EVALUATION OF NATURAL VENTILATION SYSTEMS IN TALL BUILDINGS CONSIDERING ALTITUDE BASED ENVIRONMENTAL VARIATIONS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

İLKER KARADAĞ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
BUILDING SCIENCE IN ARCHITECTURE

DECEMBER 2013

Approval of the thesis:

EVALUATION OF NATURAL VENTILATION SYSTEMS IN TALL BUILDINGS CONSIDERING ALTITUDE BASED ENVIRONMENTAL VARIATIONS

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ABSTRACT

EVALUATION OF NATURAL VENTILATION SYSTEMS IN TALL BUILDINGS CONSIDERING ALTITUDE BASED ENVIRONMENTAL VARIATIONS

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December 2013, 97 pages

Buildings relied on natural ventilation strategies alone for many centuries up to the post-World War II period in which cheap energy started to liberate architecture from its connection with the natural environment. Then, the economic downturn in the 1970s, fuelled by the worldwide energy crisis in 1973 drew the attention to reduction and conservation of energy, the response was the model of the sealed glass box with an acceptance of the air-conditioning system. This resulted in Sick Building Syndrome (SBS) caused by the quality of the internal air and created the basis for widespread criticism in the 1970s and 1980s. Now, the current key decision should be the re-introduction of the natural ventilation systems into the tall buildings, since natural ventilation embodies a number of advantages such as reduced CO2 emissions, elimination of SBS, better internal air quality, reduced energy consumption with reducing demand on Heating, Ventilating and Air-conditioning systems.

In this study, naturally ventilated tall buildings are evaluated with respect to their natural ventilation systems' efficiency. While doing this, some key parameters to assess natural ventilation systems is benefitted. Besides, the characteristics and gradient of vertical variations of environmental parameters influencing natural ventilation directly, such as temperature, wind velocity and direction, humidity and air pressure are examined to make it clear whether they provide new or improved strategies for natural ventilation or not. It is concluded that, natural ventilation systems encompasses more than simply operable windows and narrow plans, and to use natural ventilation systems in tall buildings, generic principles of natural ventilation as a background should be researched and this should be followed with investigation of advanced systems that enable natural ventilation at higher levels of the tall buildings.

Keywords: Tall Buildings, Natural Ventilation, Sick Building Syndrome, Altitude.

ÖZ

ORTA DOĞU TEKNİK ÜNİVERSİTESİ

YÜKSEK BİNALARDAKİ DOĞAL HAVALANDIRMA SİSTEMLERİNİN İRTİFA TABANLI ÇEVRESEL VARYASYONLARI DA GÖZETEREK DEĞERLENDİRİLMESİ

Karadağ, İlker

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Aralık 2013, 97 sayfa

Yapılar yüzlerce yıl doğal olarak havalandırıldı, fakat 2. Dünya Savaşı sonu dönemle birlikte, ucuz enerji yaygınlaştı ve yapıların doğal çevreyle ilişkisi kopmaya başladı. Daha sonra, 1970-73 periyodunu içine alan dönemdeki küresel bir ekonomik kriz, dikkatleri enerjinin korunumuna ve enerji tüketiminin azaltılmasına çekti. Bu süreçte, mekanik olarak havalandırılan yalıtılmış cam kutular çözüm olarak görüldü. Fakat bu tercih iç mekanlardaki hava kalitesinin ciddi oranda düşmesine, sağlık sorunlarına ve

sonuç olarak Hasta Bina Sendromuna yol açtı. Bu durumun çözümüne yönelik yapılara tekrar doğal havalandırma sistemlerinin entegre edilebilir, çünkü doğal olarak havalandırılan yapılarda karbondioksit salınımı düşer, iç mekan hava kalitesi yükselir, enerji tüketimi büyük ölçüde azalır ve Hasta Bina Sendromuna yol açan faktörler elemine edilir.

Bu çalışmada doğal olarak havalandırılan yüksek yapılar kullandıkları doğal havalandırma sistemlerinin etkinliği yönünden değerlendirilir. Bunu yaparken, bazı anahtar parametreler kullanılır. Bunun yanı sıra, sıcaklık, rüzgar hızı ve yönü, nem ve hava basıncı gibi doğal havalandırmayı doğrudan etkileyen çevresel parametrelerin yükseklik arttıkça nasıl değiştiği de incelenir ve bunun yüksek binalarda doğal havalandırma kapsamında yeni prensiplerin geliştirilmesine imkan sağlayıp sağlamadığı analiz edilir. Bu çalışma sonucunda, doğal havalandırma sistemlerinin basit anlamda sadece açılabilir pencerelerden ve yapı derinliğinin dar tutulmasından çok daha fazlasını gerektirdiği görülür. Yüksek yapılarda doğal havalandırma sistemlerinin etkin bir şekilde kullanılabilmesi için doğal havalandırma prensipleri ile ilgili kapsamlı bir altyapı bilgisi gerektiği ve bununla da yetinilmeyip yüksek yapılarda rüzgar hızının kritik olmaya başladığı katlarda kullanılabilecek ileri düzey sistemlerin araştırılması gerektiği sonucuna varıldı.

Anahtar Kelimeler: Yüksek Binalar, Doğal Havalandırma, Hasta Bina Sendromu, İrtifa.

to my family...

ACKNOWLEDGEMENTS

I would like to express my sincere to Dr. Ayşem Berrin Zeytun Çakmaklı for her guidance throughout the study. This study would not have been possible without her supporting advice and invaluable comments.

I am also grateful to Prof. Dr. Soofia Tahira Elias Özkan for her essential contributions and Asst. Prof. Dr. Ayşegül Tereci, Assoc. Prof. Dr. Neşe Dikmen and Ms. Françoise Summers for their suggestions to this work.

My special thanks and love go to my wife for her continuous support.

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LIST OF ABBREVIATIONS

AHU	Air Handling Unit
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BMS	Building Management System
CFD	Computational Fluid Dynamics
CIBSE	Chartered Institution of Building Services Engineers
CTBUH	Council on Tall Buildings and Urban Habitat
DALR	Dry Adiabatic Lapse Rate
HVAC	Heating, Ventilating and Air Conditioning
km	kilometer
m	meter
m/s	meter per second
PMV	Predicted Mean Vote
SALR	Saturated Adiabatic Lapse Rate
SBS	Sick Building Syndrome
UHI	Urban Heat Island

CHAPTER 1

INTRODUCTION

In this chapter the argument for the study, its objectives, the procedure followed and the disposition of the various chapters within the thesis are presented.

1.1. Argument

Tall buildings have been increasing in both height and number exponentially and generate an important level of greenhouse gases because of their high dependency upon HVAC (heating, ventilating, and air conditioning), increasing with additional building height. As the dependency upon air conditioning increases, environmental impacts and energy use of tall buildings also increases.

For many centuries, buildings relied on natural ventilation strategies alone, however in the post-World War II period, cheap energy liberated architecture from its connection with the natural environment. Prior to that period, all buildings were naturally ventilated as a matter of necessity since mechanical ventilation systems were not yet advanced enough to sufficiently condition the space (Wood & Salib, 2013). However the economic downturn in the 1970s, fuelled by the worldwide energy crisis started in 1973 put a brake on the race for the tallest buildings and drew the world's attention to the model of the sealed glass box. Despite the oil crisis, which brought economic and environmental pressure, the international acceptance of the air-conditioning system added to the increasing health problems and resulted in Sick Building Syndrome (SBS) caused by the quality of the internal air. This created the basis for widespread criticism in the 1970s and 1980s of the glass box building with fully artificially controlled environments, as seen in the Europe, US and the other parts of the world. As a consequence, towards the end of the 1980s and beginning of the 1990s, environmental issues started to be contemplated, demanding more climate responsive solutions and more energy-efficient buildings (Goncalves & Umakoshi, 2010). Since, natural ventilation embodies a number of advantages such as reduced CO_2 emissions, elimination of SBS, better internal air quality, reduced energy consumption with reducing demand on Heating, Ventilating and Air-conditioning (HVAC) systems; the current key decision should be the re-introduction of the natural ventilation systems into the tall buildings.

Natural ventilation requires no electrical energy for fans, which can constitute 25% of the electrical energy consumption in a mechanically ventilated building. In addition, occupants of buildings prefer to have control over their environment and prefer not to be isolated from the external environment completely (Etheridge, 2012). Particularly in the UK, energy consumption guidelines indicate that energy consumption in office buildings can achieve savings of between 55 and 60% with the introduction of natural ventilation (representing 127-145 kW h/m2 per year; Chartered Institution of Building Services Engineers- CIBSE 2004). Moreover, natural ventilation is a very attractive solution to provide both good indoor air quality and acceptable comfort conditions in many regions. Natural ventilation offers solutions to user complaints originated from mechanical ventilation systems, such as being noisy, creating health problems, requiring routine maintenance and consuming energy. Briefly, integration of natural ventilation into the tall building design ensures healthier and more comfortable environment (Allard, 1998). However, the operation of naturally ventilated tall buildings encompasses more than simply operable windows and narrow plans. Therefore, to re-introduce natural ventilation systems into tall buildings, generic principles of natural ventilation as a background should be researched and this should be followed with investigation of advanced systems that enable natural ventilation at higher levels of the tall buildings.

Vertical variations in environmental parameters such as air temperature, wind speed, humidity and air pressure have directly influence on natural ventilation in tall buildings. For instance in a hot- humid climate, decrease in the humidity levels with increasing height increases occupants' comfort levels, similarly in a hot-dry climate decreasing temperatures with increasing height reduce cooling loads. Therefore, the literature related with the tall buildings needs further research as to architectural design guidelines regarding vertical variations of environmental parameters and building height relationship in the context of natural ventilation to reduce the dependency on air-conditioning systems.

1.2. Objectives

The main objective of this thesis is to create a design guideline for the people who wants a better understanding of the options available for naturally ventilating tall buildings and to make them more aware of the environmental parameters vary with increasing height called air temperature, wind speed, humidity and air pressure and how these variations assist the design process of tall buildings and in detail natural ventilation strategies of them.

The other objectives of the thesis are:

- To investigate the characteristics of four main climate types and set guidelines for natural ventilation in these climates.
- To give the generic principles of altitude based variations in the environmental parameters taken within research scope.
- To compile natural ventilation strategies as a base for further researches and as a design guideline for architects and building professionals.

1.3. Procedure

This thesis seeks to create a guideline by means of compiling a number of natural ventilation strategies considering altitude for tall buildings.

In this dissertation, firstly principles of natural ventilation are given, then to employ natural ventilation strategies in tall buildings in different climates, characteristics of four main types of climate are given in terms of natural ventilation. To naturally ventilate tall buildings, architectural guidelines related with natural ventilation should be known, therefore issues related with the principals of natural ventilation in tall buildings called building form and orientation, facade design, ventilation openings, shading features are sought. While doing this, a number of tall buildings employing natural ventilation at greater or lesser rate are exemplified.

Secondly, the nature of vertical changes in atmospheric processes is investigated to make it clear if they assist new or improved strategies for natural ventilation. Then the advantages of height in the design of the tall buildings as well as integrating results of past related studies are evaluated.

Lastly, a series of natural ventilation systems of tall buildings in different climates are evaluated to make it clear if the key features needed to naturally ventilate a tall building are considered in these strategies. Local climate and altitude variations are also evaluated. Strengths of the natural ventilation strategies are given and also evaluated in terms of their effectiveness. In addition, some potential areas of concern that should be taken into account while attaining the same natural ventilation strategies with the regarding case buildings are given.

1.4. Disposition

The study is presented in five chapters. The first chapter is composed of the argument, objectives, and an overview of general methodology. It concludes with the disposition of subject matter that follows in the remaining chapters.

The second chapter is composed of a literature review including main characteristics of different climates in terms of natural ventilation, design guidelines as to natural ventilation and nature of altitude based vertical climatic variations.

The third chapter presents study material and method used to conduct the research.

The fourth chapter includes of analysis and results as to the use of principles of vertical climate and their possible application to natural ventilation of tall buildings. It provides conceptual natural ventilation strategies that can ensure a design manual for architects.

The fifth chapter gives the conclusions and defines further recommended research significant to re-introduce natural ventilation in tall buildings.

CHAPTER 2

LITERATURE REVIEW

This literature review is based on information taken from a number of published sources and websites. It covers topics related to climate responsive design, natural ventilation strategies and nature of altitude based vertical climatic variations in tall buildings.

2.1. DEFINITION OF TALL BUILDING

Tall buildings require a high level of technological input in order to function properly from architectural, environmental and engineering points of view. The principal architectural features of the building, being the architectural form, circulation and building systems, function in a very different manner than in a low-rise building. The differences are related to a number of issues, such as: maximizing net-to-gross area ratios, the way the structure responds to wind loads, how the internal spaces are environmentally controlled, fire and safety design issues, vertical circulation and the way the building affects the environment of its surroundings, to name the most important factors. All these challenges make the tall building a unique architectural expression, with a significant role in urban design and planning (Goncalves & Umakoshi, 2010).

With the introduction of steel in the building sector, together with the advent of the lift in 1853, the first threshold of five storeys was overcome and the first 'skyscraper' of the modern era was built in Chicago the Home Insurance Building, 42m high, in 1885. With technological developments in the beginning of the 20th century, buildings reached the limit of up to 20 storeys. Above this threshold came the need for more detailed and sophisticated vertical circulation strategies, rather than a single group of lifts. For this reason the limit of 20 storeys was considered for decades as the definition of the tall building in North American and European cities. Similarly, the Council on Tall Buildings and Urban Habitat (CTBUH) also adopted the limit of 20 storeys to define tallness. The latest definition (www.ctbuh.org) of the CTBUH states that the tall building is not strictly defined by the number of storeys or its height, but whether or not the design, use and operation of the building are influenced by aspects of tallness. In that respect, considering the different areas of engineering, such as fire control, vertical circulation, structure and building services, the limits imposed by height vary significantly (Goncalves & Umakoshi, 2010).

In urban terms, the definition of a tall building depends on the height of the surrounding buildings, therefore, 'tall' is a relative condition. For instance, neither a 5-storey nor a 20-storey building is accepted as a tall building in cities such as New York or Chicago. The large number of buildings above 20 floors means that this height no longer represents a distinguishing feature in these urban centers. In New York and Chicago standard heights are typically 40 and 60 storeys, respectively, representative of economic efficiency indicators. By contrast, there are only a few buildings in Europe that are over 40 floors. Only from the mid-1990s, design proposals for buildings over 40 storeys has begun to emerge in some of the European cities, such as London, Frankfurt, Rotterdam and Paris (Goncalves & Umakoshi, 2010).

A sensibly approach towards the definition of a tall building brings together two distinct aspects of a project: the relationship between form and proportion of the structure (slimness) and height in the context where the building is introduced, though height is a relative parameter in both cases. With regard to structural engineering, the slenderness of the building is actually more significant than its height. By the same token, from an urban design perspective the height of the building alone is less significant than the difference between the building and its surroundings (Goncalves & Umakoshi, 2010).

2.2. NATURAL VENTILATION IN TALL BUILDINGS

The history of architecture reveals that artificial cooling and mechanical ventilation were not common in tall buildings before the tall building construction boom in New York and Chicago in the 1950s. During these years mechanical and electrical systems acquired a significant role in the internal environments of buildings, within the context of modem architecture. In other words, building systems should take care of the internal environments, because architects did not have to consider the thermal performance of a building’s form and envelop anymore (Gonçalves & Umakoshi, 2010).

The oil crisis of 1973 leaded to a global concern for the reduction and conservation of energy and brought a turning point in the design of tall buildings. Together with this, the poor environmental quality of busy and polluted dense urban centers created the perfect scenario for the sealing of buildings and the dependence on artificially controlled environments. This approach towards energy consumption, associated with the introduction of air-conditioning systems, led to different problems such as Sick Building Syndrome (Gonçalves & Umakoshi, 2010).

2.2.1. Sick Building Syndrome

In the 1970s, health care providers were faced with increasing numbers of people having headaches and allergic-like reactions to unspecified stimuli. Some of the reactions included lethargy, fatigue, headache, dizziness, eye irritation, and sensitivity to odors. Through exploration over several years, these reactions were linked to common symptoms of people in specific buildings and a lack of symptoms when these people were not in the buildings. This spectrum of specific and nonspecific complaints, when tied to a particular building, became known as sick building syndrome (SBS) (Heimlich, 2008).

There are several reasons causing SBS, however one is accepted as most crucial called reduced ventilation rates that is used to conserve energy, increased the contamination of indoor air pollutants, and decreased the quality of air. This situation give an increase to complaints caused by psychological and health problems related with indoor air pollution (Levin, 1986). There are three major sources of poor indoor air quality, namely, hermetically sealed buildings and their synthetic furnishings, reduced ventilation rates and human bio effluents (Yeang, 1999).

The best way to deal with potential reactions to a sick building is to understand the reasons a building may be sick. According to Wineman (1986) the two most important factors influencing the comfort of a tall building occupant are good air circulation, and the temperature in the workplace. More than 50% of poor indoor quality is due to inadequate ventilation (Yeang, 1999). As buildings become sealed or an interior is redesigned and the flow of air changes, therefore air may not move as freely and the contaminants can accumulate in the closed space. Poorly designed or maintained ventilation systems (HVAC) also create problems, especially in situations where the pollutants can build up over time due to poor air exchange (Heimlich, 2008). Auliciems (1989) points out that air which is recirculated in the air-conditioning systems cannot be filtered well and that air carries noxious substances. Indoor pollutants accumulates or be distributed away from the source. Also there is the problem of condensation, which creates an appropriate environment for the growing of harmful microorganisms. The employment of natural ventilation can help to mitigate noise and health problems associated with HVAC systems, ensure a healthier and more comfortable environment for occupants. To integrate natural ventilation to the tall buildings, airflow change rates for the spaces with different functional requirements should be known, because there is a direct relation between air change and pollution level. As seen in the Figure 2.1, level of indoor pollution decreases exponentially as the natural ventilation airflow rate increases.

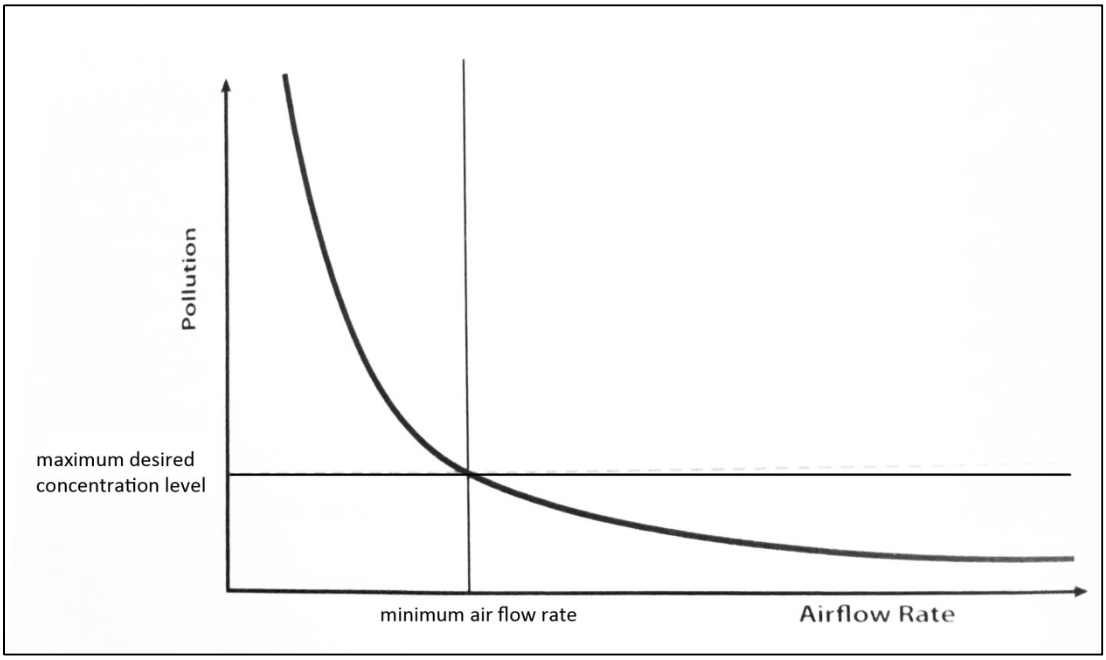

Figure 2.1. Indoor air pollution versus airflow rate (Allard & Alvarez, 1998)

A minimum airflow rate is required to prevent indoor pollution from exceeding the maximum permitted concentration levels. In the Table 2.1, common Air Change Rates per hour (ACR) for buildings / rooms can be seen.

