Natural ventilation and energy efficiency of a building envelope in tropical climate

Wu, Xiaoying

2014

Wu, X. (2014). Natural ventilation and energy efficiency of a building envelope in tropical climate. Master's thesis, Nanyang Technological University, Singapore.

<https://hdl.handle.net/10356/61655>

<https://doi.org/10.32657/10356/61655>

NANYANG TECHNOLOGICAL UNIVERSITY

School of Mechanical and Aerospace Engineering

**Natural Ventilation and Energy
Efficiency of a Building Envelope in
Tropical Climate**

WU XIAOYING

(B.Eng, Nanyang Technological University)

A Thesis Submitted to Nanyang Technological University
In Fulfillment of the Requirements for the Degree of
Master of Engineering

2013

ACKNOWLEDGEMENTS

I would like to express my greatest appreciation to my supervisor, Assoc. Prof. Li Hua for his immense guidance, training and support throughout the long journey of this project. I am also extremely grateful for the incredible amount of patience he had with me, and for the untiring help during my difficult moments. He has imparted in me the skill of problem solving, article writing, creative expression and perseverance which led to the fruition of this scientific work. This project has been a most enriching experience for me in research, thanks to Assoc. Prof. Li Hua.

I am deeply grateful to ERI@N for providing the research scholarship throughout my Master candidature. Without the strong support of my colleagues in ERI@N, including Prof. Subodh, Mr. Nilesh, Mr. Koh Leong Hai, Ms. Zhou Jian, Dr. Chien Szu-Cheng, this work could not be possible. Their superb guidance, technical support and services are essential for completion of this study. And my special thanks go to my examiners who have taken their precious time and effort to read through and assess my thesis.

I have the great luck to work with a group of wonderful and delightful colleagues in AIT, especially, Dr. Popovac Mirza. His guidance is really essential to me.

I want to thank Ms. Tong Shanshan for guiding me at the first beginning of my simulation work. We do have spent pleasure time together to study and discuss the CFD simulation. I thank all the people for their valuable suggestions and stimulating discussions.

I have to say, I am very lucky to have my best friend Ms. Yan Lina with me. Without her support and understanding, it will not be a pleasant journey for me.

Finally, I would like to show my deepest gratitude to my mother (Ren Sushuang), father (Wu Jufang), brother (Wu Xiaobin) and my husband (Yang Bin). Without their encouragement and understanding, this work could not be completed successfully.

ABSTRACT

With the development of economy, environmental issues become more critical. Improving building energy efficiency is one of the key solutions to reduce the environmental pollution. Building envelopes as a major component in building design play a very essential role in building energy efficiency. In general, the building envelopes separate the indoor and outdoor, and perform as a protection layer of living space from the extreme harsh environment. Apart from the protection function, the building envelopes should be aesthetic and energy efficient at the same time.

Natural ventilation is a very commonly-used traditional strategy to achieve human comfort and energy saving simultaneously. With the development of technology, currently various building forms can be built in reality. This gives natural ventilation more potential in application. Therefore, the effect of building forms on natural ventilation becomes very important for architects and developers.

In the present thesis, the academic contributions into the research area of building performance in energy efficiency are achieved in the following two aspects.

Modeling and Simulation of Natural Ventilation for Effect of Building Forms

- Regarding the structured building, it is found that common space achieves the poorest natural ventilation over a year, excluding rooftop. This is attributable to the low porosity of building.
- Regarding the porous building, it is concluded that, with the increase of the percentage of void inside the building, common spaces results in higher wind

speed, and the percentage of thermal comfortable area also increases, contrary to structured building.

- Regarding the free-form architecture building, it is observed that the wind velocity profile inside the atrium is highly correlated to the floor level. This is attributed to the stack effect. In addition, the internal airflow speed is almost independent of the external wind.

Modeling and Simulation of Energy Efficiency for Effect of Building Envelope

- In terms of external building envelope, a reduction in cooling load is achieved by increasing either the vertical length L , or by reducing the horizontal distance D between building envelope and wall.
- It is shown that a maximum energy efficiency of 13% is achieved by increasing length L to 50% of the building height H .
- In general, the external envelope tends to make a more significant contribution to improvement of energy efficiency for buildings with windows, compared with windowless building.

TABLE OF CONTENTS

ACKNOWLEDGEMENTS	I
ABSTRACT	III
TABLE OF CONTENTS.....	V
LIST OF FIGURES	IX
LIST OF TABLES	XV
CHAPTER 1 INTRODUCTION	1
1.1 Background	1
1.2 Tropical Climate of Singapore.....	4
1.3 Natural Ventilation.....	7
1.3.1 Definition of Natural Ventilation	7
1.3.2 Classification of Natural Ventilation.....	8
1.4 Building Envelope	11
1.4.1 Definition of Building Envelope	11
1.4.2 Classification of Building Envelope Design	13
1.5 Motivation and Objectives	16
1.6 Organization of Report	20
CHAPTER 2 LITERATURE REVIEW	22
2.1 Energy Efficiency of Building Envelope	22
2.1.1 Envelope Thermal Transfer Value (ETTV)	22
2.1.2 Correlation between Building Design and Energy Efficiency	24
2.1.3 Overhang Shading Devices	26

2.1.4	Louvers Shading Devices	28
2.1.5	Double Skin	29
2.2	Effect of various Building Envelope on Natural Ventilation.....	31
2.2.1	Louvers Shading Devices	31
2.2.2	Double Skin	32
2.3	Thermal Comfort Analysis Models for Naturally Ventilated Spaces	34
CHAPTER 3 NATURAL VENTILATION FOR EFFECT OF BUILDING FORMS		37
3.1	Methodology for Simulation of Natural Ventilation	37
3.1.1	Laminar Flow or Turbulence Flow	38
3.1.2	Turbulence Flow Model	39
3.1.3	Computational Domain	40
3.1.4	Boundary Conditions.....	41
3.1.5	Post Processing.....	41
3.2	Project I: A Structured Research Building CleanTech Two	42
3.2.1	Description of Model.....	44
3.2.2	Boundary Condition	45
3.2.3	Results and Discussion	46
3.2.4	Summary	51
3.3	Project II: A Porous Academic Building North Spine Academic Building.....	53
3.3.1	Description of Model.....	54
3.3.2	Boundary Conditions.....	55
3.3.3	Results and Discussion	56
3.3.4	Summary	62

3.4	Project III: A Free-Form Academic Building Learning Hub.....	62
3.4.1	Description of Model.....	64
3.4.2	Boundary Conditions.....	67
3.4.3	Results and Discussion.....	68
3.4.4	Summary	73
 CHAPTER 4 ENERGY EFFICIENCY FOR EFFECT OF BUILDING		
	ENVELOPE	75
4.1	Methodology for Simulation of Building Energy	75
4.1.1	Geometries of Simulation Models.....	76
4.1.2	Assumption and input of Simulation Model	82
4.1.3	Post Process	89
4.2	Effect of Plane-Plate Envelope	90
4.2.1	Effect of Distance between Building Envelope and Wall on the relationship of Energy Efficiency and Length of Building Envelope	90
4.2.2	Effect of Length of Building Envelope on the relationship of Energy Efficiency and Distance between Building Envelope and Wall.....	94
4.2.3	Effect of Angle θ between Building Envelope and Wall on Energy Efficiency	97
4.2.4	Effect of Location of Window on Energy Efficiency	103
4.2.5	Remarks	106
4.3	Effect of Curved-Shell Envelope	107
4.3.1	Effect of Distance between Building Envelope and Wall on the relationship of Energy Efficiency and Length of Building Envelope	107

4.3.2	Effect of Length of Building Envelope on the relationship of Energy Efficiency and Distance between Building Envelope and Wall.....	110
4.3.3	Remarks.....	112
4.4	Effect of Vertical Green Envelope.....	113
4.4.1	Effect of Mesh Size on Energy Efficiency	113
4.4.2	Effect of Porosity Ratio on Energy Efficiency.....	114
4.4.3	Remarks.....	117
4.5	Effect of Internal Smart Blinds	117
4.5.1	Effect of Smart Blinds on indoor ambient temperature	117
4.5.2	Effect of Smart Blinds on wall temperature of east façade.....	119
4.5.3	Remarks.....	122
CHAPTER 5 CONCLUSION AND FUTURE WORK.....		124
5.1	Conclusion	124
5.2	Future work.....	127
PUBLICATIONS ARISING FROM THE THESIS		129
REFERENCES		130

LIST OF FIGURES

Figure 1.1 Rising trend of global energy consumption in different countries. [3]	2
Figure 1.2 Typical breakdown of energy consumption within a commercial building with the biggest use of electricity by air-conditioning and mechanical-ventilation (ACMV).....	3
Figure 1.3 Sun-path diagram in Singapore, in which the sun traverses directly above the equator in September and off the equator in June and December [7].....	5
Figure 1.4 Direction of prevailing wind in Singapore.	6
Figure 1.5 Cross ventilation through a building.	9
Figure 1.6 Stack ventilation within a building.....	10
Figure 1.7 Building envelope with exterior and interior environment [11].....	12
Figure 1.8 Self-shaded envelope of Concourse in Singapore.	14
Figure 1.9 An example of exterior louvers shading design [12].....	14
Figure 1.10 Overhang design in eave condition [13].....	15
Figure 1.11 Double skin envelope [12].....	16
Figure 1.12 External building envelope adopted in this thesis.	18
Figure 1.13 Basic case adopted in this thesis.....	19
Figure 1.14 Special cases resulted from the general case.	20
Figure 2.1 Relative ranking of influencing parameters on ETTV when WWR varies [15].	25
Figure 2.2 Energy saving efficiency from exterior shading observed from variation in AC electricity usage density in office buildings.....	26
Figure 2.3 Four different configurations of shading devices [22].	29

Figure 2.4 Impact of different insulation on energy savings of a double-skin in a north-south building [24].	30
Figure 2.5 Velocity vectors on a longitudinal-section (a) wind-tunnel experiment (CEDVAL), (b) CFD simulations [34].	34
Figure 3.1 Impression drawing of CTT building. (Source: JCPL).	42
Figure 3.2 Computational domain of CFD simulation for CTT project including existing and future buildings in CleanTech Park within next 20 years.	43
Figure 3.3 CTT building model in CFD simulation by gambit software.	43
Figure 3.4 Diagram of CTT model setup for ventilation simulation.	44
Figure 3.5 Velocity vectors in north wind scenario.	47
Figure 3.6 Velocity vectors in northeast wind scenario.	48
Figure 3.7 Velocity vectors in south wind scenario.	49
Figure 3.8 Site plan of Clean Tech Park.	49
Figure 3.9 Velocity vectors in southeast wind scenario.	50
Figure 3.10 Average wind velocity in a year.	52
Figure 3.11 Impression drawing of NSAB building (Source: ADDP).	53
Figure 3.12 Computational domain of the NSAB model	54
Figure 3.13 Top view of NSAB and neighbor buildings in CFD simulation model.	54
Figure 3.14 Plane view of velocity contour of seven levels within NSAB under north wind scenario.	58
Figure 3.15 Cross section view: (a) cross section line; (b) velocity vector within the small atrium area; (c) velocity contour.	58
Figure 3.16 Plane view of velocity contour of seven levels within NSAB in northeast wind scenario.	59

Figure 3.17 Cross section view: (a) cross section line; (b) velocity vector within the small atrium area; (c) velocity contour.....	59
Figure 3.18 Plane view of velocity contour of seven levels within NSAB in south wind scenario.	60
Figure 3.19 Cross section view: (a) cross section line; (b) velocity vector within the small atrium area; (c) velocity contour.....	60
Figure 3.20 Plane view of velocity contour of seven levels within NSAB in southeast wind scenario.	61
Figure 3.21 Cross section view: (a) cross section line; (b) velocity vector within the small atrium area; (c) velocity contour.....	61
Figure 3.22 Impression drawing of LH building. (Source: NTU)	63
Figure 3.23 Computational domain for LH model	65
Figure 3.24 Cross section view of LH model.	65
Figure 3.25 Top view of LH model in CFD simulation.	66
Figure 3.26 Cross section view (Level 5) of LH building model in which gaps and staircases together with four selected measured points are shown.	66
Figure 3.27 Velocity vectors of 9 floors for north wind scenario.....	69
Figure 3.28 Circulation winds in between the buildings.	70
Figure 3.29 Velocity vectors of 9 floors for northeast wind scenario.	71
Figure 3.30 Velocity vectors of 9 floors for south wind scenario.	72
Figure 3.31 Velocity vectors of 9 floors for southeast wind scenario.	73
Figure 4.1 Geometry of the basic energy simulation model without window.....	76
Figure 4.2 Geometry of basic energy simulation model with window on east wall.....	77
Figure 4.3 Geometric parameters of plane-plate envelope.	77

Figure 4.4 Geometric parameters of curved-shell envelope for the effect on building energy efficiency in the vertical envelope design (a) and the horizontal overhang design (b).	78
Figure 4.5 Geometry of simulation models with vertical green envelope with 50% porosity ratio for building with window (a) and windowless building (b).	80
Figure 4.6 Geometry of simulation models with vertical green envelope which has porosity ratio of 10% (a), 20% (b), 30% (c), 40% (d), 50% (e), 60% (f), 70% (g), 80% (h) and 90% (i).	80
Figure 4.7 Geometry of simulation model with internal smart blind.	81
Figure 4.8 Schedule of lighting system on weekdays.	84
Figure 4.9 Schedule of lighting system on Saturday.	84
Figure 4.10 Schedule of occupancy on weekdays.	85
Figure 4.11 Schedule of occupancy on Saturday.	85
Figure 4.12 Schedule of equipment on weekdays.	86
Figure 4.13 Schedule of equipment on Saturday.	86
Figure 4.14 Effect of distance (D) between building envelope and wall on the relationship of energy efficiency and length (L) of external plane-plate building envelope for building with window.	91
Figure 4.15 Effect of distance (D) between building envelope and wall on the relationship of energy efficiency and length (L) of external plane-plate building envelope for building without window.	93
Figure 4.16 Effect of length (L) of building envelope on the relationship between building cooling load and distance (D) between plane-plate envelope and wall for building with window.	94

Figure 4.17 Effect of length (L) of building envelope on the relationship between building cooling load and distance (D) between plane-plate envelope and wall for building without window.	96
Figure 4.18 Effect of the angle θ between plane-plate envelope and wall on building cooling load for the building with window at $D/H = 0.025$	98
Figure 4.19 Effect of angle θ between plane-plate envelope and wall on building cooling load for building with window at $D/H = 0.125$	99
Figure 4.20 Effect of angle θ between plane-plate envelope and wall on building cooling load for building with window at $D/H = 0.25$	99
Figure 4.21 Effect of angle θ between plane-plate envelope and wall on building cooling load for building with window at $D/H = 0.5$	100
Figure 4.22 Effect of angle θ between plane-plate envelope and wall on building cooling load for building with window at $D/H = 0.75$	100
Figure 4.23 Effect of angle θ between plane-plate envelope and wall on building cooling load for building with window at $D/H = 1$	101
Figure 4.24 Effect of angle θ between plane-plate envelope and wall on building cooling load for windowless building.....	103
Figure 4.25 Bar chart of indoor cooling load with or without window and with envelope on east or west.....	105
Figure 4.26 Effect of distance between Building Envelope and Wall (D) on the relationship of energy efficiency and length of external plane-plate building envelope (L) for building with window and vertical curved-shell envelope.	107

Figure 4.27 Effect of distance between Building Envelope and Wall (D) on the relationship of energy efficiency and length of external plane-plate building envelope (L) for building with window and horizontal curved-shell envelope. .	108
Figure 4.28 Effect of length of building envelope (L) on the relationship between building cooling load and distance between plane-plate envelope and wall (D) for building with window and vertical curved-shell envelope.....	110
Figure 4.29 Effect of distance between building envelope and wall (D) on building cooling load for building with window and horizontal curved-shell envelope. .	111
Figure 4.30 Three simulation models of vertical green envelope with 50% porosity and different mesh size of 1m (a), 0.5m (b), and 0.25m (c).	114
Figure 4.31 Effect of porosity ratio of building envelope on cooling load for building with window.....	115
Figure 4.32 Effect of porosity ratio of building envelope on cooling load for building with window.....	116
Figure 4.33 External solar radiation and indoor ambient temperature at the center point inside the building with smart blind (solid blue), no blind (solid red) and static blind (solid green) on 21 st June.	119
Figure 4.34 External solar radiation and indoor ambient temperature on east façade of the building with smart blind (solid blue), no blind (solid red) and static blind (solid green) on 21 st June.	121

LIST OF TABLES

Table 1.1 Typical Energy Consumption in Major Countries for Office Buildings [5-6]. ..	3
Table 1.2 Mean wind speed and frequency of prevailing winds in Singapore.	7
Table 1.3 Monthly statistics of wind directions in Singapore.	7
Table 2.1 Impact of different design factors on annual cooling load.	24
Table 2.2 Energy saving efficiency from exterior shading observed from variation in AC electricity usage density in office buildings.....	27
Table 3.1 Boundary conditions for CTT model.....	45
Table 3.2 Average wind speed for all the public areas in CTT.	51
Table 3.3 Boundary conditions for CFD simulation of NSAB.....	56
Table 3.4 Area-weighted average wind speed and percentage of thermal comfort inside the common spaces in seven levels for four wind scenarios.	62
Table 3.5 Boundary conditions for Learning Hub natural ventilation simulation.....	67
Table 3.6 Percentage of comfort areas.....	74
Table 4.1 Blind tilt angle and openness factor calculated based on vector of solar incident ray.	82
Table 4.2 Cooling load contribution for energy simulation.....	83
Table 4.3 Solar radiation intensity and outdoor temperature in Singapore on 21 st June [51].	88
Table 4.4 Boundary conditions in CFD simulation.	88
Table 4.5 Material properties used in CFD simulation [12].	89
Table 4.6 Minimum cooling load by varying D/H for building with window and plane- plate envelope.	92

Table 4.7 Minimum cooling load with varying L/H for building with window and plane-plate envelope.	95
Table 4.8 Comparison study of minimum cooling load with θ	102
Table 4.9 Minimum cooling load with varying L/H for building with window and vertical curved-shell envelope.	108
Table 4.10 Minimum cooling load with varying L/H for building with window and horizontal curved-shell envelope.	109
Table 4.11 Minimum cooling load with varying D/H for building with window and vertical curved-shell envelope.	111
Table 4.12 Ambient temperature at the center point inside the building with smart blind or static blind or without blind.....	118
Table 4.13 Average surface temperature on building east façade with smart blind or static blind or without blind.....	120

CHAPTER 1 INTRODUCTION

In this chapter, the importance of building energy performance in recent years is overviewed, followed by the global trend of building energy consumption in different countries. The definition and classification of natural ventilation and building envelope are then introduced correspondingly. Finally, the motivation of this study and organization of this report are outlined.

