UNIVERSITY OF NAIROBI

FACULTY OF THE BUILT ENVIRONMENT AND DESIGN

DEPARTMENT OF ARCHITECTURE

DESIGN STRATEGIES FOR WALL MOUNTED THERMAL CHIMNEYS IN THE TROPICAL UPLANDS CLIMATE:

A Case of Nairobi

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B52/38838/2020

‘There is no subject directly connected to life on which there is so large an amount of popular incomprehension as ventilation.’

Jackson (1859 p.461).

DEDICATION

To God Almighty for this far you have brought me.

To my family members for their unwavering support.

DECLARATION

This thesis is my original work and to the best of my knowledge has not been presented for the award of a degree in the University of Nairobi or any other institution. The thesis is submitted in part fulfilment of the examination requirements for the award of the Master of Architecture degree, Department of Architecture & Building Science, University of Nairobi for the academic year 2021/2022.

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ACKNOWLEDGEMENTS

My utmost gratitude goes to God, the Supreme giver of life for his sufficient grace and for giving me the strength, ability and passion to undertake this study.

To my parents Nicodemus Abungu and Benta Abungu, thank you for your dedication, encouragement and invaluable input on my study. To my sisters Berryl and Lynn, thank you for being my eternal cheerleaders and for encouraging me in all my pursuits. This would not have been possible without your unwavering and unselfish love given to me at all times.

To my tutors Arch. Musau Kimeu and Arch. Jospeh Mukeku thank you for accepting the responsibility of being my supervisors, for your tireless efforts, enthusiasm and great efforts to explain things clearly and simply. To Arch. Linda Nkatha, thank you for your constant and detailed input on my thesis during all the presentations.

To all the lecturers in the Department of Architecture and Building Science: Arch. Mumbi Maina, Arch. Margaret Kedogo, Arch. Tom Anyamba, Arch. Peninah Mutonga, Arch. Robert Rukwaro, Arch. Daniel Too, Arch. Oyugi and all whom I did not mention but hold dear, I am grateful for the support and lessons throughout this programme.

To my classmates: Sheila Owuor, Annelinda Mwania, Paul Ngugi, Aziz Hussein and Eric Murithi, thank you for the happy moments during the programme.

To my friends: Brian Amke, Kumary Kiunga, Barry Paul and Samuel Gatonye, thank you for the help during my field study and analysis, support, resourcefulness and invaluable insight on my research. To Duncan Wamugi, Geoffrey Mosoti, Joy Joan, Sharon Njiru, Abigail Wahome and Viva Kanana, you were all part of the cause in making my study a success.

ABSTRACT

Over the last two decades, passive ventilation systems such as thermal chimneys are increasingly being advocated for in buildings due to their ability to provide high air changes per hour by using simple systems and relying on natural forces such as temperature difference and wind speed. The high air changes per hour are important for the health, well-being and productivity of building occupants. This is especially true for offices which require a minimum of 4 air changes per hour. Achieving such air changes per hour in Nairobi may prove to be difficult without the use of active design strategies. This is due to the increase in the number of developments as well as in the complexities and capacities of developments which has led to an increase in the demand for building systems to provide sufficient air change rates for the occupants. This research sets out to establish design strategies for thermal chimneys in Nairobi, in order to make it possible for office buildings to have at least 4 air changes per hour.

In this study, the author reviews literature documenting the appropriate ways of designing thermal chimneys. This forms the basis of the parameters that have been used during the field work study. The research uses case studies as the strategy for comprehensive coverage of the topic of study. The findings of the study reveal that all of the case studies have air changes per hour that are below the recommended minimum air changes per hour for office spaces. Thermal chimneys are then designed for each office in order to create environments with appropriate air changes per hour that are within the recommended range. Their performance and effects on air changes per hour are investigated using computational fluid dynamics simulations. Suggestions for optimum construction design of thermal chimneys have been put forward based on a number of simulation results. This provides direction for future developments of offices in Westlands, Nairobi.

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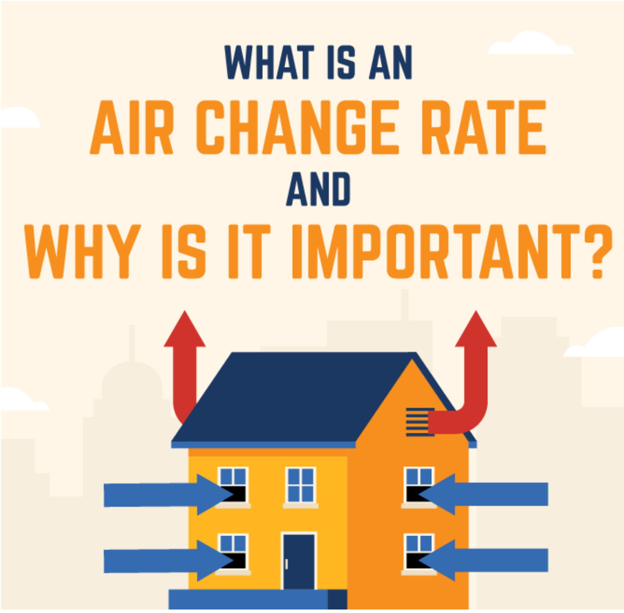

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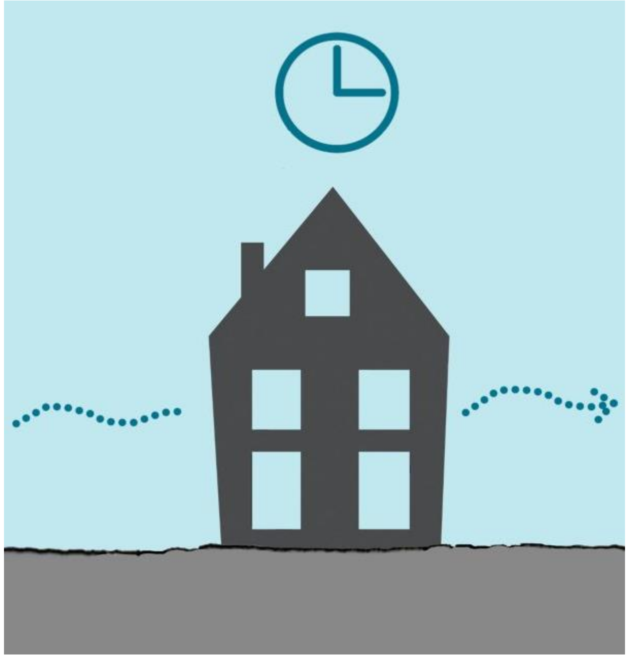
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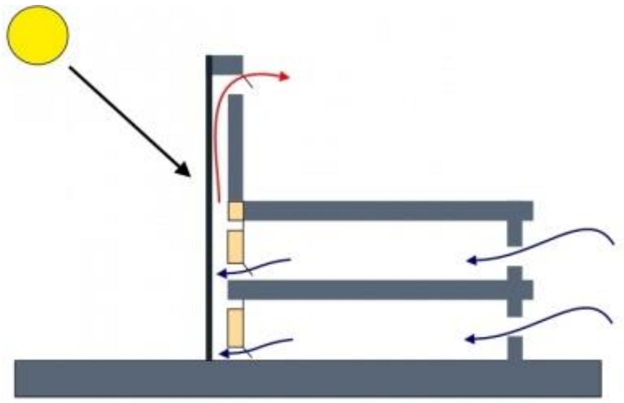
1.0 BACKGROUND STUDY

Increased awareness of the need for effective, efficient and environmentally sound building ventilation has sparked new interest in thermal chimneys over the last two decades. In recent years, a number of experimental, numerical and theoretical investigations have contributed to the current understanding of thermal chimneys as simple and practical tools that are applied to enhance passive ventilation in buildings (Soubhi et al. 2012). Thermal chimneys are systems of passive ventilation that use solar radiation to produce convective currents. An air temperature difference is created and an air density gradient between the inside and the outside of the chimney is obtained, which induces a natural upwards movement of air. In the tropical climates such as the tropical uplands climate, thermal chimneys are majorly used for ventilation and heat dissipation (Sudprasert et al., 2016), while in the temperate and polar climates, thermal chimneys are used as heat accumulators to increase the temperature inside the space (Herrero, 2006). When properly designed, thermal chimneys in the tropical climates can be used to provide the recommended ventilation rates for users within the space.

Ventilation is the supply and removal of air, to and from any space, in order to control the level of air contaminants, humidity or temperature within that space (ASHRAE, 2001). It is estimated that the minimum air change rate for any space is 4 air changes per hour, but for comfort purposes, it is essential to have more air changes in order to meet the occupants' oxygen requirements, for dilution of odours, dilution of carbon dioxide concentration and to minimize the increase in air temperature in case there are extreme sensible heat gains (Jones, 1994).

Due to the relatively high temperatures experienced in the tropical climates during the day, direct ventilation for sufficient air changes is not recommended because of undesirable body heat gain by convection (Soubhi et al. 2012). In such situations, passive systems such as thermal chimneys come in handy. The tropical uplands climate experiences air temperatures of between 24^0C to 30^0C during the day and 10^0C to 13^0C in the night. The relative humidity levels range from a low of



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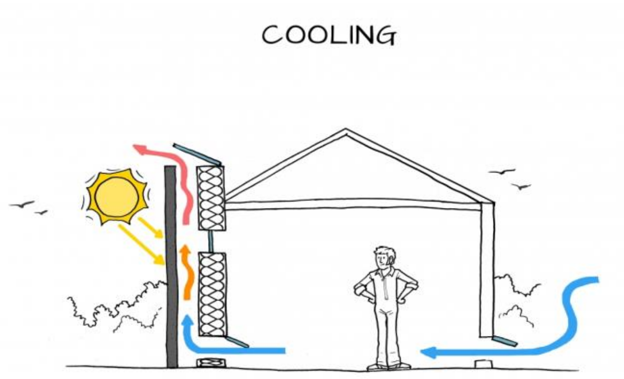
Source: https://www.designingbuildings.co.uk/wiki/Solar_chimney



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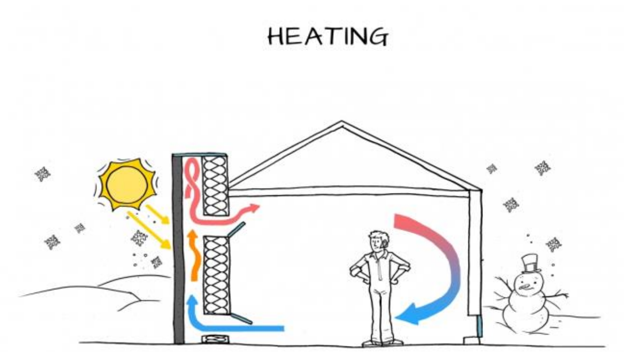
Source: https://www.designingbuildings.co.uk/wiki/Solar_chimney



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Source: https://www.designingbuildings.co.uk/wiki/Solar_chimney

44% to high of 99%. The rainfall may exceed 1000mm in one month and the wind velocities rarely exceed 15m/s (Koenigsberger, 1975). All built forms within the tropical uplands climate need to have sufficient air changes in order to increase the comfort and productivity of building users, prevent transmission of communicable diseases as well as reduce prevalence of sick building syndrome (SBS) symptoms.

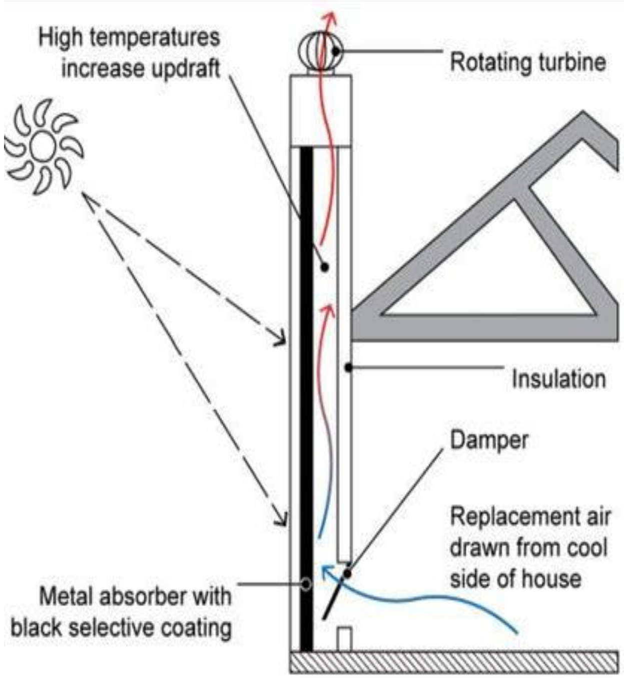
Few attempts have been made to study the design of thermal chimneys for buildings in the tropical uplands climate, to enable them to provide the recommended air changes per hour. In addition to this, there is an insufficiency of theoretical basis and experimental results for the application of thermal chimneys in the tropical uplands climatic region, with regards to the working mechanism and typical structure of thermal chimneys, the influencing parameters related to ventilation efficiency, temperature distribution and air patterns. It is these aspects of thermal chimneys that this thesis seeks to document and analyze in detail.

1.1 PROBLEM STATEMENT

Passive ventilation systems are increasingly being advocated for in buildings due to their ability to provide high air changes per hour by using simple systems and relying on natural forces such as temperature difference and wind speed (James et al., 2009). Passive ventilation modes are classified as wind-induced, buoyancy-driven, and hybrid ventilation (Chartier & Silva, 2009). When effectively designed for in buildings, these modes ensure that users of the habitable spaces receive the recommended minimum of 4 air changes per hour (Santamouris & Kolokotsa, 2013).