Table 2.1. Air Change Rates per hour (ACR) for buildings / rooms (Allard, 1998)

Building / Room	Air Change Rates - *ACR* - *(1/hr)*	Building / Room	Air Change Rates - *ACR* - *(1/hr)*
All spaces in general	min 4	Court Houses	4 - 10
Attic spaces for cooling	12 - 15	Dental Centers	8 - 12
Auditoriums	8 - 15	Department Stores	6 - 10
Bakeries	20	Dining Halls	12 -15
Banks	4 - 10	Dining rooms (restaurants)	12
Barber Shops	6 - 10	Dress Shops	6 - 10
Bars	20 - 30	Drug Shops	6 - 10
Beauty Shops	6 - 10	Engine rooms	4 - 6

Table 2.1. (continued)

Boiler rooms	15 - 20	Factory buildings, ordinary	2 - 4
Bowling Alleys	10 - 15	Factory buildings, fumes and moisture	10 - 15
Cafeterias	12 - 15	Fire Stations	4 - 10
Churches	8 - 15	Foundries	15 - 20
Club rooms	12	Galvanizing plants	20 - 30
Clubhouses	20 - 30	Garages repair	20 - 30
Cocktail Lounges	20 - 30	Garages storage	4 - 6
Computer Rooms	15 - 20	Homes, night cooling	10 - 18
Laundries	10 - 15	Jewelry shops	6 - 10
Libraries, public	4	Kitchens	15 - 60
Lunch Rooms	12 -15	Restaurants	8 - 12
Luncheonettes	12 -15	Retail	6 - 10
Nightclubs	20 - 30	School Classrooms	4 - 12
Malls	6 - 10	Shoe Shops	6 - 10
Medical Centers	8 - 12	Shopping Centers	6 - 10
Medical Clinics	8 - 12	Shops, machine	5
Medical Offices	8 - 12	Shops, paint	15 - 20
Mills, paper	15 - 20	Shops, woodworking	5
Mills, textile general buildings	4	Substation, electric	5 - 10
Mills, textile dye houses	15 - 20	Supermarkets	4 - 10
Municipal Buildings	4 - 10	Town Halls	4 - 10
Museums	12 -15	Taverns	20 - 30
Offices, public	3	Theaters	8 - 15
Offices, private	4	Turbine rooms, electric	5 - 10
Police Stations	4 - 10	Warehouses	2
Post Offices	4 - 10	Waiting rooms, public	4
Precision Manufacturing	10 - 50	Pump rooms	5

2.2.2. Thermal Comfort Standards

The aim for ventilating buildings is to provide a comfortable internal environment and suitable air quality; therefore it is important to understand the issues of thermal comfort standards before considering detailed aspects of natural ventilation strategies.

The concept of thermal comfort was defined by Fanger (1970), using the concept of Predicted Mean Vote (PMV). The PMV predicts thermal sensitivity with a scale in which -3 represents very cold, 0 represents neutral and +3 represents very hot. The American Society of Heating, Refrigeration, and Air-Conditioning Engineers (ASHRAE) Standard 55 is based on the PMV model, to decide on thermal comfort levels in mechanically conditioned spaces. According to Brager & de Dear (2002) "ASHRAE Standard 55 contains, arguably, a narrow definition of thermal comfort which cannot be easily achieved in naturally ventilated buildings, even in relatively mild climatic zones". In 2004, ASHRAE Standard 55 issued an additional method on deciding required thermal conditions for naturally ventilated spaces as seen in the Figure 2.2.

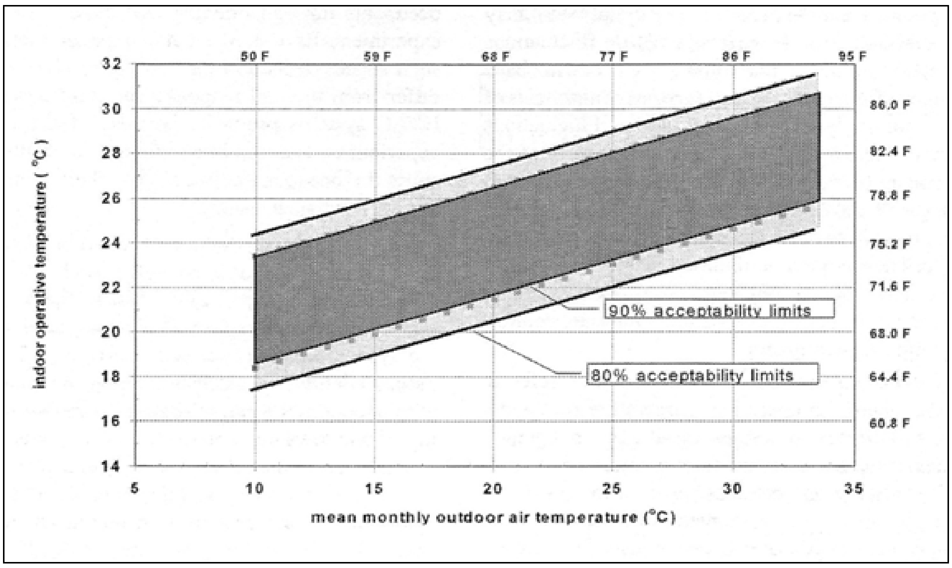

Figure 2.2. Required operative temperature ranges for naturally ventilated spaces (ASHRAE Standard 55, 2010)

The achievement of comfort standards with natural ventilation needs an optimized building design, based on environmental principles and architectural rules, aiming to balance heat gains/losses. Facades should be designed according to solar and wind orientations and their performance in relation to the typical configuration of a building's internal spaces, including plan depth, room floor to ceiling height and even occupation parameters, such as density and periods of use (Gonçalves & Umakoshi, 2010)

It is important to find a balance between optimum indoor air quality, ventilation effectiveness, energy use, and thermal comfort. Comfort zones are usually between 18°C and 24°C with a relative humidity between 30-60 percent (Yeang, 2006). However thermal comfort standards can be influenced significantly by context. People living or working in mechanically ventilated spaces tend to estimate homogeneity of air temperature and humidity, with little tolerance of variations. On the contrary, people living and/ or working in naturally conditioned buildings adapt to more variable indoor thermal comfort conditions that reflect outdoor local climate variations (Brager & de Dear, 2002). Inherently, their preference and tolerance extend over a wider temperature range than that of ASHRAE Standard 55.

Users like windows and contact with external air; this is especially so in cities where the climate is predominantly mild, as well as in more extreme conditions where the contact with the outside environment is possible only for a few months in the year (Etheridge, 2012). The tolerance to variations in internal environment and comfort is affected by a wide range of cultural, climatic and socio-economic factors. When designing a naturally ventilated building, it is beneficial to adopt an adaptive thermal comfort standard which takes these cultural, social, climatic, and contextual factors into account. In addition, when building occupants have control over their environment, thermal comfort ranges can be further extended beyond the normal range (Brager & de Dear, 2002). As concluded by ASHRAE (2009), "The value of using an adaptive model to specify set points or guide temperature control strategies is likely to increase with the freedom that occupants are given to adapt".

2.2.3. Considerations for Different Climates

Different climates pose different environmental requirements, therefore various design strategies can be generated to achieve human comfort. Such strategies can lead to significant energy savings and therefore a better energy performance whether the building is to be naturally ventilated for the whole year or simply during periods of the year when the climate is favorable (Gonçalves & Umakoshi, 2010). The followings outline some of the specific natural ventilation considerations for each of four main climate types.

Hot-Dry Climate

This climate is characterized by high air temperatures surpassing 37°C for much of the year, low humidity levels, almost no precipitation, and ample day/night temperature fluctuations. Mitigating solar heat gain is an essential strategy in this climate. Buildings should ideally be oriented along an east-west axis with the main facade openings positioned toward the north and south. This orientation reduces solar gain during the more problematic lower-sun angle periods in the mornings and afternoons, especially in summer (Givoni, 1998).

Natural ventilation during the daytime may be difficult due to the high external air temperatures, and also the amount of particulates (especially sand) in the air (Marcondes, 2010). Some regions can offer a seasonal changeover mixed-mode strategy to achieve an optimal environment. During the hotter months, night-time ventilation can be an effective strategy; utilizing the often significant drop from day-to-night-time air temperatures to flush out internal heat gains built up during the day. For this aim, thermal mass can be utilized to restrict internal heat gains and to delay thermal exchanges between the exterior and interior. In fact, effective night ventilation is mainly important for the cooling of building’s exposed structural mass, because without effective cross-ventilation at night, the building’s interior may be unbearably hot during the nights (Etheridge, 2012). Marcondes (2010) emphasizes the same issue by stating that night-time ventilation can be an efficient passive strategy as it benefits from lower external air temperatures to help cool down a building's fabric and dissipate internal heat loads. The same author also notes that the environmental performance of night ventilation can be significantly increased if coupled with internally exposed building materials of high thermal inertia, functioning as heat sinks.

Evaporative cooling strategies coupled with a continuous airflow could also be used to increase the moisture content in the typically dry air, lower the temperature, and improve internal comfort. Evaporative strategies include localized evaporative cooling within the facade system or the use of a large centralized water source to help condition a specific area such as a water feature/ fountain in the lobby of a building (Etheridge, 2012).

Hot-Humid Climate

A temperate climate typically requires the architectural design to have the greatest adaptability throughout the year, employing devices such as high thermal insulation and passive heating during the cold season, but shading and higher ventilation rates during the hot season. This requirement for a level of adaptability of the systems in the building requires a careful study of the daily, seasonal and yearly variations of the local climate. Such adaptable strategies will typically include controlled ventilation that varies according to external conditions, and shading that reduces solar radiation in the summer but can allow it in winter (Yeang, 2005).

In this climate, narrow floor plates may be utilized for efficient cross-ventilation through the space. High floor-to-ceiling heights can be utilized to keep warmer air stratified upwards, away from the occupants, and also increase natural ventilation through stack effect (Marcondes, 2010). Increasing the air rate can lead a better internal environment through the process of psychological cooling (Wood & Salib, 2013). For this aim, vertical wing walls can be utilized to catch a wider angle of oblique wind and accelerate it through a narrowing gap into the space, across the space, and out the other side.

If the feasibility of having a fully naturally ventilated building in a tropical climate does not seem possible, another solution is to separate the building into natural and mechanical ventilation zones, with separate consideration of spaces that require a high degree of environmental consistency (e.g., office work spaces), and those that could tolerate more variation (e.g., circulation and social/gathering spaces) (Yeang, 2005). This strategy decreases the overall building cooling loads in a hot-humid climate.

Cold Climate

Cold climates are characterized by low average air temperatures (lower than -3 °C during winter) and low solar radiation as most are located above 40° north latitude. The most important consideration when designing in such extreme climate conditions is the conservation of heat. This can be addressed through both the form of the building and the building envelope. Compact shapes provide more concentrated floor-to- envelope area, which reduces the facade heat loss/gain. Curvilinear shapes also have a better aerodynamic performance which may assist in the natural ventilation strategies in the building. The building should look to benefit from passive solar heating, especially in winter, by orienting the glazed areas of the facade toward the more intense solar radiation. Special attention, however, is needed when specifying the glazing components - considering the low thermal resistance of glass. The use of double and triple glass panels with gas-filled air cavities has become common practice in cold climates. Furthermore, a water feature can help to humidify the incoming dry air in winter (and can be chilled to help dehumidifying it in summer), since this is another problem with natural ventilation in cold climates (Wood & Salib, 2013).

Temperate Climate

A temperate climate typically requires a level of adaptability of the systems in the building, thus a careful study of the daily, seasonal and yearly variations of the local climate is needed. Such adaptable strategies will typically include controlled ventilation that varies according to external conditions, and shading that reduces solar radiation in the summer but can allow it in winter (Marcondes, 2010).

Considerations such as wall-to-floor ratios, window-to-floor ratios, and building orientation will help determine the success of a natural ventilation strategy for a building in a temperate climate (Wood & Salib, 2013). Furthermore, especially in Europe, double-skin facades use has become a common strategy to naturally ventilate tall buildings.

2.2.4. Main Architectural Design Guidelines for Natural Ventilation

Natural ventilation is based on fundamental heat transfer mode by supplying and removing air through an indoor space by natural techniques. As the air flowing next to a surface carries away heat, and lowers its temperature. Air movement through a building results from the pressure difference between indoor and outdoor. This pressure difference can be achieved by wind forces coming from the outside or by temperature difference between inside and outside. This pressure difference is driven by two primary natural forces that affect greatly on the building design, these two pressure difference are:

- Wind pressure: it is based on air movement from high to low pressure zones; it considered the main principle of cross ventilation systems.

- Buoyancy effect: it is based on the hot air rises and the cool air comes instead of it, this effect is the main principal of stack ventilation systems.

The shape of a building together with the location of the ventilation openings dictates the natural ventilation‘s manner of operation. One usually differentiates between three different ventilation principles for natural ventilation: single-sided ventilation, cross ventilation and lastly stack ventilation. The ventilation principle indicates how the exterior and interior airflows are linked, therefore, how the natural driving forces are utilized to ventilate a building. The principle also indicates how air is introduced into the building, and how it is exhausted.

Single-sided ventilation

In single-sided, only one side of the ventilated enclosure has opening(s). Fresh air enters the space through the same side it is exhausted from as indicated in the Figure 2.3. A space in a cellular layout with opening on one side and closed internal door on the other side exemplifies this type of ventilation.

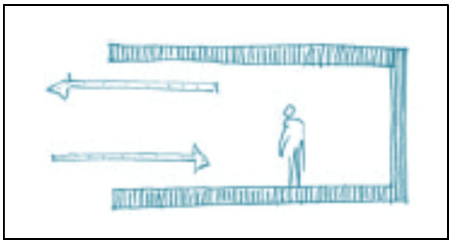

Figure 2.3. Single-sided ventilation

In single-sided ventilation, effective depth is a maximum of 2.5 times floor-to-ceiling height. Ventilation rate can be enhanced by the buoyancy effect in cases where ventilation openings are provided at different heights. The greater vertical distance between the openings and the greater temperature difference between the inside and the outside, the stronger the effect of the buoyancy. When compared with other strategies, lower ventilation rates are generated and air does not penetrate far into the spaces (CIBSE Application Manual AM10, 2005).

Cross Ventilation

Cross ventilation relies on the flow of air between the two sides of a building's enclosure. Fresh air enters the space through the windward side and extracted from the leeward side as indicated in the Figure 2.4.

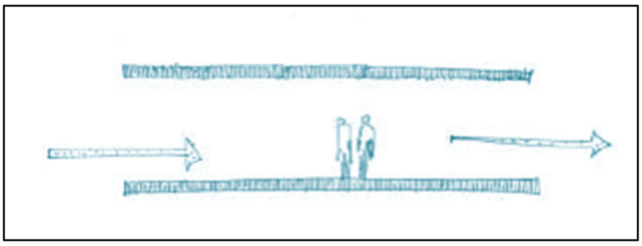

Figure 2.4. Cross ventilation

In cross ventilation, effective depth is 5 times floor-to-ceiling height (CIBSE Application Manual AM10, 2005).

Stack ventilation

Stack ventilation relies on temperature, density and pressure differences between the interior and exterior or between certain zones in a building. In stack ventilation, entry of fresh air into a building is at a low level, while it is extraction at a high level (a reverse flow can occur during certain conditions) as indicated in the Figure 2.5.

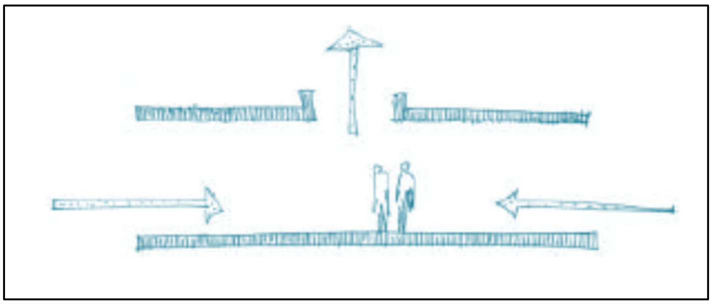

Figure 2.5. Stack ventilation

Stack ventilation is effective across a width of 5 times floor-to-ceiling height from the inlet to where the air is exhausted. Stack effect needs a certain height between the inlet and the outlet. This can be ensured by a variety of methods involving increasing the floor-to-ceiling height, applying an atrium or chimney, or tilting the profile of the roof.

2.2.4.1. Building Form, Orientation and Layout of Spaces

The risks and challenges associated with natural ventilation in a high-rise building are considerably greater than in low-rise structures, since wind speed increases, and airflow patterns become less predictable at height. As air contacts the windward face of a building, approximately one-third of the air travels upward/over the building and the remainder flows downward, forming a vortex at the ground as seen in the Figure 2.6. The vortex effect is amplified and more air passes around the sides and over the top of the structure as the building height increases. However, such challenges can be mitigated depending on the form of the building. A tall, slender rectilinear building or a curvilinear building, such as 30 St. Mary Axe, London provides a viable solution as seen in the Figure 2.7.

The form of the building influences the possible environmental conditioning strategies. The geometric configurations that promote self-shading, as well as the porosity of the building mass can have a profound impact on the environmental performance of a building, especially when considering natural ventilation and wind loads on the facades/built form (Gonçalves & Umakoshi, 2010).

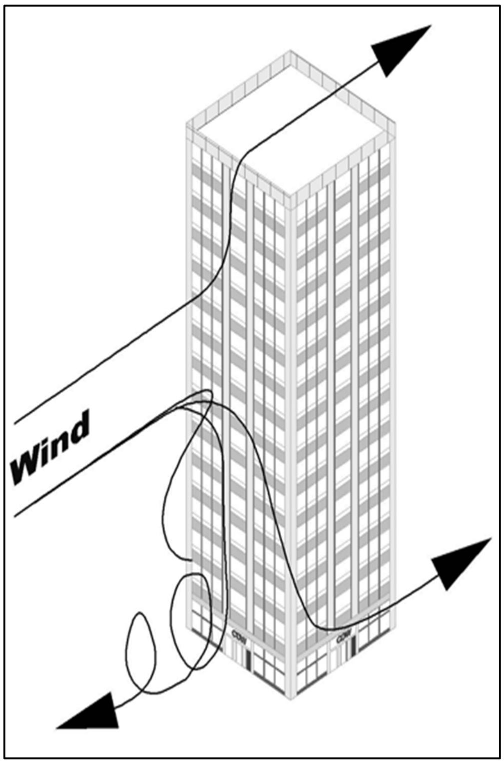

Figure 2.6. Vortex effect at the base of a tall building (http://www.ashireporter.org)

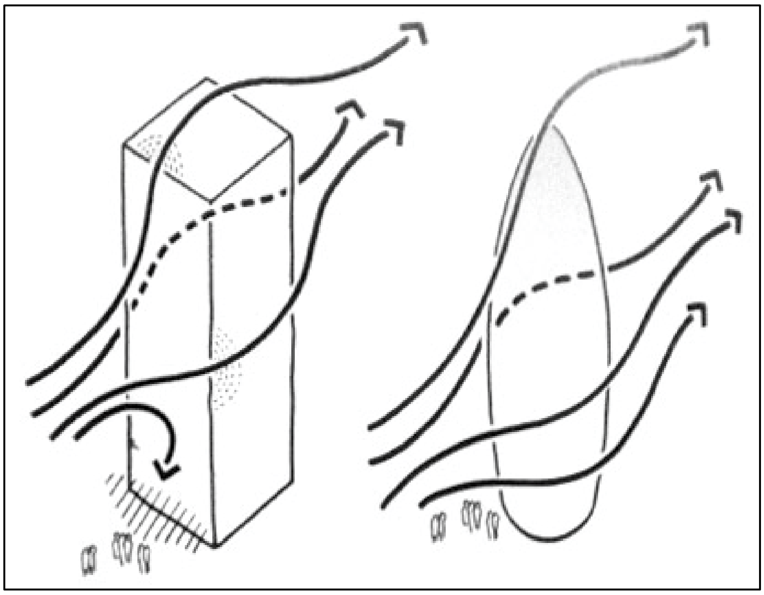

Figure 2.7. Airflow distribution around a rectilinear building (left) and 30th Saint Mary Axe Tower (right) (courtesy of Foster and partners)

Building Orientation

The efficient orientation of a tall building with regard to the prevailing wind and sun significantly enhances the promises of natural ventilation. Although the predominant forces for naturally ventilating a tall building are likely to be buoyancy-induced, if wind (cross-ventilation) is the primary driving force, it is important to orient the main windward openings in the direction of the prevailing wind. On the contrary, there is greater flexibility with building orientation with regard to the prevailing wind direction, when both wind and buoyancy driving forces are used concurrently. For instance, the main windward openings in GSW Headquarters, Berlin are located on the east side despite the wind predominately blowing from the west, therefore in this case, stack effect and solar heat gain create buoyancy-induced cross-ventilation and maintain sufficient airflow rates and comfort levels, even on hot days in the absence of wind (Wood & Salib, 2013).

Strong winds from a predominant direction can thus be exploited to allow for single-sided and/or double-sided cross ventilation (Marcondes, 2010). Especially in tall buildings, while using wind-driven natural ventilation, the main aspects to be considered is the potential greater magnitudes of wind and buoyancy effects at higher levels.

Yeang (1994) states that, the theoretical strategy for inducing wind flow into a building or blocking it, is based on prevailing wind conditions. Desired and undesired winds in different climates depend mostly on local climatic conditions. Generally for the hot-humid climates, much ventilation rates are desired, on the other hand for the hot-dry climates cross ventilation is needed, but care should be taken to filter out high-speed winds. As seen in Figure 2.8, importance of cross ventilation varies in different climate types, namely in cold climates wind coming from prevailing directions is blocked, however in hot-dry (arid) climate, prevailing winds highly benefitted for cross ventilation.