1.1 Background

With the development of economic, global energy consumption rises as shown in Figure 1.1 , and the environmental issue becomes more and more critical. All the items, such as air pollution, water pollution, land pollution, climate change and global warming, appear in daily life more and more frequently. Generally, most of the environmental crises originate from energy related problems. Without solving the energy issues, there will be no sustainable development.

The building and construction industry is a highly-contaminative, high energy-consuming and high carbon-emissive industry. For example, in United States, 41% of primary energy is consumed by building sectors [1], and in Singapore, buildings consume about 31% of total electricity, and after adding households' consumption the number jumps to 49% of all electricity [2]. The trend of energy consumption in buildings [3] is shown in Figure 1.1, in which, electricity, natural gas and petroleum are the total building expenditures. Energy use in buildings was increased by 61.3%, compared with year 1980. Thus, the building energy efficiency becomes critical nowadays.

Within the typical lifespan of a building, there are two phases: construction and operation. In the construction phase, major energy consumption comes from building materials, transportation and construction. For example, cement is a very common building material. In China, 1 ton of CO₂, 0.74 kg of SO₂ and 130 kg of dust are generated, in order to produce one ton of cement. The production of raw materials, such as steel, cement, flat glass, ceramic, brick and aggregates, consumes over 1.6×10^8 ton of coal per year, about 13% of China's total energy output [4]. In the operation phase, the main energy use is by electricity, which is used for air-conditioning system, lighting system, vertical transportation system, ventilation system, equipment and other miscellaneous, in order to maintain indoor comfort and human life.

Figure 1.1 Rising trend of global energy consumption in different countries. [3]

Figure 1.2 Typical breakdown of energy consumption within a commercial building with the biggest use of electricity by air-conditioning and mechanical-ventilation (ACMV).

Table 1.1 Typical Energy Consumption in Major Countries for Office Buildings [5-6].

Energy end-uses	USA (%)	UK (%)	Spain (%)	Singapore (%)
HVAC	48	55	52	52
Lighting	22	17	33	12
Equipment (appliances)	13	5	10	25
DHW (domestic hot water)	4	10	—	-
Food preparation	1	5	—	-
Refrigeration	3	5	—	-
Others	10	4	5	11

← Highest Consumption

The percentage distribution of energy consumption inside an office building is shown in Figure 1.2 [5]. The office building energy consumptions in four countries is compared as shown in Table 1.1. There are three key energy end uses inside an office building, namely

heating, ventilation and air-conditioning (HVAC) systems, lighting systems and equipment. These end-uses total to about 86% of the total energy consumption. However, the energy consumption by equipment is very user dependent and developers could control this part during the building design. Thus, the two controllable big energy consumers are HVAC and lighting system. HVAC takes around 50% of the total energy consumption, and lighting around 20% of the total energy consumption. Hence, in order to improve building performance, HVAC and lighting systems are the focus parts to reduce energy consumption.

1.2 Tropical Climate of Singapore

Understanding the climate around the building is also very important since the performance of the building is climate dependent. In this report, buildings in Singapore are chosen to be studied.

Singapore lies within the tropical climatic belt, with geographical coordinates 1.37 of north latitude and 103.75 of east longitude. Its tropical climate is characterized by uniform temperature and pressure, high humidity and abundant rainfall. There are no distinct wet or dry seasons. Normally the maximum rainfall occurs in December and April, and the drier months are usually in February and July. The temperature differences in Singapore are not distinct, with the minimum diurnal temperature ranging from 23°C to 26°C and the maximum diurnal temperature from 31°C to 34°C. Similarly, there is no significant variation in pressure. The diurnal relative humidity ranges in the high 90% in the early morning to around 60% in the mid-afternoon. The mean relative humidity value is 84% and it often reaches 100% during prolonged heavy rain.

Besides the factors mentioned above, solar-energy, the major heat gain in natural and artificial ventilated buildings in the tropics, is another important components of the climate. In Singapore, the sun traverses east-west directly above our buildings most of the time, which is shown in Figure 1.3. In summer, the sun is in the north of Singapore, while in winter, the sun is in the south. In this report, 21st June is used to represent the summer time and similarly 21st December is used to represent the winter time. Normally the north and south sides of the building are only exposed to the sun during half of the year, and the east and west sides of the building are exposed to the sun everyday within a year.

Figure 1.3 Sun-path diagram in Singapore, in which the sun traverses directly above the equator in September and off the equator in June and December [7].

Figure 1.4 Direction of prevailing wind in Singapore.

The wind situation is also very important in building energy efficiency, especially for naturally ventilated buildings. In Singapore, there are two main monsoon seasons: north monsoon (from December to early March) and south monsoon (from June to September). Both seasons are separated by two relatively short inter-monsoon periods (late March to May and October to November). The map of Singapore with indicated directions for north and south monsoons was shown in Figure 1.4. During the north monsoon period, the northeast or north winds prevail, with wind speed reaching up to 11 m/s in the months of January and February. Southeast or south winds prevail during the south monsoon period with wind speed reaching up to 6 m/s. The sky is mostly cloudy, with frequent afternoon showers during these times. Light and variable winds occur during the two inter-monsoon periods. The mean wind speed for the prevailing winds in Singapore is shown in Table 1.2 [8]. The monthly statistics of wind direction is shown in Table 1.3 [9].

Table 1.2 Mean wind speed and frequency of prevailing winds in Singapore.

Wind Direction	Mean Speed (m/s)	Frequency
North	2	22.2%
Northeast	2.9	22.2%
South	2.8	27.8%
Southeast	3.2	27.8%

Table 1.3 Monthly statistics of wind directions in Singapore.

Month	Wind Direction
Jan	N/NE
Feb	N/NE
Mar	N/NE
Apr	variable
May	S/SE
Jun	S/SE
Jul	S/SE
Aug	S/SE
Sep	S/SE
Oct	variable
Nov	variable
Dec	N/NE

1.3 Natural Ventilation

1.3.1 Definition of Natural Ventilation

Natural ventilation is the process of supplying and removing air through an indoor space without using mechanical systems. Natural ventilation is important in removing heat, water vapor and CO₂ released by human body, and hence controls indoor thermal comfort.

In relation to the criterion of good energy efficient design and indoor thermal comfort, natural ventilation becomes a very attractive solution to ensure both good indoor air quality and acceptable comfort conditions in many regions. Natural ventilation seems to provide an answer to many complaints about the usage of mechanical ventilation systems, and it can provide a more energy efficient, healthier and more comfortable environment if integrated properly.

However ‘natural’ also means that behavior is random and efficient control of the building is difficult. Furthermore, in many urban environments outdoor air conditions and acoustics may not be acceptable because of air and noise pollution. Natural ventilation in this kind of situation need special design features in order to avoid a direct link between indoor and outdoor environments. In order to be effective, natural ventilation also requires a high degree of permeability within the building. In the case of deep plan design, in which the horizontal distance from one side external wall to the other side external wall is many times greater than the floor to floor height, fresh air delivery or a good mixture of air may not be possible without special design considerations. Physical features such as neighboring building walls, trees and others, which may influence air movement, must be taken into account in natural ventilation design.

1.3.2 Classification of Natural Ventilation

There are two types of natural ventilation in buildings: wind driven ventilation and buoyancy driven ventilation. Wind driven ventilation, or cross ventilation, is formed by pressure difference between inlet and outlet. The inlet is the opening where the wind can blow through and enter the indoor environment, and the outlet is the opening where the

wind can blow through and leave the indoor space. Sometimes the inlet and outlet could be the same opening depending on the building design. Cross ventilation could be further classified into single-sided ventilation and double-sided ventilation. Buoyancy driven ventilation is formed by temperature difference between inlet and outlet. It could be further classified into stack effect, night cooling and thermal mass based on temperature difference mechanisms.

1.3.2.1. Wind Driven Ventilation

The concept of cross ventilation is simple and has to do with pressure difference between the outdoor and indoor environment. When wind hits one side of a building (the windward side), the air speeds up in order to flow around the building to the opposite side of the building (the leeward side). This creates a positive pressure on the windward side and a negative pressure on the leeward side. If windows in a building are open, air is forced to enter from the windward side and leave at the leeward side, which creates a force for air crossing through the building, as shown in Figure 1.5. In order to produce the maximum total airflow through a space, both inlet and outlet openings should be as large as possible, and the inlet opening should be much smaller than the outlet one.

Figure 1.5 Cross ventilation through a building.

1.3.2.2. Buoyancy Driven Ventilation

The concept of the stack effect has to do with temperature differentiation between the indoor and outdoor environment as shown in Figure 1.6. Hot air rises within a building and escapes through an opening on the roof and pulls cooler air from outside into the building. This creates a cross airflow within the interior space and creates ventilation for the building. A stack increases this effect, and the longer the stack the greater the airflow obtained. Stack ventilation works regardless of whether there is any prevailing wind available. Even though the movement of air is at a relatively slow speed, the results from the stack effect may be adequate to supply fresh air and produce convection cooling. However, these forces are rarely sufficient to create the required air movement for thermal comfort in certain hot zones of a living space. The only natural force can be relied on for this purpose is the dynamic effect of wind, and great effort must be made to capture this force.

Figure 1.6 Stack ventilation within a building.

The concept of night cooling rests on the fact that outdoor temperatures are usually lower at night than during the day. Cooler night air is brought into the interior space to flush out warm stale air that has accumulated during the day. The night cooling concept is relatively simple to be implemented, but the security risks should be considered. If the

windows are left open during the night, over-cooling may occur and then condensation issues on the inner face of windows occur when air-conditioning is used on the next day.

Thermal mass is incorporated into a building structure to absorb heat during the daytime hours, in order to keep the interior space cool. Cooler outside air can be brought in to bring the temperature of the thermal mass back down to preoccupancy levels at night. Typically, this mass is incorporated into ceiling spaces and walls in the form of masonry construction. This is an effective method of providing ventilation to buildings. However, the use of thermal mass is the most challenging in hot and humid climate, where night temperatures remain elevated. It should be strategically located to prevent overheating in such climate.

1.4 Building Envelope

1.4.1 Definition of Building Envelope

Building envelope, also known as building enclosure, is one of the fundamental components in a building. It separates unconditioned exterior environment from conditioned interior space, as illustrated in Figure 1.7. Building envelope furnishes appearance of buildings and also functions as load bearing, active or passive environmental control and creative expression for architect [10]. The envelope is made up of all the exterior components of the building, including walls, roof, foundations, windows, and doors.

Figure 1.7 Building envelope with exterior and interior environment [11].

Generally the functions of the building envelope can be categorized into 3 groups: structural support, control and finish. The structural maintains all the mechanical loadings imposed on the building. The control function is to govern flow of mass and energy such as moisture, air, heat and sound in between interior and exterior environments. The finish function is to end the enclosure surfaces and the interfaces of the envelope, meaning that the façade design and interfaces of wall are all considered as the finish function of envelope.

Building envelope, working as the middle layer between the indoor and outdoor, plays a very important role in mass and energy transfer, especially in Singapore whose climate is hot and humid. Human tends to use air-conditioning system to achieve indoor thermal comfort. Due to the temperature difference between the indoor and outdoor, there is heat conduction through the walls, roofs, floors and windows. There is also solar radiation through the glass windows and heat loss due to air infiltration. All these activities

increase the internal cooling load, and results in an increase in the energy consumption and cost. In order to achieve better building energy efficiency, there is a need to regulate the design of building envelopes to minimize heat gains into the interior spaces and energy lost.

1.4.2 Classification of Building Envelope Design

Based on the number of layers, building envelopes are classified into single skin envelope and double skin envelope. For the single skin envelope, based on shading strategies, it is further classified into self-shading building envelope and with-shading devices building envelope.

1.4.2.1. Single-Skin Envelope

For single-skin envelope, there are two common shading strategies: self-shading and extra shading devices. The self-shaded design is shown in Figure 1.8, and the louvers and the overhang shading device design are shown in Figure 1.9 and Figure 1.10 separately. Generally architectures prefer to use overhangs in building because it also gives the building character. The main function of overhang is to protect the windows or walls from outdoor climate and performs like shading device and rain shelter.

Figure 1.8 Self-shaded envelope of Concourse in Singapore.

Figure 1.9 An example of exterior louvers shading design [12].

Figure 1.10 Overhang design in eave condition [13].

1.4.2.2. Double-Skin Envelope

The double skin façade or double skin envelope illustrated in Figure 1.11 is a system of building consisting of two skins placed in such a way that air flows in the intermediate cavity. The ventilation of the cavity can be natural, fan supported or mechanical. Apart from the type of the ventilation inside the cavity, the origin and destination of the air can differ depending mostly on climatic conditions, the use, the location, the occupational hours of the building and the HVAC strategy. Double skin façade could be classified into multi-storey façade, shaft box façade, corridor façade and box window façade, based on different geometries of building façade [12]. In addition, based on the natural of ventilation inside the cavity between the first and second skins, double skin façade could also be categorized as active double skin façade and passive double skin façade. If the ventilation inside the cavity is driven by mechanical method, such as fans, it is named as

active double skin. Otherwise, it is named as passive double skin, meaning that there is no power consumed to introduce the ventilation inside the cavity.

Figure 1.11 Double skin envelope [12]

1.5 Motivation and Objectives

Singapore is a tropical country with hot and humid climate. Here air-conditioning system plays an essential role in people's daily work and life. Therefore, the energy efficiency of building envelope becomes essential, and natural ventilation as a method to reduce the dependency on air conditioning system becomes very important as well. So in this thesis, the effect of building forms on the natural ventilation and the effect of parameters of building envelope on the building energy efficiency are studied through mathematical modeling and simulation.

For the effect of building forms on the natural ventilation, three real buildings are studied by modeling and simulation to find out how the building form affects the natural

ventilation in real building projects. The first one is CleanTech Two (CTT) building which has structured architecture design. The second one is North Spine Academic Building (NSAB) which has porous architecture design, located inside NTU. Finally, the third one is Learning Hub (LH) building which has free-form architecture design located inside NTU. There are two main reasons for choosing these three buildings. One is that all these three buildings are targeted to get Green Mark Platinum award which require at least 30% of energy saving and even NSAB is targeted to get Green Mark Platinum^{Plus} which require more than 40% energy saving. Such big energy saving requirement results that the building should be designed in a passive way to avoid the energy consumption by air-conditioning which is a big energy consumer. The other is that the building time of three buildings is very near (CTT was planned in 2011 and is under construction now, NSAB is in the planning stage now and will be under construction in 2015 and LH was planned in 2012 and is also under construction now), and such near time means that the available technologies, materials, construction work are almost the same. In one sentence, these three buildings have the similar target and same available resources.

For the effect of parameters of building envelope on the energy efficiency, although many researchers have done relevant studies in this area with the focus on a very specific design, such as overhang, double skin façade, louvers and self-shading, there is no general guideline for design of building shading devices outside the building envelope, in terms of building energy efficiency. Therefore, this research aims to develop a general guideline for building envelopes in terms of energy efficiency through a holistic investigation of all key parameters involved in a shading device.

The model used in this study is shown in Figure 1.12, in which a single-storey building with $10 \times 10 \times 4 \text{ m}^3$ is assumed, and the red lines represent a general building envelope outside the building wall. The basic case is shown in Figure 1.13, in which there is only building wall without any shading devices or double skin.

Figure 1.12 External building envelope adopted in this thesis.

Figure 1.13 Basic case adopted in this thesis.

This general building envelope includes the double skin design and overhang design, which can be illustrated in Figure 1.14.

- Horizontal overhang design is resulted when the $\theta = 90^\circ$.
- General overhang design is resulted when $D = 0$ and $\theta \neq 90^\circ$.
- Double skin design is resulted when $\theta = 0^\circ$ and $D \neq 0$. The only difference between the two cases at the bottom is the 1st part of the building envelope. One has the 1st part and the other has not.

The objective of this study is to develop a guideline for design of a building envelope with highly efficient energy through parametric studies. As indicated in the Figure 1.12, the parameters are:

- D : the length of the 1st part of building envelope.
- L : the length of the 2nd part of building envelope.

- Porosity of building envelope.
- Fenestration location on the wall.
- The angle θ between building envelope and wall.

Figure 1.14 Special cases resulted from the general case.

1.6 Organization of Report

Chapter 1 presents the background information related to this study, motivation and objectives of this study.

Chapter 2 provides a review of building energy efficiency studies and natural ventilation studies of three type of shading devices: overhang, louvers and double skin. The indoor

comfort standard and regulations on building envelope energy performance are also included. Building design factors on building energy efficiency are covered as well.

Chapter 3 investigates the effect of building forms on the natural ventilation via computational fluid dynamic (CFD) simulation.

Chapter 4 investigates the effect of external envelope on building energy efficiency via energy simulation using EnergyPlus and Open Studio, and the effect of internal shading device on building energy efficiency via CFD simulation.

Chapter 5 concludes all the findings and details the recommendation the future work.

CHAPTER 2 LITERATURE REVIEW

This chapter reviews the energy efficiency with various building design factors, followed by the standard of indoor thermal comfort. The regulations on building envelope energy efficiency are then discussed. Previously published research work on the energy efficiency of three kinds of building shading devices, overhang, louvers and double skin is reviewed. Finally, research work on natural ventilation of louvers and double skin is also reviewed.

2.1 Energy Efficiency of Building Envelope

2.1.1 Envelope Thermal Transfer Value (ETTV)

An envelope thermal performance standard known as Overall Thermal Transfer Value (OTTV) was published by Building Control Regulations in 1979, in order to regulate building envelopes designs and control solar heat gains by buildings. However, the standard is only applicable to air conditioned non-residential buildings. In early 2000, a major review on OTTV was conducted to work out a more accurate calculation that was named Envelope Thermal Transfer Value (ETTV) [14]. ETTV was still only applicable to non-residential buildings that are air-conditioned during day time.

In 2008 the ETTV is extended to cover the residential buildings [15], in which the air-conditioners are usually turned on during the daytime. In order to differentiate roof from ETTV, Residential Envelope Transmittance Value (RETV) was proposed, in which the air-conditioners are usually turned on during evening.