Passive ventilation is one of the most important design criteria in buildings since it has various advantages over mechanical ventilation systems, with regards to number of air changes per hour as well as installation and maintenance costs (Khanal & Lei, 2011). As an effective way to protect the building users, passive ventilation methods have generated intense interest for improving indoor air quality in recent years. Among these passive ventilation solutions, the use of thermal

Figure 1.6: New developments coming up in Nairobi
Source:https://www.reddit.com/r/Kenya/comments/hg83hm/shot_from_karura_forest_nairobi_skyline/



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Source: https://www.designingbuildings.co.uk/wiki/Solar_chimney

chimneys in buildings is a promising approach for guiding passive ventilation. These thermal chimneys are being given global attention due to their ability to induce ventilation by relying on natural forces such as temperature difference and wind speed (Zhai, Song & Wang, 2011).

According to a report by the Kenya National Bureau of Statistics, Nairobi's construction sector recorded a 16.2% growth in the third quarter of 2020, making it the fastest developing county in Kenya. This increase in the number of developments as well as in the complexities and capacities of developments has led to an increase in the demand for building systems to provide sufficient air change rates for the occupants. This has consequently led to employment of mechanical ventilation systems which are expensive to install, maintain and often do not deliver the recommended minimum of 4 air changes per hour (Pavelchak et al., 2000). This could have been negated if the passive ventilation systems such as thermal chimneys had been effectively designed for and installed, since they have the general advantage of providing very high air change rates using natural forces, which may greatly exceed minimum ventilation requirements (James et al., 2009). However, the increment in volume and intricacy of modern buildings has created an insufficiency in the existing studies on performance and design of thermal chimneys in the tropical uplands climatic region, which is experienced in areas such as Nairobi. According to Punyasompun et al. (2013), this lack of theoretical research has led to limitations and poor application of thermal chimneys, leading to insufficient air change rates in the habitable spaces.

At least 4 air changes per hour is important for the health, well-being and productivity of building occupants (Frontczak et al. 2012). Adverse health outcomes associated with poor air change rates in buildings include increased prevalence of sick building syndrome (SBS) symptoms, respiratory disease, allergic symptoms, and sensory irritation. Furthermore, this can increase the transmission risk for certain communicable diseases such as the Coronavirus disease. These eventually affect occupant health and productivity, contributing to increased health care cost, productivity loss, and absenteeism (Leung et al. 2007).

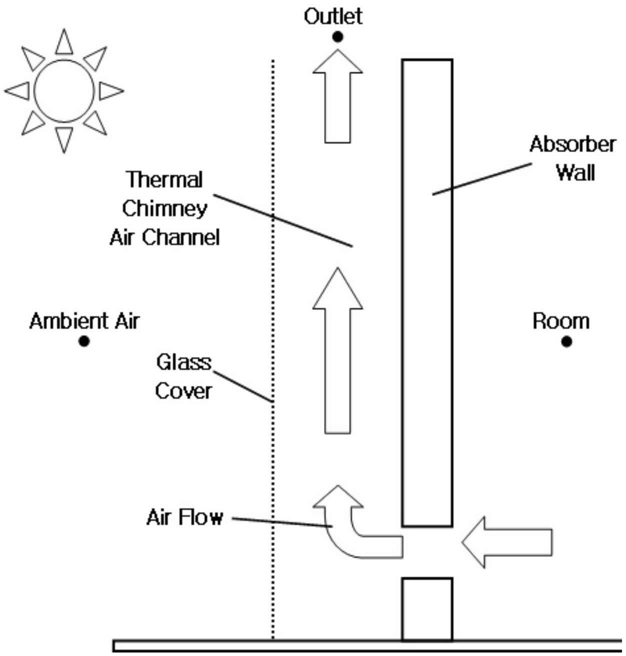

Figure 1.8: Section of a building illustrating ventilation through a thermal chimney
Source: https://www.designingbuildings.co.uk/wiki/Solar_chimney

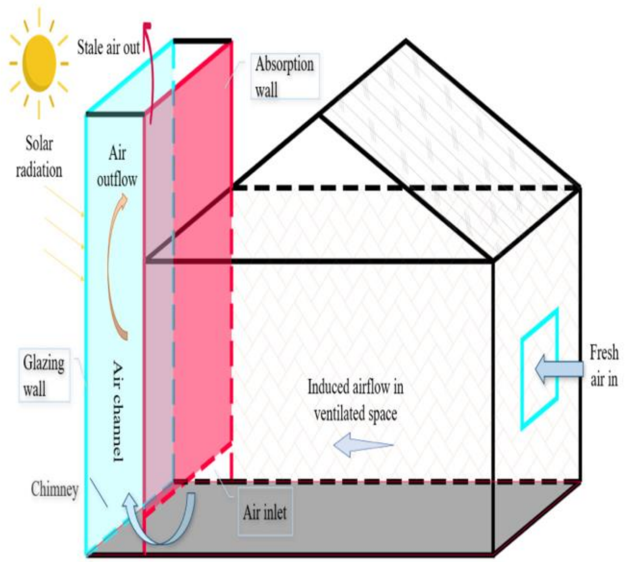

Figure 1.9: Section of a building illustrating ventilation through a thermal chimney
Source: https://www.designingbuildings.co.uk/wiki/Solar_chimney

This study seeks to investigate the design of thermal chimneys in the tropical uplands climatic regions such as Nairobi, in order to enhance air change rates. Additional factors that will be investigated include the working mechanism and typical structure of thermal chimneys, the influencing parameters related to ventilation efficiency, temperature distribution, air pattern and the various possibilities for enhanced performance in the tropical uplands climatic region. This study also seeks to make recommendations for the design strategies of thermal chimneys in the tropical uplands climatic region.

1.2 AIMS AND OBJECTIVES

i. Document the configurations, installation parameters and materials used in the design of thermal chimneys.
ii. Analyze the air changes per hour in the office buildings in Nairobi.
iii. Develop design strategies for thermal chimneys in the tropical uplands climate.

1.3 RESEARCH QUESTIONS

i. What are the configurations, installation parameters and materials used in the design of thermal chimneys?
ii. What are the air changes per hour in the office buildings in Nairobi?
iii. What are the design strategies for thermal chimneys in the tropical uplands climate?

1.4 JUSTIFICATION OF STUDY

The findings of this study will be useful in providing a unified theoretical basis and sufficient experimental results for the application of thermal chimneys in the tropical uplands climatic region. The differences in the literature indicate that thermal chimneys have not yet been thoroughly studied and developed. More theoretical support and numerical verification is needed to ensure that the use of thermal chimneys is popularized in practical applications. The results of this study will also provide some insights and information on how to improve the stability of the


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Source: https://www.arup.com/projects/eastgate

thermal chimney system to cope with the tropical uplands climatic conditions and prolong the durability of the system.

1.5 SIGNIFICANCE OF STUDY

This study will be of interest to architects, mechanical engineers and various professionals in the construction industry who seek to understand the design of thermal chimneys in buildings to enhance air change rates, as well as the various possibilities for enhanced performance.

This study will add to the existing body of knowledge on design of thermal chimneys. It provides an initial direction for future scholars who may be interested in in furthering research on design of thermal chimneys in the tropical uplands area.

1.6 SCOPE AND LIMITATIONS

The research scope is limited to Nairobi, Westlands area. This has been chosen due to the high construction development rates, proximity to the author's current location, climatic conditions as well as presence of significant case studies within this location that will be used in the study.

The study scope is limited to thermal chimneys only. Thermal chimneys coupled with other systems have not been included in the study.

The case studies in the aforementioned area have been selected based on their accessibility, architectural richness and availability of information. The office building typology will be used for this study. Case studies are limited to buildings built at most ten years ago (2012-2022).

Computational fluid dynamics simulations and analysis of various thermal chimney models within the selected case studies will be used to supplement the field work.

The environmental factors that will be focused on are air temperature and wind speed due to their direct impact on ventilation rates within the buildings.

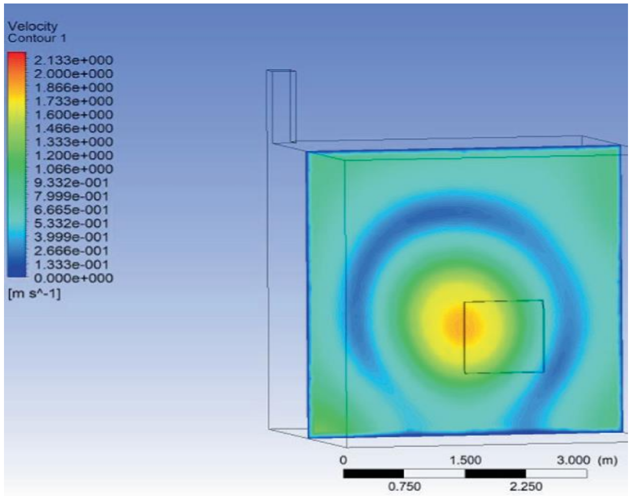

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Figure 1.14: Thermal chimneys at the BRE Office in Watford
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

The limitations during the study are time constraints and monetary constraints.

1.7 STRUCTURE OF THE RESEARCH

i. Chapter one: Introduction

This chapter gives a background study on the subject matter, first by introducing and defining thermal chimneys, then stating the general purposes for ventilation, recommended air changes per hour and outlining the climate of the tropical uplands region. Highlighting the problem as the contentious issue of thermal chimney design in tropical uplands climate, the chapter goes on to identify the key objectives of the study. Being a scientific study, the aims are to document the configurations, installation parameters and materials used in the design of thermal chimneys in the tropical uplands climate, analyze the air changes per hour of the spaces that have the thermal chimneys and develop design strategies for thermal chimneys in the tropical uplands climate. Because of the limitation of resources the scope of the study is limited to specific case studies in Nairobi, Westlands area. The significance of the study is to fill the gap in the existing knowledge on design of thermal chimneys in the tropical uplands climatic region.

ii. Chapter two: Literature review

This chapter gives a general overview of ventilation, then goes ahead to specifically analyze the indoor air quality needs in tropical uplands climatic regions. In addition to this, it also analyses different thermal chimney typologies and various calculations to determine the volumetric flow rates within each typology. It amalgamates information from various case studies to give an in depth understanding of the phenomenon of design of thermal chimneys. It also outlines the required air changes per hour for various rooms based on their uses. This chapter further goes into the various design parameters that should be used for thermal chimneys.

Figure 1.15: Auditorium at the Learning Resource Centre in Kenya
Source: http://buildesign.co.ke/the-lrc/

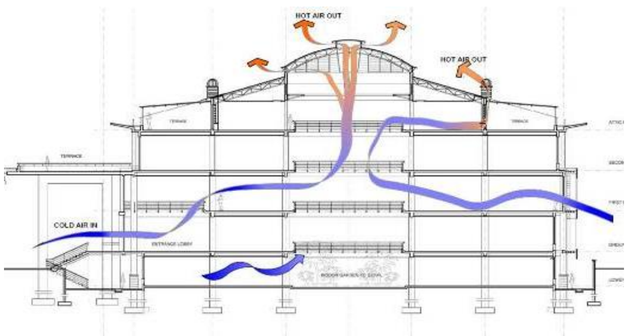


Figure 1.16: Section of the library at the Learning Resource Centre in Kenya
Source: http://buildesign.co.ke/the-lrc/

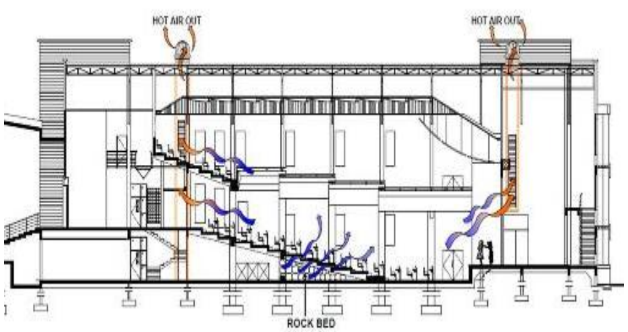


Figure 1.17: Section of the auditorium at the Learning Resource Centre in Kenya
Source: http://buildesign.co.ke/the-lrc/

iii. Chapter three: Research Methods

This chapter spells out how this study is undertaken and further describes the research design, research strategy, data collection techniques, data analysis methods and presentation. With an attempt to define and explore design of thermal chimneys in Nairobi, Westlands area, the case study design strategy serves as the most appropriate research method because it is specific but flexible and expansive enough to adapt the various complexities that encompass the subject of study. This chapter goes on to identify the major sources of data collection as secondary: the critical literature review, and primary: the field study, using interviews, observation, physical measurements and scientific measurements presented in the form of photographs, analytical notes, tables, charts and architectural images.

iv. Chapter four: Urban environmental analysis of Westlands

This chapter analyses the environmental concerns of the built environment in Nairobi, with a focus on Westlands. In addition, a historical study of the evolution of the area's building typologies and forms over the years is undertaken which in turn introduces the five buildings being investigated for thermal chimney design parameters in Chapter 5.

v. Chapter five: Findings and discussions

In this chapter, all the data obtained from fieldwork is used for the analysis of thermal chimney design applied in the selected case studies as well as answering the research questions set at the introduction of the research.

vi. Chapter six: Conclusions and recommendations

This chapter draws conclusions on the design strategies for thermal chimneys in the selected case studies. It also outlines recommendations on design of thermal chimneys in tropical uplands climatic regions.