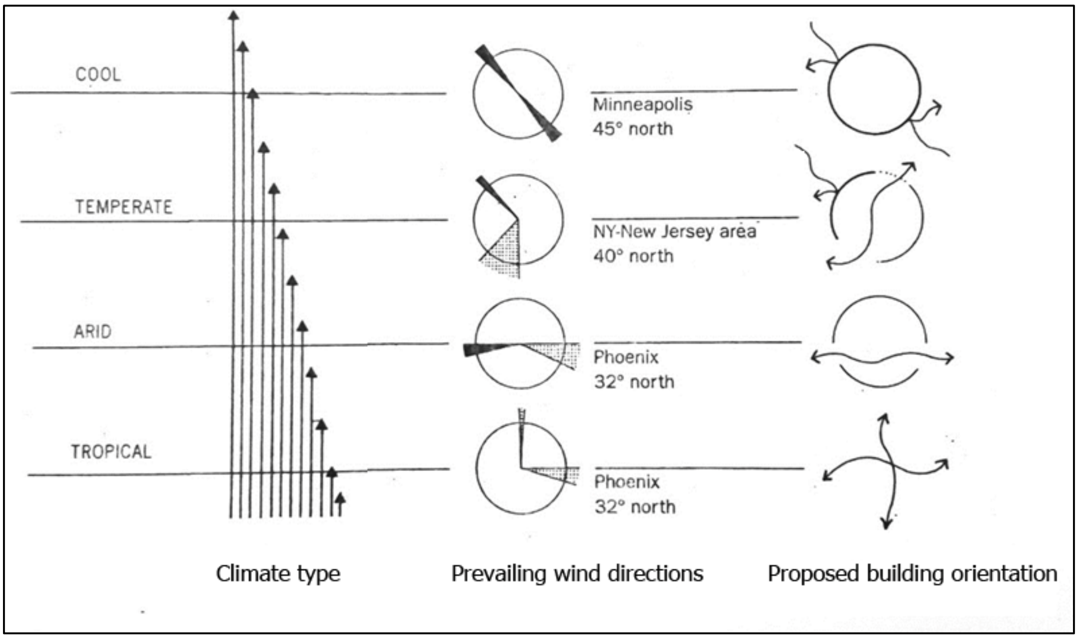

Figure 2.8. Requirements for cross ventilation in different climates
(base graphic: Yeang, 1994)

Having the two driving forces, wind and buoyancy in combination may enhance the prospects of a naturally ventilated building. For tall buildings to rely exclusively on natural ventilation, an inward flow of air must be maintained even when winds are weak, there is no wind, or the wind is not blowing from the desired direction. With little or no wind, buoyancy-induced ventilation can provide an alternative/additional driving force to ensure the effectiveness of natural ventilation, further stack effect can also be exploited through the use of an interior atrium or sky garden, through a thermal flue or solar chimney, or through vertical circulation cores (Gonçalves & Umakoshi, 2010).

Layout of Spaces

The planning and spatial configuration of a tall building determines the possibility and effectiveness of natural ventilation largely. Prior to the advent of air-conditioning, high-rise buildings in the late 1890s and early 1900s utilized limited plan depths combined with open (central) courts to ensure natural ventilation. Iconic tall buildings such as the Chrysler and Empire State Buildings demonstrates the importance of wall-to-core depth (limited to 8-9 meters during that time) as indicated in the Figure 2.9 and Figure 2.10. The form of these tall buildings and the depth of their plans were still driven by the need for daylight and natural ventilation.

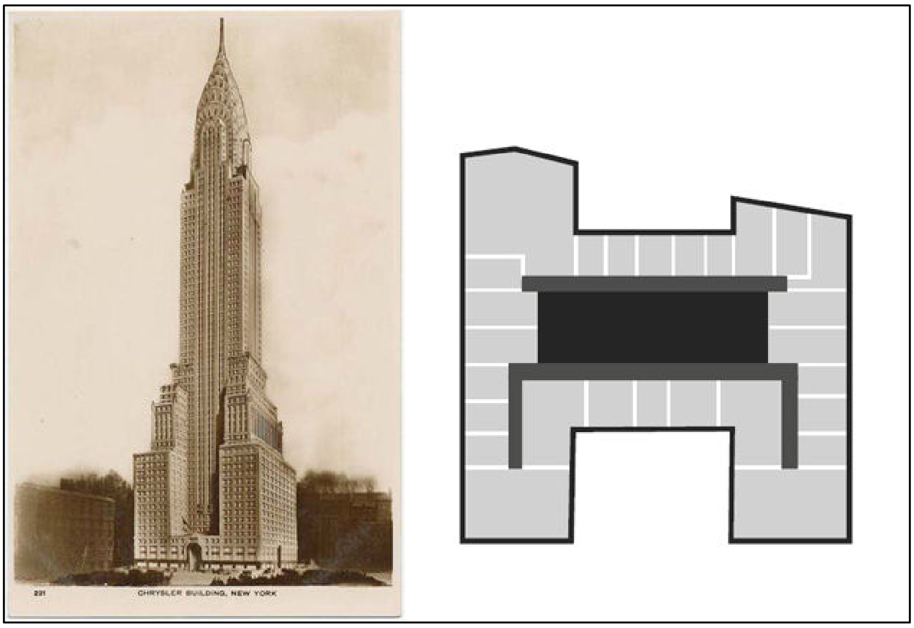

Figure 2.9. Chrysler building- general view and typical floor plan (google images)

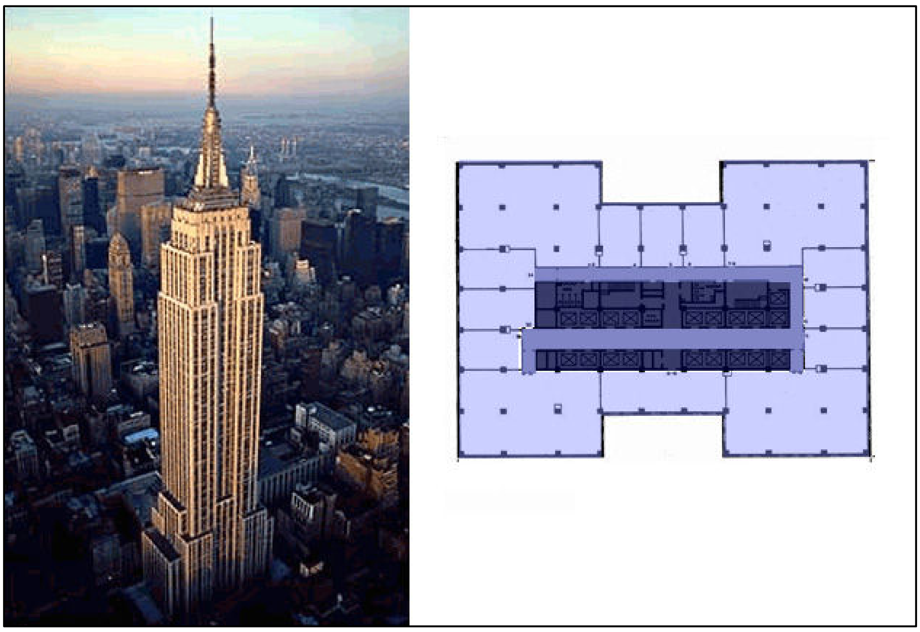

Figure 2.10. Empire State building - general view and typical floor plan (google images)

Coming to more recent cases, Commerzbank Tower with a plan depth of 16.5 meters is able to provide natural ventilation with more desirable deep lease depths. To achieve this, a central atrium and sky gardens were benefitted, and circulation cores were moved to the edges of the building as indicated in the Figure 2.11. Thanks to this, building occupants have sufficient daylight and natural ventilation. Moreover, the relocation of the vertical circulation elements and service facilities allow for flow of fresh air across the spaces (Wood & Salib, 2013).

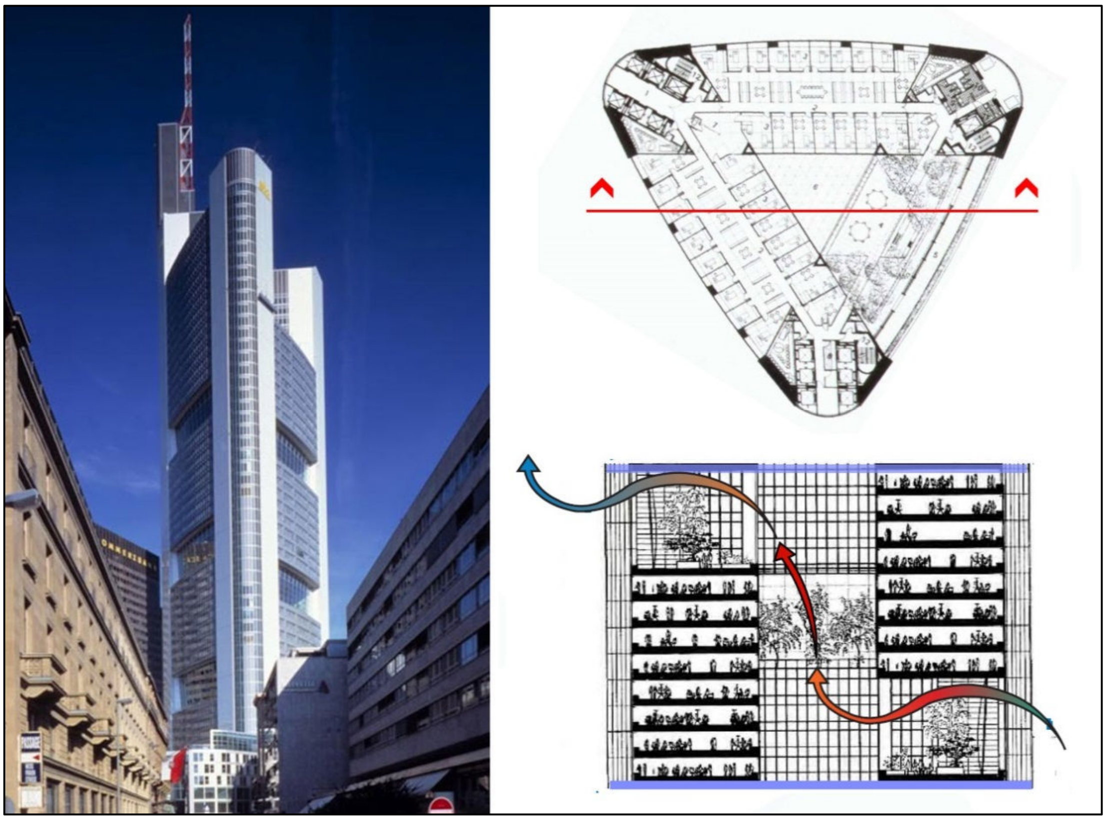

Figure 2.11. Commerzbank Tower, general view (left), plan and partial section (right) (base drawings: Foster and partners)

Additionally, it should be noted that the implementation of natural ventilation can require a radical change in the interior layout from that of a conventional tall office building which typically has cellular offices along the perimeter and open-plan office spaces at the center. Cellular and open-plan layouts both utilize low partition walls in the open-plan offices and gaps between enclosed rooms and the ceilings to permit airflow from one side of the office space to the other with minimal obstructions (Gonçalves & Umakoshi, 2010).

Lastly, floor to ceiling heights, as being another major architectural feature to enhance natural ventilation in tall buildings, should be considered. Higher floor to ceiling heights enable more air flow through the interior space, also creating opportunity for openings at different heights, with higher level windows increasing pressure differences and therefore air change rates. The UK's manual of best practice, British Council for Offices Guide (2000) recommends a minimum floor to ceiling height of 3m for offices, in contrast to the traditional measure of 2.7m found in the great majority of conventional offices (artificially conditioned, with false ceiling and raised floor). With the removal of a centralized mechanical system and the utilization of a decentralized mixed-mode system, Post Tower, Bonn, Germany operates without the necessity of multiple mechanical floors (Blaser, 2003). As seen in Figure 2.12, in doing so, floor-to-ceiling height increases compared to a traditional system with dropped ceilings and ducts.

Figure 2.12. Higher floor to ceiling heights enabling more airflow in Post Tower (http://architizer.com/ projects/post-tower/)

2.2.4.2. Facade System

The decision to naturally ventilate tall buildings is related to the careful design of the facades in order to deal with high air pressure and velocity, and the impact of solar radiation on air flow patterns (Gonçalves & Umakoshi, 2010).

Single-skin facades with operable windows (usually protected from the wind on high floors by external panels) are seen in a number of examples of naturally ventilated tall buildings, mainly with cellular internal layouts. In parallel, sophisticated solutions of double-skin facades have been presented as a guarantee for efficient cross ventilation in tall building with open- plan layouts (Marcondes, 2010). There has been a tendency in recent years - especially in Europe - toward employing double-skin facades to enhance natural ventilation, however there are numerous benefits of such twin-layer envelopes, selecting the appropriate glazing is crucial to getting the necessary performance. In a double-skin facade, the outer glazing layer provides additional protection against weather conditions and external noise (both urban level and wind induced) and allows greater control of incident wind speeds, therefore enhancing the prospect for natural ventilation in tall buildings. During the heating season, solar gain in between the layers of the double skin facade may serve to preheat fresh air before it enters the building, conversely, during the cooling season; the cavity is ventilated in order to carry away solar heat gain (Wood & Salib, 2013).

Regarding the facade design, some specific aspects are important for the efficiency of natural ventilation, including the area, position and distribution of apertures of windows, and existence of external elements, such as shading devices or structural components (Gonçalves & Umakoshi, 2010).

Shading Devices

The facade system should be carefully considered in the design of a tall building with respect to solar control which affects performance of a building's ventilation strategy. If the sun shading devices are not properly positioned, the facade could experience overheating in the summer (Meyer, 2008).

Solar control can be ensured both interior and exterior shading elements. Torre Cube Tower, Guadalajara, Mexico can be an example of a tall building benefitting outer solar control. In this building, an outer diaphanous screen is used for solar protection to reduce glare and excessive solar heat gain as seen in Figure 2.13.

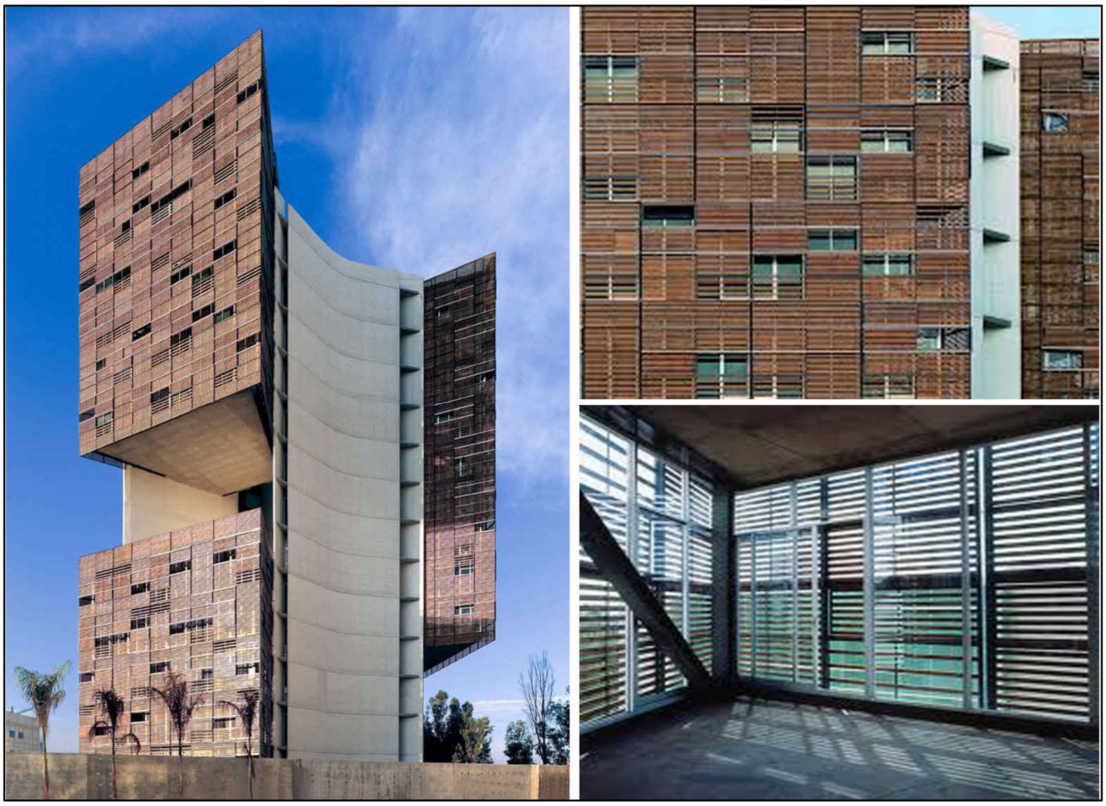

Figure 2.13. Torre Cube Tower- general view and shading devices detail
(courtesy of Estudio Carme Pinos)

Lastly, it should be noted that, solar control is needed in many climates, therefore in the selection and detailing of them, to not cut the outside view completely should be considered, otherwise connection between the occupants and their environment may not be ensured. In Post Tower, Bonn, Germany highly reflective and adjustable blinds are integrated within the cavity of the double-skin facades as seen in the Figure 2.14. These shading devices protect the office spaces against direct solar heat gain and help reduce glare inside the offices. Since these blinds are perforated, they offer good views to the surrounding landscape even when they are in fully closed position.

Figure 2.14. Post Tower- general view and highly reflective, adjustable blinds (courtesy of Murphy/Jahn Architects)

Ventilation Openings

Facade design requires specific considerations for the position and sizing of openings to ensure proper pressure distribution within the natural ventilation system. Many of tall buildings in operation have proved that tall office buildings can be naturally ventilated through operable windows (with wind shields) and single-skin facades (Gonçalves & Umakoshi, 2010). The Highlight Towers, Munich have a single-skin facade, but still naturally ventilated through pivoting panels integrated in the facade as seen in the Figure 2.15. In this case, fixed triple-glazed windows feature high-performance and heat-reflecting properties while a narrow, operable glass panel enables direct natural ventilation. Further a perforated stainless steel panel with soundproofing properties is mounted behind the pivoting panel to provide protection against the sun, wind, and rain (Schmidth, 2006).

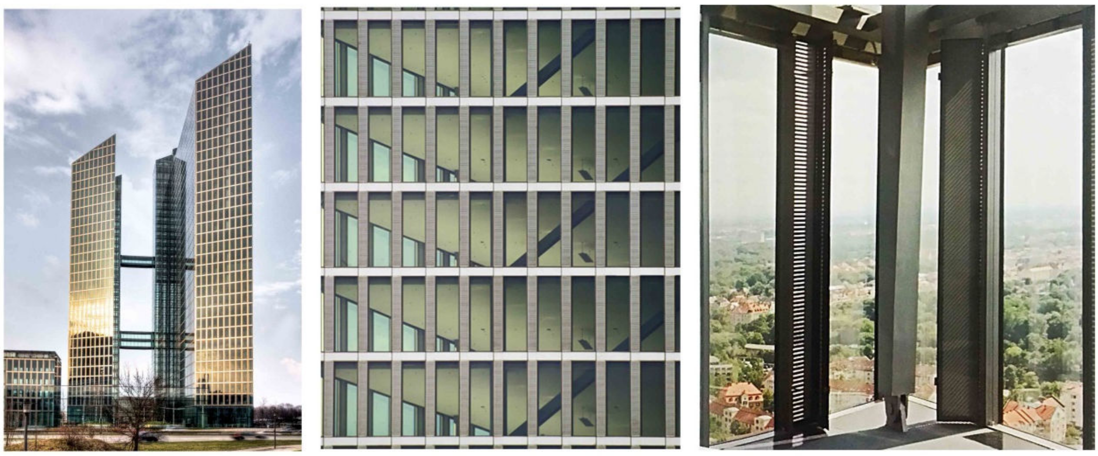

Figure 2.15. Highlight Towers- general view and ventilation openings (courtesy of Murphy/Jahn Architects)

In the case of 1 Blight Street Tower, aerofoil-shaped louvers were designed to naturally ventilate perimeter offices through double skin facade. This louvers located at the edge of each floor slab allow fresh air to enter at the bottom of each cavity and exhaust at the top as seen in the Figure 2.16 (Meyer, 2008).

Post tower is another tall building benefitting natural ventilation, however in that case, a double skin facade system allowing air intake and extract through flaps at the bottom of each facade panel is used. On hot summer days, these operable flaps are opened to their maximum angle to ensure sufficient airflow within the cavity, while in winter, these openings are closed to a minimum so the facade cavity acts a thermal buffer, reducing heat loss. Detail of the ventilation system is indicated in the Figure 2.17.