In ETTV there are three heat gain components, the heat conduction through opaque walls, heat conduction through glass windows, and solar radiation through glass windows. ETTV is evaluated as the average heat gain over the whole envelope area of the building. The maximum permissible ETTV was set at 50 W/m^2 [14]. The formula is given as

$$ETTV = \text{Heat Conduction Wall} + \text{Heat Conduction Glass} + \text{Solar Radiation Glass}, \quad (2.1)$$

$$ETTV = 11.9 (1 - WWR)U_w + 3.37 (WWR)U_f + 210.9 (WWR)(CF)(SC), \quad (2.2)$$

where WWR is the window to wall ratio, U_w the thermal transmittance of opaque wall ($\text{W/m}^2\cdot\text{K}$), U_f the thermal transmittance of fenestration ($\text{W/m}^2\cdot\text{K}$), CF the correction factor for solar heat gain through fenestration, and SC the shading coefficients of fenestration.

The thermal transmittance or U-value of a construction is defined as the quantity of heat that flows through a unit area of a building section under steady-state conditions in unit time per unit temperature difference of the air on either side of the section. It is given by:

$$U = \frac{1}{R_T} \quad (2.3)$$

$$R_T = R_0 + \frac{b_1}{K_1} + \frac{b_2}{K_2} + \dots + \frac{b_n}{K_n} + R_i \quad (2.4)$$

where R_0 is the air film resistance of external surface, R_i the air film resistance of internal surface with unit of $\text{m}^2\text{K/W}$, K_1 , K_2 , K_n the thermal conductivity of basic material with unit of $\text{W/m}^2\text{K}$ and b_1 , b_2 , b_n the thickness of basic material with unit of m.

2.1.2 Correlation between Building Design and Energy Efficiency

The correlation between building design factors and energy consumption was studied by Lin H.T in 2011 [4]. An analysis on the impact of various envelope related factors on air-conditioning load was performed through a model of 10-storey office building located in seven different climates ranging from the tropics to the extreme cold: Singapore, Hong Kong, Taipei, Shanghai and Harbin [4]. As shown in Table 2.1, the first important factor is insulation, which is most prominent in cold climates like Harbin and Beijing. Conversely, the second important factor is the shading factor, which carries a heavier weightage in hot humid climates like Singapore. The third important factor is the ratio of window-to-wall, with the ratio affecting energy savings by 36 to 49% in most climates, except extreme cold climate where Harbin is located in. The fourth factor was the building-orientation, whose influence on energy was relatively low compared with the window-to-wall ratio.

Table 2.1 Impact of different design factors on annual cooling load.

	Building Orientation	Window Ratio	Shading at windows	Exterior Insulation	Other
Extreme Cold (Harbin)	5.0%	17.9%	0.0%	72.3%	4.7%
Cold (Beijing)	7.7%	36.3%	15.8%	29.0%	11.2%
Northern Subtropical (Shanghai)	3.6%	37.1%	8.7%	44.8%	5.9%
Northern Subtropical (Tokyo)	4.7%	43.2%	20.1%	20.3%	11.7%
Southern Subtropical (Taipei)	5.5%	49.0%	42.7%	0.0%	6.5%
Southern Subtropical (Hong Kong)	4.8%	44.2%	45.7%	0.0%	6.3%
Tropical (Singapore)	10.0%	40.4%	47.0%	0.0%	6.3%

Chua and Chou studied the parameters influence on ETTV in 2010 [16], as shown in Figure 2.1. It was shown that SC (shading coefficient) and WWR (window to wall ratio) had strong influence on the ETTV. The influence of U_w and α_s (absorptance of the opaque wall) decreased as WWR was increased, while it was quite considerable at a low WWR of 0.36. As day-lighting is an important aspect of energy-saving strategy, it is often not advisable to alter WWR of most existing buildings [17]. In Taiwan existing buildings have significant annual energy savings by using appropriate window glass, followed by shading devices, whereas the roof construction produced less energy-efficient benefits [18].

Figure 2.1 Relative ranking of influencing parameters on ETTV when WWR varies [15].

2.1.3 Overhang Shading Devices

The energy saving effect of exterior shading devices in different climate zones was compared by Lin H.T. [4]. The model is a ten storey building with floor area of $25 \times 50 \text{ m}^2$ and window to wall ratio of 50%. It was shown in Figure 2.2 that the total air-conditioner (AC) energy consumption decreased in southern subtropical Taipei and rose both in the warmer tropical and cooler cold climates as a result of growing cooling load for the former and heating load for the latter. The exterior shading was not only very effective in the tropics and subtropics, but had some effect in the cold climate as well. A 1 m horizontal sunshade had energy efficiency of 15.8%, 15%, 12.9%, 5.6%, 3.5% and 11.0% in Singapore, Hong Kong, Taipei, Tokyo, Shanghai and Beijing respectively and only reaches 0.7% in the extreme cold Harbin, as shown in Table 2.2. This indicated a growing trend for modern offices to be “heat-sensitive”.

Figure 2.2 Energy saving efficiency from exterior shading observed from variation in AC electricity usage density in office buildings.

Table 2.2 Energy saving efficiency from exterior shading observed from variation in AC electricity usage density in office buildings.

	<i>No shading</i>	<i>0.5 m Horizontal Shading</i>		<i>1.0 m Horizontal Shading</i>	
	Total AC energy consumption (kWh/m ² .a)	Total AC energy consumption (kWh/m ² .a)	Energy Saving	Total AC energy consumption (kWh/m ² .a)	Energy Saving
Singapore	92.4	82.1	11.1%	77.8	15.8%
Hong Kong	76.3	69.6	8.8%	64.9	14.9%
Taipei	70.4	64.8	8.0%	61.3	12.9%
Tokyo	75.9	72.8	4.1%	71.6	5.7%
Shanghai	88.7	86.3	2.7%	85.6	3.5%
Beijing	116.5	106.2	8.8%	103.8	10.9%
Harbin	166.7	165.2	0.9%	165.6	0.7%

In 2005, Kumar *et al.* evaluated the performance of solar passive cooling techniques such as solar shading insulation of building components and air exchange rate [19]. It was found that a decrease in the indoor temperature by about 2.5°C to 4.5°C was noticed by adding solar shading insulation. Results modified with insulation and controlled air exchange rate showed a further decrease of 4.4°C to 6.8°C in room temperature. For a shaded and selectively ventilated building with one window, 2 cm of thermal insulation gave the same result as 8~10 cm of insulation for a conventional building, which was non-shaded and not ventilated.

In 2012, Yu *et al.* investigated a methodology to analyze the energy and CO₂ emission payback periods of external overhang shading in a university campus in Hong Kong [20]. It was shown that after application of the solar shading system, the annual space cooling load was reduced by about 139,250 kWh, which is equivalent to reduction of about 44.1%. However, the data was collected only from May to November. If the data collected was annually based, the results would be more reliable.

In 2011, Wong *et al.* studied the building energy efficiency of different configurations of shading device in reducing heat gain under afternoon sun for the west facing naturally ventilated classrooms [21]. Field physical measurements were conducted to compare the space with and without the shading devices. The study found out that the performance of 4-panel configuration was more efficient than complete setting configuration in reducing heat gain into the building. Normally it is naturally ventilated when the wind speed is higher than certain value in Singapore.

2.1.4 Louvers Shading Devices

Kim *et al.* carried out a series of simulations by an energy analysis program, to investigate the thermal performance of exterior shading device in residential building [22]. In this study, four different configurations of shading devices were compared, as shown in Figure 2.3. They are (1) the horizontal overhang, which was of great use and dependent on its projecting depth, (2) the conventional blind system, in which the slat angle gave the ability to control sunlight, (3) a light shelf, so that both internal and external light shelves with slats were equipped to improve day lighting performance while allowing direct sun, and (4) the proposed exterior shading device as a target variable in this study. It was shown in the results that the proposed experimental shading device promises the most efficient performance with various adjustments of the slat angle. A secondary advantage was that it also provided better views for occupants. In 2012, Kim *et al.* proposed an integrated design in which louvers were added inside the cavity of double skin envelope [23]. The energy efficiency of such louvers was studied and a parametric study of the width of the louver on energy efficiency was carried out. In the results, it was shown that it would save 6% more annual cooling energy by adding the

louvers inside the cavity, but the energy saving did not increase significantly by increasing the width of louver, only maximum 1% of energy saving was achieved.

Figure 2.3 Four different configurations of shading devices [22].

2.1.5 Double Skin

After the double-skin was developed, this technology aims to provide an energy saving solution in building industry. However, how efficient was this technology or what was the limitation of this technology? In order to answer such questions, Elisabeth *et al.* compared the consumption of heating and cooling in a building with or without double-skin when the heating and cooling natural strategies were or were not used, according to the level of insulation and the orientation of the double-skin [24]. The result was shown in Figure 2.4 that, where the DSF means double skin façade, the addition of a double-skin always caused an increase in the cooling loads and such increasing became more obvious

when natural cooling strategy was not applied. Therefore, it was recommended that the addition of a double-skin can be considered only if the strategies of natural cooling can be applied.

Figure 2.4 Impact of different insulation on energy savings of a double-skin in a north-south building [24].

In addition, Lin [4] thought double skin was not very suitable in cold climate and became even worse in hot climate. In 2010, existing main research methods on the thermal performance of double skin façade and shading devices was reviewed [25]. Such recommendations were made, which were applying ventilated double skin façade with controlled shading device system would be a new efficient way for the commercial buildings in the hot-summer and cold-winter zone to meet the task of sustainable building design in China.

In 2012, Kim *et al.* proposed different designs of double skin façade and carried out the building energy efficiency analysis by using computational tools [20]. The parameters studied were the width of cavity, and the width of louvers which were treated as shading devices inside the cavity and the shape of the cavity. It was shown in the results that 90 cm was the optimum value for the width of cavity, which helped to cut down annual cooling energy by 40%.

2.2 Effect of various Building Envelope on Natural Ventilation

2.2.1 Louvers Shading Devices

The impact of louvers on the indoor natural ventilation was studied through CFD simulation [26]. In this study, the wind velocity profile and pressure distribution in the natural ventilated building model were plotted and studied. The rotation angles of the shutter and different incidence angles of the wind affect natural ventilation rate were studied as well. The influences of shutters on the discharge coefficients were analyzed, and use principles of the louver equipped in the building were proposed.

Similarly, in 2007 Tablada *et al.* investigated the natural ventilation strategy of exterior louvers which were treated as passive cooling device in residential buildings [27]. In this study, the implementation of the louver systems, the natural ventilation strategies, and the evaluation and quantification of the (dis)comfort was performed by coupling CFD and Building Energy Simulation (BES) calculations. Values of indoor air speed and pressure coefficients were obtained from CFD calculations and were further used as input in BES calculations and comfort analysis. It was found that, for the particular case, overheating problems could be improved by passive means by the application of several

strategies, like the use of existing balconies with external louver systems and whole day natural cross ventilation.

2.2.2 Double Skin

The natural ventilation in the double skin façade with various building orientations was studied by Elisabeth *et al.* [28]. The possibility of natural ventilation in double skin façade was discussed and it was found that the cross-ventilation was less effective than single sided ventilation for the same ventilation rate. It was found that, in order to obtain a ventilation rate of 4 volume per hour, the size of the openings was a function of the stack effect, and of the wind orientation and speed [29].

Similarly, Ding *et al.* carried out a reduced scale model experiments and simulation to evaluate the natural ventilation performance of a double skin with a solar chimney [30]. It was found that increasing the height of the solar chimney could improve the ventilation rate. As there are always limitations on the acceptable height of the solar chimney, the solar chimney was recommended to be more than two-floor high.

In 2007, Kim *et al.* proposed opening design on both single skin envelope and double skin envelope and investigated the natural ventilation performance accordingly by using CFD simulation [31]. The results showed that inlets and outlets on the double skin envelope could not provide improved ventilation volume than single skin envelope, but adding openings on the double skin envelope would help to increase ventilation rate and indoor air circulation.

In 2011, Kim *et al.* proposed three different methods to achieve energy saving through controlling the openings on the outer skin [32]. The effects of different control models on natural ventilation and heating loads in office buildings in winter was investigated.

The fluid mechanics of natural ventilation within double skin façade in multi-storey buildings was studied by Mongotti *et al.* [33]. The main driving force in this study was the temperature difference, which is the buoyancy effect. This study explored how the height of the facade and the sizes of the openings in the room and the facade can be optimized for each mode of operation.

Xu *et al.* investigated a 2D CFD simulation to simulate the natural ventilation of a combined venetian blind and double skin envelopes [34]. By comparing the simulation results with the experiment data, it was found that a good agreement was achieved between experiment and simulation results, as shown in Figure 2.5. Hence, CFD simulation was prove as a reliable tool to analyze the ventilation in the double skin facade with a venetian blind.

Figure 2.5 Velocity vectors on a longitudinal-section (a) wind-tunnel experiment (CEDVAL), (b) CFD simulations [34].

2.3 Thermal Comfort Analysis Models for Naturally Ventilated Spaces

The standard of thermal comfort has been published since 1994 in ISO 7730 [35-37]. The most common thermal comfort model used is the traditional Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) model for air-conditioned buildings [37]. PMV and PPD are accepted as ISO 7730 and are calculated by empirical equations. The PMV equation uses a steady-state heat balance for the human body. The equation is derived empirically and the thermal sensation vote indicates the personal deviation from the heat balance [-3 (cold) to +3 (hot); a seven point scale, 0 = neutral (optimum)]. The PPD equation indicates the variance in the thermal sensation of the group of persons exposed to the same conditions. Dissatisfaction with the thermal environment, discomfort, was defined for those who vote cold (-3), cool (-2), warm (+2) and hot (+3). In PMV-

PPD model, the percentage of dissatisfaction is never 0% even in the optimal thermal condition where $PMV=0$. PMV and PPD are calculated based on six variables: activity (metabolic rate), clothing (ensemble insulation), air temperature, air velocity, mean radiant temperature (MRT) and humidity. The values of the variables for the activity and clothing are determined via ASHRAE Fundamentals [38]. The PMV and PPD values are calculated based on six basic variables: activity, clothing, air temperature, air velocity, mean radiant temperature and humidity. However, it is proven that the PMV index is inadequate in the case of naturally ventilated buildings, and the human body in a naturally ventilated environment feels more comfortable than in a mechanically controlled thermal environment [39-41].

In 2002, Fanger and Toftum introduced the extended PMV_{NV} comfort model, which is more suitable for naturally ventilated buildings in warm climate and can be considered consistent with traditional PMV model [37]. This PMV_{NV} model introduced an expectancy factor e which is multiplied with PMV to reach the mean thermal sensation vote of the occupants of the naturally ventilated building in a warm climate. In 2012, Shafqat and Patrick combined this PMV_{NV} model with Computational Fluid Dynamic (CFD) method to evaluate the thermal comfort conditions in an atrium building [42]. However, it was pointed out that this PMV_{NV} model still showed discrepancy in predicting actual thermal sensations, especially at lower temperatures [43]. This model is an extension of PMV-PPD model. This model introduces an expectancy factor e , which is to be multiplied with PMV to reach the mean thermal sensation vote of the occupants of the actual non-air-conditioned building in a warm climate.

$$PMV_{NV} = PMV * e \quad (2.5)$$

The factor e is estimated to vary between 1 and 0.5. For air-conditioned building, it is 1. For non-air-conditioned buildings, the expectancy factor is assumed to depend on the duration of the warm weather over the year and whether such buildings can be compared with many others in the region that are air-conditioned. If the weather is warm all the year or most of the year, and there are no or few air-conditioned buildings, expectancy factor e may be 0.5. If there are many air-conditioned buildings, the expectancy factor e may be 0.7. For Singapore, the value of expectancy factor is 0.7 [34].

CHAPTER 3 NATURAL VENTILATION FOR EFFECT OF BUILDING FORMS

In this chapter, three real buildings are investigated for the effect of building form on natural ventilation inside the building via Computational Fluid Dynamic (CFD) simulation. The first one is CleanTech Two (CTT) building which has structured architecture design. The second one is North Spine Academic Building (NSAB) which has porous architecture design, located inside NTU. Finally, the third one is Learning Hub (LH) building which has free-form architecture design located inside NTU. In each project, the model description is introduced first, followed by the results and discussion, and then a short summary is covered. The methodology of simulation of natural ventilation for the three projects is the same; therefore, the methodology is introduced only in the first section.

3.1 Methodology for Simulation of Natural Ventilation

There are no standard solutions to all CFD problems. Depending on the goals and problems, different settings need to be implemented or altered in the software to provide an accurate and consistent result. Generally, natural ventilation is dependent on both wind speed and gravity. Gravity can be considered zero, if only ventilation due to wind is studied [44]. In this case, heat input can be set to any value and the resulting effect on the ventilation rate is ignorable. However if buoyancy effect is considered, heat input value needs to be adjusted accordingly. Heiselberg *et al.* [45] suggested that buoyancy flow has to be treated with caution as it is possible to have multiple states exist in natural

ventilation of simple buildings. Buoyancy effect should be accounted if the relative magnitude of the forces due to buoyancy and pressure is high.

In this chapter, ANSYS Fluent software is engaged to simulate the air flow around and inside the building. ANSYS Fluent software contains the broad physical modeling capabilities needed to model flow, turbulence, heat transfer, and reactions for industrial applications ranging from air flow over an aircraft wing to combustion in a furnace, from bubble columns to oil platforms, from blood flow to semiconductor manufacturing, and from clean room design to wastewater treatment plants.

3.1.1 Laminar Flow or Turbulence Flow

Normally Reynold number is used to define that a flow is either laminar or turbulent. If $R_e < 2300$, it is laminar flow; if $R_e > 4000$, it is turbulent flow; if $2300 < R_e < 4000$, it is transition flow. The equation for flow in a pipe is:

$$R_e = \frac{\rho u d}{\mu} \quad (3.1)$$

where ρ is the density of the fluid flowing inside the pipe, u mean velocity of the fluid, d diameter of the pipe and μ the viscosity of the fluid.

Normally all the natural ventilation in the urban environment is turbulent flow. For example, the average north wind velocity in Singapore is 2 m/s. The domain used for natural ventilation simulation usually is 5 times larger than the target building. For example the domain is $100 \times 100 \times 100 \text{ m}^3$. In this case $\rho = 1.225 \text{ kg/m}^3$, $\mu = 1.78 \text{ e}^{-5} \text{ kg/m.s}$, $u = 2 \text{ m/s}$, $d = 100 \text{ m}$, thus, $R_e \approx 1.37 \text{ e}^7$ which is much larger than 4000.