Figure 1.18: Thermal chimneys at Lycee Francais Charles de Gaulle in Damascus
Source: https://www.e-architect.com/syria/lycee-francais-charles-de-gaulle

Figure 1.19: Thermal chimneys at Lanchester Library in Coventry
Source: https://manchesterhistory.net/architecture/2000/lanchester.html

Figure 1.20: Thermal chimneys at Portcullis House in Westminster
Source: https://www.northernarchitecture.us/artificial-lighting/portcullis-house-westminster.html

1.8 LIST OF TERMINOLOGIES

i. Thermal chimney - systems of passive ventilation that use solar radiation to produce convective currents. An air temperature difference is created and an air density gradient between the inside and the outside of the chimney is obtained, which induces a natural upwards movement of air.

ii. Air changes per hour (ACH) - a measure of how many times the air within a defined space is replaced each hour.

iii. Computational fluid dynamics (CFD) – the process of mathematically modeling a physical phenomenon involving fluid flow and solving it numerically using the computational prowess.

iv. Trombe wall: A thick wall that is painted a dark color in order to absorb thermal energy from incident sunlight and covered with a glass on the outside with an insulating air-gap between the wall and the glazing.

Nomenclature:

v. ***A*** - area, m^2

vi. ***C*** - coefficient

vii. ***Cp*** - specific heat capacity, J/kg^0C

viii. ***d*** - air gap thickness, m

ix. ***f*** - wall friction coefficient

x. ***g*** -gravitational acceleration, m/s^2 ($9.81 m/s^2$)

xi. ***H*** - cavity height, m

xii. ***h*** - heat transfer coefficient, $W/m \cdot {}^0C$

xiii. ***k*** - pressure loss coefficient

xiv. ***q*** - heat input intensity, W/m^2

xv. ***Q*** - heat input, W

Figure 1.21: Thermal chimneys at Torrent Research Centre in Ahmedabad
Source: https://www.archidev.org/spip.php?article1115&lang=fr

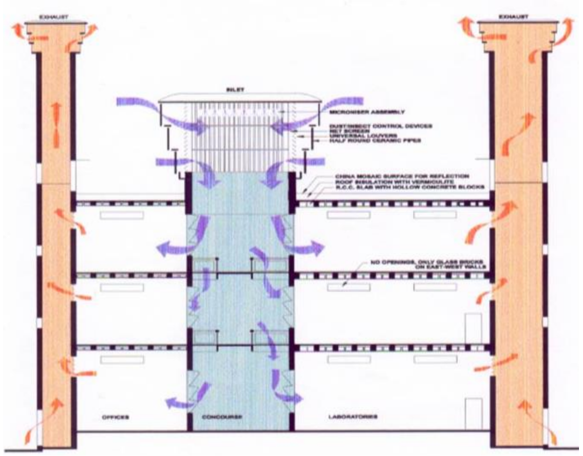


Figure 1.22: Ventilation system at Torrent Research Centre in Ahmedabad
Source: https://www.archidev.org/spip.php?article1115&lang=fr

xvi. ***Slope*** - regression slope

xvii. ***T*** - temperature, ^{0}C

xviii. ***V*** - volumetric flow rate, m^{3}/s

xix. ***w*** - cavity width, m

xx. ***θ*** - inclination angle from the horizontal

xxi. ***θ’*** - calculated inclination angle

Subscripts:

xxii. ***0*** – ambient conditions

xxiii. ***c*** – cavity

xxiv. ***d*** – discharge

xxv. ***hot*** – hot cavity wall

xxvi. ***in*** – inlet

xxvii. ***out*** – outlet

xxviii. ***r*** – ratio between outlet and inlet

xxix. ***room*** – room configuration

xxx. ***wall*** – cavity wall

CHAPTER TWO: LITERATURE REVIEW

Figure 2.1: Thermal chimneys at Monash Science Centre in Australia
Source:
http://www.solaripedia.com/13/139/1263/monash_science_centre_wall.html

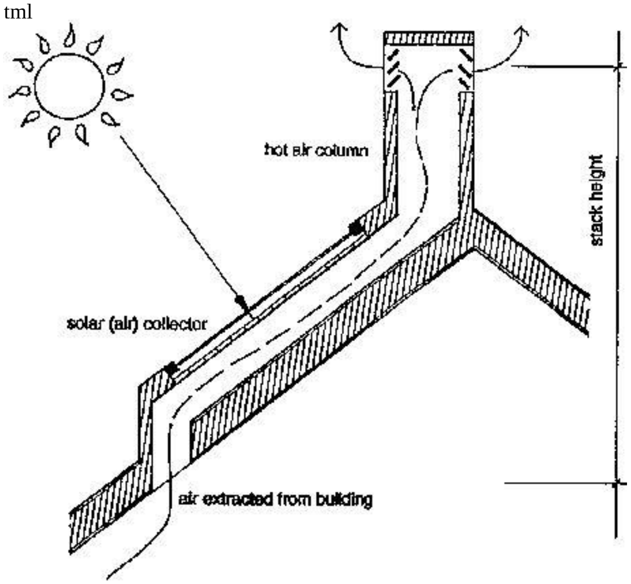


Figure 2.2: Inclined roof mounted thermal chimney with a solar collector and louvres
Source: https://www.researchgate.net/figure/Proposed-Solar-Induced-Ventilation-Strategy-which-Combines-Roof-Solar-Collector-and_fig10_299390015

2.0 INTRODUCTION

Thermal chimneys provide a unique opportunity to adequately ventilate a building by ensuring that the occupants receive sufficient air changes per hour. This chapter seeks to highlight the tropical uplands climate characteristics and appropriate design parameters for thermal chimneys based on literature review and relevant case studies. This will ground the research on proper philosophical starting points.

2.1 TROPICAL UPLANDS CLIMATE DESIGN

This climate is experienced in areas that are more than 900 to 1200m above sea level. Examples of cities that experience this climate include Addis Ababa, Bogota, Mexico City and Nairobi. The seasonal variations are small in the upland climatic regions that are near the equator.

2.1.1 CHARACTERISTICS OF TROPICAL UPLANDS CLIMATE

i. Air temperature: The air temperatures range is between 24^0C to 30^0C during the day and 10^0C to 13^0C in the night. In some locations, the temperature may fall below 4^0C making ground frost a common phenomenon in such areas. Both the diurnal range is large, while the annual range depends on the latitude. For example, near the equator, the annual range is small while at the tropics the annual range may be up to 11^0C or 12^0C.

ii. Relative humidity: The relative humidity levels range from a low of 45% to high of 99% and vapour pressure ranges from 800 to 1600N/m^2.

iii. Precipitation: The rainfall is variable, but is rarely less than 1000mm. The rainfall intensity normally reaches 80mm/hr.

iv. Sky conditions: Cloud cover is normally at 40%. The sky conditions are usually clear or partly cloudy.

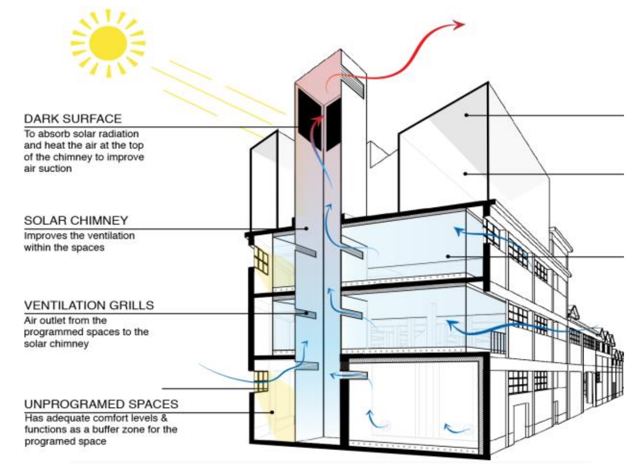


Figure 2.3: Wall mounted thermal chimney with a dark absorber surface and louvres
Source: https://www.behance.net/gallery/47925383/3rd-Prize-Young-Architects-Competition/modules/285900021

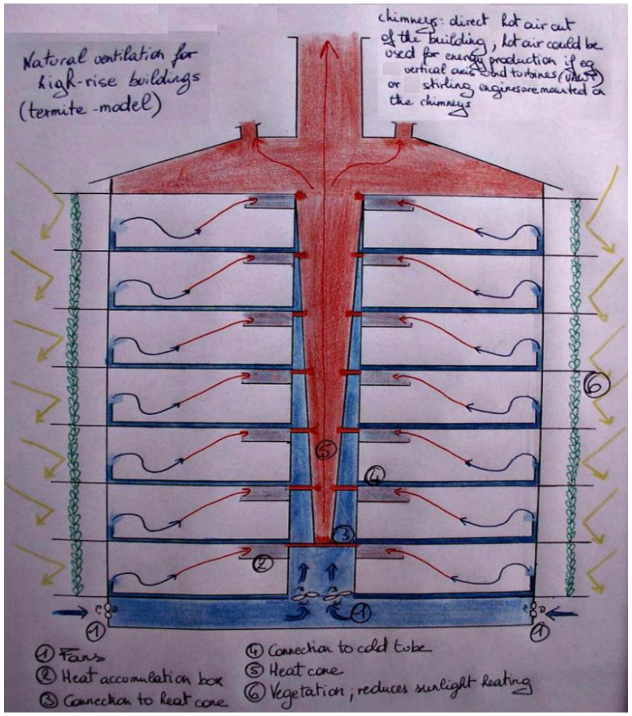


Figure 2.4: Thermal chimney ventilation system at the Eastgate Centre in Zimbabwe
Source: https://www.arup.com/projects/eastgate

v. Solar radiation: Solar radiation reaching the ground is normally strong and direct during the clear periods. The ultra violet radiation is stronger at higher altitudes and becomes more diffuse as cloud cover increases.

vi. Wind: Wind velocities rarely exceed 15m/s. The winds are variable, but the predominant ones are the north-easterlies and south-easterlies. (Koenigsberger et al., 1975).

2.2 VENTILATION

Ventilation is the supply and removal of air, to and from any space, in order to control the level of air contaminants, humidity or temperature within that space (ASHRAE, 2001). The two types of ventilation are natural and mechanical ventilation.

2.2.1 NATURAL VENTILATION

Natural ventilation uses naturally available forces instead of mechanical means, to supply and remove air in an enclosed space. The main types of natural ventilation in buildings are stack driven ventilation, wind driven ventilation and hybrid ventilation. The stack driven ventilation relies on air temperature differences to generate air movement. Wind driven ventilation relies on the speed of the prevailing wind to pull and push air through the building interiors. Hybrid ventilation is a combination of the stack driven ventilation and wind driven ventilation (Steven et al., 1994).

The benefits of natural ventilation include:

i. Improved Indoor air quality (IAQ)
ii. Energy savings
iii. Reduction of greenhouse gas emissions
iv. Occupant control
v. Reduction in building user sicknesses
vi. Increased worker productivity

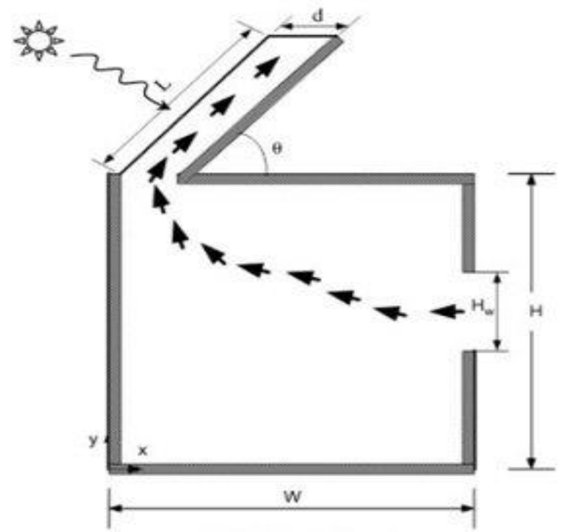


Figure 2.5: Inclined roof mounted thermal chimney with a solar collector
Source: https://www.researchgate.net/figure/Proposed-Solar-Induced-Ventilation-Strategy-which-Combines-Roof-Solar-Collector-and_fig10_299390015

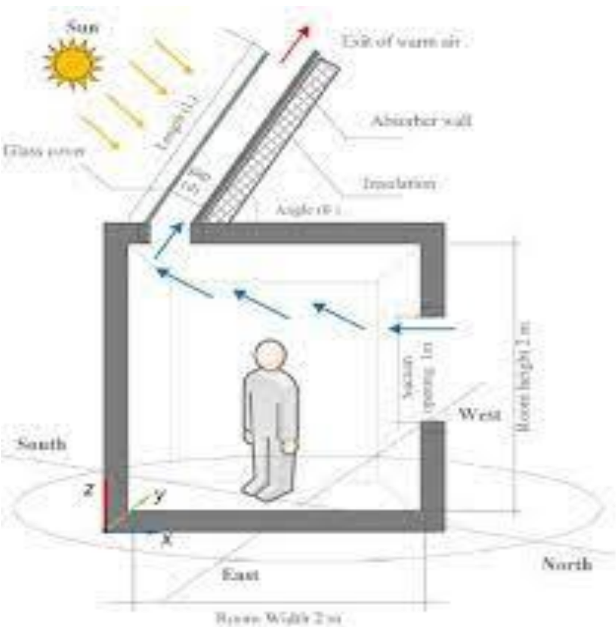


Figure 2.6: Inclined roof mounted thermal chimney with a solar collector
Source: https://www.researchgate.net/figure/Proposed-Solar-Induced-Ventilation-Strategy-which-Combines-Roof-Solar-Collector-and_fig10_299390015

Techniques and architectural features used to naturally ventilate buildings include:

i. Operable windows
ii. Thermal chimneys
iii. Wind catchers
iv. Screens
v. Permanent vents
vi. Roof cowls
vii. Night purge ventilation
viii. Clerestory windows and vented skylights
ix. Wind capture façades

2.2.2 MECHANICAL VENTILATION

Mechanical ventilation is fan driven flow of outdoor air into or out of a building. Mechanical ventilation systems include supply fans, which push outdoor air into a building, exhaust fans, which draw air out of building and thereby cause equal ventilation flow into a building through fenestrations, or a combination of both. Systems used to mechanically ventilate buildings include (Steven et al., 1994):

i. Fans
ii. HVAC air handlers
iii. Heat recovery ventilators
iv. Energy recovery ventilators