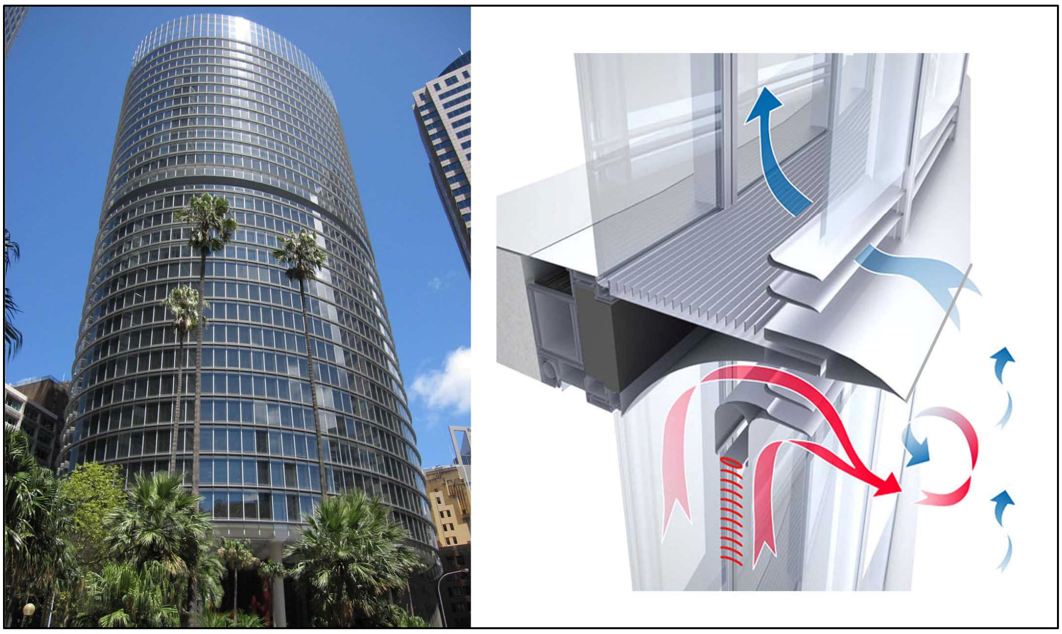

Figure 2.16. 1 Blight Street Tower-general view and aerofoil shaped louvers
(courtesy of Ingenhoven Architects)

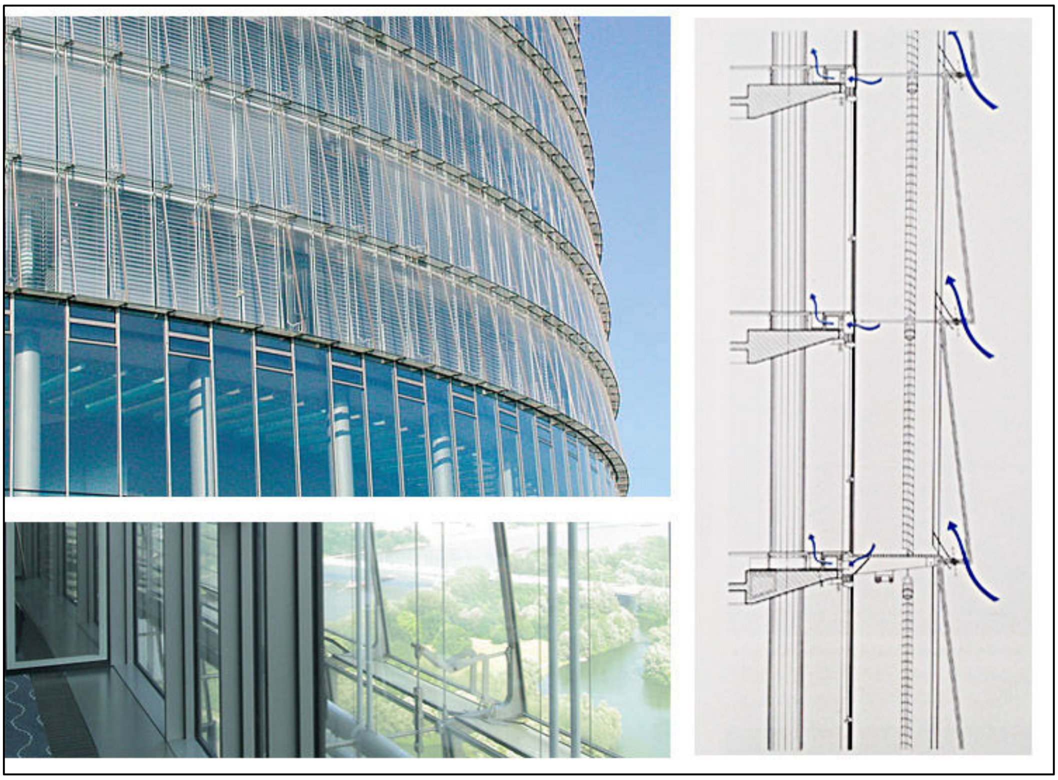

Figure 2.17. Post Tower- facade view and ventilation openings
(courtesy of Murphy/Jahn Architects)

Another naturally ventilated tall building using ventilation flaps is KFW Westerkade, Frankfurt. In that case, the offices are naturally ventilated through a double skin facade consisting of an outward- pivoting glass flaps opening up to 90° and an inner layer with side-hung windows as indicated in the Figure 2.18 and Figure 2.19.

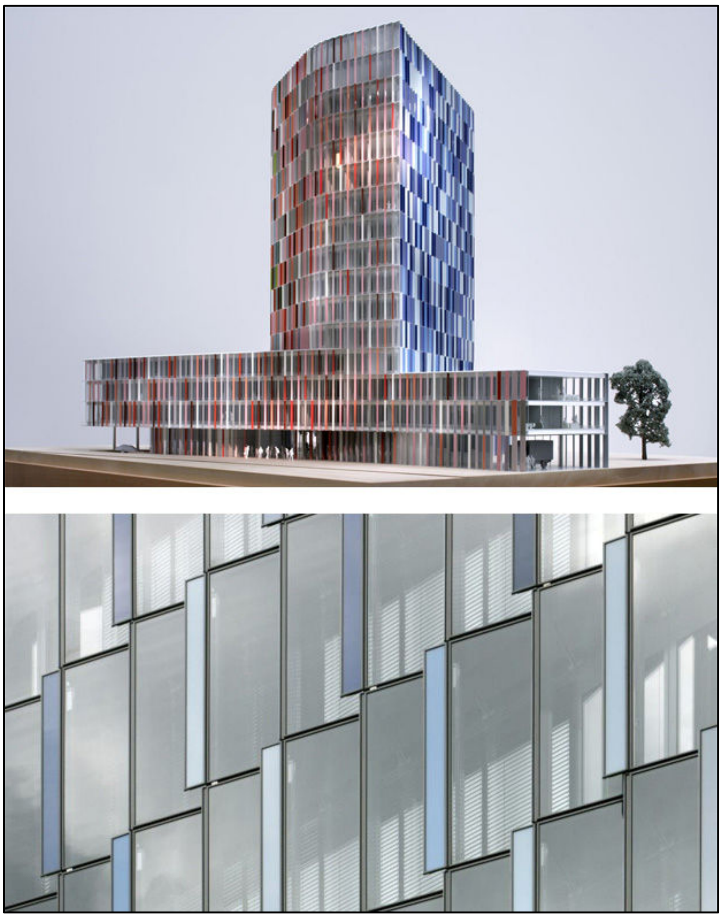

Figure 2.18. KFW Westerkade building- general view (top) and facade view (bottom) (courtesy of Sauerbruch Hutton Architects)

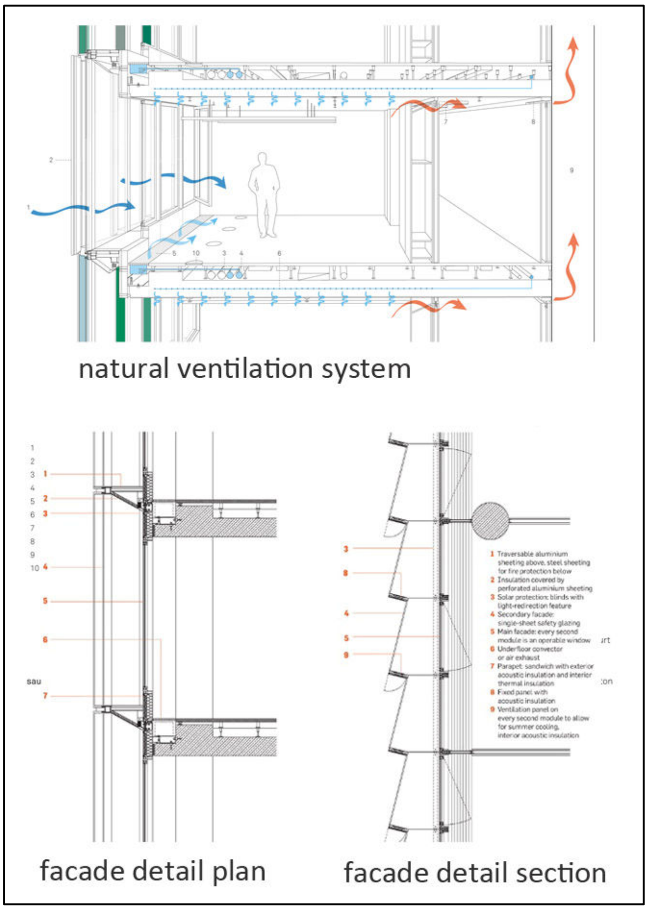

Figure 2.19. KFW Westerkade building- natural ventilation system and facade detail (courtesy of Sauerbruch Hutton Architects)

Aerodynamic Elements

Aerodynamic elements can be utilized to capture the wind through a wider incident angle and induce more effective natural ventilation, when there is little wind or the building openings are not able to be oriented to the prevailing wind direction. The use of aerodynamic elements and forms may lead to a purely naturally ventilated tall building in combination with other sustainability features (Wood & Salib, 2013).

Further, aerodynamic elements can be used to enhance the natural ventilation strategy. In the case of GSW Headquarters Tower, a wing roof shaped in profile like an upside-down airplane wing is benefitted to generate an additional uplift force in the atriums. When the wind is not blowing in the prevailing direction, a series of fins suspended from the wing roof are used to make wind eddy, which prevents the risk of down currents over the outlet of the atriums or vertical voids. The detail of the wing roof is indicated in the Figure 2.20.

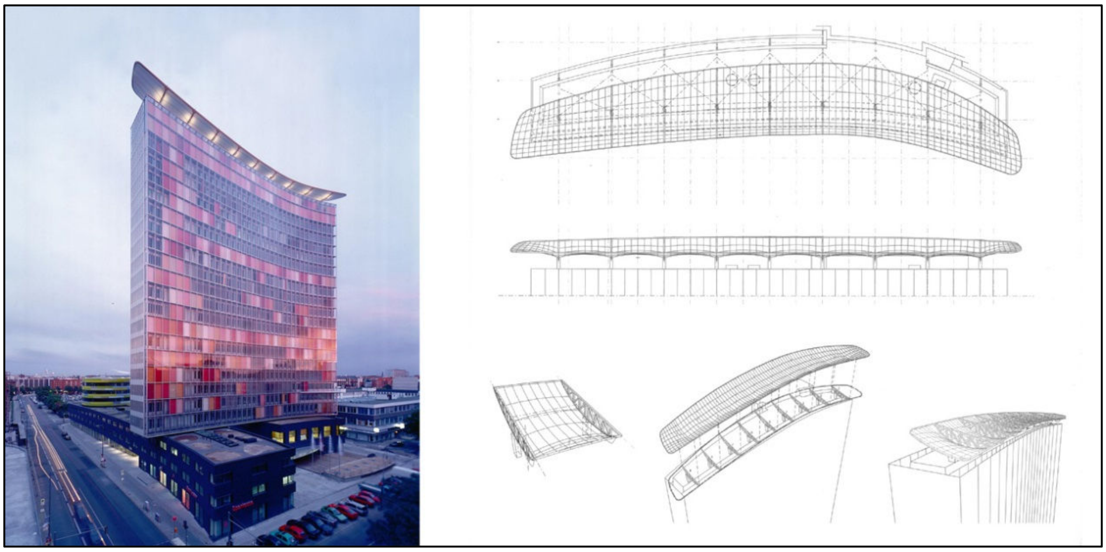

Figure 2.20. GSW Headquarters Tower - general view (left) and wing roof (right) (courtesy of Sauerbruch Hutton Architects)

Within the relatively calm tropical winds of hot-humid climates, wing walls can be used to direct winds into the building from a wider range of directions than the prevailing wind, further to capture and to create greater positive pressure on the windward side of the buildings, so the natural ventilation strategy does not need to rely solely on the naturally created negative pressures on the leeward side of the buildings to draw ventilation through. In theory, this induces a high air change rate necessary to achieve thermal comfort conditions in a tropical climate. However, if the wing wall strategy was used in a location with higher average wind speeds, the pressure differentials across the building envelope could be too great, causing problems such as difficulties with opening windows and doors and controlling the high airflow rates (Jahnkassim, 2004).

While some buildings utilize large aerodynamic elements, other buildings use smaller elements to enhance natural ventilation. Since, high-rise buildings experience significantly different wind speeds and pressures differentials at various heights and locations across the facade, and the double-skin openings need to somehow account for these (Wood & Salib, 2013). In the case of Commerzbank, Frankfurt small aerofoil sections at the top/bottom of the double skin facade openings are used to improve airflow through the ventilated cavity and avoid the short-circuiting of air as seen in the Figure 2.21 (Lambot, 1997).

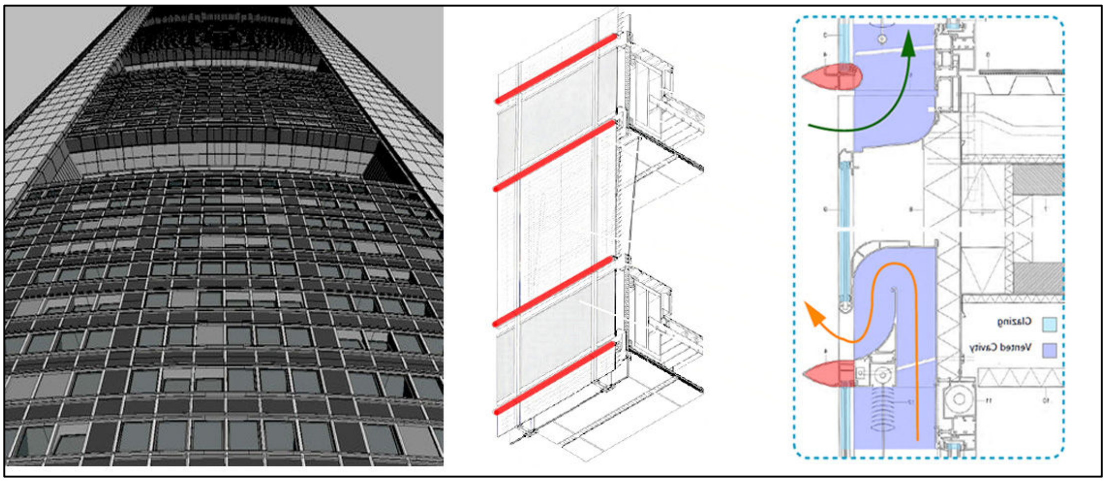

Figure 2.21. Commerzbank Tower - close view of the facade and opening detail (courtesy of Foster and Partners)

2.2.4.3. Sky Garden and Atrium

The success of natural ventilation has been related to an architectural design approach differentiated from the basic conventional commercial model, especially challenging building shape and, therefore, the configuration and the dimensions of the floor plate, with narrower plans in evidence. Other design aspects commonly found in the new model are more complex facades, the grouping of floors in vertical segments, and additional spaces such as atriums, sky-courts or sky-gardens (Gonçalves & Umakoshi, 2010).

The use of sky gardens in the design of naturally ventilated tall buildings has become quite common as seen in Figure 2.22. From a natural ventilation viewpoint, the sky gardens can be used for air intake, air extraction, a combination of the two, or to induce ventilation in inward-facing offices. But in most scenarios, sky gardens are used as extraction chimneys which exhaust air from the building through stack effect (Wood & Salib, 2013). However in some cases, sky gardens provide air intake and pre-heat incoming cold air during the heating season as seen in Figure 2.23. In all cases, sky gardens function as buffer zones which moderate the temperatures between interior and exterior.

Figure 2.22. Commerzbank Tower – sky garden (courtesy of Foster and Partners)

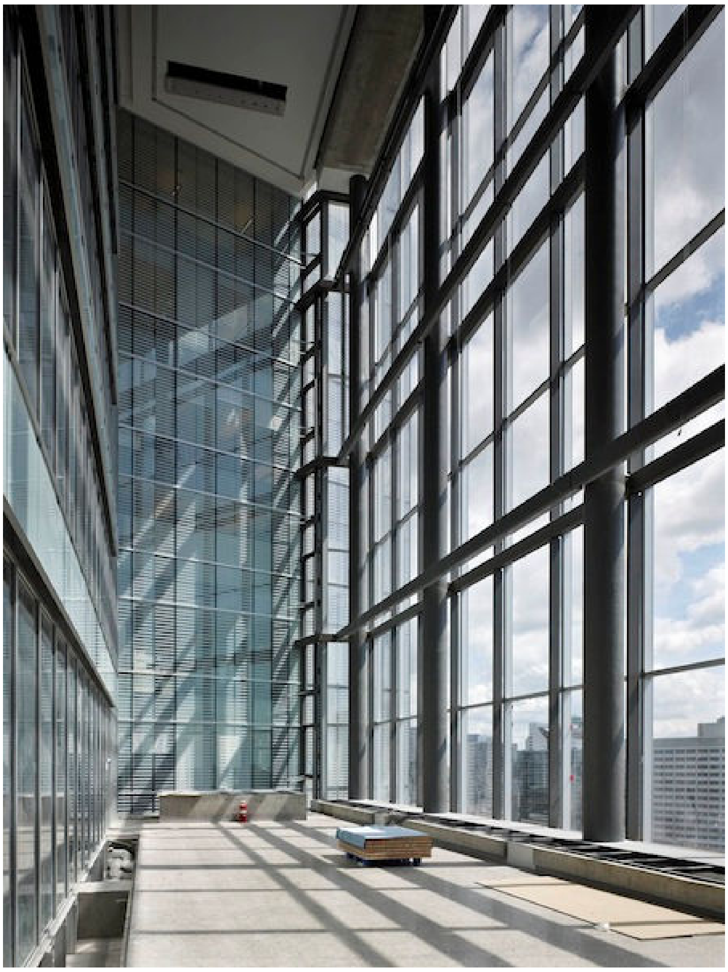

Figure 2.23. Manitoba Hydroplace Headquarters- sky garden
(http://manitobahydroplace.com/Integrated-Elements/Wintergardens)

Since stack effect is complex and can be seen as a problem in extreme climates, it needs careful analysis. Vertical segmentation prevents the development of extreme stack flows which may cause excessive drafts and occupant discomfort. When the atrium or shaft is the primary source for fresh air, segmentation can reduce the variation of airflow rates between different floors. Besides reducing the risk of creating large pressure differences and excessive drafts, there are other benefits to segmenting a vertical void into multiple sky gardens or atria. In the case of a fire, smoke can be mitigated to one specific segment of a tower (Pomeroy, 2008). Segmentation also allows tenants to be visually and acoustically separated from other tenants in the building as in the case that 30 St. Mary Axe, London (Jenkins, 2009). Segmentation can also provide multiple social spaces in closer proximity to the occupants as in Commerzbank, which has one sky garden for every four floors (Lambot, 1997).

Coming to the more specific issues of the verticality, high wind speeds above certain heights which are specific to tall buildings, can impose constraints on the use of natural ventilation, even if the temperature and quality of the air are within acceptable parameters. In those cases, it has been shown by a number of built and designed examples how atriums and other types of voids, as well as detailed facade solutions, can enable natural ventilation in tall buildings, creating buffer zones between the extreme external conditions and the internal spaces (Pomeroy, 2008).

Furthermore, the creation of communal areas, gardens or atriums, has been an effective architectural strategy to make natural ventilation possible in deeper parts of the floor plate in tall buildings, also functioning as buffer zones mediating air temperature and speed. Height in atriums creates stack-effect which can be combined with cross ventilation. The height of the atrium is a key parameter for the efficiency of the strategy. In that sense, internal voids in tall buildings are divided into superimposed atriums in order to control air pressure and, therefore, the stack effect (Gonçalves & Umakoshi, 2010).

2.2.4.4. Thermal Mass and Night-time Ventilation

Since the primary purpose of natural ventilation is to provide acceptable air quality and human comfort, the use of other sustainable strategies which complement natural ventilation can help reduce the cooling load and enhance comfort conditions. The performance of natural ventilation can benefit by exposing thermal mass and utilizing night-time cooling (Wood & Salib, 2013).

Night-time ventilation can be an efficient passive strategy in office towers because it takes advantage of lower external air temperatures during the night to cool down the building and purge the internal heat loads gained throughout the day, which are stored in the fabric of the building. This prospect can be enhanced by exposing more thermal mass for the storage of heat, such as through exposed concrete slabs. It is important to note that night-time ventilation is more effective in climates that experience significant day/night temperature differences (Marcondes, 2010).