3.1.2 Turbulence Flow Model

Multiple turbulence models are available to study the turbulence effect. Typically it is not realistic to apply direct-numerical simulation at present. Therefore, the turbulence models should be used for a successful simulation.

The turbulence models can be divided into two groups: large-eddy simulations (LES), and turbulent transport model (Reynolds averaged Navier-Stocke equation modeling, RANS). Generally LES can provide much more information about the flow field and the dispersion process than the RANS approach which directly gives only the mean field and provides only statistical estimates for the turbulent transport. This has been proven in many areas [46-48]. However, LES requires finer grid distribution which will increase the computing time dramatically. Chen and Srebric [49] recommend RANS equations with turbulent transport models for steady airflow simulation.

The most widely used RANS models are the two-equation turbulence models, k - ε and k - ω models in which k represents the turbulent kinetic energy, ε is the turbulent dissipation rate and ω is the specific dissipation rate. The k - ε models can be separated into standard model, renormalization group theory (RNG) model and realizable model.

A hybrid solar-assisted natural ventilation system in the Engineering building of the Concordia University have solved for radiation intensity transport equations (RTEs) in addition to turbulence models [50]. To account for radiation, Solar Load model and Discrete Transfer Radiation Model (DTRM) were used, to calculate solar radiation and radiation exchange in between façade surfaces respectively. Four turbulence models (k - ε standard, k - ε RNG, k - ε realizable and k - ω shear stress transport (SST)) were compared

and it was found that all models deliver sufficient accuracy compared to the experimental data. However, k- ω SST gave a higher accuracy compared to k- ϵ models. RNG model performs better than standard k- ϵ model near wall surfaces [51]. Also, RNG model provides reasonable accuracy compared to large-eddy simulation (LES) that is more computational intensive but with higher accuracy. Stavrakakis *et al.* [52] who also compared standard k- ϵ model and RNG model, found that both models gave reasonable accuracy for natural ventilation in a livestock building and a greenhouse. However the standard k- ϵ model converged in less iteration than the RNG k- ϵ model.

3.1.3 Computational Domain

To make sure the wind has fully developed, the domain should be large enough. According to Best Practice Guideline [53], following requirements should be matched when setting up the model:

- Only the building should be represented if its distance from the region of interest is less than $6H_n$, where H_n is the building height. Otherwise, the building is too far to have an influence.
- For urban areas with multiple buildings, the top of the computational domain should be $5H_{max}$ away from the tallest building with height H_{max} , where H_{max} is the building height of the tallest building within the domain.
- For urban areas with multiple buildings, the lateral boundaries of the computational domain can be placed closer than $5H_{max}$ to that part of the built area, where H_{max} is the building height of the tallest building within the domain.

3.1.4 Boundary Conditions

Various boundary conditions are available in Fluent such as “wall”, “velocity inlet”, “pressure-outlet”, and “symmetry”. In the study of ventilation in a greenhouse Hou and Ma [44], the boundary condition for sky is set to be “symmetry” while ground and buildings surfaces are set to be “wall”, and thermal boundary conditions are set to be adiabatic for building surfaces while fixed temperatures are imposed on roof and floor levels. On the other hand, Hussain and Oosthuizen [50] imposed mixed thermal boundary conditions on building surfaces. They factored in convection and radiation heat transfer. Radiation exchange in between façade and the sky was also taken into account. Besides, glazing effect of façade glass was also calculated to provide a better result.

3.1.5 Post Processing

Normally the residuals of three momentums in x , y , z direction and the energy are used to judge if the simulation is complete. Normally when the residuals are less than 10^{-3} , the results could be trusted. The residuals are not the only condition to judge the competency of the simulations, but also the flux in and out of the domain. Generally, the difference between the flux into the domain and the flux out of the domain should be less than 0.001. Finally, the user could plot the pressure contour and velocity vectors from the simulation results and judge the results based on the physics knowledge.

For natural ventilation, the purpose of CFD simulation is to check the comfort level for people. Normally the temperature contour and wind velocity vector on the plane which is about 1.5 meters above the ground should be drawn for all the activity areas. The streamline helps the users to understand the flow mechanism as well.

3.2 Project I: A Structured Research Building CleanTech Two

Located on a large contiguous green field site, CleanTech Park has a natural undulating terrain and matured lush greenery with natural streams running through it. CleanTech Park is developed by JTC in three phases. When completed in 2030, this Park will have twenty five buildings. The first of these, the six-story and 2-towered Clean Tech One was completed in 2012. CTT is the second building as shown in Figure 3.1, and currently is under construction and going to be completed by 2014. The gross floor area (GFA) of CTT is 38,000 m².

Figure 3.1 Impression drawing of CTT building. (Source: JCPL).

Figure 3.2 Computational domain of CFD simulation for CTT project including existing and future buildings in CleanTech Park within next 20 years.

Figure 3.3 CTT building model in CFD simulation by gambit software.

Figure 3.4 Diagram of CTT model setup for ventilation simulation.

3.2.1 Description of Model

The computational domain of CFD simulation is shown in Figure 3.2, in which the domain is made up with eight boundary surfaces, numbered as ①, ②, ③, ④, ⑤, ⑥ (sky), ⑦ (ground), and ⑧ representing a forest located in the north side of CTT. Inside the domain, the target building CTT with the height of 37.5 m above ground is circled in red, and the surrounding buildings include one existing building CleanTech One and other future buildings within next twenty years. The tallest building within the domain is circled in blue with a height of 38 m.

More detailed CTT model is shown in Figure 3.3. In general it is necessary to use a mathematical model simplifying for problem simulation with desired accuracy. Based on these, several assumptions are made and they are:

- A flat surface is assumed for the ground.
- Most details of CTT are captured except the louvers and green walls.
- Simple blocks are used to represent surrounding buildings. Only the shape, relative height and location are considered, except other details.
- Porous structure is used to represent the forest as indicated by ⑧.

- As shown in Figure 3.4, the inbound vertical wind profile is given by the Logarithmic law with the reference height of 15 m.

3.2.2 Boundary Condition

The boundary conditions for CTT model are shown in Table 3.1, in which the locations of boundaries are shown in Figure 3.2. The boundary conditions vary with wind scenarios, which are classified into north, northeast, south and southeast wind. In each wind scenario, the average wind speed indicated in Table 1.2 is used.

Table 3.1 Boundary conditions for CTT model.

Boundary	Wind Scenario			
	North	North & Northeast	South	Southeast
①	Velocity Inlet Wind Speed $v_{\text{wind}} = 2 \text{ m/s}$	Velocity Inlet Wind Speed = 2.9 m/s	Pressure Outlet	Pressure Outlet
②	Pressure Outlet	Pressure Outlet	Pressure Outlet	Pressure Outlet
③	Pressure Outlet	Pressure Outlet	Velocity Inlet Wind Speed = 2.8 m/s	Velocity Inlet Wind Speed = 3.2 m/s
④	Pressure Outlet	Pressure Outlet	Velocity Inlet Wind Speed = 2.8 m/s	Velocity Inlet Wind Speed = 3.2 m/s
⑤	Velocity Inlet Wind Speed = 2 m/s	Velocity Inlet Wind Speed = 2.9 m/s	Pressure Outlet	Pressure Outlet
⑥	Symmetry			
⑦	Wall			
⑧	Porosity Zone with Inertial Resistance = 0.45 m^{-1}			

A porous media is used to simulate the block effect of the forest, based on the inertial loss coefficient C [50].

$$C = 2 C_d \times \alpha_z \quad (3.2)$$

where α_z is the leaf area index per unit volume at certain height, and C_d the effective drag coefficient. In this simulation, these two parameters proposed by Patton [54] are given as $\alpha_z = 0.25$, $C_d = 0.15$, and thus $C = 0.075$.

3.2.3 Results and Discussion

By the methodology mentioned in Section 3.1, the result of simulation converged after 1000 iterations. The results are organized by four wind scenarios: north, northeast, south, and southeast winds. In each wind scenario, the distributions of the velocity vectors are plotted in three horizontal planes, $z = 1.5$ m, 14 m and 19.4 m (z is the coordinate in the height direction above the ground). The average wind speed of the common areas in the three horizontal planes are computed and then compared with the Green Mark Standard at $v = 0.6$ m/s [8].

3.2.3.1 North Wind Scenario

From Figure 3.5, it is seen that the average wind velocities are larger than 0.6 m/s in Public Area 3 and Communal Landscaped Deck. For other common areas however, the wind velocity is lower than 0.6 m/s, especially for the Lorry & Container Park where is almost equal to zero.

Figure 3.5 Velocity vectors in north wind scenario.

3.2.3.2 Northeast Wind Scenario

From the Figure 3.6, it is observed that the average wind velocities in most common areas are larger than 0.6 m/s, except the Lorry & Container Park. However, compared with the north wind scenario, the ventilation situation in the Lorry & Container Park is improved when wind blows from northeast. The possible reason is that the perpendicular area is increased between the opening and the wind direction, and thus wind enters this park much easier.

Figure 3.6 Velocity vectors in northeast wind scenario.

3.2.3.3 South Wind Scenario

From Figure 3.7, it is found that the average wind velocities in most common areas are lower than 0.6 m/s, except the Public Area 3. Compared with north wind scenario, natural ventilation situation in all the common areas becomes worse. The possible reason is that the wild field helps to accelerate the north wind, where the area is outside of the blue box but within the dark green box, as illustrated in Figure 3.8.

Figure 3.7 Velocity vectors in south wind scenario.

Figure 3.8 Site plan of Clean Tech Park.

3.2.3.4 Southeast Wind Scenario

From Figure 3.9, it is concluded that the average wind velocities in most common areas are lower than 0.6 m/s, except the Public Area 3 and Communal Landscaped Deck. Compared with the south wind scenario, the ventilation situation on all the common areas becomes better, especially the Communal Landscaped Deck. The possible reason is that the perpendicular area increases between the opening and the wind direction, and wind can enter this park much more easily.

Figure 3.9 Velocity vectors in southeast wind scenario.

3.2.4 Summary

From all the above four wind scenarios, the average wind speeds in all the public areas are summarized in Table 3.2. It is clearly shown that Public Area 3 and Communal Landscaped Deck have good natural ventilation, compared with the Green Mark Standard 0.6 m/s [9].

Table 3.2 Average wind speed for all the public areas in CTT.

Average Speed (m/s)	North Wind	Northeast Wind	South Wind	Southeast Wind
Public Area 1	0.2	0.6	0.2	0.25
Public Area 2	0.3	0.8	0.2	0.3
Public Area 3	0.8	0.7	1	1.2
Lorry Park & Container Park	0.1	0.4	0.3	0.4
Communal Landscaped Deck	0.75	1.8	0.4	2

As different wind scenarios have different frequencies stated in Table 1.2, the average wind speed is obtained as

$$V_{\text{Average Velocity}} = \sum_{i=1}^4 (V_i F_i) \quad (3.3)$$

where V_i is the wind speed of certain wind scenario in a certain cell, F_i the frequency of the certain wind scenario, and $V_{\text{Average Velocity}}$ the average wind speed in a certain cell in a year. After combining four wind scenarios via Eq. (3.3), the results are shown in Figure 3.10.

It is clearly seen that the middle part of rooftop on the south block has higher average wind velocity of 2 ~ 2.5 m/s. The communal landscaped deck and Public Area 3 have good ventilation where the average wind velocity is larger than Green Mark Standard of

0.6 m/s [9], while the ventilation in other public areas needs to be improved, where the average wind velocity is lower than 0.6 m/s.

Figure 3.10 Average wind velocity in a year.

3.3 Project II: A Porous Academic Building North Spine Academic Building

Normally the word “porous” is used to describe a material which has many holes inside. However, now it is extended to describe a building which has may void inside and such voids help to enhance the natural ventilation. According to the master plan of NTU published in 2012, there will be ten new buildings in the campus in the next several years. One of them is the North Spine Academic Building (NSAB) illustrated in Figure 3.11. NSAB is right now in design phase and the target of this project is to achieve as much as 40% energy saving. Therefore, natural ventilation becomes attractive as one of the energy saving strategies in the design stage, which building can be enhanced further by increasing the porosity.

Figure 3.11 Impression drawing of NSAB building (Source: ADDP).

Figure 3.12 Computational domain of the NSAB model

Figure 3.13 Top view of NSAB and neighbor buildings in CFD simulation model.

3.3.1 Description of Model

NSAB is a seven-storey building with the ground floor named as “Basement Four (B4)” and the other levers from bottom to top are “Basement Three (B3)”, “Basement Two (B2)”, “Basement One (B1)”, “Level One (L1)”, “Level Two (L2)” and “Level Three (L3)”.

The simulation model is shown in Figures 3.12 and 3.13. The neighboring buildings, N4, N3, N4.1 and LT 2A, are included and NSAB is circled in red. Inside NSAB, all the

toilets are designed in a naturally ventilation manner. In order to simulate the NSAB model, the following assumptions are made:

- A flat surface is assumed for the ground, but the height differences between the buildings are considered.
- The toilets are naturally ventilated, and the screen inside the toilets has 50% porosity.
- Simple blocks are used to represent surrounding buildings, N3, N4, N4.1 and LT 2A.
- As shown in Figure 3.4, the inbound vertical wind profile is given by the Logarithmic law with reference height of 15 m.
- k- ϵ realizable turbulence model is used with the backflow turbulent intensity of 5% and viscosity ratio of 5% [55].
- For the solar radiation model, Solar Ray Tracing model [56] is engaged with Longitude of 103.667 °, Latitude of 1.35 ° and Time Zone 8.
- 13:00 pm on 21st June is chosen as the simulation time, when the solar intensity is the highest within a day.
- The solar irradiation value and outside temperature are from epw file of energy simulation.

3.3.2 Boundary Conditions

The boundary conditions are shown in Table 3.3, in which the locations of boundaries are shown in Figure 3.12. The boundary conditions vary with wind scenarios, which are classified into north, northeast, south and southeast wind. In each wind scenario, the average wind speed indicated in Table 1.2 is used.

Table 3.3 Boundary conditions for CFD simulation of NSAB.

Boundary	Wind Scenarios			
	North Wind	Northeast Wind	South Wind	Southeast Wind
①	Velocity Inlet Wind Speed = 2 m/s	Velocity Inlet Wind Speed = 2.9 m/s	Pressure Outlet	Pressure Outlet
②	Pressure Outlet	Velocity Inlet Wind Speed = 2.9 m/s	Pressure Outlet	Velocity Inlet Wind Speed = 3.2 m/s
③	Pressure Outlet	Pressure Outlet	Velocity Inlet Wind Speed = 2.8 m/s	Velocity Inlet Wind Speed = 3.2 m/s
④	Pressure Outlet	Pressure Outlet	Pressure Outlet	Pressure Outlet
⑤	Symmetry	Symmetry	Symmetry	Symmetry
⑥	Wall	Wall	Wall	Wall
Screen inside the toilets	Pressure Jump 50% porosity			

3.3.3 Results and Discussion

Based on the methodology mentioned in Section 3.1 of this chapter, the simulation result is converged after 1000 iterations. The results are organized by four wind scenarios: north wind, northeast wind, south wind and southeast wind, as detailed in the following sub-sections. In each wind scenario, both the plane and cross-sectional views of velocity contour are plotted at all seven levels, in which the average wind speed of the common areas in three horizontal planes are computed and then compared with the Green Mark Standard (0.6 m/s) [9].

3.3.3.1 North Wind Scenario

From Figures 3.14 and 3.15, it is seen that the wind has the highest speed in Basement Four compared with the other levels, and it achieves its maximum speed at about 2.7 m/s inside the common space of Basement Four. One possible reason is the tunneling effect, and the other is that Basement Four has big opening in neighbor buildings, such that the wind can easily enter NSAB. The wind speed in Levels 1 to 3 is the lowest compared with that in other levels. The wind speed inside the small atrium is about 0.1~1.2 m/s.

3.3.3.2 Northeast Wind Scenario

From Figures 3.16 and 3.17, it is observed that the whole wind flow pattern is similar to that in north wind scenario. The only difference is that the wind speed everywhere is increased.

3.3.3.3 South Wind Scenario

From Figures 3.18 and 3.19, it is found that the wind pattern in south wind scenario is very similar to that in north and northeast wind scenarios, but the wind speed everywhere is larger than that in north wind scenario, but smaller than that in northeast wind scenario.

3.3.3.4 Southeast Wind Scenario

From Figures 3.20 and 3.21, it is concluded that the wind pattern in south wind scenario is very similar to that in north, northeast and south wind scenarios, but the wind speed everywhere is the largest among these four wind scenarios.

Figure 3.14 Plane view of velocity contour of seven levels within NSAB under north wind scenario.

Figure 3.15 Cross section view: (a) cross section line; (b) velocity vector within the small atrium area; (c) velocity contour.

Figure 3.16 Plane view of velocity contour of seven levels within NSAB in northeast wind scenario.

Figure 3.17 Cross section view: (a) cross section line; (b) velocity vector within the small atrium area; (c) velocity contour.

Figure 3.18 Plane view of velocity contour of seven levels within NSAB in south wind scenario.

Figure 3.19 Cross section view: (a) cross section line; (b) velocity vector within the small atrium area; (c) velocity contour.

Figure 3.20 Plane view of velocity contour of seven levels within NSAB in southeast wind scenario.

Figure 3.21 Cross section view: (a) cross section line; (b) velocity vector within the small atrium area; (c) velocity contour.

3.3.4 Summary

Thermal comfort inside the small atrium is calculated based on PMV_{NV} -PPD model and shown in Table 3.4. It is shown that for southeast wind scenario, the situation is very good, where percentage of satisfaction (PS) is about 90%. However, PS is only 49% for northeast wind scenario. Thermal comfort inside toilets is not good, where PS is less than 10% for all the toilets.

Table 3.4 Area-weighted average wind speed and percentage of thermal comfort inside the common spaces in seven levels for four wind scenarios.

	NE-Wind		SE-Wind		N-Wind		S-Wind	
	Velocity (m/s)	PS (%)	Velocity (m/s)	PS (%)	Velocity (m/s)	PS (%)	Velocity (m/s)	PS (%)
L3	1.74	66.9	1.79	84.1	0.67	16.19	1.01	56.34
L2	1.61	56.7	1.79	75.9	0.63	9.81	0.72	32.31
L1	1.88	49.2	2.42	73.8	0.66	7.35	0.75	29.83
B1	2.03	61.8	2.18	59.6	0.89	15.92	1.13	48.45
B2	1.97	56.0	2.70	56.3	0.73	7.04	1.09	43.49
B3	1.87	45.0	1.82	54.5	0.7	2.19	0.93	29.83
B4	2.97	63.2	3.09	50.7	1.33	11.01	1.86	59.63
Toilets		<10		<10		<10		<10

3.4 Project III: A Free-Form Academic Building Learning Hub

The new Learning Hub (LH) is one of fourteen new buildings at NTU within the next three years, under the University's Campus Master Plan that will transform the NTU campus into a University City. LH broke ground on 12th October 2012, and currently it is under construction.

