may be not applicable to other countries or regions that have significantly different climate conditions with Hong Kong.

As some conditions set in this study are restrictive including the window sizes, window types and window opening angles, further study to evaluate their influence on the natural ventilation performance is needed. Given care should be given to thermal comfort in utilizing natural ventilation which is not covered in this study, further works to help enhance natural ventilation performance without sacrificing thermal comfort is recommended. Furthermore, while the influence of the different window types, openings configurations and surrounding building conditions on natural ventilation performance were ascertained in this study, their relative influence are yet to be investigated.

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