According to Gonçalves & Umakoshi (2010) the use of internal thermal mass (mainly in ceilings) is very often found in naturally ventilated office buildings, acting as heat sinks. The same author also notes that active strategies to lower energy consumption, such as chilled beams and chilled ceilings, are usually applied to improve the capacity of the thermal mass. The mixed-mode strategy calls for the maximization of the use of the building fabric and envelope to achieve comfortable indoor thermal conditions, and then the supplementation of this with mechanical systems.

2.3. VARIATIONS IN CLIMATE WITH ALTITUDE

Environmental parameters varying with height involve air temperature, air humidity and wind speed, etc. Air temperature is seen to reduce with increasing height; humidity is also seen to decrease with altitude. Wind speed is seen to increase with altitude, however due to the effects of building clusters and terrain roughness, turbulence will reduce with increasing height. Higher wind velocities lead to rising driving rain on the facades. Air pressures variations between the bottom and top of tall buildings may cause to high velocity winds that not occur in the natural environment (Clair, 2010).

Internal conditions in tall buildings are affected with external climate, for instance with increasing height, temperature and wind speed differences occur and this leads to facade infiltration and ex-filtration. Increase in wind velocities with height may result in cooling of the building facade. Energy required to move air for mechanical ventilation purposes increases with increased altitude, while decreased air pressure with height can decrease energy required to spin fans in HVAC system. Besides, accessing cooler air for mechanical and natural ventilation increases with altitude thanks to clearance from ground level (Clair, 2010).

Operational energy loads are seen to increase with increased height mostly due to increased energy requirements for HVAC system and vertical circulation. However, for a tall building in cold climate, energy loads is seen to decrease at each level toward the roof.

Clair (2010) summarizes the altitude based variations that may have influence on energy loads:

> The effects of solar radiation, building shading and the stack effect on the tall buildings suggest that higher temperatures and cooling loads may be experienced at the upper levels and lower temperatures at the lower levels. Conversely, lower heating loads are seen in wintertime to upper building

levels in a cold climate due to rising heat from the stack effect and increased infiltration of cold air at lower levels.

2.3.1. Variations in Air Temperature with Altitude

Temperatures mostly decrease with height from the ground, however there are some exceptions. In The U.S. Climate Change Science Program Handbook, (2010) variation in air temperature with altitude is stated as follows:

> The rate at which the temperature changes with height is defined as lapse rate which can vary with location and season, and depends strongly on the atmospheric humidity. The lapse rate for a dry atmosphere, when there are no moist processes and the air is rising quickly enough to be unaffected by other heating/cooling sources, is close to 10ºC/ km. The lapse rate now called as Dry Adiabatic Lapse Rate (DALR) whose value decreases linearly with elevation in troposphere (lapse rate in lower atmosphere). However, because of moist convection, there is condensation of moisture, formation of clouds and release of latent heat as the air parcels rise, causing the lapse-rate to be much less, as low as 4ºC/km in very humid atmospheres. The lapse rate now called as Saturated Adiabatic Lapse Rate (SALR) whose value varies due to different amounts of water will be condensed depending upon air temperature; warm air will result in a lot of latent heat release, cool air will produce less latent heat. The Standard Atmosphere model indicates a lapse rate of approximately 1 °C with each 150m of additional height or 6.5 °C per 1000m.

There are three distinct ways to determine variations in air temperature with altitude (lapse rate): ASHRAE method, DALR and SALR method.

Leung & Weistmantle, (2008), explains ASHRAE method as follows:

> The ASHRAE method (Fundamentals Handbook of ASHRAE-2005) is applicable to a standard atmosphere. Based on the summer design, dry bulb is 46.1 ºC at ground level, so the temperature at the top of a 1-km hypothetical tower would be 39.6 ºC as indicated in the Figure 2.24. In winter design condition, while the ground-level temperature is 10 ºC, the top of the tower is 3.5 ºC.

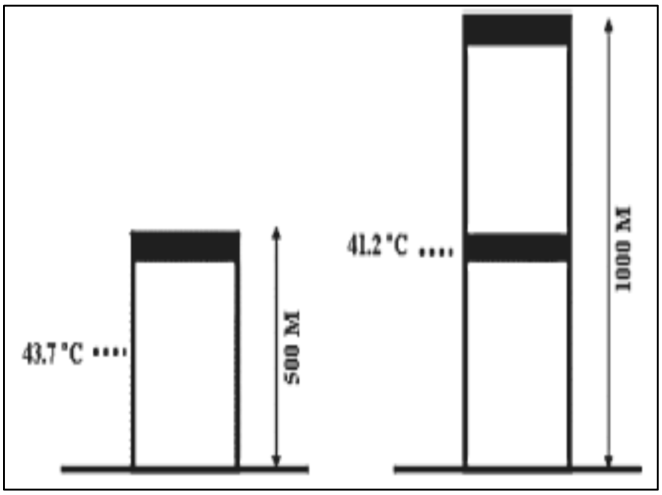

Figure 2.24. Outside temperatures at the mid-level of a 500m and 1000m hypothetical tall buildings (Leung & Weistmantle, 2008)

Temperature variations with altitude when ASHRAE method used can be seen in Figure 2.19. Leung & Weistmantle, (2008), explains DALR method as follows:

> The DALR method is more applicable to the summer design conditions in hot climates, when the outside condition behaves similar to an air parcel with less than 100 percent relative humidity (i.e., its temperature is above its dew point) (Leung & Weistmantle, 2008). The dry-bulb summer design temperature is 46.1 ºC, which has a capacity to carry a lot of moisture. Under this condition, heat gain or loss from outside the air parcel due to condensation is minimal. As seen in Figure 2.25, the DALR is approximately constant at 9.78 ºC/ km (Leung & Weistmantle, 2008).

Leung & Weistmantle, (2008), explains SALR method as follows:

> The SALR method assumes the atmosphere is saturated with moisture and defines the variation in SALR as 4.9 ºC/km. The temperature drop is less since condensation of moisture releases significant amount of latent heat to lessen the impact of temperature drop due to adiabatic expansion. This is only applicable in times when the atmosphere is saturated with moisture.

In Figure 2.26, the temperature lapse rate for DALR and SALR methods can be seen when the condensation level accepted as 500m from the ground.

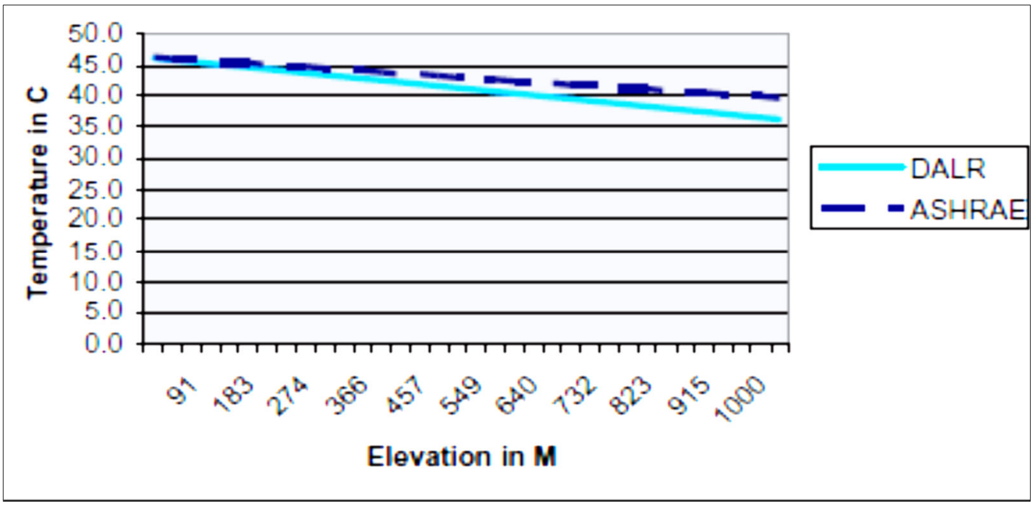

Figure 2.25. Temperature variations in ASHRAE and DALR methods
(Leung & Weistmantle, 2008)

Air temperature variations with altitude are influenced by urban context. Oke (1991) summarizes influenced parameters as follows:

- ground surface character,
- increased shade at lower levels and exposure to solar radiation at higher levels,
- fluctuating wind patterns and air mixing,
- solar absorption and re- radiation with the impact of vertical surfaces

In summary air temperature is seen to decrease with increasing height from the ground. The temperature lapse rate can vary in urban environments with the influences of building clustering and the urban heat island effect.

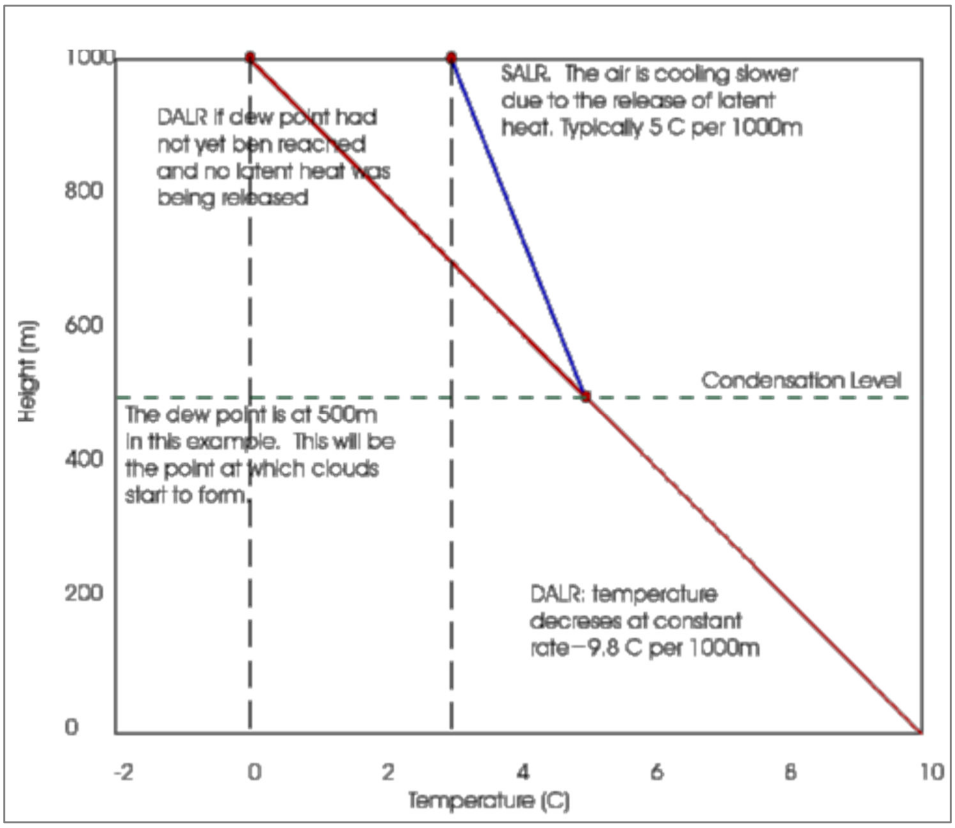

Figure 2.26. Temperature variations of DALR and SALR methods (assumed condensation level is 500m) (source: http://pages.bangor.ac.uk/~oss006/meteorology/lapseratesalevel.html).

Implications for Architectural Design of Tall Buildings

Respectively lower temperatures at higher altitudes have been benefitted for a long time and not a new idea. Traditional wind tower design may be exemplified to use of height above the ground. Similarly a tall building proposal CapitaGreen Tower, Singapore uses wind scoops to utilize cooler air at higher altitudes (Figure 2.27).

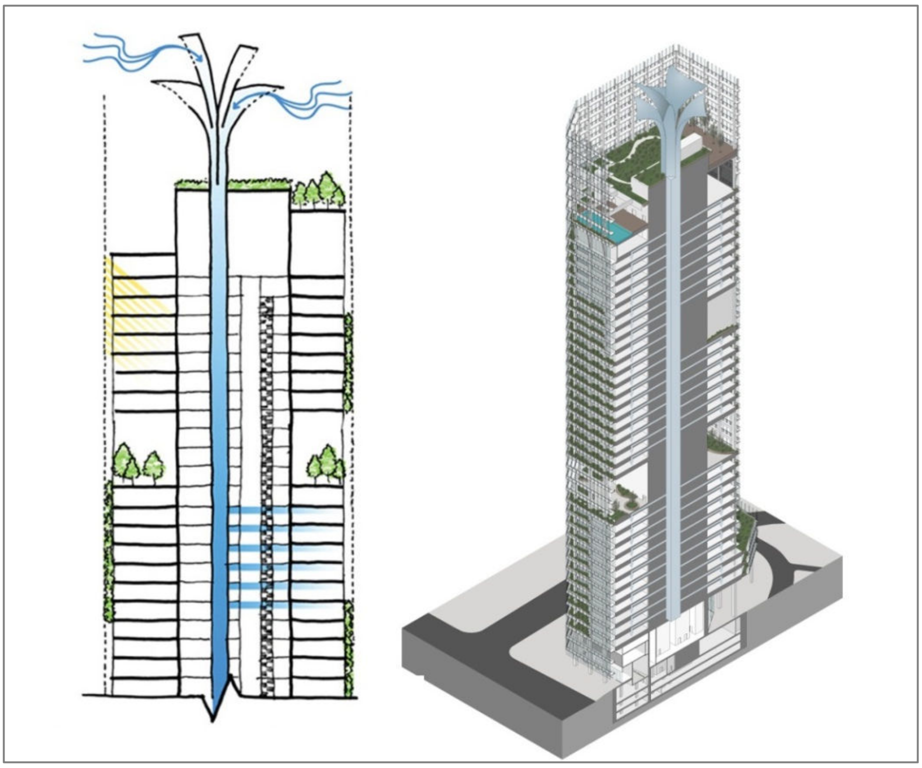

Figure 2.27. CapitaGreen Tower - wind scoops
(http://www.cct.com.sg/for-tenants/your-capitaletter/ january-2012)

Leung & Weistmantle, (2008) states the possible influences of temperature lapse rate on tall buildings as follows:

> There are three main benefits for tall buildings that are dominated by cooling: lower cooling energy due to conduction heat gain, low sensible heat gain from unwanted infiltration and lower cooling energy from the desired ventilation air. Based on indoor condition of 23ºC, conduction heat gain can be reduced up to 46%. Similar percentage can be achieved for both infiltration and sensible portion of ventilation air. Total energy savings using the mid-level of a 1 km as an example, will result in summer design hour load reduction of 9%.

2.3.2. Variations in Humidity with Altitude

In The U.S. Climate Change Science Program Handbook, (2010) variation in air humidity with altitude is stated as follows:

> Humidity increases when more water evaporates, and decreases when it rains or the humid air is displaced by less humid air. Generally, higher temperatures will lead to higher humidity, as more water will evaporate. Humidity is not directly affected by altitude. However, humidity is affected by air density and temperature. At high altitudes, the air is usually much thinner (lower pressure) and often the temperature is lower. At low temperatures and low pressures, air cannot hold as much water. Thus the humidity is necessarily low when the air is thin and cold. At high temperatures and high pressures, air can hold much more water. However, air that is hot and thick doesn't necessarily have a high humidity; but it does have the potential to hold more water.

Humidity is influenced by the ground in a similar way as temperature where evaporation from the ground surface is directed upwards as vapour leading to decreasing humidity (or vapour pressure) with height. On the other hand, wind downdrafts at building faces, higher levels of shade near the base of tall buildings, and the urban heat island may have influence on the humidity levels. However, Oke (1991) state that, the influences of the city on the change in humidity with altitude are very low. Leung and Weismantle (2008) also confirm the tendency for decreased humidity levels with increasing height.

In summary, humidity decreases with increasing height while the stability of humidity increases with additional height from the ground.

Implications for Architectural Design of Tall Buildings

Humidity reduces with increasing altitude with presenting further benefits for natural ventilation. Mechanical systems using evaporative cooling also function more efficiently with decreasing humidity levels. Furthermore, lower humidity levels increase occupants' comfort levels and outdoor comfort especially in hot-humid climates.

2.3.3. Variations in Wind Speed with Altitude

Wind speed and direction is mainly influenced by large-scale differences in air pressure with the flow of air being from areas of higher pressure to areas of lower pressure and depends on the roughness of the terrain and the stability of the atmosphere (if there is much convection, or not). As to variations in wind speed and direction, Lowry (1991) states that:

> Wind speeds typically increase with additional height and over the course of the day. At lower levels there is a distinct diurnal pattern in mid-latitudes where wind speeds peak at midday and reduce at night time. At heights above 100 m the reverse is the case with wind speed peaking during the night and being minimized in the middle of the day. This variation of wind speed is due to the decreasing influence of the ground at night.

Fluctuations in wind velocity and direction increase with terrain roughness and varied building heights (American Society of Civil Engineers (ASCE) Handbook, 2010). As seen in Figure 2.28, the terrain roughness decreases the wind speeds at all heights while preserving the trend of increasing wind speed with height, therefore the reference wind speed of 100% at 10m altitude at an airport occurs at 30m in a suburban area and at 150m in an urban area.

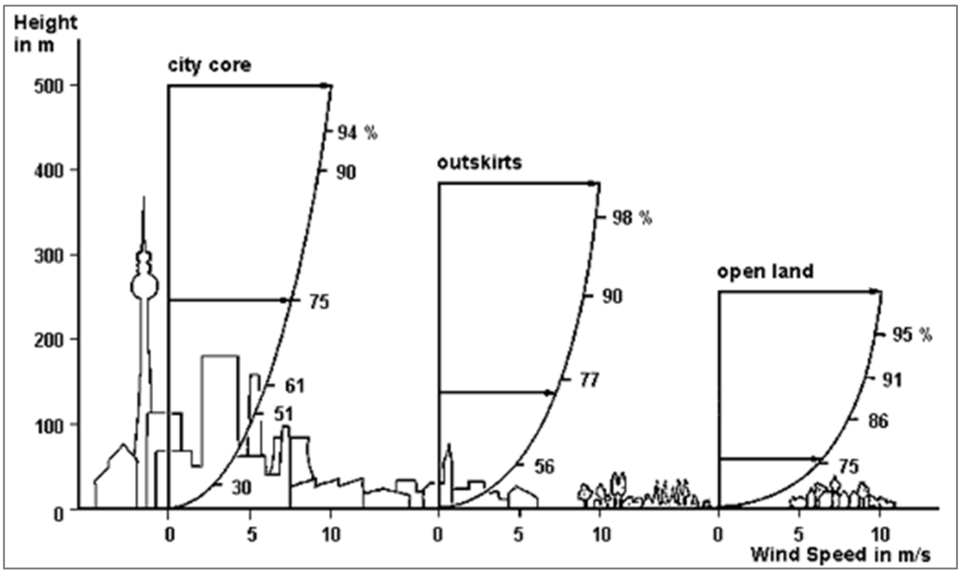

Figure 2.28. Decrease in wind velocities due to terrain roughness (American Society of Civil Engineers Handbook, 2010)

The relationship between wind speed and altitude is described in Handbook of Fundamentals (ASHRAE, 2001). The wind speed measured at a meteorological station can be extrapolated to other altitudes with an equation. The wind speeds are supposed to be measured at a meteorological station in an open field at a standard altitude of 10 m above the ground.

Urban areas show a higher level of air turbulence by 30-50%, even if this reduces with increasing height (Oke, 1991). Increased local wind speeds lead to increased convective heat transfer from the building fabric influencing the heating and cooling loads at each level (Sharples, 1984). Wind direction in the urban boundary layer can change direction by up to 10-20 ° bending around the city from both sides up to 200-300m (Oke, 1991). Furthermore, as seen in Figure 2.24, landscape and solid building blocks lead to updrafts and downdrafts due to their rougher shape and their warmer surfaces.

Airflow and Wind Patterns

Tall buildings are mostly located in dense urban areas, therefore unique micro-climatic conditions occur which can induce unusual wind patterns around the building and these unusual wind patterns can be influenced by several factors such as surrounding building heights, spacing between adjacent buildings, aerodynamic roughness, surrounding building geometries (e.g., height-to-width ratios, wall-to-plan area ratios, and aspect ratio), building volume characteristics, urban heat island (UHI) influences, etc. (Gonçalves & Umakoshi, 2010). It may be difficult to model these complex wind patterns, however several tools such as urban field measurements, wind tunnel studies, and CFD model simulations can help address the site-specific challenges (Figure 2.29).