This hub has nine stories with total height of 34.2 m, and each level has the height of 3.8 m. It is designed with a structure without conventional corridors. As a flower like layout, it is made up of several “petals” (involving 55 tutorial rooms), atrium and 3 staircase blocks, as shown in Figure 3.22. In Level 1, there are only petals in the north, south and west side. From Level 2 to Level 6, there are 13 petals. In Levels 7 to 9, there are 10, 6 and 4 petals respectively. It also allows the students to enter from all directions around into a large central space which links all the separate “petals” together. Each “petal” tower consists of classrooms and is build up gradually. Gardens, shaded terraces, and pergolas are designed on selected upper levels and rooftops, as shown in Figure 3.22. All the rooms are air-conditioned. On the other hand, the public spaces (e.g. the corridors and atrium area) are designed to be naturally ventilated.

Figure 3.22 Impression drawing of LH building. (Source: NTU)

3.4.1 Description of Model

The computational domain for LH model is shown in Figure 3.23, in which the domain is made up of six boundary surfaces, numbered as ①, ②, ③, ④, ⑤ (sky), and ⑥ (ground). Inside the domain, LH with building height of 34.2 m and three nearest neighbor buildings, Business school with building height 1.9 m lower than LH, School of Humanities and Social Sciences (HSS) with building height 12.5 m lower than LH and Innovation Center (26.45 m lower than LH) are considered in this simulation.

As shown in Figure 3.24, this is a nine story building with each level height of 3.8 m, and formed by 13 blocks and the interconnected “corridors”. Only the individual rooms are air-conditioned; the corridors and atrium areas are designed to be naturally ventilated. The staircases are with 50% porosity which enhances the natural ventilation in the atrium and corridors. The detailed LH model in CFD simulation is shown in Figure 3.25. In order to build up the simulation model, there are some assumptions:

- The ground is assumed to be a flat surface, but the height difference between LH and surrounding buildings are considered.
- Simple blocks are used to represent surrounding buildings, HSS, Innovation Center and Business School.
- The shapes of all Learning Hub blocks from Level 2 to Level 9 are assumed to be the same, but all the other details are considered.
- The envelopes of staircases of LH have 50% porosity.
- As shown in Figure 3.4, the inbound vertical wind profile is given by the Logarithmic law with the reference height of 15 m.
- Turbulence model and solar ray tracing model is the same as that in NSAB project.

Figure 3.23 Computational domain for LH model

Figure 3.24 Cross section view of LH model.

Figure 3.25 Top view of LH model in CFD simulation.

Figure 3.26 Cross section view (Level 5) of LH building model in which gaps and staircases together with four selected measured points are shown.

3.4.2 Boundary Conditions

The boundary conditions for LH model is shown in Table 3.5, in which the locations of boundaries are shown in Figure 3.23. The boundary conditions vary with wind scenarios, which are classified into north, northeast, south and southeast wind. In each wind scenario, the average wind speed indicated in Table 1.2 is used. To simulate the envelope of staircases which have porosity of 50%, Porous Jump model [57] is used. Porous jump conditions are normally used to model a thin "membrane" that has pressure-drop characteristics. In this Porous Jump mode, there are two important parameters, the thickness of the "membrane" and the pressure jump coefficient which define the pressure drop over this "membrane".

Table 3.5 Boundary conditions for Learning Hub natural ventilation simulation.

Boundary	North Wind	Northeast Wind	South Wind	Southeast Wind
①	Velocity Inlet Wind Speed = 2 m/s	Velocity Inlet Wind Speed = 2.9 m/s	Pressure Outlet	Pressure Outlet
②	Pressure Outlet	Velocity Inlet Wind Speed = 2.9 m/s	Pressure Outlet	Velocity Inlet Wind Speed = 3.2 m/s
③	Pressure Outlet	Pressure Outlet	Velocity Inlet Wind Speed = 2.8 m/s	Velocity Inlet Wind Speed = 3.2 m/s
④	Pressure Outlet	Pressure Outlet	Pressure Outlet	Pressure Outlet
⑤	Symmetry	Symmetry	Symmetry	Symmetry
⑥	Wall	Wall	Wall	Wall
Envelopes of Staircases	Porous Jump Thickness: 0.1 m; Pressure-Jump Coefficient: 31.24 m ⁻¹			

3.4.3 Results and Discussion

Based on the methodology mentioned in Section 3.1 of this chapter, the simulation result converged after 1000 iterations. The results are organized by wind directions: north wind, northeast wind, south wind and southeast wind. In each wind scenario, the contours of static pressure and velocity vectors are provided. All the results are based on the horizontal plane which is 1.5 meters height above the floor. The reason for choosing such plane is that 1.5 meter height is the height of people activities.

In all the figures below, z is the coordinate of height. For example $z = 1.5$ m means that the height of the plane is 1.5 m above the ground. Similarly, $z = 31.9$ m means that the plane is 31.9 m above the ground. All the circled areas in light blue are the blocks of LH building. The area surrounded by these blocks is the atrium area, which is interested for natural ventilation.

3.4.3.1 North Wind Scenario

From Figure 3.27, it is clearly seen that from Level 1 to 2, the maximum wind velocity in the atrium area decreases, and the areas with wind velocity larger than 0.6 m/s [8] decrease. This is because the size of blocks increases and the distance between blocks decrease, so it reduces the possibility of wind entering into the atrium area. From Level 2 to 6, the wind profiles are almost the same.

From Level 6 to 7, the area with wind velocity larger than 0.6 m/s increases. There are two possible reasons for this situation. One is that some blocks are removed compared to Level 6. The other is that the HSS building is located in the northeast of LH and is 12.5 m

lower than LH, meaning that the effect of wind blockage due to HSS building almost disappears from Level 7 and above.

The major difference between Level 7 and 8 is that the block located in the north is removed, so that a good channel is created for cross ventilation. This situation also happens in Level 9. However, the average wind velocity in Level 9 increases compared that in Level 8. This is because that the Business School Building located in the northwest of LH is 1.7 m lower than LH, meaning that the blockage effect due to Business School almost disappears from level 9.

Figure 3.27 Velocity vectors of 9 floors for north wind scenario.

Figure 3.28 Circulation winds in between the buildings.

3.4.3.2 Northeast Wind Scenario

Similar to North Wind Scenario, from Level 1 to Level 2, the maximum wind velocity in the atrium area decreases and the areas with wind velocity larger than 0.6 m/s decrease largely, as shown in Figure 3.29 This is because that the size of blocks increases and the distance between blocks decreases; as a result it reduces the possibility of wind entering into the atrium area.

It is found that there is almost no wind from Level 2 to Level 4 in northeast wind scenario, which is very different from north wind scenario. This is due to the blockage effect of HSS building. The wind blows from northeast and HSS is located just in the northeast of Learning Hub. Such blockage effect of HSS is much bigger than that in the north wind scenario. In Level 5 and 6, there are some winds, although the blockage effect of HSS still exists. One possible reason is the circulations of wind in between buildings when wind blows from lower building to higher building, as illustrated in Figure 3.28. Such circulation enables the wind to blow through the gaps in between the blocks.

The reasons for the difference between Level 6 and 7 are the same as that in north wind scenario. One is that some blocks are removed compared with Level 6. The other is that the effect of wind blockage almost disappears due to HSS building. In Level 7, a channel for cross ventilation is created by removing two blocks. Similarly, another channel for cross ventilation is created in Level 8 by removing one north block.

It is found that the average wind velocity in Level 9 increases compared that with Level 8 in northeast wind scenario, which is similar to north wind scenario. The possible reason is that blockage effect due to Business School almost disappears from Level 9.

Figure 3.29 Velocity vectors of 9 floors for northeast wind scenario.

3.4.3.3 South Wind Scenario

The flow patterns of Level 2 and 3 are almost the same, as shown in Figure 3.30. The wind flow patterns of Level 4, 5 and 6 are almost the same. From Level 7 to 9, areas with velocity larger than 0.6 m/s increases. The possible reason is that some blocks are removed, which results in enhancing the cross ventilation.

Figure 3.30 Velocity vectors of 9 floors for south wind scenario.

3.4.3.4 Southeast Wind Scenario

The wind flow patterns of Level 3, 4, 5 and 6 are almost the same. From Level 7 to 9, areas with velocity larger than 0.6 m/s increases. The possible reason is that some blocks are removed, which results in enhancing the cross ventilation.

Figure 3.31 Velocity vectors of 9 floors for southeast wind scenario.

3.4.4 Summary

Based on the discussions above, several conclusions are made as follows. (1) North wind scenario is the worst among four wind scenarios. This is mainly due to the blockage effect by the Business school. (2) In Level 2 to 6, the ventilation is very bad especially for the north and northeast wind scenarios.

The percentage of areas with velocity greater than 0.6 m/s is shown in Table 3.6. It is shown that the best situation of natural ventilation in the atrium occurs when southeast wind prevails. This always happens from June to September in Singapore, when 47.2% of total atrium area are naturally ventilated. The worst case happens when north wind prevails, which always happens from December to March. In this case, the atrium areas from Level 2 to Level 7 are totally not naturally ventilated at all.

Table 3.6 Percentage of comfort areas.

Levels	North Wind	Northeast Wind	South Wind	Southeast Wind
Level 1	5 %	10 %	35%	60%
Level 2~Level 6	0 %	Level 2~4: 0% Level 5: 3 % Level 6: 5%	20%	20%
Level 7	0 %	50%	75%	80%
Level 8	20%	70%	75%	95%
Level 9	30%	70%	80%	90%

CHAPTER 4 ENERGY EFFICIENCY FOR EFFECT OF BUILDING ENVELOPE

In general, there are three most commonly-used architectural shading designs in buildings, namely the external overhang design, vertical greenery shading, and internal venetian blind. In this chapter therefore, the three shading envelope designs are studied via energy and CFD simulations: (1) external building envelope including the plane-plate and curved-shell envelopes, (2) the vertical green envelope, and (3) internal smart blind. The building energy simulation is conducted by the EnergyPlus-based software, OpenStudio, in order to study the effect of various building envelope parameters on the indoor cooling load, due to the external building and vertical green envelopes respectively. For analysis of effect of the internal venetian blind, the CFD simulation software, Fluent, is used for modeling and simulation of the temperature profile inside the building.

4.1 Methodology for Simulation of Building Energy

OpenStudio is an open source software for modeling and simulation of building energy, developed by National Renewable Energy Laboratory (NREL), in order to simulate building energy based on EnergyPlus and carry out the advanced daylight analysis based on Radiance. A graphical energy-modeling tool, OpenStudio, includes the functions of visualization, and schedules editing, loads constructions and materials editing, a drag and drop interface to make input of resources for spaces and zones, a visual HVAC and service water heating design tool, and output visualization. In the present work, OpenStudio is used to simulate the building energy consumption for various types of

building envelope, such as the plane-plate envelope, curved-shell envelope and vertical green envelope.

For the effect of the internal venetian blind on the energy efficiency, ANSYS Fluent is used to study the indoor temperature and airflow of the indoor environment subject to internal blind. The typical value of solar radiation in Singapore used in the present CFD simulation work is the same as the default in OpenStudio, namely the weather data used in EnergyPlus [58].

4.1.1 Geometries of Simulation Models

In the present work, a single-storey building without window is used in the simulation model, as shown in Figure 4.1, with the width of 10 m, the length of 10 m and the height of 4 m. In order to investigate the effect of building envelope coupled with window, a model with window is presented and shown in Figure 4.2.

Figure 4.1 Geometry of the basic energy simulation model without window.

Figure 4.2 Geometry of basic energy simulation model with window on east wall.

4.1.1.1 Plane-Plate Envelope

For the effect of geometry of the plane-plate envelope on energy efficiency, three parameters are studied in details via modeling and simulation. They are the length of building envelop (L), the distance between the building envelope and wall (D), and the angle of the building envelope and wall (θ), as shown in Figure 4.3. In addition, the building height (H) is used to normalize the parameters L and D . In the present numerical simulations, the L/H ranges from 0 to 1, D/H from 0 to 1, and θ from 0° to 90° .

Figure 4.3 Geometric parameters of plane-plate envelope.

4.1.1.2 Curved-Shell Envelope

For the curved-shell building envelope, there are two commonly-used positions: the horizontal overhang and vertical envelope, as shown in Figure 4.4. For analysis of the effect of geometry of curved shell envelope on energy efficiency, two parameters are studied in details via modeling and simulation. They are the length of building envelop (L) for the horizontal overhang design, and the distance between the building envelope and wall (D) for the vertical envelope design.

Figure 4.4 Geometric parameters of curved-shell envelope for the effect on building energy efficiency in the vertical envelope design (a) and the horizontal overhang design (b).

4.1.1.3 Vertical Green Envelope

For the effect of vertical green envelope on the building energy efficiency, a porous model is used to simulate its shading effect by capturing the porosity ratio of the whole vertical green envelope. The porosity ratio is the ratio between area of hole and area of whole envelope and varies from 0 to 1, whereby 0 means there is no holes on the envelope and 1 means there is no envelope. The simulation models of vertical envelope with different porosity ratio are shown in Figure 4.5, in which the distance between the vertical green envelope and building wall is constant in order to focus on the effect of porosity ratio. In the present model, the distance between the vertical green envelope and building wall is 1m which is referred to as the Clean Tech One building.

In order to investigate the correlation of vertical green envelope and window in terms of building energy efficiency, here with-window and windowless scenarios are carried out. In each scenario, there are 9 simulation models with porosity ratio 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90%. Figure 4.6 shows the simulation model of vertical green envelope with 50% porosity.

Figure 4.5 Geometry of simulation models with vertical green envelope which has porosity ratio of 10% (a), 20% (b), 30% (c), 40% (d), 50% (e), 60% (f), 70% (g), 80% (h) and 90% (i).

Figure 4.6 Geometry of simulation models with vertical green envelope with 50% porosity ratio for building with window (a) and windowless building (b).

4.1.1.4 Internal Smart Blind

For the effect of internal smart blind on building energy efficiency, Fluent is used to simulate the indoor temperature and airflow. Compared with static blind, the smart blind can adjust its tilt angle to face directly towards the sun, according to the sun's elevation angle by communicating with the luminance sensor. In the case of rainy days, the humidity sensor is involved as well.

The simulation model is shown in Figure 4.7, in which the room is a cubic box of $1.5 \times 1.5 \times 2 \text{ m}^3$, and the blind has a length of 1.5m, width of 0.05 m and thickness of 0.003 m. The distance between two neighbor blinds is 0.05m meaning that, when the blinds are closed, there is no gap between the two neighbor blinds. In the present simulation work, the west wall of the building is a window made up of glass material and other walls are made up with concrete.

Figure 4.7 Geometry of simulation model with internal smart blind.

The blind tilt angle is calculated based on the vector of solar incident ray which is calculated by solar calculator in ANSYS Fluent and shown in Table 4.1 From the blind title angle, the vertical distance of gap between two neighbor blinds can be calculated. Since the window is located on the west façade, the direct solar radiation can only enter into the building during the afternoon time from 1:00 pm to 6:00 pm. Therefore, the smart blind is fully opened from 8:00 am to 12:00 pm.

Table 4.1 Blind tilt angle and openness factor calculated based on vector of solar incident ray.

Time	Vector of solar incident ray			Blind Tilt Angle (°)	Vertical Blind Gap Distance (cm)	Openness Factor
	x	y	z			
8:00 am	-0.3924003	0.8916435	0.2258182	90	5	100%
9:00 am	-0.3870584	0.8056033	0.4485411	90	5	100%
10:00 am	-0.3827416	0.6681235	0.6380594	90	5	100%
11:00 am	-0.3788352	0.4784777	0.7921761	90	5	100%
12:00 pm	-0.3765128	0.2596771	0.8892727	90	5	100%
1:00 pm	-0.3756232	0.02318264	0.9264825	68	3.12	62%
2:00 pm	-0.3765139	-0.2100136	0.9022924	64	2.84	57%
3:00 pm	-0.3782829	-0.4383183	0.8153399	55	2.11	42%
4:00 pm	-0.381805	-0.628249	0.677885	43	1.32	26%
5:00 pm	-0.3861023	-0.7824106	0.4886294	29	0.64	13%
6:00 pm	-0.3913333	-0.8796299	0.2703876	16	0.19	4%

4.1.2 Assumption and input of Simulation Model

For modeling of the plane-plate, curved-shell and vertical green envelope, OpenStudio software is used with the default model of AHARE Medium Office [59]. In the Medium Office model, the default values are used to simulate the cooling load, as shown in Table

4.2, in which the density of people is given as 0.054 people/m^2 , the density of lighting energy 9.688 W/m^2 , the plug load 5.813 W/m^2 , and air infiltration rate 0.150 h^{-1} . As well known, the total indoor cooling load consists of two parts, the sensible load and latent loads. In this thesis, sensible load refers to the sensible heating gains from outdoor environment through convection, conduction or solar radiation, and latent load refers to the latent heat gains from outdoor environment when moisture is added to the space by means of vapor emitted by the occupants or generated by a process or through air infiltration. It is thus assumed that the human body contributes to the sensible and latent loads, and the equipment and lighting contribute to the sensible load only.

Table 4.2 Cooling load contribution for energy simulation

Contribution Factors	People density (people/m²)	Plug load (W/m²)	Lighting load (W/m²)	Air infiltration rate (h⁻¹)
Energy density	0.054	5.813	9.688	0.150

In order to simulate the one-year energy consumption, the schedules are assumed as follows, which are applicable for simulation of the plane-plate envelope, the curved-shell envelope and the vertical green envelope. In general, the schedules include three main activities for the simulation model, namely the schedule of lighting system, the schedule of occupancy, and the schedule of equipment, as shown in Figures 4.8 to 4.13. Inside these figures, the y-axis represents the normalized value from 0 to 1. In Figure 4.8, for example, the value of y-axis is 0.86 at 8:00 am, meaning that the lighting load is 86% of the maximum lighting load.

4.1.2.1 Schedule of Lighting System

Figure 4.8 Schedule of lighting system on weekdays.

Figure 4.9 Schedule of lighting system on Saturday.