Disadvantages of using mechanical ventilation systems include:

i. Contaminants may be drawn into the habitable spaces
ii. Can contribute to back drafting of combustion appliances

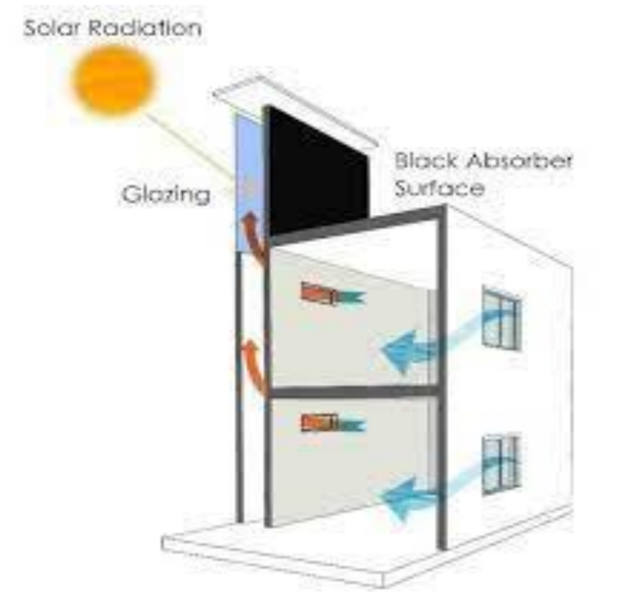


Figure 2.7: Wall mounted thermal chimney with a dark absorber surface and glazing
Source: https://www.behance.net/gallery/47925383/3rd-Prize-Young-Architects-Competition/modules/285900021

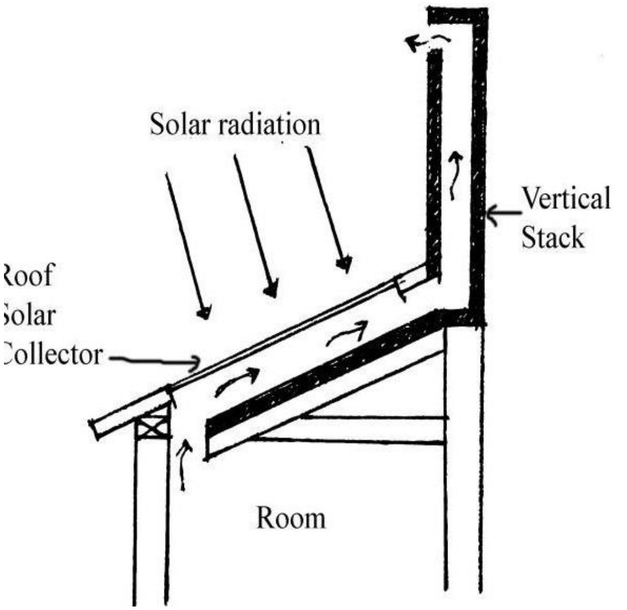


Figure 2.8: Inclined roof mounted thermal chimney with a solar collector
Source: https://www.researchgate.net/figure/Proposed-Solar-Induced-Ventilation-Strategy-which-Combines-Roof-Solar-Collector-and_fig10_299390015

iii. High installation and operation costs

2.2.3 VENTILATION RATE REQUIREMENTS FOR BUILDINGS

The ventilation rate of a building, Q, is the rate at which external air (fresh air) flows into the building. This rate is normally is expressed in units of air changes per hour (ACH), calculated as the total air volume supplied in 1hour divided by the room volume. Simply put, it is a measure of how many times the air in the room is replaced. Higher ACH values mean better ventilation. The formula is as follows (Bansal et al., 2005):

ACH= Q/Vol

Where;

Q= Volumetric flow rate of air in m^3/hr

Vol= Volume of room in m^3

Another formula is:

ACH= (CFM x 60)/ V

Where;

CFM= cubic feet per minute; (the figure is multiplied by 60 to convert it to cubic feet per hour)

V= Volume of room in ft^3

Mechanical ventilation devices normally have their CFM figures or volumetric flow rate figures indicated on them. For naturally ventilated rooms, volumetric flow rates can be obtained using the following formula:

Q= V x A

Figure 2.9: Perspective of an auditorium
Source: https://www.pinterest.com/pin/39899146689226848/

Figure 2.10: Perspective of a cafeteria
Source: https://www.fooda.com/blog/how-corporate-cafeteria-management-companies-work/

Figure 2.11: Perspective of a cathedral
Source: https://www.insider.com/inside-the-most-beautiful-cathedrals-in-the-world-2020-5

Where;

Q= Volumetric flow rate in m^3/s

V= Velocity of air through the fenestration in m/s

A= Area of fenestration in m^2

For this formula, the volumetric flow rate per second should be multiplied by 3600 to convert it to volumetric flow rate per hour.

By using the formulas above, it is possible to determine the air changes per hour that a particular room is getting. The table below outlines the recommended air changes per hour for various rooms.

BUILDING / ROOM	NUMBER OF AIR CHANGES PER HOUR
All spaces in general	4
Assembly Halls	4-8
Attic spaces for cooling	12-15
Auditoriums	12-15
Bakeries	20-30
Banks	4-10
Barber Shops	6-10
Bathrooms	3-8
Bars	20-30
Beauty Shops	6-10
Boiler Rooms	15-30
Bowling Alleys	10-15
Cafeterias	12-15
Chemical Stores	5+

Figure 2.12: Perspective of a court house
Source: https://www.ibzstore.com/?category_id=3080261

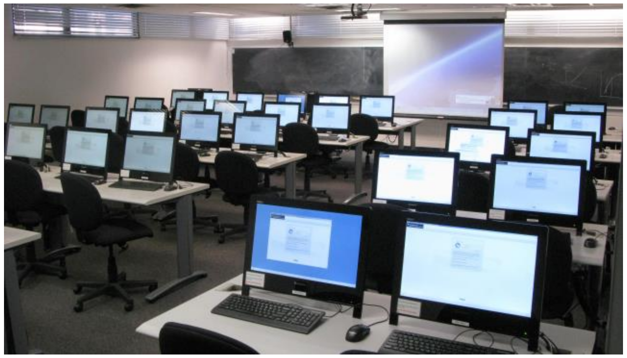


Figure 2.13: Perspective of a computer room
Source: https://www.sipa.columbia.edu/sipait/computer-labs

Figure 2.14: Perspective of a fire station
Source: https://www.archdaily.com/tag/fire-station

Churches	8-15
Classrooms	6-20
Club Rooms	12+
Clubhouses	20-30
Cocktail Lounges	20-30
Computer Rooms	15-20
Court Houses	4-10
Cellars	3-10
Commercial Kitchens	30+
Compressor Rooms	10-20
Conference Rooms	8-12
Dairies	8-12
Dance Halls	6-9
Dental Centres	8-12
Pharmacies	6-10
Engine Rooms	15-30
Entrance Halls & Corridors	3-5
Factory Buildings	2-4
Factory Buildings with Fumes/Moisture	10-15
Fire Stations	4-10
Foundries	15-20
Fume Cupboards	40-50
Galvanizing Plants	20-30
Garages (Repair)	20-30
Garages (Showroom)	6-8
Garages (Storage)	4-6
Gyms	6+
Hospital Rooms (Sterilising)	15-20

Figure 2.15: Perspective of a medical lab
Source: https://www.hawkeyecollege.edu/programs/medical-laboratory-technology

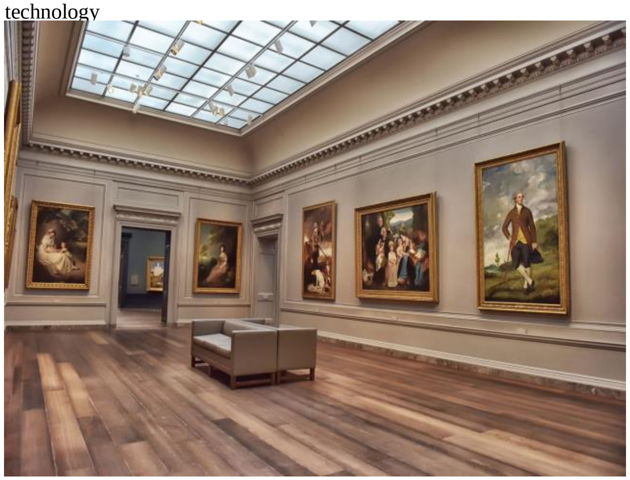


Figure 2.16: Perspective of a museum
Source: https://www.britannica.com/topic/museum-cultural-institution

Figure 2.17: Perspective of a police station
Source: https://www.kenyans.co.ke/news/50501-report-reveals-nairobis-7-most-dangerous-police-stations

Hospital Rooms (Wards)	6-8
Hospital Rooms (X-Ray)	10-15
Kitchens (General)	15-60
Laboratories	6-15
Laundries	10-20
Lunch Rooms	12-15
Nightclubs	20-30
Machine Shops	6-12
Medical Centres	8-12
Medical Clinics	8-12
Medical Offices	8-12
Mills (Paper)	15-20
Mills (Textile General Buildings)	4
Mills (Textile Dye Houses)	15-20
Municipal Buildings	4-10
Museums	12-15
Offices (Public)	3+
Offices (Business)	4-8
Office Lunch Rooms	7-8
Office Copy Rooms	10-12
Office Computer Rooms	10-14
Paint Shops	10-15
Paper Mills	15-20
Photo Dark Rooms	10-15
Pig Houses	6-10
Police Stations	4-10
Post Offices	4-10
Poultry Houses	6-10

Figure 2.18: Perspective of a pump room
Source: https://www.poolspamarketing.com/trade/features/designing-for-functional-operations-practical-considerations-for-commercial-pump-rooms/

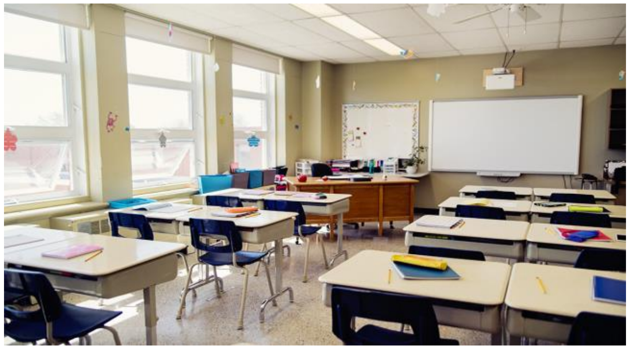


Figure 2.19: Perspective of a classroom
Source: https://www.iteach.net/blog/room-412-getting-your-classroom-ready/

Figure 2.20: Perspective of a supermarket
Source:
https://www.collinsdictionary.com/dictionary/english/supermarket

Precision Manufacturing	10-50
Public Buildings (Hallways)	6-8
Public Foyers	8-10
Public Restrooms	10-12
Public Smoking Rooms	15-20
Pump Rooms	5+
Railroad Shops	4+
Residences	1-2
Restaurants (Dining Area)	8-10
Restaurants (Food Staging)	10-12
Restaurants (Kitchens)	30+
Restaurants (Bars)	15-20
Retail	6-10
School Classrooms	6-20
Shoe Shops	6-10
Shopping centres	6-10
Shops (Machine)	5+
Shops (Paint)	15-20
Shops (Wood Working)	5+
Showers (Public)	10+
Showers (Private)	6
Substation (Electric)	5-10
Supermarkets	4-10+
Swimming Pools	20-30
Taverns	20-30
Textile Mills	4+
Toilets (Public)	6-15
Town Halls	4-10

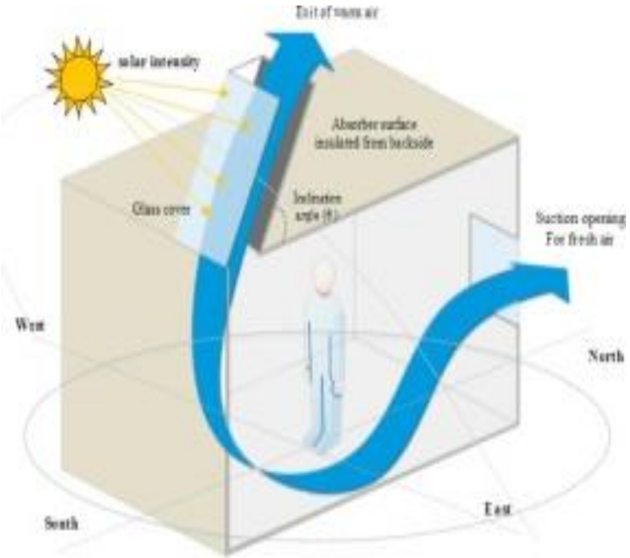


Figure 2.21: Inclined roof mounted thermal chimney with a glazed surface
Source: https://www.sciencedirect.com/science/article/abs/pii/S0038092X19300817

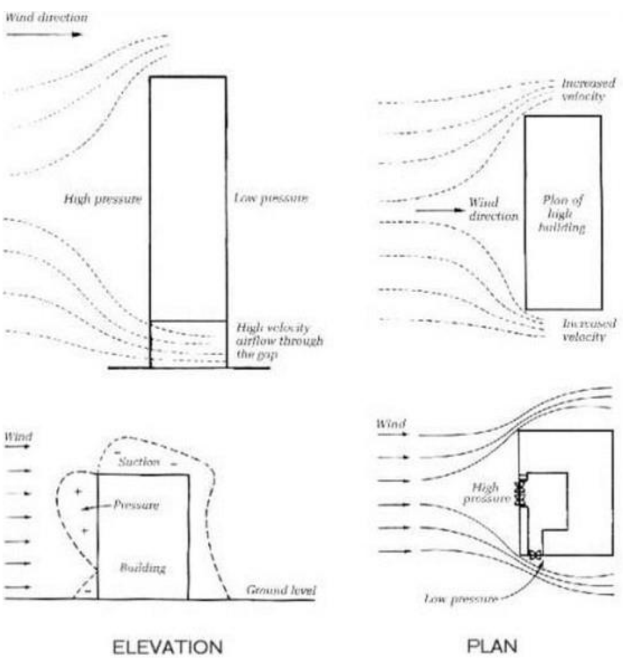


Figure 2.22: Wind movement patterns around a rectangular building
Source: https://www.researchgate.net/figure/Airflow-around-buildings-Figure-2-Plume-impact-on-taller-downwind-building_fig1_237575922

Theatres	8-15
Turbine Rooms (Electric)	5-10
Waiting Rooms (Public)	4
Warehouses	6-30+
Welding Workshops	15-30
Wood Working Shops	8+

Table 2.1: Air change rate requirements for various buildings
Source: https://www.engineeringtoolbox.com/air-change-rate-room-d_867.html. Author modified.