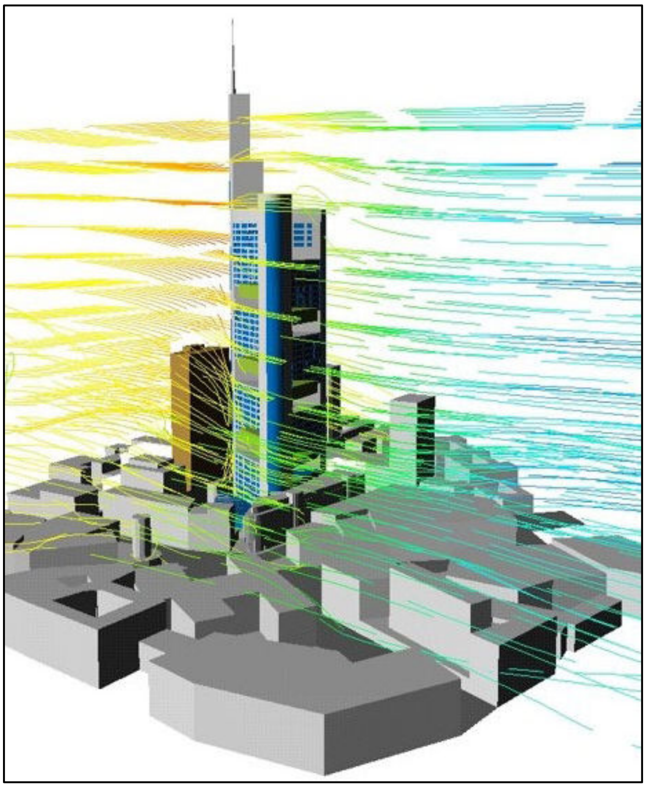

Figure 2.29. Airflow distribution around Commerzbank Headquarters Tower (courtesy of Foster and partners)

In summary, wind speeds increase with increasing altitude due to the lessening influence of the ground and buildings whilst air turbulence decreases with increasing height.

Implications for Architectural Design of Tall Buildings

Tall buildings face another set of challenges than low-rise buildings, therefore distinctions in natural ventilation concepts can be seen by focusing on the height of buildings. The utilization and characteristics of the two natural driving forces associated with natural ventilation, thermal buoyancy and wind, are influenced by the height of the building. The wind velocity and wind direction is more stable the higher up from the ground level, as the wind is less influenced by surrounding buildings and vegetation. The vertical distance between the air inlets and the outlets is significant for the driving pressure that can be obtained with buoyancy, therefore a tall building tends to utilize other ventilation elements than a low-rise building. Additionally, and maybe just as important a reason for variations in ventilation concept between tall and low buildings, are the different challenges these various generic building types face. A high-rise building faces for instance a higher wind pressure than a low-rise building. This driving force can be utilized for ventilation (Kleiven, 2003).

Locating the points of exhaust to take advantage of the inducing effect of wind flow downstream of the direction of the prevailing wind will assist in the removal of unwanted air. Wind turbines prefer to be at the upper part of the building to take advantage of higher wind speed (Leung & Weistmantle, 2008).

Higher wind speeds with height will also contribute to greater cooling of building fabric by means of convection and infiltration (Lowry, 1991).

2.3.4. Variations in Air Pressure with Altitude

Air pressure is the force exerted by the weight of air above and so decreases with additional height above sea level due to there being less air above to exert a force downwards. The vertical reduction in external air pressure causes the air to expand forming the basis for the vertical reduction in air temperature discussed earlier.

In the urban environment air pressure is further influenced by the effects of wind around building clusters creating positive and negative air pressure zones related to prevailing wind directions and speeds. In the case of tall buildings these differences in external air pressure influence:

- vertical movement of wind externally in the form of updrafts and downdrafts.
- indoor air pressure differences, driving heat upwards through building voids with air flow moving from high to low pressure.
- levels of infiltration and ex-filtration through the building envelope due to pressure differences across the exterior wall.

Pressure differences between the building interior and exterior together with the building height form a stack effect which drives air vertically (the chimney effect) and through the building envelope (infiltration and exfiltration) as indicated in the Figure 2.30 (Clair, 2010).

Warmer indoor air rises up through the building in the heating season and escapes at the top through openings or leakage. The rising warm air reduces the pressure inside the lower levels of the building, forcing cold air to infiltrate through openings and leakage. The stack effect is reversed in the cooling season with air flowing downward within the building but is weaker due to reduced temperature differences between the interior and exterior.

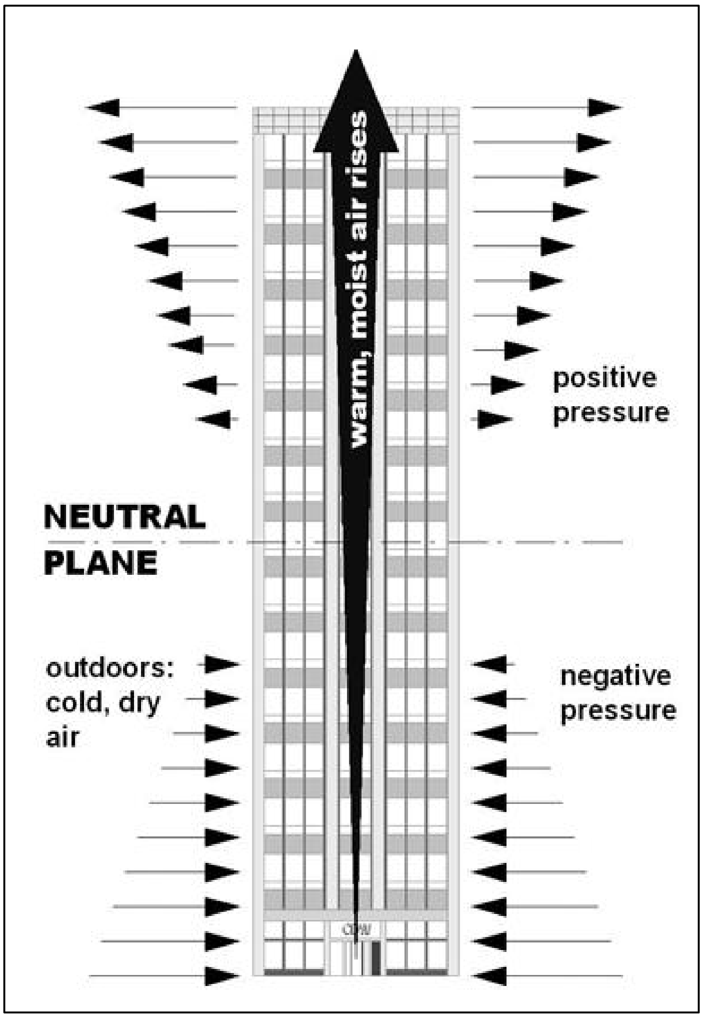

Figure 2.30. Stack effect that developed in a tall building (http://www.ashireporter.org)

CHAPTER 3

MATERIAL AND METHOD

In this chapter, the details of the material and methodology used in the study are given as distinct sections. The first one identifies descriptions and selection criteria of the subject material. The second one covers the methodology and process that is followed to evaluate the material.

3.1. MATERIAL

Several tall buildings employing natural ventilation in a greater or lesser degree are taken as research material. When selecting these buildings, height is an important criterion which makes tall buildings different from low-rise buildings with respect to natural ventilation. Therefore tall buildings taking height as a key parameter in their natural ventilation strategy are chosen. The other criterion is selecting tall buildings from different climates, as local climate characteristics have direct influence on the natural ventilation strategy and the possibility to naturally ventilate a tall building.

When compared the other types of climate, most times temperate one is more convenient to naturally ventilate a tall building. Therefore many of the selected tall buildings in this study are located in temperate climate and are characterized by a clear distinction in ventilation strategy between summer and winter (or cooling and heating season). However, tall buildings from other climates except hot dry climate are also chosen. In a hot dry climate due to high external temperatures natural ventilation can be difficult and also sand particulates in the air. For this climate, a tall building can be naturally ventilated during the night-time and evaporative cooling strategies can be used as mentioned in the literature review. However, due to harsh climatic conditions specific to this climate, a naturally ventilated tall building cannot be found.

For the temperate climate, RWE Headquarters Tower is chosen.

RWE Headquarters Tower is located in Essen, Germany. When selecting this building the aero dynamical building form facilitating natural ventilation, and featured ventilation openings called as “fish-mouth device” are important criteria. Besides, on the contrary of a conventional tall building, elevators are detached from the central core with ensuring an open central space free of obstructions, this layout assist the natural ventilation system and makes the building featured.

For the hot humid climate Menara UMNO is chosen.

Menara UMNO is located in Penang, Malaysia. The form and orientation of the tower are a result of site limitations. Due to this limitation, the building could not be orientated to take prevailing winds directly. However the building mitigates this limitation with using “wind wing walls” to capture a wider range of prevailing winds, and this makes the building featured in terms of natural ventilation. Although fairly common in low-rise buildings, Menara UMNO Tower is first tall building employing such wing wall system.

For cold climate Manitoba Hydroplace Headquarters is chosen.

Manitoba Hydroplace Headquarters is located in Winnipeg, Canada in where extreme climatic conditions are experienced. Due to potential heat loss, natural ventilation is rarely used in cold climate. To overcome this limitation, the building massing and orientation are key strategies. In this local climate, to balance humidity levels in interior is another design problem, it is also overcome with a special feature. All this merits make this building featured in such a harsh climate with respect to natural ventilation.

3.2. METHOD

The tall buildings selected as research material are evaluated in terms of strengths and fallbacks of their natural ventilation strategy. When evaluating research material, some key parameters are benefitted. These parameters are selected with respect to their influence on natural ventilation. These influences may be at greater or lesser degree for each parameter, however all this parameters directly affects efficiency of a natural ventilation system.

Selected parameters are building form and orientation, layout of spaces, facade system, altitude based design, night-time ventilation and thermal mass, occupants' control on ventilation, and lastly prospects for future developments in the site. The reasons on selecting these parameters are explained as follows.

Building Form and Orientation

The risks and challenges associated with natural ventilation in a tall building are considerably greater than in low-rise buildings due to increasing wind speed and less predictable airflow patterns. Building form should response these variations to facilitate natural ventilation and to increase duration of time that the building naturally ventilated. Therefore, the forms of the case buildings are evaluated to make it clear whether the natural ventilation strategy is a key parameter on the forming of the building or not.

Layout of Spaces

The planning and spatial configuration of a tall building determines the possibility and effectiveness of natural ventilation largely. To facilitate natural ventilation, a radical decision is needed in the layout of spaces, since partitions in the spaces may prevent flow of the air. For these reasons, natural ventilation strategies of the case buildings are evaluated with respect to their regarding design on layout of spaces.

Facade System

The decision to naturally ventilate tall buildings is related to the careful design of the facades in order to deal with high air pressure and velocity on air flow patterns. Therefore specific considerations for the position and sizing of openings are required to ensure proper pressure distribution within the natural ventilation system. Many of tall buildings in operation have proved that tall office buildings can be naturally ventilated through operable windows. However in doing this, some considerations should be taken such as wind speeds increasing with height and high air pressures resulting from increasing stack effect with height. Besides, the impact of solar radiation should be considered since it has impact on both airflow patterns and heat gain/loss. For all these reasons, case buildings are also evaluated to make it clear whether their facade systems are designed with considering these requirements or not.

Night-time Ventilation and Thermal Mass

Since the primary purpose of natural ventilation is to provide acceptable air quality and human comfort, the use of other sustainable strategies which complement natural ventilation can help reduce the cooling load and enhance comfort conditions. The performance of natural ventilation can benefit by exposing thermal mass and benefitting night-time cooling in cooling demanded seasons. Therefore, case buildings are evaluated to make it clear whether their natural ventilation systems benefit such a complementary system or not.

Altitude Based Design

The literature as to the characteristics and vertical gradient of environmental parameters named temperature, wind velocity and direction, and humidity are also benefitted when evaluating case buildings. To compensate changes in these parameters, building form should be designed in harmony with vertical environmental variations. Therefore, natural ventilation strategies are examined to make it clear if the local climate and altitude variations are considered in their regarding design processes.

Occupants' Control on Ventilation

Building occupants have control on their environment show greater flexibility to thermal changes. In most of the tall buildings, a central BMS system which controls temperature ranges in the spaces is used, however this system can be preferred to de-centralized one which gives users control on indoor environment. But in the latter, extreme environmental conditions should be foreseen. With considering advantages and fallbacks of both systems, case buildings are evaluated to make it clear whether their BMS systems give occupants selection and control with respect to thermal condition of the internal environment or not.

Prospects for Future Developments in the Site

The development of future adjacent tall buildings may negatively affect wind flow and speeds and thus the natural ventilation strategy. For this reason, in the planning of a tall building's natural ventilation system, this possible limitation should be foreseen, otherwise required airflow rates cannot be ensured and prevailing wind direction can be obstructed by future tall building constructions. Natural ventilation strategies are investigated to make it clear whether the possible future developments in the site are considered in their regarding design processes or not.

CHAPTER 4

ANALYSIS AND RESULTS

4.1. ANALYSIS

In this section, analyses of the case buildings are presented. As mentioned previously, three case study buildings are evaluated in terms of efficiency of their natural ventilation systems. While doing this, the parameters mentioned in the methodology are benefitted. Nearly for each parameter, supplementary drawings and images are presented to support results. Analyses for each case buildings are given in distinct sub-sections.

4.1.1. RWE HEADQUARTERS TOWER

Completed in 1997, the tower is 127 meters height and consists of 31 stories. The building is located in Essen, Germany which experiences mild winters and warmer summers. The climate of the location is classified as temperate. Prevailing wind direction is west and average wind speed is 2.7 m/s. Mean annual temperature is 10 °C and average relative humidity is 75% (the climatic data is derived from German Weather Service). The natural ventilation strategy relies on single-sided ventilation through a double skin facade system. Approximate percentage of year natural ventilation can be utilized is 75% (Ingenhoven, 2001).

Building Form and Orientation

The tower is composed of a base, a shaft and a capital as seen in the Figure 4.1. The aerodynamic cylindrical form of the tower assists airflow around the facade and minimizes wind loads on the envelope, thus facilitating natural ventilation system. Besides this, a circular building form has the largest ratio of floor area to perimeter length when compared to rectangular forms, thanks to this, heat gain/loss occurring through external envelope decreases.

Figure 4.1. RWE Headquarters Tower – general view

(courtesy of Ingenhoven Architects)

Layout of Spaces

The building has a circular plan with a service and circulation core at its center. However, elevators are mostly detached from the office spaces, and attached to the southeast of the tower in a separate form as seen in the Figure 4.2. The office spaces were located along the building perimeter to be directly ventilated as seen in the Figure 4.3.

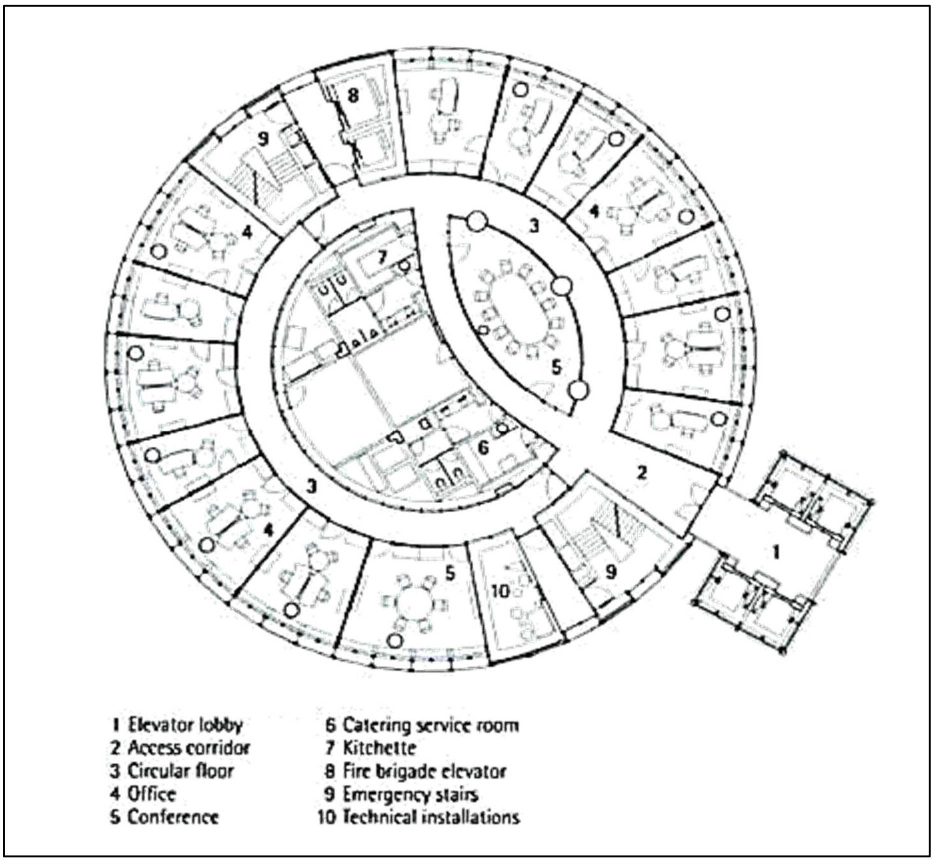

Figure 4.2. RWE Headquarters Tower – typical floor plan

(courtesy of Ingenhoven Architects)

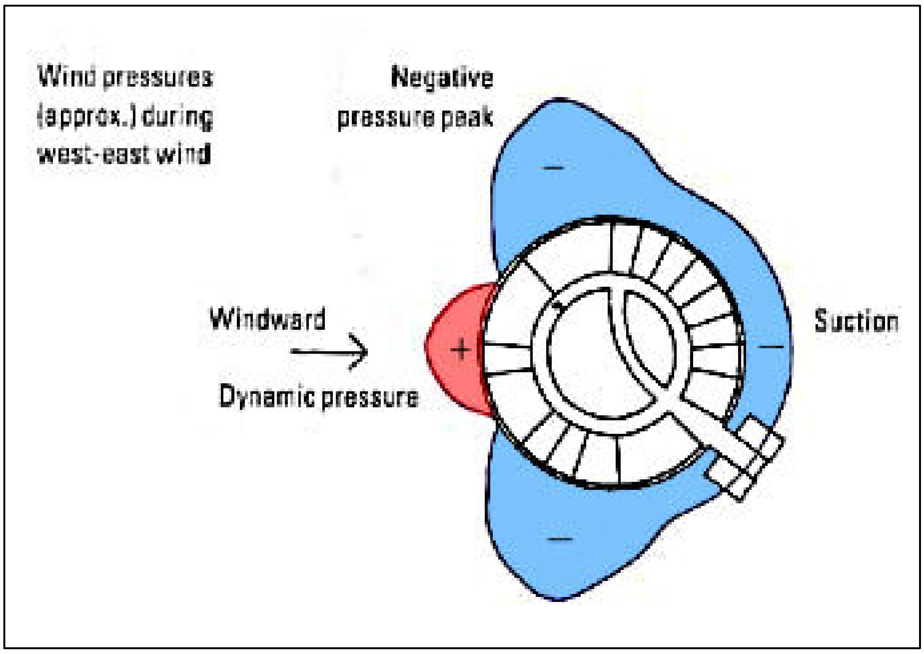

Figure 4.3. RWE Headquarters Tower – air pressure differences around the building (base drawings: Ingenhoven Architects)

Facade System

The offices are naturally ventilated through a fully-glazed double skin facade. All functions of the ventilation system, daylight control, sunscreens and blinds are integrated into the custom-detailed facade elements. The space inside the facade is supplied with outside air through an arrangement of intake and exhaust louvers. As seen in the Figure 4.4, to prevent exhaust-air influx into the lower floors, the exhaust louver is diagonal in relation to the intake louver.

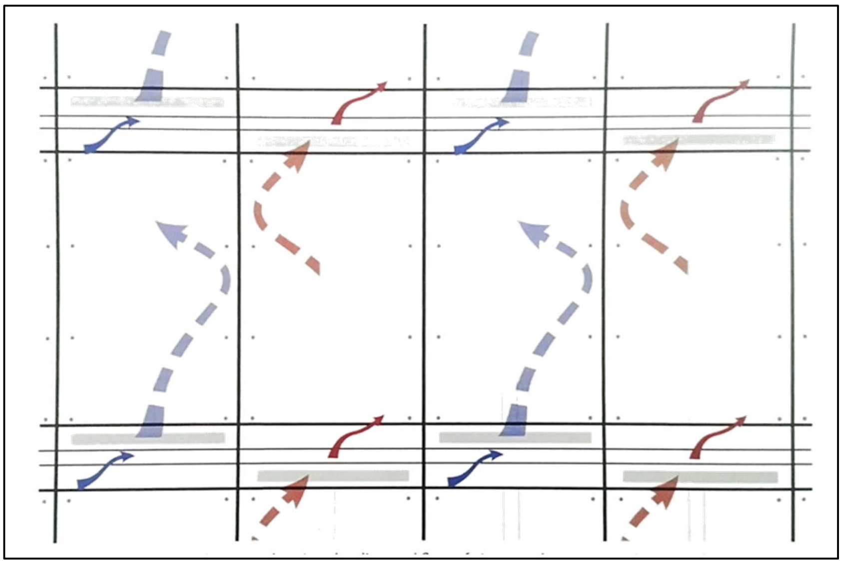

Figure 4.4. RWE Headquarters Tower – arrangements of intake and outtake louvers (courtesy of Ingenhoven Architects)

The double skin consists of an exterior layer made of fixed glass panels - 2 x 3.6m modules that permit air circulation through corresponding slots, and an interior layer with operable panels as seen in the Figure 4.5. The interior layer of the double skin facade features sash windows extending from floor to ceiling with fixed and sliding glass panels which can be opened up to 15 cm. These two layers are 50 cm apart from each other with a solar protection system installed between them.