The schedule of lighting system used in the study is the default value in OpenStudio. The lighting system is turned off on Sunday and turned on during weekdays and Saturday, as shown in Figures 4.8 and 4.9 respectively. During weekdays, the lighting is turned on starting from 5:00 am and turned off after 11:00 pm, and the peak load starts from 8:00 am to 5:00 pm. On Saturday, the lighting is turned on starting from 6:00 am and turned off after 5:00 pm, and the peak load starts from 8:00 am to 2:00 pm.

4.1.2.2 Schedule of Occupancy

Figure 4.10 Schedule of occupancy on weekdays.

Figure 4.11 Schedule of occupancy on Saturday.

The schedule of occupancy used in this study is the default value in OpenStudio. People do not come to the building on Sunday and come to work during weekdays and Saturday shown in Figures 4.10 and 4.11 respectively. During weekdays, the people start to come to office from 6:00 am and leave after 10:00 pm, and from 8:00 am to 5:00 pm all the people are assumed in the office except of the lunch time from 12:00 pm to 1:00 pm. On Saturday, 50% of people come to the office since 8:00 am and leave after 2:00 pm.

4.1.2.3 Schedule of Equipment

Figure 4.12 Schedule of equipment on weekdays.

Figure 4.13 Schedule of equipment on Saturday.

The schedule of equipment used in this study is the default value in OpenStudio. It is assumed that the equipment is partially turned on during weekdays and Saturday, and turned off on Sunday, as shown in Figures 4.12 and 4.13 respectively. During weekdays, the percentage of the equipment in usage increases from 40% to 86% from 6:00 am to 8:00 am, and then remains 80% until 5:00 pm except of lunch time from 12:00 pm to 1:00 pm. Then it starts to decrease after 5:00 pm and returns to 40% from 11:00 pm. On Saturday, the percentage of the equipment in usage increases from 30% to 50% in the

period between 6:00 am and 8:00 am and starts to decrease after 2:00 pm, and then returns to 30% after 5:00 pm.

4.1.2.4 Assumptions and Inputs for CFD Simulation

For modeling of internal smart blind, Fluent is engaged to simulate the internal temperature and airflow with or without smart blind or with static blind. The solar load model in Fluent is engaged to calculate radiation effects from the sun ray that enters the computational domain. The solar load model includes a solar calculator utility that can be used to construct the sun's location in the sky for a given time-of-day, date, and position. As for the ventilation, k- ϵ renormalization group theory (RNG) model is used to capture the buoyance driven ventilation inside the building.

Following assumptions are made for the present CFD simulation:

- It is assumed that no air-conditioning is provided inside the building.
- The shading effect from neighbor buildings is not considered, in order to focus on the effect of smart blind on building energy efficiency.
- For Benchmark D mentioned in 4.1.3 Post Process, the static blind is assumed to be flat all the time.

The solar radiation intensity value and outdoor temperature used in the CFD simulation is shown in Table 4.3. Diffuse solar radiation is due to the sunlight that has been scattered by molecules and particles in the atmosphere, while direct radiation comes from the sun on a cloudless day.

Table 4.3 Solar radiation intensity and outdoor temperature in Singapore on 21st June [51].

Time	Global horizontal radiation (W/m ²)	Direct normal radiation (W/m ²)	Diffuse radiation (W/m ²)	Dry Bulb Temperature (°C)
8:00 am	22	0	22	27.4
9:00 am	149	59	129	29
10:00 am	305	106	246	29
11:00 am	442	95	373	29.8
12:00 pm	542	107	451	31
1:00 pm	597	193	420	31
2:00 pm	601	192	424	29.2
3:00 pm	628	280	386	30
4:00 pm	570	345	312	30
5:00 pm	435	375	215	30.6
6:00 pm	226	196	151	30

The boundary conditions in the present CFD simulation are shown in Table 4.4. Except that the west wall is made up with glass that is semi-transparent, the other walls are made up with concrete that is opaque. The U value is calculated based on Equations 2.3 to 2.4 and listed in Table 4.5. As for all the materials used in the CFD simulation, the material properties are shown in Table 4.5 including the density, specific heat and thermal conductivity.

Table 4.4 Boundary conditions in CFD simulation.

	Boundary Condition	Boundary Condition	Materials	Thickness (m)	U value (W/(m ² ·K))
East	Wall	Opaque	Concrete	0.21	1.6756
North	Wall	Opaque	Concrete	0.21	1.6756
South	Wall	Opaque	Concrete	0.21	1.6750
Roof	Wall	Opaque	Concrete	0.25	0.5277
Ground	Wall	Opaque	Concrete	0.21	2.1305
West	Wall	Semi-Transparent	Glass	0.006	5.2800
Blind	Wall	Opaque	Aluminium	0.003	6.0970

Table 4.5 Material properties used in CFD simulation [12].

	Concrete	Carpet	Glass	Aluminium	Building Insulation
Density (kg/m^3)	2400	288	2220	2719	10
Specific Heat ($\text{J/kg}\cdot\text{K}$)	750	1380	830	871	830
Thermal Conductivity ($\text{W}/(\text{m}\cdot\text{K})$)	1.442	0.06	1.15	202.4	0.1

4.1.3 Post Process

For analysis of building energy consumption, the post process of energy simulation is conducted. Here the final indoor district cooling load with unit of Giga-Joule (GJ) is used as a key parameter for comparison and analysis of the effect of various envelope parameters. In order to study the improvement by adding the external building envelope, two benchmark models are used in the study: Benchmark A and Benchmark B.

- Benchmark A is the model without window and envelope, and it has the cooling load of 26.14 GJ.
- Benchmark B is the model with window of $1 \times 8 \text{ m}^2$ located on the west side and without external envelope, and it has the cooling load of 32.88 GJ.

These two benchmarks are used for comparison with the following case studies by varying different parameters, in order to analyze the effect of external building envelope.

For analysis of building energy consumption, the post process of CFD simulation is conducted. Here the ambient temperature of center point inside the building and the surface temperature of east wall are used as key parameters for comparison and analysis

of the effect of smart blind. In order to study the improvement by adding the internal smart blind, two benchmark models are used in the study: Benchmark C and Benchmark D.

- Benchmark C is the model without internal blind.
- Benchmark D is the model with static blind which cannot change its tilt angle.

These two benchmarks are used for comparison with the smart blind case with different tilt angle at different time period, in order to analyze the effect of internal smart blind.

4.2 Effect of Plane-Plate Envelope

4.2.1 Effect of Distance between Building Envelope and Wall on the relationship of Energy Efficiency and Length of Building Envelope

In this section, the vertical plane-plate envelope length L is normalized against the building height H to elucidate the effect of the envelope length L on building indoor cooling load, as shown in Figure 4.14. This figure is plotted for the variation of cooling load with L/H for given D/H , in which the y-axis represents the indoor cooling load with unit of GJ and the x-axis the L/H .

Figure 4.14 Effect of distance (D) between building envelope and wall on the relationship of energy efficiency and length (L) of external plane-plate building envelope for building with window.

Figure 4.14 shows the relationship between the cooling load and the ratio L/H for different ratios D/H , where L denotes the envelope length, H the building height, and D the distance between building envelope and wall. For the case of $D/H = 0.025$, the cooling load decreases with increasing L/H from 0 to 1, and reaches the minimum if $L/H = 1.014$. By comparing with Benchmark B with the cooling load of 32.88 GJ, there is cooling load saving of 14.93% at the minimum point. Similarly, for the case of $D/H = 0.125$, the cooling load decreases with increasing L/H from 0 to 0.861, and then increases when L/H is larger than 0.861. If the cooling load reaches the minimum point where L/H is 0.861, a cooling load saving of 14.7% is achieved if compared with

Benchmark B. For the case of $D/H = 0.25$, the cooling load decreases with increasing L/H from 0 to 0.8, and then increases when $L/H > 0.8$. At the minimum point where $L/H = 0.8$, a cooling load saving of 14.66% is achieved when compared with Benchmark B. For the case of $D/H = 0.5$, the cooling load decreases with increasing L/H from 0 to 0.762, and then increases when $L/H > 0.762$. At the minimum point where $L/H = 0.762$, a cooling load saving of 14.22% is achieved if compared with Benchmark B. For the case of $D/H = 1$, the cooling load decreases with increasing L/H from 0 to 0.753, and then increases when $L/H > 0.753$. At the minimum point where $L/H = 0.753$, a cooling load saving of 13.42% is achieved when compared with Benchmark B. All these numbers are listed in Table 4.6.

Table 4.6 Minimum cooling load by varying D/H for building with window and plane-plate envelope.

D/H	At minimum cooling load		Percentage of energy saving compared with Benchmark B (%)
	L/H	Cooling Load (GJ)	
0.025	1.014	27.972	14.93
0.125	0.861	28.048	14.70
0.250	0.800	28.061	14.66
0.500	0.762	28.205	14.22
1.000	0.753	28.464	13.43

With a larger distance D , the effect on energy efficiency by L is smaller than that for a small distance D . For a given distance D , it is found that the cooling load decreases first and then increases after it reaching a minimum point, while increasing the length of envelope for a building with window. The values of L/H at the minimum cooling loads reduce with increasing D/H . It is also seen that, if the vertical length L increases to 50%

of the height of the building, the effect on energy efficiency is improved significantly, i.e. cooling load saving of 13%. However, if L increases further, the effect on energy efficiency becomes insignificantly. This is attributable to the maximum blocking of solar radiation by a long external envelope, which reduces the solar heat gain into the building. In addition, it is observed that the maximum difference between the percentage of cooling load saving is 1.5% at these minimum points, which occurs between 0.025 and 1 of D/H .

As for the windowless building, the cooling load decreases with increasing length of envelope L and the improvement of energy efficiency by increasing L becomes smaller than when distance D is small. Compared with with-window buildings, the improvement on energy efficiency by installing such external building envelope is not significant, with maximum cooling load saving of 1.95% compared with Benchmark A with 26.14 GJ.

Figure 4.15 Effect of distance (D) between building envelope and wall on the relationship of energy efficiency and length (L) of external plane-plate building envelope for building without window.

Generally, energy efficiency can be improved by increasing the length L of external plane-plate building envelope, especially for building with window. In order to maximize

the energy efficiency, L/H should be chosen in the range of 0.75 to 1. Normally a maximum energy saving of 14.93% can be achieved by optimizing the length of envelope for with-window building. For windowless building, there is no much improvement on energy efficiency by varying the length of plane-plate building envelope.

4.2.2 Effect of Length of Building Envelope on the relationship of Energy Efficiency and Distance between Building Envelope and Wall.

In this section, the horizontal distances D between the external plane-plate building envelope and wall, is normalized against the building height H to elucidate the effect on building indoor cooling load, as shown in Figures 4.16 and 4.17. These figures are plotted for the variation of cooling load with D/H for given L/H , in which the y-axis represents the indoor cooling load with unit of GJ and the x-axis the D/H .

Figure 4.16 Effect of length (L) of building envelope on the relationship between building cooling load and distance (D) between plane-plate envelope and wall for

building with window.

Table 4.7 Minimum cooling load with varying L/H for building with window and plane-plate envelope.

L/H	Minimum Point for Cooling Load		Percentage of energy saving compared with Benchmark B (%)
	D/H	Cooling Load (GJ)	
0	1.240	29.418	10.530
0.25	0.756	28.679	12.778
0.5	0.162	28.403	13.615
0.75	0	28.261	14.048
1	0	28.125	14.462

Figure 4.16 shows the relationship between the cooling load and the ratio D/H for different ratios L/H , where D the distance between building envelope and wall, H the building height, and L denotes the envelope length. For the case of $L/H = 0$, the cooling load decreases with increasing D/H from 0 to 1, and reaches the minimum when D/H is 1.24. By comparing with the Benchmark B with the cooling load of 32.88GJ, cooling load saving of 10.53% is achieved at the minimum point where D/H is 1.24. For a case of $L/H = 0.25$, the cooling load increases with increasing D/H from 0 to 0.756, and then increases when D/H is larger than 0.756. At this minimum point where D/H is 0.756, cooling load saving of 12.78% is achieved if compared with Benchmark B. For a case of $L/H = 0.5$, the cooling load is decreased with increasing D/H from 0 to 0.162, and then increases when D/H is larger than 0.162. At the minimum point where D/H is 0.162, cooling load saving of 13.02% is achieved if compared with Benchmark B. For a case of $L/H = 0.75$ or $L/H = 1$, the cooling load increases with increasing D/H from 0 to 1. The minimum point occurs when D/H equals to a negative number which is not possible

which means that in reality distance D should be remain unchanged a small number when L/H equals to 0.75 or 1. All these numbers are listed in Table 4.7.

It is found that for a with window building, when $L/H \leq 0.5$, the cooling load decreases first and then increase after reaching a minimum point with increasing D , and the value of D/H where the minimum cooling load occurs reduces with increasing L/H . However, when $L/H > 0.5$, the cooling load increases with increasing distance D and the improvement of energy efficiency is not significant by varying distance D compared with that when $L/H \leq 0.5$. Therefore, the distance D should be kept as small as possible when $L/H > 0.5$, in order to maximize the energy efficiency.

Figure 4.17 Effect of length (L) of building envelope on the relationship between building cooling load and distance (D) between plane-plate envelope and wall for building without window.

As for the windowless building, the cooling load decreases firstly and then increases with increasing distance D when $L/H \leq 0.75$. When $L/H > 0.75$, the cooling load increases with increasing distance D . However, compared with with-window building, the improvement on energy efficiency by installing the building envelope is not significant, with maximum 1.95% cooling load saving.

Generally, building energy efficiency can be improved by varying the distance D between plane-plate envelope and wall, and the improvement is significant for with-window building. In order to maximize the energy efficiency, building envelope D/H should be in the range of 0.162~1.24 when $L/H \leq 0.5$ and 0 when $L/H > 0.5$, with cooling load saving of 10.5~13.6 % and 14~14.5% compared with Benchmark B. As for windowless building, there is no much improvement on energy efficiency by changing the distance D .

4.2.3 Effect of Angle θ between Building Envelope and Wall on Energy Efficiency

In this section, the angle θ between the external plane-plate building envelope and wall is studied to clarify the effect on indoor cooling load, as shown in Figures 4.18 o 4.25. The y -axis represents the indoor cooling load and the x -axis represents the angle θ .

As shown in Figure 4.18, where $D/H = 0.025$, the cooling load decreases first, and then increases after reaching a minimum point with increasing the angle θ when $L/H \leq 0.5$. Then cooling load profile with angle θ becomes very flat when $L/H > 0.5$. Similarly, for $D/H \in (0.025, 1]$, the cooling load decreases first, and then increases after reaching a minimum point with increasing the angle θ when $L/H \leq 0.5$ and the cooling load profile

with angle θ becomes flat when $L/H > 0.5$, as shown in Figures 4.19 to 4.23. However, the cooling load profiles with angle θ become more flat with increasing D/H at same L/H .

In order to investigate the effect of angle θ on cooling load, the cooling load savings at $\theta = 0^\circ$ is used to compare with the minimum cooling load. It is found that the maximum cooling load saving difference of 4.41% is achieved by increasing θ from 0° to 45° , for $L/H = 0.25$ and $D/H = 0.025$, as shown in Table 4.8. However, with increasing L/H or D/H , it is found that the cooling load saving difference with varying angle θ decreases. It is seen that the cooling load saving difference between that at minimum cooling load and at $\theta = 0^\circ$ with varying angle θ becomes negligible with maximum cooling load saving difference of 0.71%, for $L/H > 0.5 \cup D/H > 0.125$.

Figure 4.18 Effect of the angle θ between plane-plate envelope and wall on building cooling load for the building with window at $D/H = 0.025$.

Figure 4.19 Effect of angle θ between plane-plate envelope and wall on building cooling load for building with window at $D/H = 0.125$.

Figure 4.20 Effect of angle θ between plane-plate envelope and wall on building cooling load for building with window at $D/H = 0.25$.

Figure 4.21 Effect of angle θ between plane-plate envelope and wall on building cooling load for building with window at $D/H = 0.5$.

Figure 4.22 Effect of angle θ between plane-plate envelope and wall on building cooling load for building with window at $D/H = 0.75$.

Figure 4.23 Effect of angle θ between plane-plate envelope and wall on building cooling load for building with window at $D/H = 1$.

Table 4.8 Comparison study of minimum cooling load with θ .

<i>D/H</i>	The parametric values making the minimum cooling load								At $\theta = 0^\circ$				Difference of cooling load saving between those at $\theta = 0^\circ$ and at minimum cooling load (%)			
	θ (°)				Energy saving compared with Benchmark B (%)				Energy saving compared with Benchmark B (%)							
	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	<i>L/H</i>	
	0.25	0.5	0.75	1	0.25	0.5	0.75	1	0.25	0.5	0.75	1	0.25	0.5	0.75	1
0.025	45.50	15.25	27.50	-10.00	6.17	16.86	14.19	14.40	1.76	13.53	13.96	14.39	4.41	3.33	0.23	0.01
0.125	33.70	15.83	11.11	-21.67	7.84	13.88	14.08	14.34	6.11	13.66	14.05	14.29	1.73	0.22	0.03	0.05
0.25	27.83	12.50	-3.75	-25.00	9.71	13.83	14.06	14.20	9.00	13.69	13.99	14.14	0.71	0.14	0.07	0.06
0.5	13.00	10.50	-13.33	-85.00	11.36	13.57	13.70	13.97	11.25	13.50	13.69	13.75	0.11	0.07	0.01	0.22
0.75	9.00	-13.50	-20.00	-7.50	11.92	13.35	13.44	13.42	11.89	13.29	13.41	13.41	0.03	0.06	0.03	0.01
1	6.67	-7.14	-12.50	-35.00	12.18	13.12	13.18	13.24	12.17	13.11	13.17	13.20	0.01	0.01	0.01	0.04

As for the windowless building shown in Figure 4.24, the cooling load does not increase significantly by varying the angle θ between building envelope and wall. The maximum cooling load saving is around 0.23% by varying the angel which is negligible.

Figure 4.24 Effect of angle θ between plane-plate envelope and wall on building cooling load for windowless building.

Generally, energy efficiency can be improved by varying the angel θ between plane-plate building envelope and wall, and the improvement is significant for with window building, especially when $L/H \leq 0.5 \cap D/H \leq 0.125$. A maximum cooling load saving difference of 4.44% is achieved with varying angle θ from 0° to 45.5° , for $L/H = 0.25$ and $D/H = 0.025$, shown in Table 4.8. With increasing either D or L , the energy saving difference decreases by varying the angle θ .