As indicated above, all spaces require a minimum of 4 air changes per hour for user comfort. Spaces such as Bars, bakeries and fume cupboards have the highest requirements for air changes while the spaces that require the least air changes per hour include public waiting rooms, post offices, police stations, public offices, residential houses and railroad shops.

2.2.4 FACTORS AFFECTING NATURAL VENTILATION IN BUILDINGS

Building orientation: The greatest pressure on the windward side of a building is generated when the elevation is perpendicular to the wind direction. This makes it possible to achieve the greatest indoor air velocities. A wind incidence of 45^0 would reduce the pressure by 50%. Therefore, in order to take advantage of the wind, the building should be oriented in such a way that the largest openings face the wind direction. According to Givoni (1998), a wind incidence of 45^0 would increase the average indoor air velocity and would provide a better distribution of indoor air movement. This is due to the greater velocity created along the windward faces, making the wind shadow much broader leading to an increase in the negative pressure which results in increased indoor air flow.

Building form: Wind pressures are generally high on the windward side of a building and low on the leeward side. Various building forms affect wind pressure distribution patterns around the building, thus affecting how air gets into the building. External features of the building can strongly

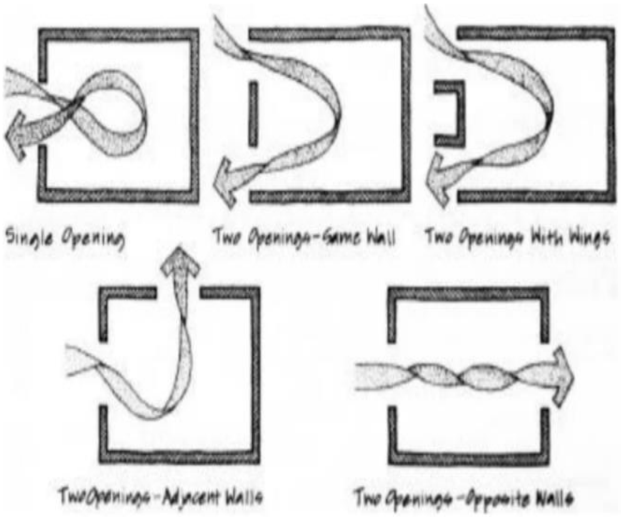


Figure 2.23: Wind movement patterns in a rectangular building
Source: https://www.researchgate.net/figure/Airflow-around-buildings - Plume-impact-on-taller-downwind-building_fig1_237575922

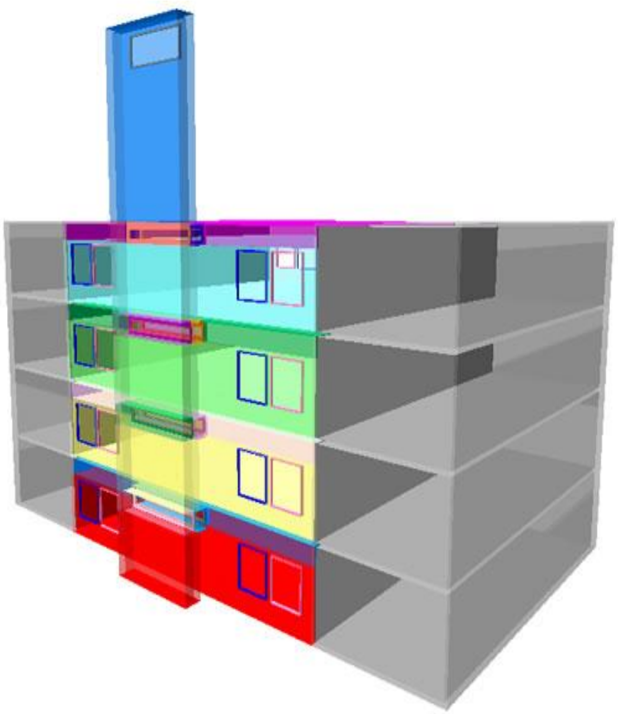


Figure 2.24: Wall mounted thermal chimney for a four storey building
Source: https://www.researchgate.net/figure/Airflow-around-buildings

influence the pressure build up around the building. Any extension of the elevational area facing the wind will increase the pressure build up around the building.

External elements/ obstructions: Wind shadows created by obstructions should be avoided in positioning the building on site and in positioning the openings in the building.

Opening location and size: For effective ventilation, the largest openings should face the wind direction. The highest indoor air velocity will be obtained when the air inlet has a small area and the outlet has a large area, due to the Venturi effect.

With a windward opening and no outlet, a pressure similar to that at the front of the building will be built up indoors, which can create discomfort.

Opening control: Adjustable sashes, canopies and louvres can be used to divert the wind flow either upwards or downwards within the building, thus affecting the indoor airflow pattern.

2.3 THERMAL CHIMNEYS

Thermal chimneys are systems of passive ventilation that use solar radiation to produce convective currents. An air temperature difference is created and an air density gradient between the inside and the outside of the chimney is obtained, which induces a natural upwards movement of air. In the tropical climates such as the tropical uplands climate, thermal chimneys are majorly used for ventilation and heat dissipation (Sudprasert et al., 2016), while in the temperate and polar climates, thermal chimneys are used as heat accumulators to increase the temperature inside the space (Herrero, 2006).

The benefits of using a thermal chimney are:

i. better ventilation rates during hot days
ii. less reliance on wind driven ventilation
iii. better control of air flow through a building

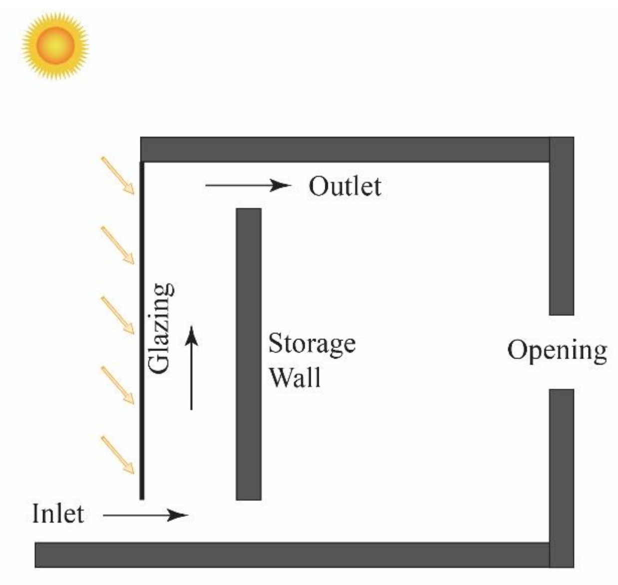


Figure 2.25: Wall mounted thermal chimney used to heat a building
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

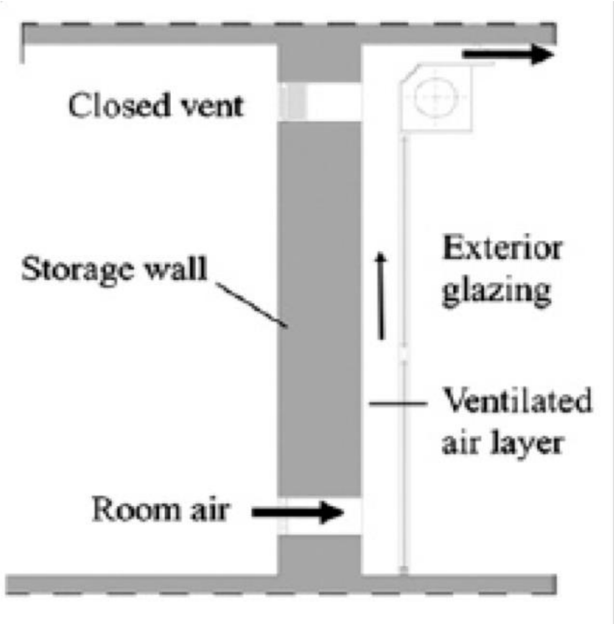


Figure 2.26: Wall mounted thermal chimney used to cool a building
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

iv. better air quality
v. better night time ventilation rates
vi. better ventilation of small spaces with minimal exposure to external elements

Potential benefits regarding passive cooling may include:

i. improved passive cooling during hot seasons
ii. improved night cooling rates
iii. improved performance of the building's thermal mass
iv. improved thermal comfort

2.3.1 TYPES OF THERMAL CHIMNEYS

The three types of thermal chimneys are wall-mounted thermal chimneys, roof-mounted thermal chimneys and combined thermal chimneys.

i. Wall-mounted thermal chimneys

The figure below shows an illustration of a Trombe wall used for heating during the cold season. It has external glazing which allows solar radiation to penetrate into the chimney for heating purposes and a thick internal storage wall. The heated air then moves upwards and enters the room through the top opening. The opening at the bottom left allows external air to get into the thermal chimney cavity while the one at the bottom right allows air from the room to get into the thermal chimney cavity.

The Trombe wall can also be used for cooling during the hot season by changing the location of openings, as shown below. The Trombe wall can be replaced by a regular sized wall cladded with phase change materials (PCM) to keep the latent heat of a storage wall. This requires less space and is lighter in weight when compared to the thick Trombe walls (Chan et al., 2010).

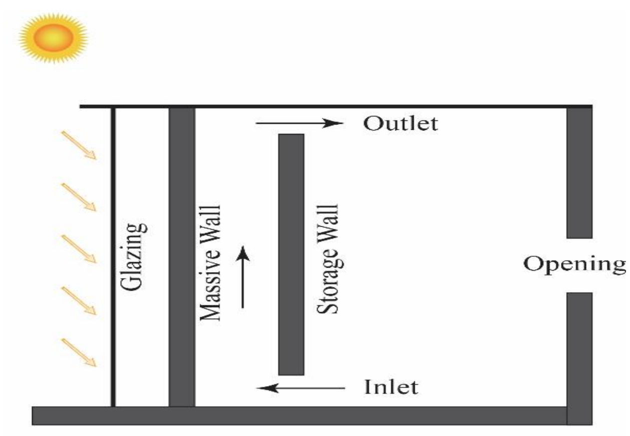


Figure 2.27: Wall mounted thermal chimney used to heat a building
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

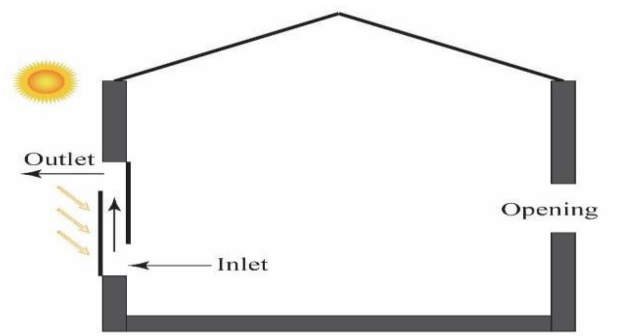


Figure 2.28: Wall mounted thermal chimney used as an air outlet
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

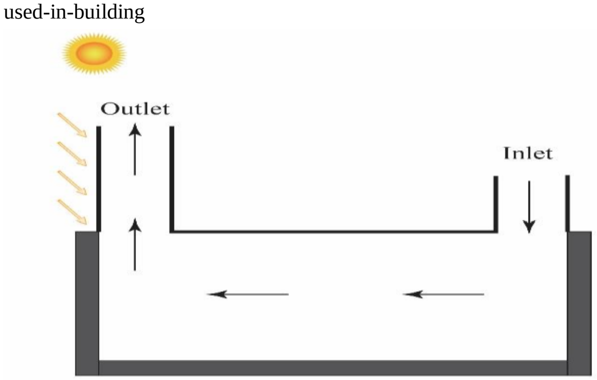


Figure 2.29: Vertical roof mounted thermal chimneys being used as an air inlet and outlet respectively
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

Based on the Trombe wall, a composite Trombe-Michel wall was also developed. Due to its structure, it can only be applied for winter heating. One of its disadvantages is that it cools the building when it actually needs to heat it up during the cold season when the storage wall becomes colder than the indoor air (Shen et al., 2007). To overcome the disadvantage, relevant materials such as phase change materials (PCM) could be used to keep the heat for later use during cold days or at night (Zrikem et al., 1987). Different from the Trombe wall, movable air in the chimney cavity is not heated by direct solar radiation, but by convection processes between the internal air and the massive wall.