The parts that support the outer facade as well as absorb or exhaust air are called "fish-mouths" which are responsible for both the intake and outtake of air in the double-skin as seen in the Figure 4.6. This is a pair of sashes, where one carries a "fish-mouth" with small holes on its upper part exclusively for intake, and another one on its lower part exclusively for outtake. Due to such a composition, the outside air from the intake "fish-mouth" is warmed inside the double-skin and diagonally ascends to be exhausted from the outtake "fish-mouth" at the neighboring sash. If both the "fish-mouths" had been laid out vertically, exhaust air would take the shortest path up to the floor above and enter it in the place of fresh environmental air. If this happened, air quality would decrease with every subsequent floor.

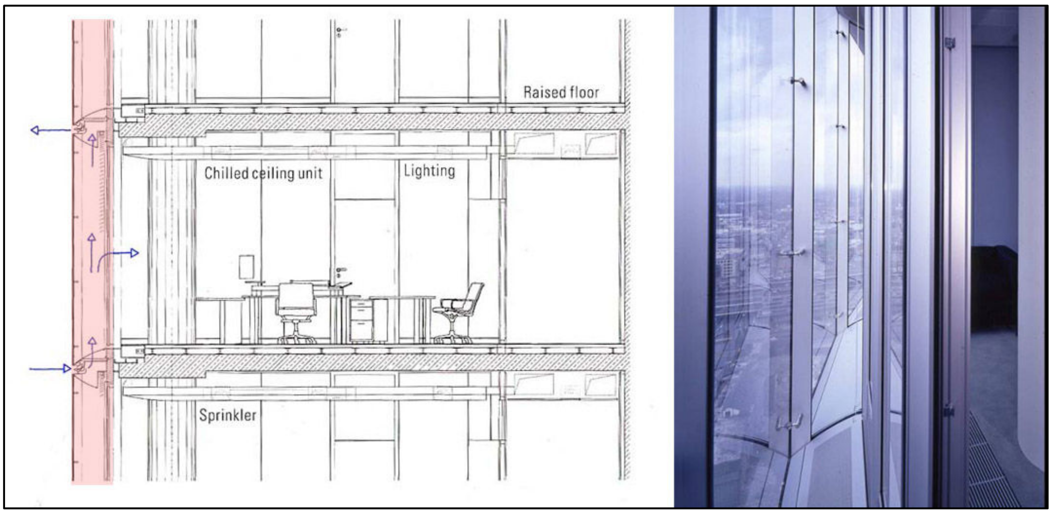

Figure 4.5. RWE Headquarters Tower – double skin facade system (courtesy of Ingenhoven Architects)

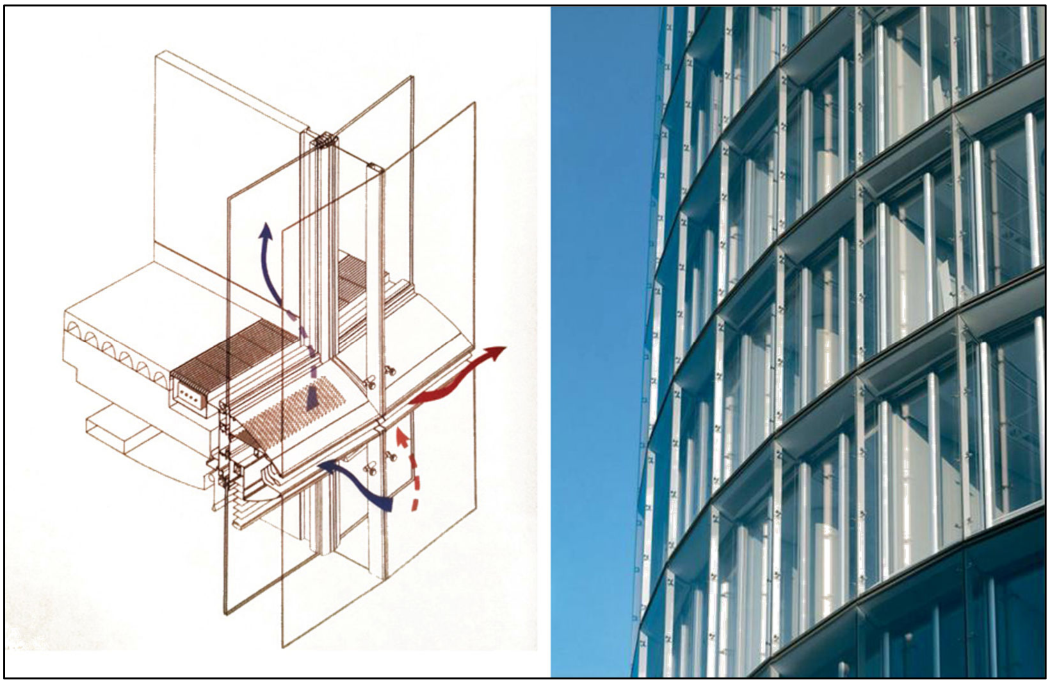

Figure 4.6. RWE Headquarters Tower – ventilation openings and close view of the facade (courtesy of Ingenhoven Architects)

Night-time Ventilation and Thermal Mass

In such a temperate climate seeing temperature changes nearly 9 °C between day and night-time in the hottest months, the use of night-time ventilation and thermal mass can complement natural ventilation by reducing the cooling load and thus enhancing comfort conditions. To ensure this, partially exposed concrete ceiling slabs which absorb excess heat during the day-time and emit the stored heat at night through night- time flush ventilation are used. This system assisting natural ventilation moderates internal temperature fluctuations and reduces heating/cooling loads during peak hours.

Altitude Based Design

Due to the difference in height, wind profiles near the skyscraper at several levels are different than the wind velocities that are measured at the local weather station. This is considered in the design process. For the height of 110m, wind velocities measured at the meteorological station multiplied by 1.2 and for the height of 60m multiplied by 1.05. As a solution, velocity of the air stream is adjusted to an optimum level with fish-mouth devices which have sensors fitted to their aperture to measure climatic conditions as seen in the Figure 4.7. The system works in such a way, if the wind velocity is too great, air stream is made slower, whereas it is made faster in case there is no enough wind. Besides, there is a difference in size between the fish-mouths above the 16th floor and those below it considering the varying wind velocities with altitude.

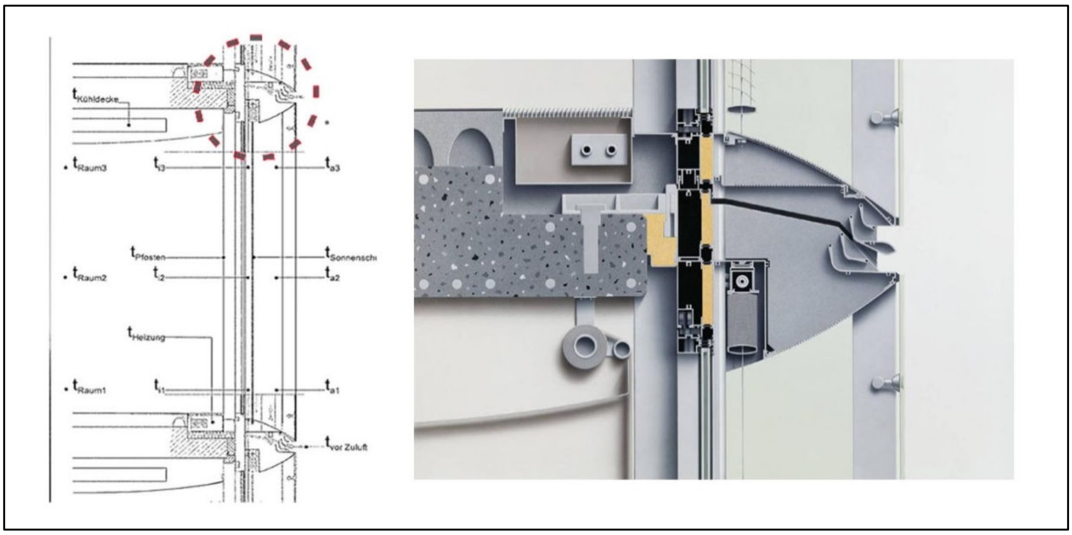

Figure 4.7. RWE Headquarters Tower – detail of the fish-mouth device

Occupants' Control on Ventilation

Occupants have a high level of control over their environment. Each office has a minimum of two sliding windows that can be directly controlled by the occupants.

Environmental conditions can be adjusted according to individual requirements by means of a control panel in each room as seen in the Figure 4.8. Control panel informed by a roof-top weather station provides an audio and visual warning when the facade must be closed due to high wind pressures. Efforts were made to make the panel as easy to use as possible.

Figure 4.8. Office control panel (left), roof-top weather station (right)

Prospects for Future Developments in the Site

The development of future adjacent high-rises may negatively affect wind flow and speeds and thus the natural ventilation strategy, however currently the surrounding buildings are low-rise and own site of the tower is large enough to have unobstructed wind flow around the building as seen in the Figure 4.9.

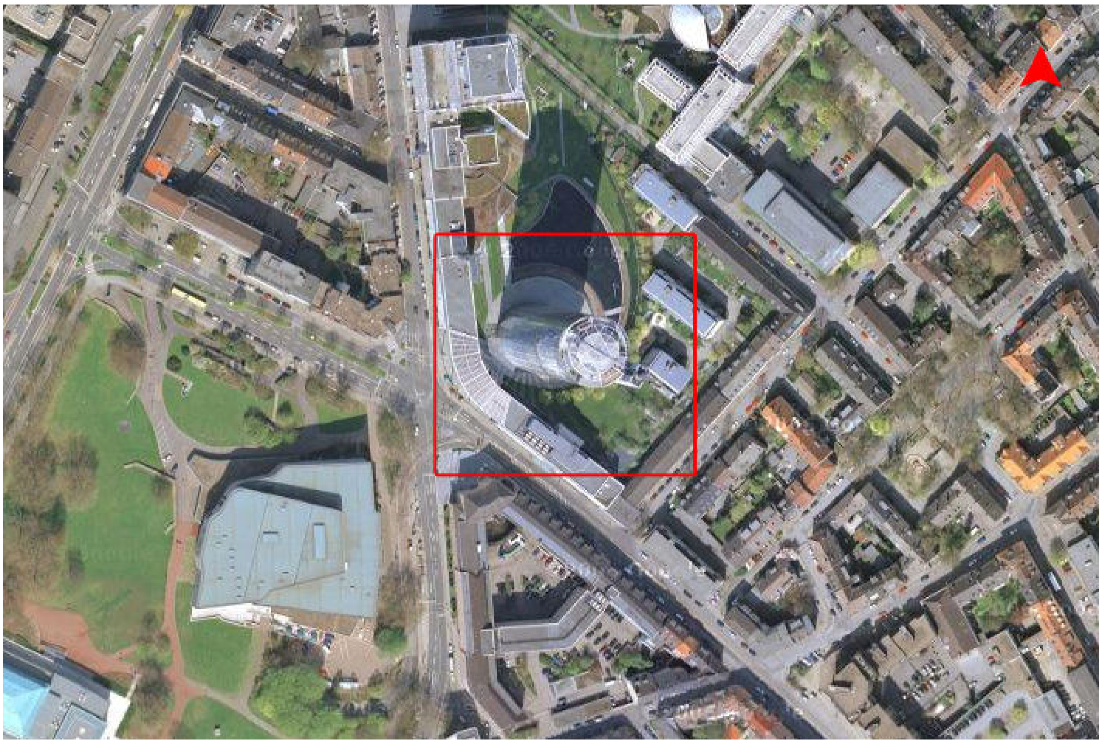

Figure 4.9. RWE Headquarters Tower – site view

(source: googşe maps)

4.1.2. MENARA UMNO

Completed in 1998, the tower is 94 meters height and consists of 31 stories. The building is located in Penang, Malaysia which experiences consistently hot weather with high humidity levels throughout the year. The climate of the location is classified as hot-humid. Prevailing wind direction is south-west and average wind speed is 2.6 m/s. Mean annual temperature is 28 °C and average relative humidity is 85% (the climatic data is derived from Malaysia Meteorological Department). The natural ventilation strategy relies on wind-driven cross ventilation through a wing wall system. Approximate percentage of year natural ventilation can be utilized is not exact since it depends on buildings' occupants.

Building Form and Orientation

Menara UMNO Tower contains a banking hall, auditorium, and car-parking levels, together with 14 floors of office space above as seen in the Figure 4.10. The building's long axis is oriented along the northeast-southwest direction, in line with the prevailing winds. The service core which was located on the eastern facade acts as a solar buffer on the wide axis of the building.

Figure 4.10. Menara UMNO Tower – view from the west facade and east facade (courtesy of TR Hamzah & Yeang Architects)

Layout of Spaces

All office floors are designed in a layout that they can be naturally ventilated. For instance, no desk location (within each typical floor) is more than 6.5 meters away from an openable-window to enable users to receive natural ventilation as indicated in the Figure 4.11. Besides, to ensure greater plan depth along the main wind flow axis (approximately 14 meters) the service core is located along the edge of the building.

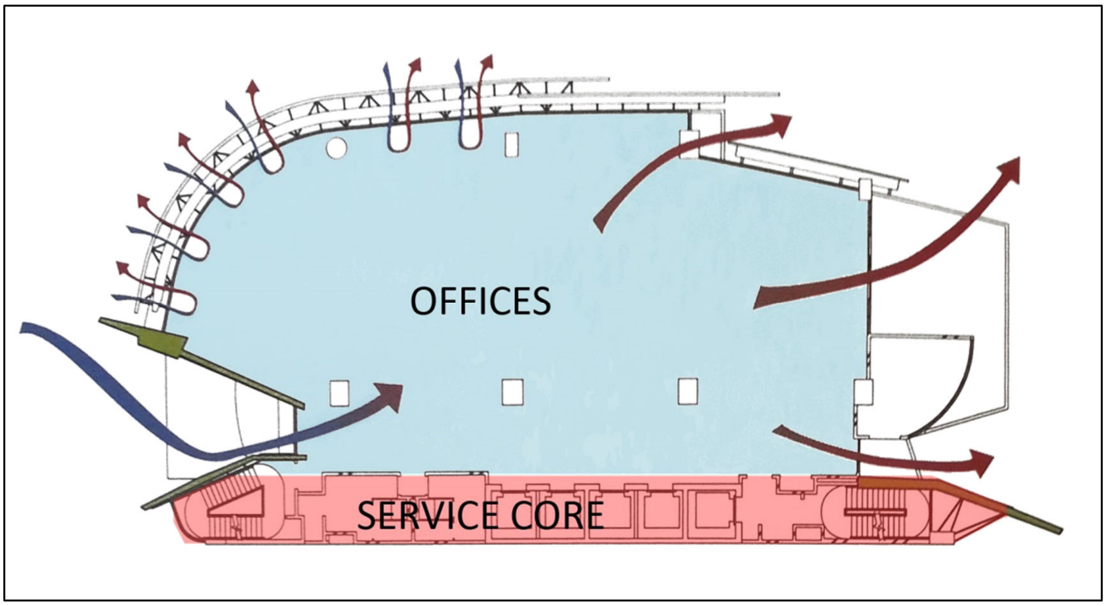

Figure 4.11. Menara UMNO Tower – typical floor plan

(base drawing: TR Hamzah & Yeang Architects)

Facade System

The tower intends to generate natural ventilation with a high air-change rate, which creates comfort conditions in the interior through air movement and temperature control (Powell and Yeang, 1999). Considering the prevailing wind, vertical wall-fins called as wind wing walls designed to direct wind to special balcony zones as seen in the Figure 4.12. The wing walls direct a greater range of prevailing winds into the building, minimizing the risks associated with natural ventilation due to changes in wind directions, and act as pockets with “air locks” for natural ventilation via windows, and full height sliding balcony doors which are adjustable to control the rate and distribution of ventilation as indicated in the Figure 4.13. Considering the relatively low average wind speeds in Penang, the wing wall becomes a crucial element of the design as it channels air into the interior at higher rates/speeds, thus serving to achieve comfort in Penang's hot and humid climate.

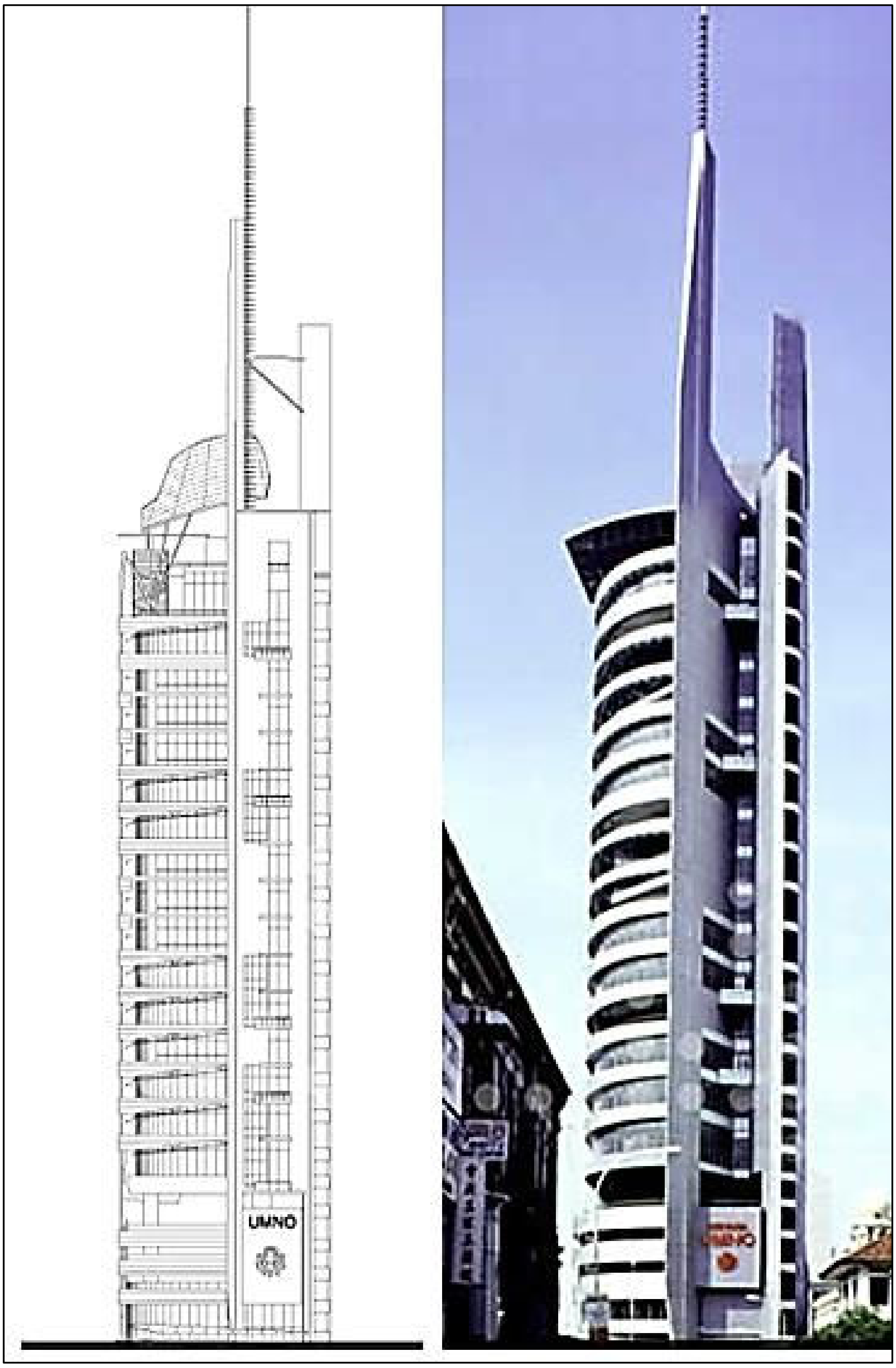

Figure 4.12. Menara UMNO Tower – view from the wing wall (south) facade (courtesy of TR Hamzah & Yeang Architects)

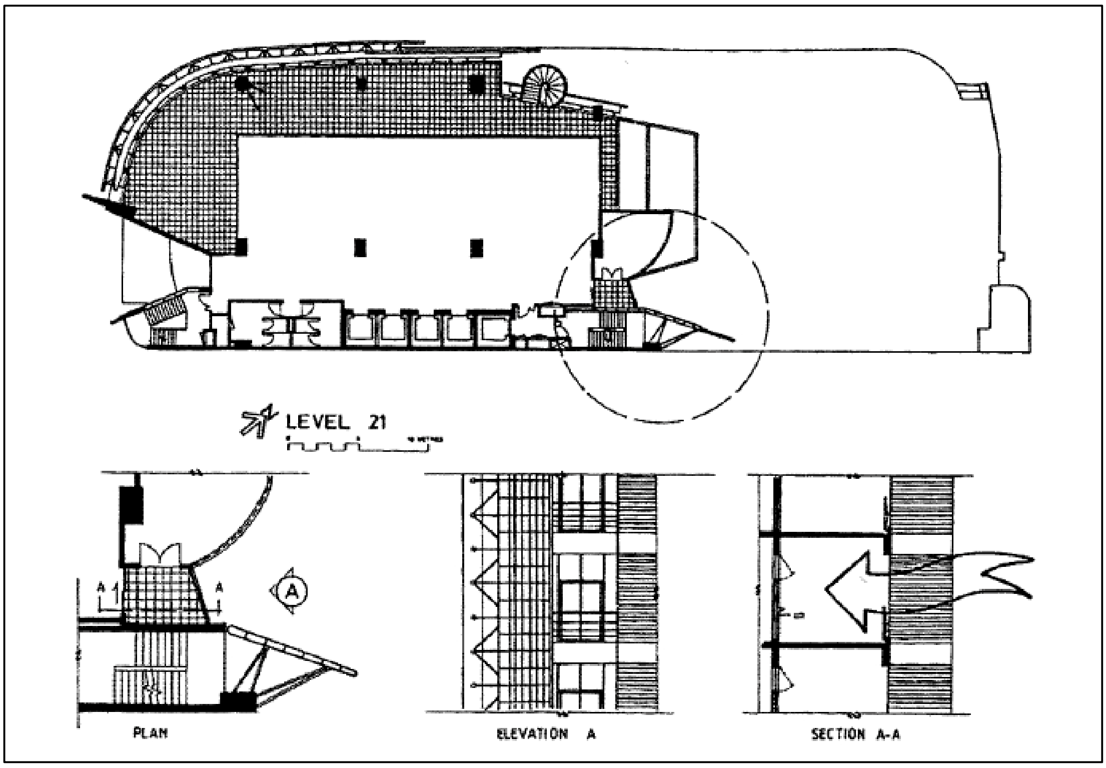

Figure 4.13. Menara UMNO Tower – Menara UMNO Tower – detail drawings of wing wall system (courtesy of TR Hamzah & Yeang Architects)

Additionally, it should be noted the ventilation concept mainly relies on wind-driven natural forces, therefore lower air flow rates would be observed if the ambient wind speeds are low or the windows are not fully opened. This may cause the internal/external air temperature difference to be less than required.