4.2.4 Effect of Location of Window on Energy Efficiency

In this section, simulation is carried out for the effect of window on building energy efficiency via comparison between the buildings with and without window, as shown in

Figure 4.25. The y -axis represents the cooling load and x -axis represents the cases of different combinations of parameter L and D . The blue and red color columns represent the cases without window but with external envelope on the east and west side respectively, and correspondingly green and purple columns represent the cases with window and external plane-plate envelope on the east and west side. In Figure 4.25, the data is categorized into six major groups with different values of parameter D , and then further classified into five minor groups with different values of parameter L .

It is found that the location of external building envelopes have negligible effect on indoor cooling load for windowless buildings and with-window building.

Figure 4.25 Bar chart of indoor cooling load with or without window and with envelope on east or west.

4.2.5 Remarks

From the simulation work above, following conclusions are made for the building with plane-plate envelope:

- For building with window, the length of plane-plate envelope L should be in the range of 0.75 to 1 with cooling load reduction of 13.43 to 14.93% compared with Benchmark B, in order to maximize the energy efficiency.
- For building with window, the distance between plane-plate envelope and wall D/H should be in the range of 0.162 to 1.24 when $L/H \leq 0.5$ and 0 when $L/H > 0.5$, with cooling load saving of 10.5~13.6 % and 14~14.5% compared with Benchmark B
- For building with window, the angle θ between plane-plate envelope and wall should be in the range of 15° to 46° when $L/H \leq 0.5$ and $D/H \leq 0.125$, with the maximum energy saving of 4.4% compared with the cooling load at $\theta = 0^\circ$. The angle θ could be any value when $L/H > 0.5$ or $D/H > 0.125$ as a result of without affecting the energy efficiency by more than 1%.
- For windowless building, there is no much improvement on energy efficiency by changing L or D or θ .

4.3 Effect of Curved-Shell Envelope

4.3.1 Effect of Distance between Building Envelope and Wall on the relationship of Energy Efficiency and Length of Building Envelope

In this section, curved shell envelope length L is normalized against building height H to elucidate its effect on building indoor cooling load, as shown in Figures 4.26 to 4.28. The y-axis represents the indoor cooling load with unit of GJ and the x-axis the L/H .

Figure 4.26 Effect of distance between Building Envelope and Wall (D) on the relationship of energy efficiency and length of external plane-plate building envelope (L) for building with window and vertical curved-shell envelope.

Figure 4.26 shows the relationship between the cooling load and the ratio of building envelope length and building height L/H for vertical curved-shell envelope. As shown in Figure 4.26, the cooling load decreases first, and then increases after reaching a minimum point with increasing L/H from 0 to 1. The profile of cooling load becomes flat with increasing the distance D between envelope and wall.

Table 4.9 Minimum cooling load with varying L/H for building with window and vertical curved-shell envelope.

D/H	At minimum cooling load		
	L/H	Cooling Load (GJ)	Percentage of energy saving compared with Benchmark B (%)
0.025	0.793	27.708	15.729
0.125	0.796	28.131	14.442
0.250	0.799	28.822	12.342
0.500	0.802	29.987	8.798
0.750	0.827	30.671	6.719
1.000	0.802	31.244	4.976

It is found that the minimum cooling load occurs when $L/H \in (0.79, 0.83)$ with improvement of 4.98~15.73% on cooling load compared with Benchmark B, for various D/H . The result is summarized in Table 4.9.

Figure 4.27 Effect of distance between Building Envelope and Wall (D) on the relationship of energy efficiency and length of external plane-plate building envelope (L) for building with window and horizontal curved-shell envelope.

Figure 4.27 shows the relationship between the cooling load and the ratio of building envelope length and building height L/H for horizontal curved-shell envelope. As shown in Figure 4.27, the cooling load decreases first, and then increases after reaching a minimum point with increasing L/H .

Table 4.10 Minimum cooling load with varying L/H for building with window and horizontal curved-shell envelope.

D/H	When cooling load reaches minimum		
	L/H	Cooling Load (GJ)	Percentage of energy saving compared with Benchmark B (%)
0.025	1.117	29.506	10.261
0.125	1.080	29.401	10.581
0.250	1.064	29.201	11.189

It is found that, the minimum cooling load occurs at $L/H \in (1.06, 1.12)$ with cooling load saving of 10.26 to 11.19% compared with Benchmark B, for various D/H , as shown in Table 4.10. As for the windowless building, the energy efficiency of curved-shell envelope is not significant, with the maximum cooling load saving of 0.75%.

Generally, energy efficiency can be improved by increasing length L of the curved-shell building envelope, especially for building with window. In order to maximize the energy efficiency, L/H should be in the range of 0.79 to 0.83 for vertical curved-shell envelope and 1.06 to 1.12 for horizontal curved-shell envelope, as a result of reducing cooling load by 4.98 to 15.73% and 10.26 to 11.19% respectively. For windowless building, there is not much improvement on energy efficiency by changing the length of building envelope.

4.3.2 Effect of Length of Building Envelope on the relationship of Energy Efficiency and Distance between Building Envelope and Wall

In this section, horizontal distances D between the curved-shell building envelope and wall, is normalized against the building height H to elucidate its effect on building indoor cooling load, as shown in Figures 4.28 to 4.30. The y-axis represents the indoor cooling load and the x-axis represents the D/H .

Figure 4.28 Effect of length of building envelope (L) on the relationship between building cooling load and distance between plane-plate envelope and wall (D) for building with window and vertical curved-shell envelope.

Figure 4.28 shows the relationship between cooling load and D/H for vertical curved-shell envelope. As shown in Figure 4.28, the cooling load decreases first, and then increases after reaching a minimum point with increasing D/H , when $L/H = 0.25$. However, when $L/H > 0.25$, the cooling load increases first and decrease after reaching a maximum point with increasing D/H .

Table 4.11 Minimum cooling load with varying D/H for building with window and vertical curved-shell envelope.

L/H	At minimum cooling load		
	D/H	Cooling Load (GJ)	Percentage of energy saving compared with Benchmark B (%)
0.25	0.253	31.089	5.447
0.50	0.000	28.230	14.142
0.75	0.000	28.085	14.583
1.00	0.000	27.946	15.006

It is found that, when $L/H = 0.25$ the minimum cooling load occurs at $D/H = 0.253$ with cooling load reduction of 5.45% compared with Benchmark B. However when $L/H > 0.25$, the minimum cooling load occurs at the point where distance $D/H = 0$ with 14.15 to 15.01% of cooling load reduction. It is also seen that the cooling load profiles are almost the same when $L/H \in [0.5, 1]$, with maximum difference between any two profiles of 0.1 GJ meaning cooling load saving of 0.3%. All the data is summarized in Table 4.11.

Figure 4.29 Effect of distance between building envelope and wall (D) on building cooling load for building with window and horizontal curved-shell envelope.

Figure 4.29 shows the relationship between cooling load and D/H for horizontal curved-shell envelope. As shown in Figure 4.29, the cooling load decreases with increasing D/H , for various L/H . However, all the profiles are very flat with maximum difference of 0.3 GJ which is cooling load saving of 0.9%. This means that for horizontal curved-shell envelope, the effect of distance D is negligible.

As for the windowless building, the energy efficacy of curved-shell envelope is not significant, with maximum cooling load saving of 0.75%.

Generally, energy efficiency can be improved by varying the distance D between curved-shell building envelope and wall, especially for building with window. For vertical curved-shell envelope, D/H should be 0.253 for $L/H = 0.25$ and 0 for $L/H > 0.25$, with cooling load saving of 5.45% and 14 to 15% respectively, compared with Benchmark B, in order to maximize the energy efficiency. For horizontal curved-shell envelope, the effect of distance D on cooling load is negligible. For windowless building, there is not much improvement on energy efficiency by changing the distance D .

4.3.3 Remarks

From the simulation work above, following conclusions are made:

- For building with window and vertical curved-shell envelope, L/H should be in the range of 0.79 to 0.83 with cooling load saving of 4.98 to 15.73%, in order to maximize the energy efficiency.
- For building with window and vertical curved-shell envelope, D/H should be 0.253 when $L/H = 0.25$ and 0 when $L/H > 0.25$, with cooling load saving of

5.45% and 14 to 15% respectively, compared with Benchmark B, in order to maximize the energy efficiency.

- For building with window and horizontal curved-shell envelope, L/H should be in the range of 1.06 to 1.12, with cooling load saving of 10.26 to 11.19%, in order to maximize the energy efficiency.
- For building with window and horizontal curved-shell envelope, the effect of distance D on cooling load is negligible.
- For windowless building, there is no much improvement on energy efficiency by varying L or D .

4.4 Effect of Vertical Green Envelope

4.4.1 Effect of Mesh Size on Energy Efficiency

In this section, the mesh dependence test is carried out to validate that the cooling load is independent of the mesh size of vertical green envelope. As shown in Figure 4.30, the simulation model of vertical green envelope is made up of small piece of square faces with three different sizes: 0.25m, 0.5m and 1m.

Figure 4.30 Three simulation models of vertical green envelope with 50% porosity and different mesh size of 1m (a), 0.5m (b), and 0.25m (c).

It is found that there is no difference on the district cooling load by changing the mesh size. Therefore, further simulation models can be developed based on the mesh size of 0.25m without affecting the final results.

4.4.2 Effect of Porosity Ratio on Energy Efficiency

In this section, porosity ratio of vertical green envelope is used to elucidate its effect on building indoor cooling load, as shown in Figures 4.31 to 4.33. The y-axis represents the indoor cooling load and the x-axis denotes the porosity ratio of vertical green envelope.

Figure 4.31 Effect of porosity ratio of building envelope on cooling load for building with window.

$$\text{Cooling Load} = 3.4209 \text{ Porosity Ratio} + 29.494 \quad (4.1)$$

From the simulation results, it is found that, for a building with window, the cooling load increases with increasing porosity ratio of vertical green envelope in a liner relationship, as shown in Figure 4.31. The relationship between cooling load and porosity ratio could be described by Eq. (4.1). The energy saving reaches the maximum of 10.30%, when porosity ratio is 0 meaning green envelope is ideally dense. When porosity ratio is larger than 0.9, the cooling load saving is lower than 1% which is negligible. Therefore, in order to make the effect on building energy efficiency, the porosity ratio should be lower than 0.9.

Figure 4.32 Effect of porosity ratio of building envelope on cooling load for building with window.

$$\text{Cooling Load} = 0.3864 \text{ Porosity Ratio} + 25.76 \quad (4.2)$$

From the simulation results, it is found that, for a windowless building, the cooling load increases with increasing the porosity ratio of vertical green envelope in a liner relationship, as shown in Figure 4.32. The relationship between cooling load and porosity ratio is found to be described by Eq. (4.2). The energy saving is maximum 1.45% when porosity ratio is 0 which means green envelope is ideally dense. When porosity ratio is higher than 0.3, the cooling load saving is lower than 1% which is negligible. Therefore, in order to make the effect on building energy efficiency, the porosity ratio should be lower than 0.3.

Generally, energy efficiency can be improved by varying the porosity ratio of vertical green envelope, especially for building with window. In order to maximize the energy efficiency, the porosity ratio should be as small as possible, which could help to reduce cooling load by 10.3% and 1.45% for building with window and windowless building.

4.4.3 Remarks

From the simulation work above, following conclusions are made:

- For building without window, the porosity ratio should be as small as possible in order to improve the building energy efficiency, with maximum cooling load saving of 1.45% compared with Benchmark A.
- For building with window, the porosity ratio should be as small as possible in order to improve the building energy efficiency, with maximum cooling load saving of 10.3% compared with Benchmark B.

4.5 Effect of Internal Smart Blinds

4.5.1 Effect of Smart Blinds on indoor ambient temperature

In this section, the three models (the west-facing building with smart blind, the static blind, and the building without blind) are simulated at various times starting from 8:00 am to 6:00 pm on an hourly basis to study the effect of the smart blinds on the indoor ambient temperature at the center point inside the building. Table 4.12 is presented for summarization of ambient temperature at the center point inside the building with different blind systems at different time, the temperature differences between Smart Blind and Benchmark C, and the temperature differences between Smart Blind and Benchmark D.

Table 4.12 Ambient temperature at the center point inside the building with smart blind or static blind or without blind.

Time	Ambient Temperature (°C)			ΔT between Smart Blind and Benchmark C (°C)	ΔT between Smart Blind and Benchmark D (°C)
	Smart Blind	Benchmark C	Benchmark D		
8:00 am	31.3	28.7	31.3	-2.6	0
9:00 am	37.2	39.5	37.2	2.3	0
10:00 am	47.2	48.2	47.2	1	0
11:00 am	51.8	53.8	51.8	2	0
12:00 pm	55.2	58	55.2	2.8	0
1:00 pm	54.2	54.5	54.5	0.3	0.3
2:00 pm	55.5	56.3	55.8	0.8	0.3
3:00 pm	58.2	59	58.5	0.8	0.3
4:00 pm	61.6	64	62.3	2.4	0.7
5:00 pm	54	58.2	56.4	4.2	2.4
6:00 pm	44.2	47.8	46.4	3.6	2.2

Figure 4.33 shows the relationship between the solar radiation input and the ambient temperature of center points inside the building with different blind systems. In Figure 4.33, left y-axis represents the ambient temperature and the right y-axis the solar radiation value, while the x-axis represents the time on hourly basis. The scattering points represents the values resulted from CFD simulation and the dotted lines the solar radiation values from the weather file of EnergyPlus [51].

It is found that overall the indoor ambient temperature with smart blinds is reduced by 0.3 to 4.2 °C and 0.3 to 2.4 °C, compared with the Benchmark C (shown in solid red line in Figure 4.33) and Benchmark D (shown in solid green line in Figure 4.33). The largest difference found in ambient temperature is 4.2 °C, which occurs at around 5 pm. The possible reason is due to the highest direct solar radiation experienced during this hour of the day, as shown in Figure 4.33. For a building with static blinds, the ambient temperature is reduced by 0 to 2.8 °C, compared with Benchmark C. The largest

difference found in ambient temperature is 2.8 °C, which occurs at around 12 pm. The possible reason is that the diffusion of solar radiation reaches the highest value during this hour of the day, as shown in Figure 4.33. The highest ambient temperature of the building occurs at 4:00 pm. This is attributable to the highest total solar radiation (here the sum of the direct radiation and diffuse radiation) experienced during this hour of the day, as shown in Figure 4.33.

Figure 4.33 External solar radiation and indoor ambient temperature at the center point inside the building with smart blind (solid blue), no blind (solid red) and static blind (solid green) on 21st June.

4.5.2 Effect of Smart Blinds on wall temperature of east façade

In this section, three models (west-facing building with smart blind, static blind and without any blind) are simulated at various times starting from 8am to 6pm on hourly

basis to study the effect of smart blinds on the surface temperature of the east wall of the building.

Table 4.13 is presented for summarization of wall temperature on east façade for three buildings with different blind systems at different time, the temperature difference between Smart Blind and Benchmark C and the temperature difference between Smart Blind and Benchmark D.

Table 4.13 Average surface temperature on building east façade with smart blind or static blind or without blind.

Time	Ambient Temperature (°C)			ΔT between Smart Blind and Benchmark C (°C)	ΔT between Smart Blind and Benchmark D (°C)
	Smart Blind	Benchmark C	Benchmark D		
8:00 am	31.3	28.91	31.3	-2.39	0
9:00 am	37.26	41.21	37.26	3.95	0
10:00 am	47.15	51.38	47.15	4.23	0
11:00 am	51.74	57.69	51.74	5.95	0
12:00 pm	55.17	62.48	55.17	7.31	0
1:00 pm	54.52	58.52	57.35	4	2.83
2:00 pm	55.75	60.78	58.14	5.03	2.39
3:00 pm	58.43	63.45	60.58	5.02	2.15
4:00 pm	59.21	69.86	61.76	10.65	2.55
5:00 pm	52.55	63.43	60.11	10.88	7.56
6:00 pm	43.42	51.83	47.8	8.41	4.38

Figure 4.34 shows the relationship between the surface temperature of east wall of the building with different blind systems and the solar radiation input. In Figure 4.34, left y-axis represents the ambient temperature and the right y-axis represents the solar radiation value while the x-axis represents the time on hourly basis. The scattering points are the values got from CFD simulation and the dotted lines are the solar radiation values from the weather file of EnergyPlus [58].

Figure 4.34 External solar radiation and indoor ambient temperature on east façade of the building with smart blind (solid blue), no blind (solid red) and static blind (solid green) on 21st June.

It is found that the surface temperature of the east wall of the building with smart blinds is reduced by 3.95 to 10.88 °C and 2.15 to 7.56 °C, compared with the one without blinds (shown in solid red line in Figure 4.34) and with static blinds (shown in solid green line in Figure 4.34 respectively). The largest difference in wall temperature is found to be 10.88 °C, which occurs at around 5 pm. The reason for this is attributable to the highest direct solar radiation experienced during this hour of the day, as shown in Figure 4.34. For a building with static blinds, the ambient temperature is reduced by 1.17 to 8.1 °C compared with the one without any blind. The largest difference in wall temperature is

found to be 8.1 °C, which occurs at around 4 pm, followed by 12pm where the temperature difference is 7.31. The reason for this is attributable to the highest total solar radiation and diffuse solar radiation experienced during this hour of the day separately, as shown in Figure 4.34. The highest ambient temperature of the building occurs at 4pm which is the same with ambient temperature. This is attributable to the highest total solar radiation (direct radiation + diffuse radiation) experienced during this hour of the day, as shown in Figure 4.34.

Generally, the ambient temperature is reduced by 0.3 to 4.2°C by using the smart blind system compared with that without blind, and the reduction reaches maximum point at 5pm. Compared with that with static blind, the ambient temperature is reduced by 0.3 to 2.4 °C by implementing smart blind system in afternoon. Similarly the average surface temperature of the east wall of the building is reduced by 3.95 to 10.88 °C by using smart blind system, compared with that without blind. Compared with that with static blind, the average surface temperature of the east wall of the building is reduced by 2.15 to 7.56 °C by using the smart blind system.

4.5.3 Remarks

From the simulation work above, following conclusions are made:

- The indoor ambient temperature with implementing smart blinds is reduced by 0.3 to 4.2 °C compared with Benchmark C.
- The indoor ambient temperature with implementing smart blinds is reduced by 0.3 to 2.4 °C, compared with Benchmark D.