A glazed solar chimney wall can be used in tropical climatic conditions. It consists of double glass panels with an air layer and openings located at the bottom and at the top. The basic mechanism of the glazed thermal chimney reduces heat gain through glass walls into the house through air circulation (Chantawong et al., 2006). However, as the performance of a solar chimney is dependent on its height and width, its applications under other climatic conditions may be hampered by weak performance due to limited size.

ii. Roof-mounted thermal chimneys

The figure below shows a typical roof-mounted thermal chimney with a solar collector. A thermal storage layer below the chimney cavity is used to extend the heating period for late usage such as during a cloudy day or night. An insulation layer at the bottom is used to minimize the heat loss from the storage layer. A roof-mounted thermal chimney can be inclined or vertical (Shi et al., 2012). For the vertical roof-mounted thermal chimney, the extra vertical chimney can be used as an inlet. Alternatively, the inlet can be a window or door within the room (Afonso et al., 2000).

iii. Combined thermal chimneys

The thermal chimney shown below is a combined thermal chimney, which has both wall-mounted and roof-mounted thermal chimneys. A vertical solar collector is located above the roof, and ducts

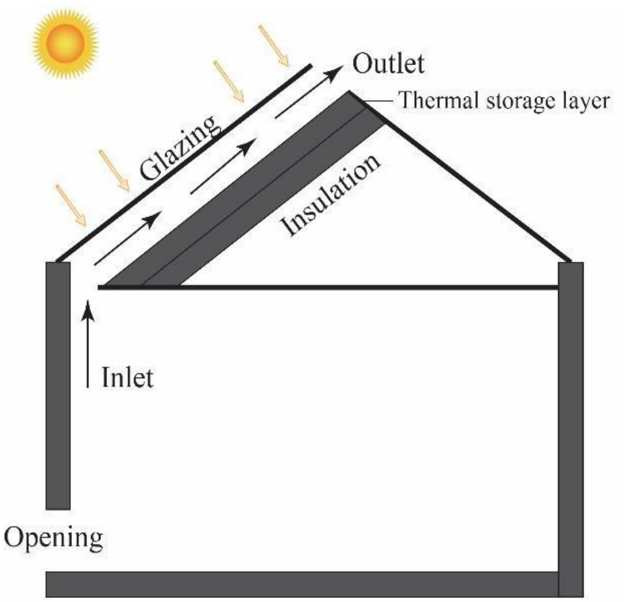


Figure 2.30: Inclined roof mounted thermal chimney with glazing and a thermal storage layer
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

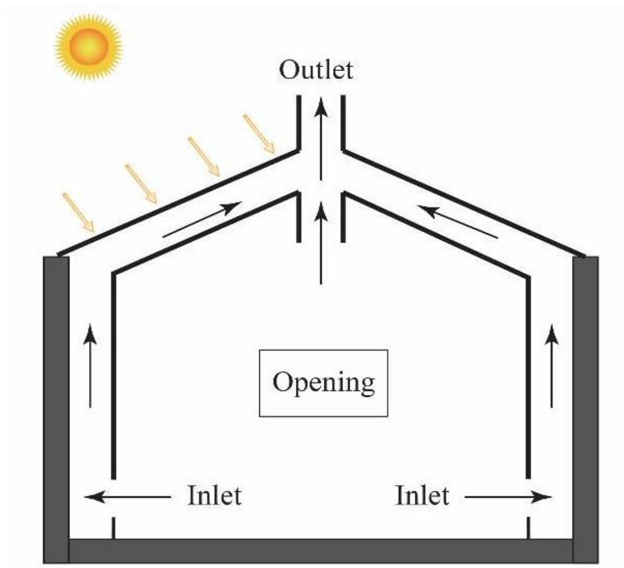


Figure 2.31: Combined roof mounted thermal chimney with both wall mounted and roof mounted thermal chimneys
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

are located along the wall and roof. Air inside the room can exhaust to the outside directly through the top of the thermal chimney (Tan et al., 2014).

These three types of thermal chimneys can have various configurations as discussed in the next section.

2.3.2 THERMAL CHIMNEY MATHEMATICAL MODELS

Mathematical models have been utilized to predict the performance of thermal chimneys. These models have been derived from mathematical deduction, or correlation based on experimental or numerical results.

There are four major types of mathematical models have been found in the literature, as shown in the table below, determined by their modelling inputs:

i. Type I shows proportional relationship between airflow rate and individual parameter.
ii. Type II predicts volumetric flow rate based on air temperature in the thermal chimney cavity. The predictions are based on temperature differences, inlet and outlet areas, thermal chimney cavity height, and inclination angle (for roof-mounted thermal chimneys).
iii. Type III uses air densities inside and outside the thermal chimney cavity for the modelling inputs. This type shows a similar form with type II, replacing air temperature with air density.
iv. Type IV is based on solar radiation. Similar to the previous two types, many coefficients have been used for modelling inputs.

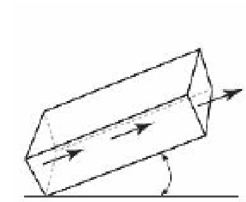
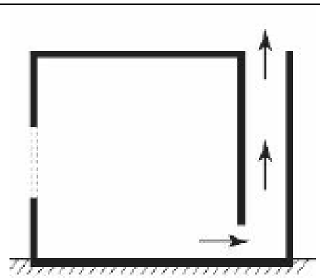
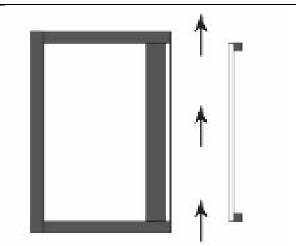
Since type II models have been developed based on only cavity configuration without considering room configuration, Shi and Zhang (2016) have developed a model considering both room and chimney configurations with easy-to-obtain inputs as shown below:

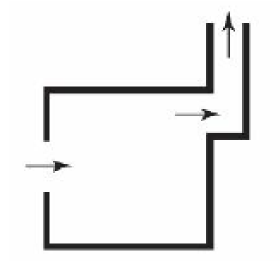
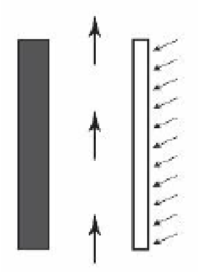
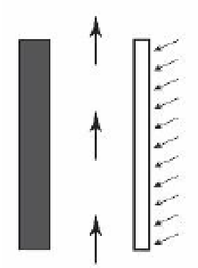
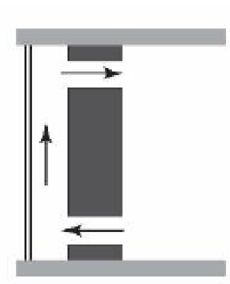
$$V = C_{room}\left[hHA_{hot}\left(T_{wall} - T_0\right)\right]^{1/3}$$

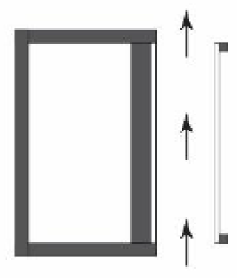
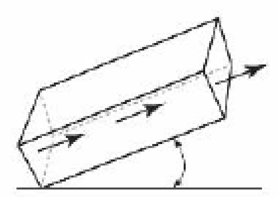
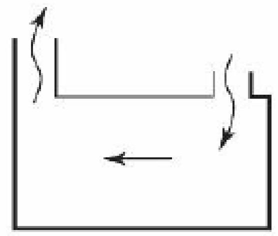
Where h is the heat transfer coefficient of cavity wall, W/m$^{2\cdot 0}$C; A_{hot} is the area of hot cavity wall; T_{wall} is the temperature of cavity wall, °C; and C_{room} is the room configuration coefficient, which can be obtained by:

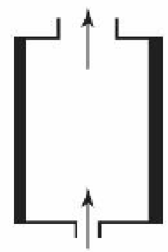
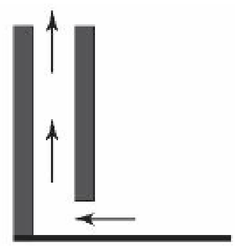
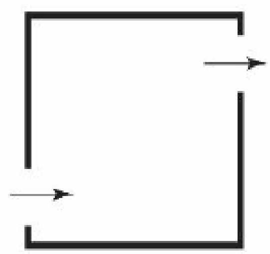
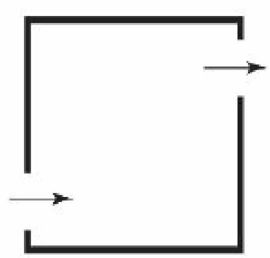
$$C_R = \frac{0.1 + 0.0016A_r - 0.003A_r^{-1}}{9.9 + 1.5A_{open}^{-1}};\ A_r = \frac{A_{in}}{A_{out}}$$

The table below shows a summary of typical mathematical models from the literature.

REFERENCE	YEAR	THERMAL CHIMNEY TYPE	ILLUSTRATION	MATHEMATICAL FORMULA
Shi et al.	2016	IV		$V = \frac{w\ sin\theta'^{\ 1/3}\ q^{1/2} d^{0.7} H^{2/3}}{Slope}$
Shi and Zhang	2016	II		$V = C_{room}\left[hHA_{hot}\left(T_{wall} - T_0\right)\right]^{1/3}$
Ryan and Burek	2016	I		$V \propto q^{0.459};\ V \propto d^{0.756};\ V \propto H^{0.600}$

Dimoudi	2016	II		$V = 23.37 A_{in} A_{out}\sqrt{\frac{gH\left(T_c - T_0\right)}{\left(k_{in} A_{out}{}^2 + k_{out} A_{in}{}^2\right) T_0 T_c}}$
Sankonidou et al.	2008	III		$V = sin\theta\, A_{out}\sqrt{\frac{2gH\ \ \rho_0 - \rho_c}{\left(f\frac{H}{d} + k_{in} + k_{out}\right)\rho_c}}$
Sankonidou et al.	2008	II		$V = C_d sin\theta \frac{\rho_c}{\rho_0} A_o \sqrt{\frac{gH\left(T_c - T_0\right)}{T_0}}$
Shen et al.	2007	II		$V = C_d A\sqrt{\frac{gH\ \ T_{out} - T_{in}}{T_{out} + T_{in}}}$

Burek and Habeb	2007	I		$V \propto Q^{0.572};\ V \propto d^{0.712}$
Ryan et al.	2005	I		$V \propto q^{0.452};\ V \propto d^{0.652};\ V \propto H^{0.539}$
Halldorsson et al.	2002	IV		$V = A\left(\frac{gqw\sin\theta H^2}{A\rho C_p T_0\left[f\frac{H}{d} + k_{in}\left(\frac{A}{A_{in}}\right)^2 + k_{out}\left(\frac{A}{A_{out}}\right)^2\right]}\right)^{1/3}$
Afonso and Oliveira	2000	II		$V = \frac{A_{out}\sqrt{2\alpha g(T_c - T_0)H}}{\sqrt{k_{in}\left(\frac{A_{out}}{A_{in}}\right)^2 + k_{out} + f\left(\frac{H}{d}\right)}}$

Sandberg and Moshfegh	1998	IV		$V = A\left[\dfrac{gqH^2 \sin\theta}{\rho_0 C_p T_0 d\left(2f\dfrac{H}{d} + k_{in} + 1\right)}\right]^{1/3}$
Gan	1998	I		$V = 143.4w^{0.6582}$ $V = 4.5725q^{0.4015}$ $V = 17.84\sqrt{H - 2.28} + 24.86$
Andersen	1995	II		$V = C_d A_{in}\sqrt{\dfrac{2gH\left(T_c - T_0\right)}{T_c}}$
Andersen	1995	IV		$V = 0.037\left(QH\right)^{1/3}\left(C_d A_{in}\right)^{2/3}$

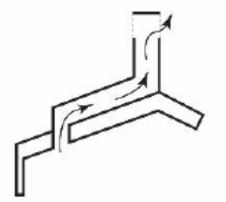
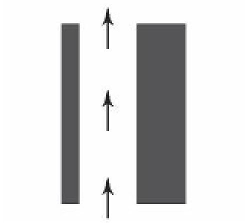
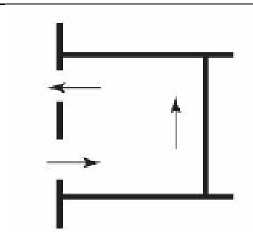
Bansal et al.	1993	II		$$V = C_d A_{out}\sqrt{\frac{2(T_c - T_0)gH\sin\theta}{T_0(1 + A_r^{2})}}$$
Awbi and Gan	1992	II		$$V = C_d A\sqrt{\frac{4gH(T_c - T_0)}{T_c}}$$
BS 5925	1991	II		$$V = C_d\left[\frac{A_{in}A_{out}}{\sqrt{(A_{in}^{2} + A_{out}^{2})}}\right]\sqrt{\frac{2gH(T_c - T_0)}{T_0}}$$

Table 2.2: Typical thermal chimney mathematical models
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building. Author modified.

Note: ***A*** is the area in m^2; ***C*** is the coefficient; $\boldsymbol{C_p}$ is the specific heat capacity in J/kg·^{0}C; ***d*** is air gap thickness in m; ***f*** is the wall friction coefficient; ***g*** is the gravitational acceleration in m/s^2 (9.81m/s^2); ***H*** is the cavity height, m; ***h*** is the heat transfer coefficient in W/m·^{0}C; ***k*** is the pressure loss coefficient; ***q*** is the heat input intensity in W/m^2; ***Q*** is the heat input in W; ***Slope*** is the regression slope; ***T*** is the temperature in ^{0}C; ***V*** is the volumetric flow rate in m^3/s; ***w*** is the cavity width in m; α is the thermal expansion coefficient (1/^{0}C); ***θ*** is the inclination angle from the horizontal in ^{0}; ***θ'*** is the calculated inclination angle in ^{0}; ρ and is the density, kg/m3.