Night-time Ventilation and Thermal Mass

Day and night temperatures typically do not vary greatly (rarely greater than 8°C) in this climate and high humidity levels may occur during night-time, however night-time ventilation can be strategically applied to remove day time heat gain with use of a BMS system.

Altitude Based Design

Wing wall system is successful on directing prevailing winds to the interior, however it may create high air change rates due to increasing wind speeds with altitude and would cause problems like flying of papers in the office spaces. To avoid this, there is a need for a BMS system to control openings and air change rates. To mitigate this, the form of the wing wall could also be reconsidered according to the environmental parameters varying with altitude.

Occupants' Control on Ventilation

The absence of a BMS may lead problems in achieving the needed airflow rates required for comfort ventilation in a hot-humid climate, since it is difficult to anticipate how the occupants will control their environment, i.e., closing windows and turning on air-conditioning as opposed to still utilizing natural ventilation by partially closing the windows. Nevertheless, occupants' have control over their natural ventilation system.

Prospects for Future Developments in the Site

The surrounding buildings are low-rise as seen in the Figure 4.14, however the development of future adjacent high-rises may negatively affect air flow and wind speeds, and thus the wind wing walls strategy.

Figure 4.14. Menara UMNO Tower – site view
(source: google maps)

4.1.3. MANITOBA HYDROPLACE HEADQUARTERS

Completed in 2008, the tower is 115 meters height and consists of 22 stories. The building is located in Winnipeg, Canada which experiences extreme variations in climate with a temperature swing between a -35 C in winter, and +35 C in summer. The climate of the location is classified as cold. Prevailing wind direction is south and average wind speed is 4.7 m/s. Mean annual temperature is 3 °C and average relative humidity is 72% (the climatic data is derived from Meteorological Service of Canada). The natural ventilation strategy relies on wind-driven cross ventilation and stack ventilation. Approximate percentage of year natural ventilation can be utilized is 35% (Kuwabara et al., 2009).

Building Form and Orientation

The mass of the tower consists of two converging 18 story office wings separated by a service core, resting on a three story podium as indicated in the Figure 4.15 (left). The form and mass of the tower are very responsive to local climatic conditions and well integrated with the natural ventilation system. The building is oriented to take advantage of the southern prevailing winds and solar heat to warm incoming cool air as indicated in the Figure 4.15 (right).

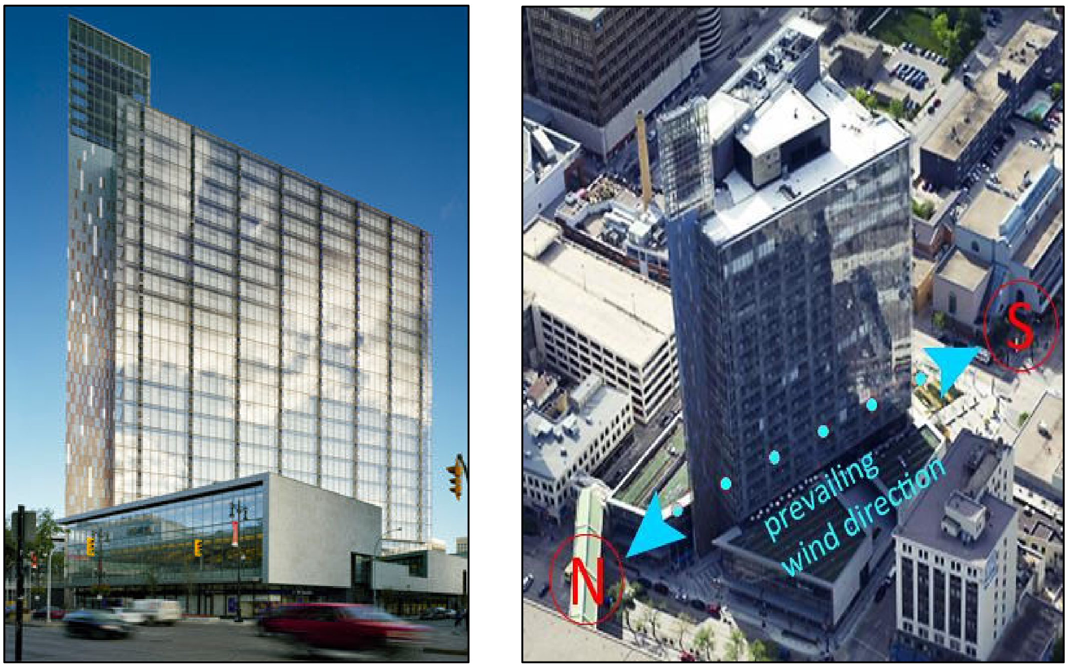

Figure 4.15. Manitoba Hydroplace Headquarters –general view (left) and aerial view (right)

(base images: http://manitobahydroplace.com/Integrated-Elements)

Layout of Spaces

The building plan was designed with an “A” configuration, splaying open to form a south atrium to catch consistent prevailing winds. Offices are in an open-plan layout and were located near the building perimeter, while private meeting spaces and service areas were moved toward the core to ensure an efficient natural ventilation system as indicated in the Figure 4.16.

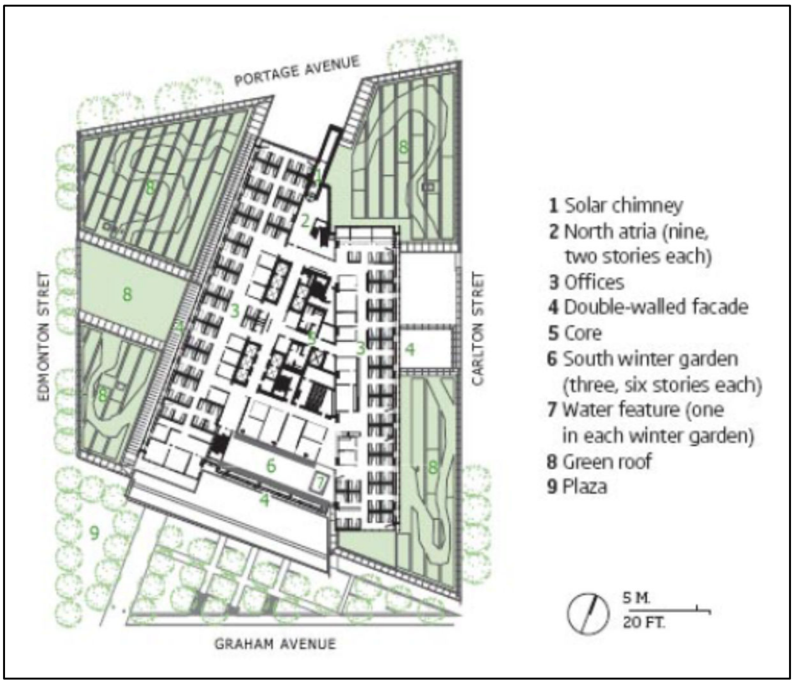

Figure 4.16. Manitoba Hydroplace Headquarters –typical floor plan

(http://manitobahydroplace.com/Integrated-Elements**)**

Facade System

A west and northeast double skin facade admit fresh air into office spaces. These two facades consist of two, low-iron glass curtain walls (single glazed interior layer and double glazed exterior layer) with a 1.3m cavity which contains operable blinds. Exterior panels are opened to take fresh air, then with manually operated windows air moves to the interior spaces as indicated in the Figure 4.17. The solar chimney at the north end of the building induces the flow of air across the office spaces and improves the efficiency of natural ventilation when the prevailing south wind is weak. The use of atria/sky gardens creates a microclimate, tempers incoming fresh air for natural ventilation, and mitigates unwanted drafts.

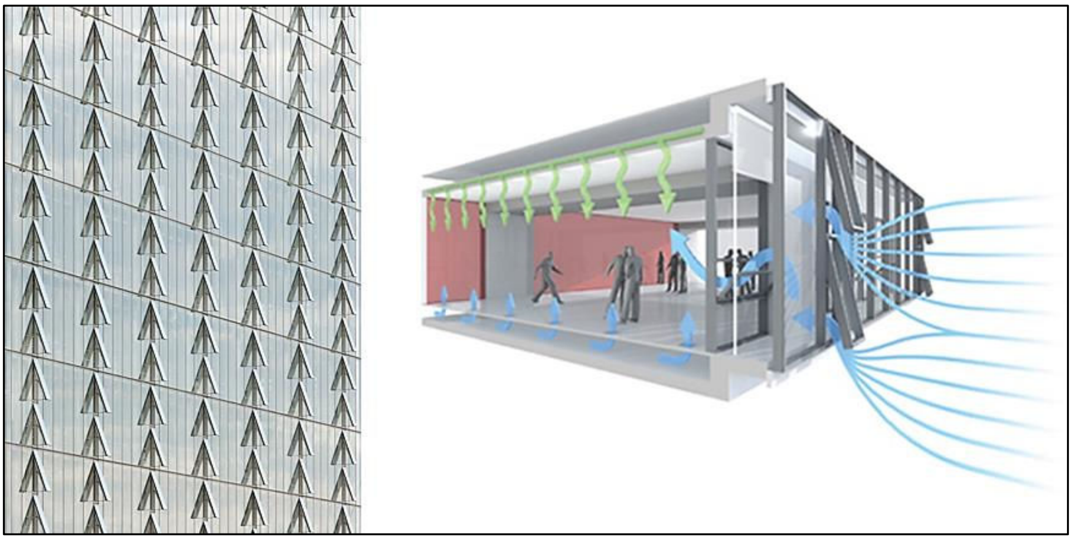

Figure 4.17. Manitoba Hydroplace Headquarters – facade view and ventilation Openings (http://manitobahydroplace.com/Integrated-Elements)

Beside these advantages, facade system needs some considerations specific to this climate. For instance, without proper control strategies as to shading and venting, the south-facing atria may be subject to overheating and therefore potentially overheat the fresh air for natural ventilation. In addition, condensation and ice could occur at fresh air intake openings (windows and vents) if opened during extremely cold weather conditions.

Night-time Ventilation and Thermal Mass

The concrete structure which is designed to create thermal mass moderates the impact of extreme temperature swings. Exposed concrete ceilings works as internal heat exchangers maintaining a comfortable temperature year-round. Besides, filling the top of the solar chimney with a high thermal capacity material (sand) maintains stack effect during cool summer nights and enhances the effectiveness of night-purge ventilation.

Altitude Based Design

The segmentation of the south-facing atrium reduces the risks of large pressure differentials at the top and bottom of the atrium as indicated in the Figure 4.18. Besides, this minimizes the risk of top floors receiving significantly warmer air than those at the bottom and avoids the complexity associated.

Figure 4.18. Manitoba Hydroplace Headquarters – segmentation of the south atrium

(base images: http://manitobahydroplace.com/Integrated-Elements)

Extending the solar chimney several stories beyond the roof level of the high-rise building serves to enhance the stack effect and ensure that the top floors of the towers are sufficiently ventilated as seen in the Figure 4.19.

Figure 4.19. Manitoba Hydroplace Headquarters – solar chimney

(base images: http://manitobahydroplace.com/Integrated-Elements)

Occupants' Control on Ventilation

The BMS automatically controls the operation of the windows, vents, shading devices and lighting, however a custom computer interface enables occupants to control/override aspects of lighting and solar shading. Besides, openings on the interior layer of the double skin facades are completely controlled by the occupants.

Prospects for Future Developments in the Site

Future developments, such as the erection of a high-rise to the south of the site, might cast a shadow on the sky gardens and have a negative impact on the performance of the natural ventilation strategy as seen in the Figure 4.20.

Figure 4.20. Manitoba Hydroplace Headquarters – site view

(source: google images)

4.2. RESULTS

At the end of the evaluation process, it is seen that case buildings nearly fulfill requirements to naturally ventilate a building as indicated in the Table 4.1. However, all of them do not have providence for future developments in the nearby site of them. Results for each of three case buildings are given briefly in distinct paragraphs as follows.

RWE Headquarters Tower fulfills six of the seven key parameters. During the evaluation process, it is seen that, the aerodynamic cylindrical form of the tower assists airflow around the facade and minimizes wind loads on the envelope, thus facilitating natural ventilation system. Additional inferences are as follow. The office spaces are directly ventilated as they located along the building perimeter. Partially exposed concrete ceiling slabs which are used to benefit night-time ventilation absorb excess heat during the day-time and emit the stored heat at night. Besides, through fish-mouth devices which have sensors fitted to their aperture to measure climatic conditions, velocity of the air stream is adjusted to an optimum level. By the way, difference in size between the fish-mouths above the 16th floor and those below it responds the varying wind velocities with altitude. Lastly, occupants have a high level of control over their environment. The development of future adjacent high-rises may reduce efficiency of the natural ventilation system with decreasing air flow speeds and changing wind flow patterns.

Menara UMNO Tower fulfills four of the seven key parameters. During the evaluation process, it is seen that, the building’s long axis is oriented along the northeast-southwest direction, in line with the prevailing winds to ensure greater plan depth along the main wind flow axis. Besides, wing walls direct a greater range of prevailing winds into the building, minimizing the risks associated with natural ventilation due to changes in wind directions, thus serving to achieve comfort in such a hot and humid climate. However, it should be noted the ventilation concept mainly relies on wind-driven natural forces, therefore lower air flow rates would be observed if the ambient wind speeds are low or the windows are not fully opened. It should be also noted that night-time ventilation can be strategically applied to remove day time heat gain with use of a BMS system. Lastly, the development of future adjacent high-rises may negatively affect air flow and wind speeds, and thus the wind wing walls strategy.

Manitoba Hydroplace Headquarters fulfills six of the seven key parameters. During the evaluation process, it is seen that, the form and mass of the tower are very responsive to local climatic conditions and well integrated with the natural ventilation system. The building takes advantage of the southern prevailing winds and solar heat to warm incoming cool air by means of efficient orientation. Besides, “A” configuration in plan layout forms a south atrium catching consistent prevailing winds. Moreover, the solar chimney at the north end of the building induces the flow of air across the office spaces and improves the efficiency of natural ventilation when the prevailing south wind is weak. The use of atria/sky gardens creates a microclimate, tempers incoming fresh air for natural ventilation, and mitigates unwanted drafts. In addition, the concrete structure creates thermal mass and moderates the impact of extreme temperature swings. The segmentation of the south-facing atrium reduces the risks of large pressure differentials at the top and bottom of the atrium. Furthermore, openings on the interior layer of the double skin facades are completely controlled by the occupants. Beside these advantages, some considerations specific to this climate are required. For instance, without proper control strategies as to shading and venting, the south-facing atria may overheat the fresh air for natural ventilation. Lastly, future adjacent tall buildings to the south of the site may cast shadow on the sky gardens and have a negative impact on the performance of the natural ventilation system.

Table 4.1. Evaluation results for the case buildings

Parameters / Case studies	Building form and orientation	Layout of spaces	Facade system	Night-time ventilation and thermal mass	Altitude based design	Occupants' control on ventilation	Prospects for future developments in the site	Total grade over "7"
RWE Headquarters Tower	√	√	√	√	√	√		6
Menara UMNO	√	√	√			√		4
Manitoba Hydroplace Headquarters	√	√	√	√	√	√		6

CHAPTER 5

CONCLUSION

In this chapter, conclusions of the study and advices for the further research are given as distinct sections. The first one draws conclusions regarding to benefits of natural ventilation systems in tall buildings. The second one covers the further research recommended to accurately evaluate natural ventilation strategies of tall buildings and influences of vertical environmental parameters on them.

5.1. CONCLUSIONS

Tall buildings have been increasing in both height and number exponentially, however there is currently no supertall building (greater than 300 meters in height) in existence that uses natural ventilation strategies. To rely %100 percent on natural ventilation does not seem possible due largely to the implications of failure of the system, however reduction of the reliance of HVAC systems is possible for tall buildings in nearly any climate region. Even elimination of HVAC systems is possible when climatic conditions moderate during all the year and there are no significant environmental variations between the seasons. However, to naturally ventilate a tall building, the most effective system for a particular site, building type and program should be created.

In this study, it is seen that, the two most important factors influencing the comfort of a tall building occupant are good air circulation, and the temperature in the workplace. At this point, poorly designed or maintained HVAC systems create problems, especially in situations where the pollutants can build up over time due to poor air exchange. However, the employment of natural ventilation mitigates noise and health problems associated with HVAC systems, ensure a healthier environment for occupants.

It is also seen that, new challenges arise in implementing a natural ventilation strategy, as the height of the tall building increases. Besides, air pressure and temperature differentials across the facade will increase with presenting a challenge in designing and sizing external envelope openings and devising a ventilation control strategy. Moreover, wind speeds can be greatly different at increasing heights than at ground level. However, vertical segmentation may offer a viable solution to potentially allow for the employment of natural ventilation for the supertall building typology. For example, each nine-story village in the Post Tower Bonn building, and 12-story village in the Commerzbank, Frankfurt behaves as a distinct unit independent of the ventilation strategy of the segment above or below. The natural ventilation strategy may be vertically extruded by adding extra segments to create the supertall building, since each segment addresses pressure differentials distinctly.

It is also derived that, besides variations in vertical environmental parameters, climate also performs a major role in the decision to naturally ventilate a typical tall building and in the feasibility for natural ventilation in a supertall building. It may be difficult to implement natural ventilation in a hot humid climate, however a hot humid climate might still promises opportunities for a supertall building. A hot humid climate with insufficient wind speed at ground level may provide the optimum environment for natural ventilation at greater elevations, since increasing height gets higher wind speeds and lower air temperatures. The differences in atmospheric conditions between the interior and exterior may result in air flow that can be used for ventilation and passive cooling.

Ultimately, it should be noted that there are numerous tall buildings in existence employing innovative natural ventilation systems, often for the greater part of the year. Many of them are profiled in the case studies and the literature review and it is derived that, most of them considers mentioned parameters in the method chapter. However, it is seen that, altitude based parameters need to be researched more. With further research in this field, efficiency of natural ventilation systems may increase.

5.2. FURTHER RESEARCH

Further research is required to examine the opportunities that the vertical climatic variations provide to natural ventilation of tall buildings. As there are relatively few tall buildings in existence which are entirely naturally ventilated, due to the potential risks, challenges, and associated limitations, the subject matter is worthy of greater investigation and future research. The followings are suggested as areas requiring further research for the enhancement of natural ventilation in tall buildings by means of altitude integration.

A comprehensive global post occupancy study needs to be undertaken of a wide range of naturally ventilated buildings from different climates, building types, functions, etc. This analysis should include both the energy usage in the building and occupants' feedback regarding the experience of natural ventilation.

Further research may be carried out on aerodynamic elements that assist and direct air to inward. A number of case studies analyzed in this dissertation utilize aerodynamic elements to assist natural ventilation, for instance, wing walls used to increase facade pressure differential and stagnant wind speeds; wing roofs used to accelerate exhaust from thermal flues; detailed aerodynamic elements in window mullions to disperse ventilation; the use of solar chimneys for unsteady wind conditions, etc.

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