- The average surface temperature of the east wall of the building with implementing smart blinds is reduced by 3.95 to 10.88 °C, compared with Benchmark C.
- The average surface temperature of the east wall of the building with implementing smart blinds is reduced by 2.15 to 7.56 °C, compared with Benchmark D.

CHAPTER 5 CONCLUSION AND FUTURE WORK

5.1 Conclusion

In this thesis, the academic contributions into the research area of building performance in energy efficiency are achieved in two aspects. One is to study the effect of building forms on the natural ventilation, which is investigated via modeling and simulation of the three real projects (CTT, NSAB and LH), as described in Chapter 3. The other is to study the effect of building envelope on the energy efficiency, which is further classified into the four envelope scenarios (the plane-plate, curved-shell, vertical green, and internal envelopes), as described in Chapter 4.

Modeling and Simulation of Natural Ventilation for Effect of Building Forms

Through the studies of the three real buildings, the following conclusions are made.

- (1) Compared with porous building such as NSAB, the common spaces in the structured buildings such as CTT have the poorer natural ventilation over a year, excluding roof-top. This is attributable to the low porosity of building.
- (2) In the porous building such as NSAB, it is found that the common spaces have wind velocity with the maximum at 3.09 m/s, contrary to structured building.
- (3) In free-form architectural buildings such as LH, the wind velocity profile found in the atrium is highly correlated to the floor levels, which is attributed to the stack effect.

Modeling and Simulation of Energy Efficiency for Effect of Building Envelope

The building envelopes studied include the external and internal envelopes. The present external envelope is further classified into the plane-plate, curved-shell and vertical green envelopes. For the internal envelope however, the smart blind system is studied.

Effect of the plane-plate envelope on building energy efficiency

For development of a general design guideline of the external plane-plate building envelope, a reduction in cooling load can be achieved by increasing the building envelope length L , decreasing the distance D , or tuning the angle θ between building envelope and wall. Through parametric study via EnergyPlus for energy simulation, the following conclusions are made.

- (1) For the building with window, L/H is recommended to range from 0.75 to 1, which results in the cooling-load reduction of 13.43 to 14.93%, compared with Benchmark B, in order to maximize the energy efficiency.
- (2) For the building with window, D/H is recommended to range from 0.162 to 1.24 when $L/H \leq 0.5$, and to remain at 0 when $L/H > 0.5$, which results in the cooling-load reduction of 10.5 to 13.6 % and 14 to 14.5% respectively, compared with Benchmark B.
- (3) For the building with window, the angel θ between plane-plate envelope and wall is recommended to range from 15° to 46° when $L/H \leq 0.5$ and $D/H \leq 0.125$, which results in the maximum energy saving of 4.4%, compared with the cooling load at $\theta = 0^\circ$. There is an influence of less than 1% on the energy efficiency when $L/H > 0.5$ or $D/H > 0.125$ with any value of the angel θ .

- (4) For the building without window, there is no much improvement on energy efficiency even if various L or D or θ are tuned.

Effect of the curved-shell envelope on building energy efficiency

As a general design guideline for external curved-shell building envelope, a reduction in cooling load can be achieved by increasing the building envelope length L , or decreasing the distance D or tuning the angle θ between building envelope and wall. Through parametric study of using energy simulation, following conclusions are made.

- (1) For building with window and vertical curved-shell envelope, L/H should range from 0.79 to 0.83, which results in cooling load reduction of 4.98 to 15.73% compared with Benchmark B.
- (2) For building with window and vertical curved-shell envelope, D/H should be 0.253 when $L/H = 0.25$, and remain at 0 when $L/H > 0.25$, which results in cooling load reduction of 5.45% and 14 to 15% respectively, compared with Benchmark B.
- (3) For building with window and horizontal curved-shell envelope, L/H should be in the range of 1.06 to 1.12, which results in cooling load reduction of 10.26 to 11.19%.
- (4) For building with window and horizontal curved-shell envelope, the effect of distance D on cooling load is negligible.
- (5) For building without window, there is no much improvement on energy efficiency by varying L or D .

Effect of vertical green envelope on building energy efficiency

As a general design guideline for vertical green envelope, building energy efficiency can be improved by decreasing the porosity ratio of vertical green envelope, especially for

buildings with window. Through parametric study of using energy simulation, following conclusions are made.

- (1) For building without window, the porosity ratio should be as small as possible in order to improve the building energy efficiency, which results in a maximum cooling load reduction of 1.45% compared with Benchmark A.
- (2) For building with window, the porosity ratio should be as small as possible in order to improve the building energy efficiency, which results in a maximum cooling load reduction of 10.3% compared with Benchmark B.

Effect of internal smart blind on building energy efficiency

For development of a general guideline for the internal smart blind, the following conclusions are made.

- (1) The reduction of the indoor ambient temperature ranges from 0.3 to 4.2°C if the smart blind system is performed compared with that without blind or with static blind. The reduction reaches the maximum at 5:00 pm.
- (2) The average surface temperature in the east wall of the building is reduced by 3.95 to 10.88 °C if the smart blind system is used, compared with that without blind, and by 2.15 to 7.56 °C compared with that with static blind.

5.2 Future work

For the natural ventilation in buildings, two future works are recommended.

- (1) One is to develop a design standard for natural ventilation in semi-outdoor spaces specified in Singapore.

- (2) The other is to study the effect of porosity on natural ventilation in buildings specified in Singapore.

For the building envelope on the energy efficiency, following recommendations are listed.

- (1) The first is to simulate multi-storey building to compensate the whole guideline, since only single-storey building is used in this thesis.
- (2) The second is to include ETTV in the data analysis, in order to make this guideline more useful for the building developers and architects.
- (3) The third is to study the effect of vertical green envelope on natural ventilation.
- (4) The fourth is to study the energy savings in terms of cooling load due to the internal blinds.
- (5) Finally the cost analysis and carbon footprint emission for building envelope is recommended to assist the developer in the decision making process.

PUBLICATIONS ARISING FROM THE THESIS

Journal Papers:

1. Xiaoying Wu, Hua Li and Shah Kwok Wei. Energy and CFD simulation on smart blind systems. (In preparation).

Conference Papers:

1. Xiaoying Wu, Szu-Cheng Chien and Hua Li. (2013). Assessment of natural ventilation potentials on free-form architecture design using CFD simulations: a Learning Hub building in Singapore, Paper represented at SB 13 Singapore Conference. Singapore. 9-10 September 2013.
2. Bharath Seshadri, Nilesh Y. Jadhav, Majid Bin Haji Sapar, Aaron P. Boranian, Danielle M. Griego, Wu Xiaoying, Szucheng Chien, I Komang Narendra, Jatin N. Sarvaiya, Doris Österreicher, Markus Brychta, Florian Stift, Mirza Popovac, Reshma Singh and Kristen Parrish (2013). High-Performance building design in Singapore: Scientific Planning and Support, Paper represented at SB 13 Singapore Conference. Singapore. 9-10 September 2013.

REFERENCES

- [1] Buildings energy data book. Department of Energy. U.S., available on:
<http://buildingsdatabook.eren.doe.gov/ChapterIntro1.aspx>.
- [2] Building and Construction Authority. (2010). Existing building retrofit. Singapore.
- [3] Buildings energy data book. Department of Energy. U.S., available on:
<http://buildingsdatabook.eren.doe.gov/TableView.aspx?table=1.2.3>.
- [4] Lin, H. T. (2011). Green Architecture: An Asian Perspective. Hong Kong: Hong Kong Arts Centre.
- [5] Luis, P., Jose, O., & Christin, P. (2007). A review on buildings energy consumption information. *Energy and Buildings*, 40, 394-398.
- [6] Singapore's Second National Communication: Under the United Nations Framework Convention on Climate Change, November 2010 (NEA).
- [7] GAISMA, available on: <http://www.gaisma.com/en/location/singapore.html>.
- [8] Building Construction Authority. (2010). BCA Green Mark: Certification Standard for New Buildings. Singapore.
- [9] Singapore National Environment Agency, (2009). Weather Wise Singapore, Singapore.
- [10] Ulrich, K., Tillmann, K., Marcel, B., & Thomas, A. (2007). *Façades: Principles of Construction*. Basel : Birkhäuser Verlag.
- [11] The challenge series. Available on: <http://www.thechallengeseries.ca/chapter-04/building-envelope/>.

- [12] Department of Construction and Architecture, Lund University. (2004). Double Skin Facades of Office Buildings. Sweden: Harris Poirazis
- [13] Shading and Wind Direction. Available on :
<http://www.righthouse.co.nz/benefits/our-integrated-approach/aspect/shading-and-wind-direction>.
- [14] Building and Construction Authority. (2004). Code on Envelope Thermal Performance for Buildings. Singapore. Available on:
<http://www.bca.gov.sg/PerformanceBased/others/ETTV.pdf>
- [15] Building and Construction Authority. (2008). Code on Envelope Thermal Performance for Buildings. Singapore. Available on:
<http://www.bca.gov.sg/PerformanceBased/others/RETV.pdf>
- [16] Chua, K.J., & Chou, S.K. (2010). An ETTV-based approach to improving the energy performance of commercial buildings. *Energy and Buildings*, 42, 491-499.
- [17] Mohimen, M. E., Hanna, G., & Krarti, M. (2005). Analysis of daylighting benefits for office buildings in Egypt, *ASME Journal of Solar Energy Engineering*, 127, 366-370.
- [18] Lai, C.M., & Wang, Y.H. (2011). Energy-Saving Potential of Building Envelope Designs in Residential Houses in Taiwan. *Energies* 2011, 4, 2061-2076.
- [19] Kumar, R., Garg, S.N., & Kaushik, S.C. (2005). Performance evaluation of multi-passive solar applications of a non-air-conditioned building. *International Journal of Environmental Technology and Management*, 5, 60-75.
- [20] Yu, H., Niu, J.L., & Chung, T.M. (2012). Energy and carbon emission payback analysis for energy-efficient retrofitting in buildings – Overhang shading option. *Energy and Buildings*, 44, 94-103.

- [21] Wong, N.H., & Tan, E., (2011). Performance of shading device in classrooms of Zero Energy Building in Singapore. Paper represented at 27th International Conference on Passive and Low Energy Architecture: Architecture and Sustainable Development. Belgium: Presses Universitaires de Louvain, 13-15 July 2011.
- [22] Kim, G., Lim, H.S., Lim, T.S., Schaefer, L., & Kim, J.T. (2012). Comparative advantage of an exterior shading device in thermal performance for residential buildings. *Energy and Buildings*, 46, 105-111.
- [23] Kim, G., Lim, H.S., & Kim, J.T., (2012). Development of a Double-Skin Façade for Sustainable Renovation of Old Residential Buildings. Paper represented 7th International Symposium on Sustainable Healthy Building, Korea.
- [24] Elisabeth, G., and Andre, D.H. (2007). Are energy consumptions decreased with the addition of a double-skin?. *Energy and Buildings*, 39, 605-619.
- [25] Zhou, J., and Chen, Y. (2012). A review on applying ventilated double-skin façade to buildings in hot-summer and cold-winter zone in China. *Renewable and Sustainable Energy Reviews*, 14, 1321-1328.
- [26] Wang, Y., Lu, P., Liu, J. P., Yao, H. B., & Chen, L. L. (2011). The analysis of the impact of the louver on the natural ventilation. Paper represented at 1st International Conference on Civil Engineering, Architecture and Building Materials. Kaikou, China: Trans Tech Publications. 18-20 June 2011.
- [27] Tablada, Abel, Carmmeliet, Jan, Baelmans, Martine, Saelens. (2009, June 22 - 24). Exterior louvers as passive cooling strategy in a residential building: Computation Fluid Dynamics and Building Energy Simulation modeling. Paper

- represented at 26th International Conference on Passive and Low Energy Architecture: Architecture Energy and the Occupant's Perspective. Québec City, Canada: Les Presses de l'Université Laval.
- [28] Elisabeth, G., & Andre, D. H. (2004). Natural ventilation in a double-skin façade. *Energy and Buildings*, 36, 137 - 146.
 - [29] Elisabeth, G., & Andre, D. H. (2004). Is day natural ventilation still possible in office buildings with a double-skin façade? *Building and Environment*, 39, 399 - 409.
 - [30] Ding, W.T., Hasemi, Y., & Yamada, T. (2005). Natural ventilation performance of a double-skin façade with a solar chimney. *Energy and Buildings*, 37, 411 - 418.
 - [31] Kim, C.R., Cho, G.Y., Lee, S.W., Yeo, M.S., & Kim, K.W. (2007). Opening design to improve the natural ventilation performance of high-rise residential buildings. Paper represented at 6th International Conference on Indoor Air Quality, Ventilation and Energy Conservation in Buildings: Sustainable Built Environment. Sendai, Japan: Tohoku University Press, 28-31 October 2007.
 - [32] Kim, Y. M., Lee, J. H., Kim, S. M., & Kim, S. Y. (2011). Effects of double skin envelopes on natural ventilation and heating loads in office buildings. *Energy and Buildings*, 43, 2118 - 2126.
 - [33] Mingotti, N., Torwong, C., & Andrew, W.W. (2011). The fluid mechanics of the natural ventilation of a narrow-cavity double-skin façade. *Building and Environment*, 46, 807 - 823.
 - [34] Xu, X. L., & Yang, Z. (2008). Natural ventilation in the double skin façade with venetian blind. *Energy and Buildings*, 40, 1498 - 1504.

- [35] ISO 7730, (1994). Moderate Thermal Environments – Determination of the PMV and PPD Indices and Specifications of the Conditions for Thermal Comfort, 2nd ed., International Standards Organisation, Geneva.
- [36] ASHRAE, (1997). ASHRAE handbook Fundamentals, American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, USA.
- [37] Fanger, P.O. & Toftum, J. (2002). Extension of the PMV model to non-air-conditioned buildings in warm climates, *Energy and Buildings* 34 (6) 533-536.
- [38] Inch. P. (2009). 2009 ASHRAE HANDBOOK FUNDAMENTALS. Available on:

http://kntu.ac.ir/DorsaPax/userfiles/file/Mechanical/OstadFile/dr_sayadi/19337425502009AshraeFundamentals.pdf.
- [39] Feriadi, H., Wong, N.H., Chandra, S. & Cheong, K.W. (2003). Adaptive behavior and thermal comfort in Singapore's naturally ventilated housing. *Building Research & Information* 31 (1), 13-23.
- [40] Wong, N.H., Feriadi, H., Lim, P.Y., Tham, K.W., Sekhar, C. & Cheong, K.W. (2002). Thermal comfort evaluation of naturally ventilated public housing in Singapore. *Building and Environment* 37 1267-1277.
- [41] Feriadi, H. & Wong, N.H. (2004). Thermal comfort for naturally ventilated houses in Indonesia. *Energy and Buildings* 36 614-626.
- [42] Shafqat, H. & Patrick H. O. (2012). Numerical investigations of buoyancy-driven natural ventilation in a simple atrium building and its effect on the thermal comfort conditions. *Applied Thermal Engineering* 40 358-372.

-
- [43] Wang, L.P. & Wong, N. H. (2007). Applying Natural Ventilation for Thermal Comfort in Residential Buildings in Singapore. *Architectural Science Review* 50.3 224-233.
- [44] Hou, C. & Ma, C. (2008). Boundary Setting in Simulating Greenhouse Ventilation by Fluent Software. *Computer and Computing Technologies In Agriculture*, 2(259), 1391-1395.
- [45] Heiselberg, P., Li, Y., Andersen, A., Bierre, M., & Chen, Z. (2004). Experimental and CFD evidence of multiple solutions in a naturally ventilated building. *Indoor Air*, 14(1), 43-54.
- [46] Shuzo, M., Akashi, M., & Yoshihiko, H. (1990). Examining the k- ϵ model by means of a wind tunnel test and large-eddy simulation of the turbulence structure around a cube. *Wind Engineering and Industrial Aerodynamics*, 35, 87-100.
- [47] Bu, Z. & Kato, S. (2010). Numerical simulation of wind-driven natural ventilation in basement and attached areaway space in single detached dwelling. Paper represented at the fifth International Symposium on Computational Wind Engineering, Chapel Hill, North Carolina, USA, 23-27 May 2010.
- [48] Nielsen, P.V. (1998). The selection of turbulence models for prediction of room airflow. *ASHRAE Transactions*, 104(1B), 1119-1127.
- [49] Chen, Q., & Srebric, J. (2002). A procedure for verification, validation, and reporting of indoor environment CFD analyses. *HVAC & R Research*, 8(2), 201-216.
- [50] Hussain, S., & Oosthuizen, P.H. (2012). Numerical investigations of buoyancy-driven natural ventilation in a simple atrium building and its effect on the thermal comfort conditions. *Applied Thermal Engineering*, 40, 358 - 372.

- [51] Evola, G. & Popov, V. (2006). Computational analysis of wind driven natural ventilation in buildings. *Energy and Buildings*. 38(5), 491 - 501.
- [52] Stavrakakis, G.M., Koukou, M.K., Vrachopoulos, M.G., & Markato, N.C. (2008). Natural cross-ventilation in buildings: Building scale experiments, numerical simulation and thermal comfort evaluation. *Energy and Buildings*. 40(9), 1666 - 1681.
- [53] Jorg, F., Antti, H., Schlunzen, H., & Bertrand, C. (2007). COST Action 732: Best practice guideline for the CFD simulation of flows in the urban environment. Hamburg, Germany: University of Hamburg.
- [54] Patton, E.G., Sullivan, P.P., & Davis, K.J. (2003). The influence of a forest canopy on top-down and bottom-up diffusion in the planetary boundary layer. *Quarterly Journal of the Royal Meteorological Society*, 129 (590), 1415-1434.
- [55] FLUENT 6.3 User's Guide. Available on:
<http://aerojet.engr.ucdavis.edu/fluenthelph/html/ug/node1354.htm>.
- [56] FLUENT 6.3 User's Guide. Available on:
<http://aerojet.engr.ucdavis.edu/fluenthelph/html/ug/node592.htm>.
- [57] FLUENT 6.3 User's Guide. Available on:
<http://aerojet.engr.ucdavis.edu/fluenthelph/html/ug/node288.htm>.
- [58] U.S Department of Energy. EnergyPlus Software Weather Data, available on:
http://apps1.eere.energy.gov/buildings/energyplus/cfm/weather_data3.cfm/region=5_southwest_pacific_wmo_region_5/country=SGP/cname=Singapore.
- [59] EnergyPlus Overview, available on:
<http://apps1.eere.energy.gov/buildings/energyplus/pdfs/gettingstarted.pdf>.