Subscripts: ***0*** is ambient conditions; ***c*** is cavity; ***d*** is discharge; ***hot*** is hot cavity wall; ***in*** is inlet; ***out*** is outlet; ***r*** is ratio between outlet and inlet; ***room*** is room configuration; and ***wall*** is cavity wall.

These formulas can be used to determine the volumetric flow rate for various types of thermal chimneys. They can also be used to size a thermal chimney if one already has the recommended volumetric flow rate for a particular room, simply by changing the subject of the formula to the parameter being looked for.

Figure 2.32: BRE Offices at Watford
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

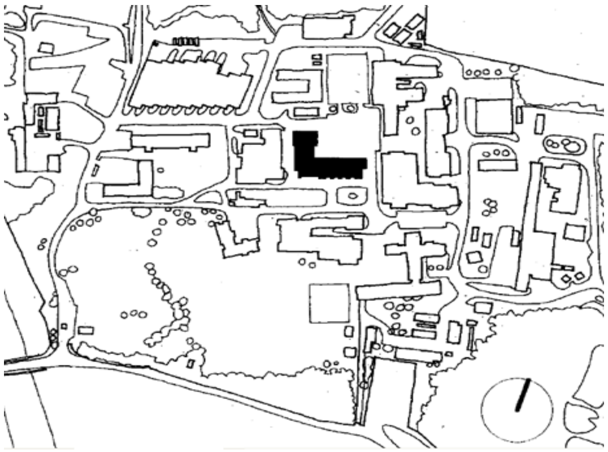
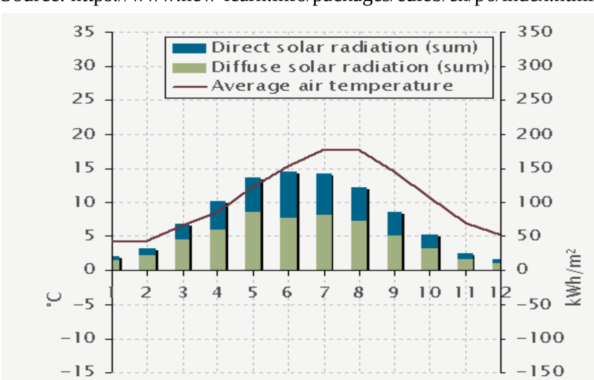


Figure 2.33: Location plan of BRE Offices at Watford
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html



Graph 2.1: Solar radiation and average air temperature data for Watford
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

2.4 CASE STUDIES

The following case studies have been documented to ground the research on proper philosophical starting points.

2.4.1 BRE ENVIRONMENTAL BUILDING, WATFORD, UK

Location: Watford, England

Primary Use: Offices and conferencing facilities

Architects: Bill Gething (Feilden Clegg Architects)

Service Engineers: Max Fordham and Partners

Year of completion: 1996 (Nov. 1995 - Dec. 1996)

Number of floors: 3

Usable floor area: 1470sqm

Number of occupants: 100 people at 12sqm per person

Heated or cooled volume: 5145m^3

Introduction

The new Environmental Building at Garston has been built as a demonstration building for the Energy Efficient Office of the Future (EoF) performance specifications, drawn up by a number of companies representing the manufacturers, designers and installers of building components and the fuel utilities, as part of the EoF project run by BRECSU. A key part of this specification is the need to reduce energy consumption and CO_2 emissions by 30% from current best practice. Air conditioning is not used in the new building - the major energy consumer in many existing office

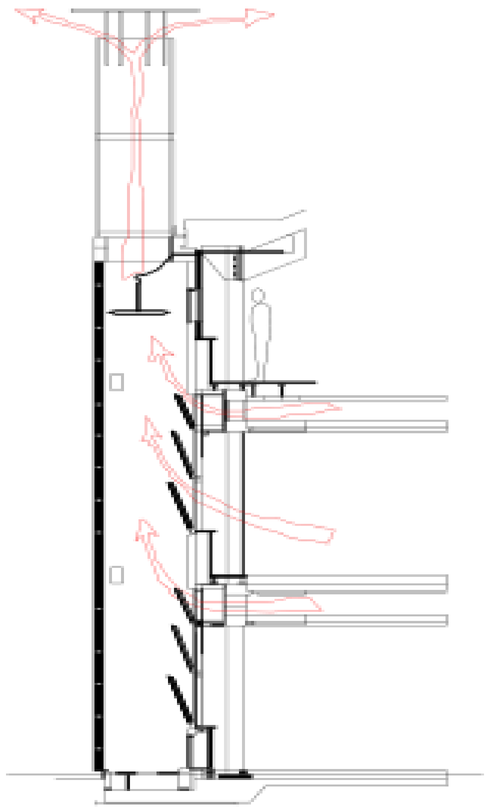


Figure 2.34: Cross section through thermal chimney and floor slabs illustrating the ventilation system
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

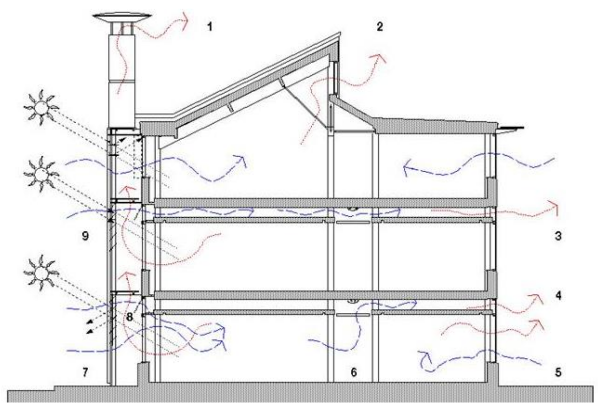


Figure 2.35: Cross section of BRE office illustrating the ventilation system
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

buildings. Other savings will be made by making better use of daylighting and by using the building's 'thermal mass' to moderate temperatures.

Ventilation and cooling

The most striking feature of the building when seen from the south side is the five distinctive ventilation shafts running up the façade. Working rather like a greenhouse, the summer sun shines into the glass-fronted shafts, warming the air inside. This warmed air naturally rises out of the stainless steel 'chimneys' and causes air from inside the building to be drawn through to replace it. On a breezy day the movement of air across the tops of these chimneys increases this 'stack' effect. On very warm, still days low-energy fans at the tops of the stacks can be turned on to give greater airflow. This air moving out from the building draws cooler, fresh air in from outside through ventilation openings. On still, windless days the air is taken from the shady north side of the building, coming in through high-level windows. On warmer or windy days (when it is windy, the air on the north side is not as cool), air is drawn in through passages in the curved hollow concrete floor slabs. Because of its bulk - or thermal mass - the concrete cools the incoming air by absorbing heat from it. Additional cooling can be achieved by circulating cold water through the slab. Cold water is drawn from a 70 metre deep borehole where the temperature is constantly around 10^0C. This is passed through heat exchangers to chill water that is circulated through underfloor pipework. The borehole water is returned to the ground via a second, shallower borehole, so no water is 'wasted'.

Overnight, the control systems can open ventilation paths right through the concrete slab to cool it further, storing this 'coolness' for the following day. The exposed curved ceiling gives more surface area than a flat ceiling would, acting as a cool 'radiator', again providing summer cooling without energy-consuming air conditioning. During the winter months the water circulating through the concrete slab is heated to give gentle underfloor heating. This is supplemented when necessary by conventional radiators around the perimeter of the office area. The water is heated by condensing

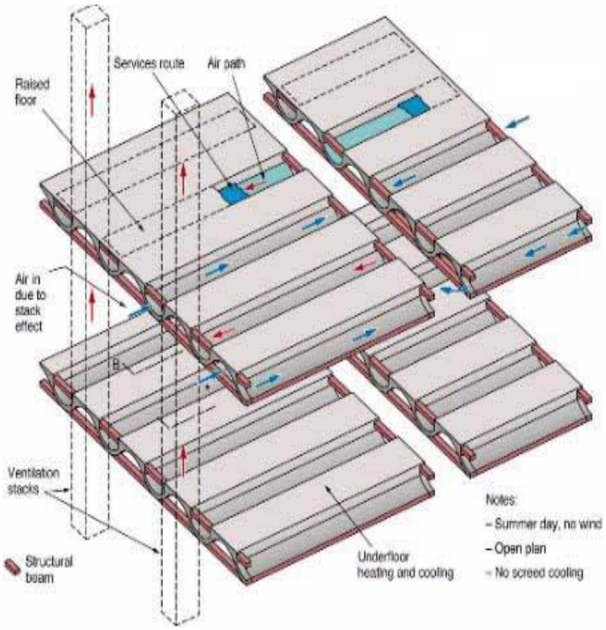


Figure 2.36: Axonometric view of BRE office floor slabs and thermal chimneys illustrating the ventilation system
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

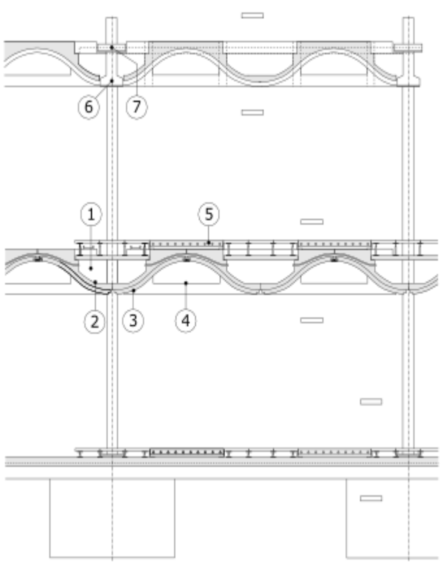
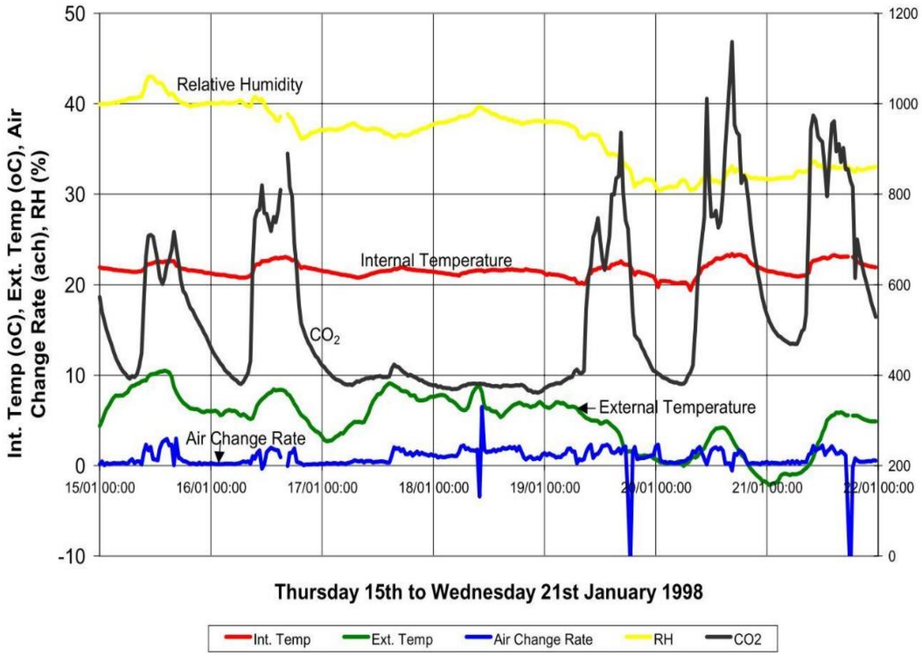


Figure 2.37: Cross section of sinusoidal BRE office floor slabs for increased surface area for heat dissipation
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

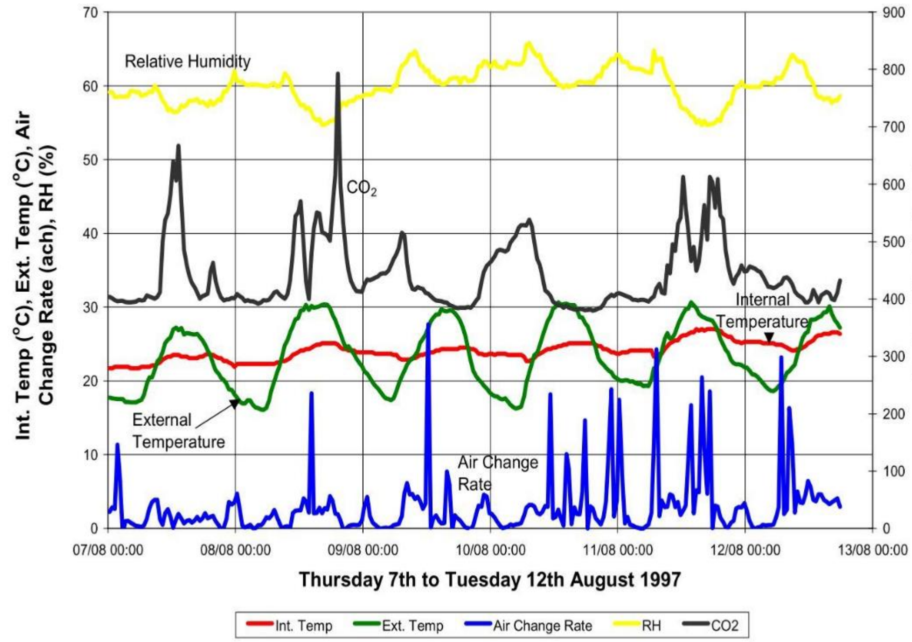
gas boilers which are 30% more efficient than ordinary boilers, mainly by recovering much of the heat that is usually wasted in the flue gases. The ventilation and heating systems are controlled by the Trend building management system (BMS), but, as with most other systems in the building, a degree of user override is provided to suit individual needs.

The readings in the graph on the left have been taken during the winter season. The air change rate peaks at about 6.5 ACH, with an average of 0.78 ACH. The periods of high ventilation rate tend to coincide with periods of occupancy. An analysis of wind speed and direction data and the background air flow rates does show some correlation between higher ventilation rates and wind directions between 100° and 250°. Carbon dioxide concentrations peaked at 1250 ppm on one occasion when the room was occupied. The relative humidity was generally between 45 to 30 %, which is acceptable. However, there were a few occasions where %RH fell below 30 %. The design condition for winter is a minimum internal temperature of 18 °C. As shown above, the minimum value was exceeded by between 2°C and 5°C.

The readings in the on the right have been taken during the summer season. The air change rates peaked at 30 ACH, with an average of 3.3 ACH and there were many occasions when the measured ventilation rate exceeded 10 ACH. This was intentional, since high rates of air change were used for cooling. An analysis of the wind speed and direction data showed some correlation between increasing ventilation and increasing wind speed. There was also a weak correlation between ventilation rate and wind direction, winds from the directions 200° to 330° tended to coincide with higher ventilation rates. The carbon dioxide levels peaked at just below 800 ppm on two occasions during occupancy, but generally concentrations were well below 600 ppm. The relative humidity levels were generally between 55% and 65% and peaked at just below 70%. For summer the design criteria is that a temperature of 25°C should not to be exceeded for more than 5% and 28°C should not to be exceeded for more than 1% of the year. As shown above, the 25°C design value was exceeded on only three occasions and the 28°C design maximum value was not exceeded at all.



Graph 2.2: Indoor and outdoor climatic data for BRE office building taken during winter
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html



Graph 2.3: Indoor and outdoor climatic data for BRE office building taken during summer
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

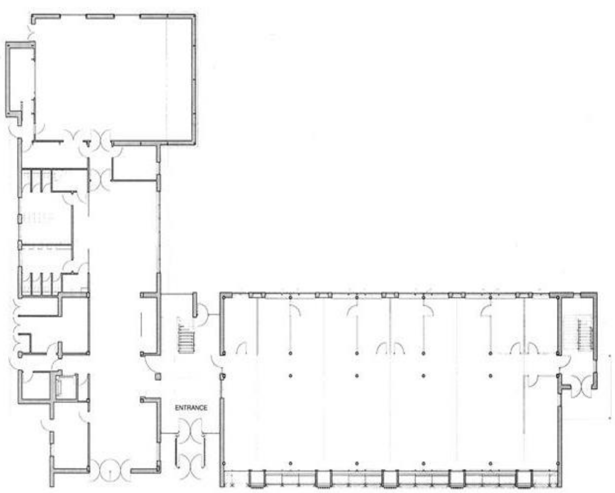


Figure 2.38: Floor plan BRE office
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

These results indicate that the building design provides a generally comfortable indoor environment. In winter, carbon dioxide and humidity levels are within acceptable values and comfortable temperatures were recorded with appropriate fresh air ventilation rates. During the summer period the measured temperature data indicate that the high thermal mass coupled with the night ventilation strategy and solar shading and minimized internal heat gains do reduce the effect of external temperatures.

Solar control and daylighting

The glazed facade in combination with the high ceilings and a relatively shallow plan depth reduce the need for artificial lighting compared with a conventional office building. On the other side the need to control glare and solar gain becomes more important. These factors are controlled by using BMS controlled external motorized glass louvres manufactured by Colt International. Each louvre

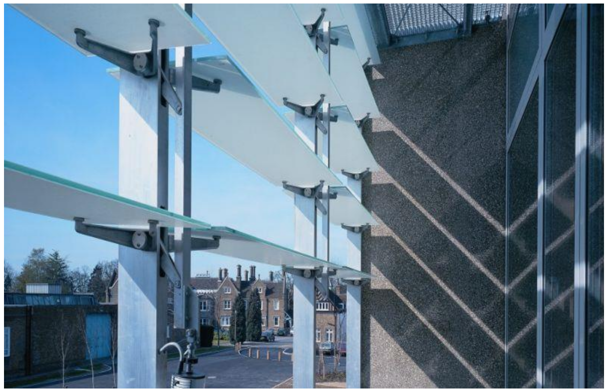


Figure 2.39: BMS controlled external motorized glass louvres
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

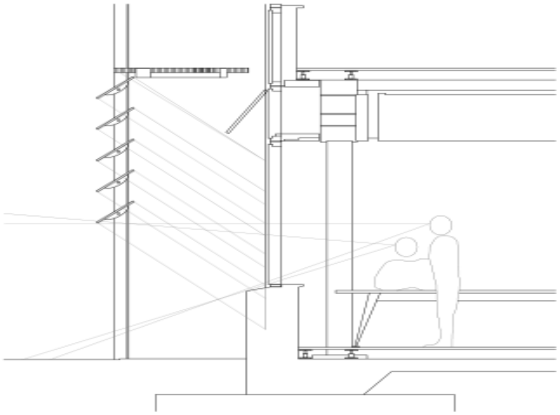


Figure 2.40: Cross section through BMS controlled external motorized glass louvres used as sun shading devices
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

Figure 2.41: Perspective of sinusoidal roof used for cooling and heating
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

has a translucent ceramic coating on the underside which obscures the direct sunshine whilst still letting diffuse light through. These are 400mm wide, set about 1.2m from the facade and with the lowest blade on each floor at 1700mm above floor level. These louvres are thin, only 10mm deep, and are set well apart so when shading is not required they are rotated to the horizontal position to maintain an excellent view out. It is also possible to rotate the blades beyond the shelves to reflect direct sunlight onto the ceiling deeper into the plan. Unlike fixed horizontal light shelves, they have a minimal impact on the diffuse light from an overcast sky entering the building. At times when direct sunshine is not a problem the louvres are angled to act as 'light shelves' - reflecting light off their smooth upper surface onto the ceilings of the offices. This reduces the amount of artificial lighting needed in the parts of the offices furthest from the windows.

The louvres are controlled by the BMS specifically to deal with solar gain; occupiers can override the automatic setting to reduce glare if they wish, however, the BMS will reset them to an optimum position at the end of the day. This avoids the situation, common in day lit buildings with internal blinds for glare control, where, once drawn, the blinds tend to be left down and artificial lighting used more than necessary.

Lighting systems

The main office areas are lit using the latest generation fluorescent lights from Philips. Their new TL5 lamps use less power than previous tubes, are much slimmer allowing for new sleeker light fittings, and contain much less mercury (just 3mg per tube compared to 15mg in the previous best case).

The light fittings themselves use advanced reflector technology to let 40% of the light shine upwards as diffuse up lighting and reflect the rest downwards to provide a good working brightness (300 lux) at the desktop level. This combination of advanced tubes and advanced optics makes the light units extremely efficient, giving an output of 104 lumens per Watt.

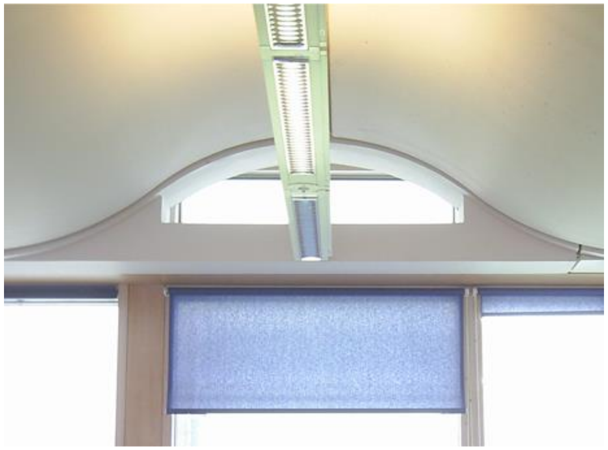
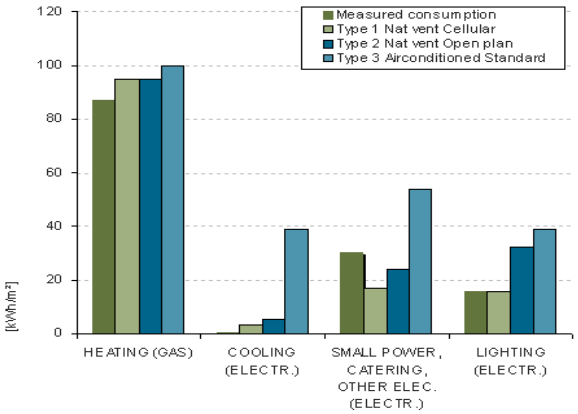


Figure 2.42: Perspective of energy saving lighting fixture at BRE office
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

Figure 2.43: Perspective of photovoltaic system at BRE office
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html



Graph 2.4: Heating, cooling and lighting data for BRE office
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

This is the first installation of this new lighting type to use dimming technology. Philips 3-way 'Helio' sensors fitted into the lighting runs measure the ambient daylight levels and adjust the lamp brightness to suit. Movement detectors in the sensors turn the lights off if the local office area is not occupied. And infra-red sensors pick up signals from the hand-held remote control units used to manually adjust the lighting brightness. The same IR sensor is used to carry the instructions to override the ventilation and solar shading systems.

Photovoltaic systems

The architects' original design included a large area of cedar cladding on the south facade to the left of the main doors as an architectural feature, visually linking with the cedar-clad seminar suite at the back of the building. When funding from the Department of the Environment, Transport and the Regions was made available to part-fund a demonstration building-integrated photovoltaic array (BIPV), this was installed as a one-for-one swap.

The array, from Intersolar Systems, uses thin film amorphous silicon cells incorporated into a glazed cladding. There is little experience of this arrangement in the UK, so this demonstration aims to find out more and report the findings back to industry.

It is hoped that in time there will be sufficient interest in BIPV arrays to allow the costs to drop to more economically competitive levels. The output from the cells (as direct current) is fed into the building's main supply panel via an inverter, providing additional power to the building from a non-polluting source. Inside the building a status panel shows the amount of electricity being generated, the percentage contribution to the building's lighting load, and the cumulative total since May 97 - the date of first occupation.

Figure 2.44: Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

Figure 2.45: Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

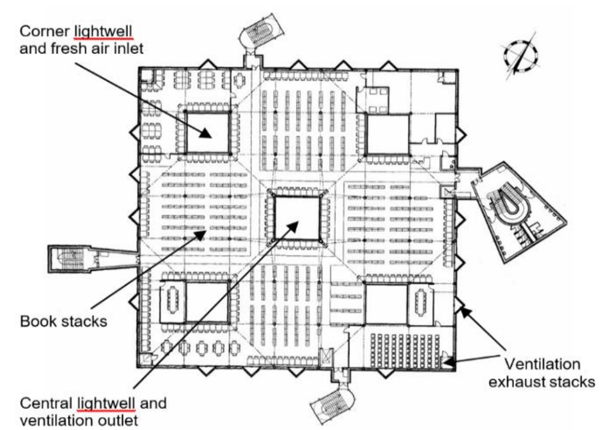


Figure 2.46: Floor plan of Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

2.4.2 FREDERICK LANCHESTER LIBRARY, COVENTRY, UK

Location: Coventry, UK

Primary use: Library

Architects: Short and Associates

Year of completion: 2000

Number of floors: 5 (4 floors and 1 basement)

Usable floor area: 9,103 sqm

Introduction

The Frederick Lanchester Library forms part of Coventry University. It has a gross floor area of 9, 100 m² and is unusual in that, although it is a deep-plan building occupying a 50 m by 50 m footprint, it is ventilated naturally with no artificial cooling, except for a separate basement area which is air-conditioned. By its nature the building has a large number of transient occupants. At the design stage 2 500 entries per day were anticipated. In practice, this has increased to 5 000. In addition a number of staff work permanently in the building. The building is open for use for approximately 4,000 hours per year.

Ventilation

In order to provide natural ventilation a tapering central light well provides extract ventilation, supplemented by 20 perimeter stacks with a 1.8 m by 1.8 m cross section. The stacks terminate 6 m above roof levels with fittings to prevent reverse flow due to wind pressure. Air entry is via a plenum under the ground floor to the base of four 6 m by 6 m square corner light wells, one serving each quadrant of the building. Heat gains from building occupants and computers warm internal air and

Figure 2.47: Interior perspective of Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

Figure 2.48: Ventilation grilles at Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

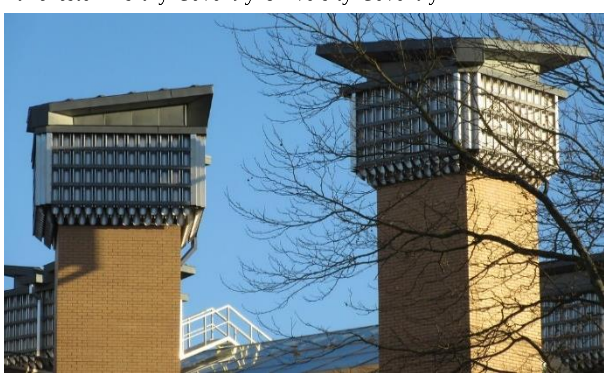


Figure 2.49: Thermal chimneys at Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

create the buoyancy forces that cause the air to rise and accumulate in a layer below the 3.9 m high ceilings.

The stack effect generated by the 20, 1.8 m square, perimeter stacks and the tapering central light well, draws the warm stale air out of the building. In winter the incoming air is warmed by pre-heating coils, which lie horizontally across the base of the 6 m square supply light wells, and trench heating at the point where air enters onto each floor. Cooling in the warm summer months is provided by passive methods. Night time venting is used to cool the exposed thermal mass of the building so that it can absorb heat during warm periods of the following day. Ventilation of the top floor is ensured by four separate ventilation stacks, which have been added to solve the problem of backflow of exhaust air from the central light well which was identified by computer simulations during the design phase. The positioning of the light wells is intended to provide good fresh air distribution and daylight provision across the deep plan floors.

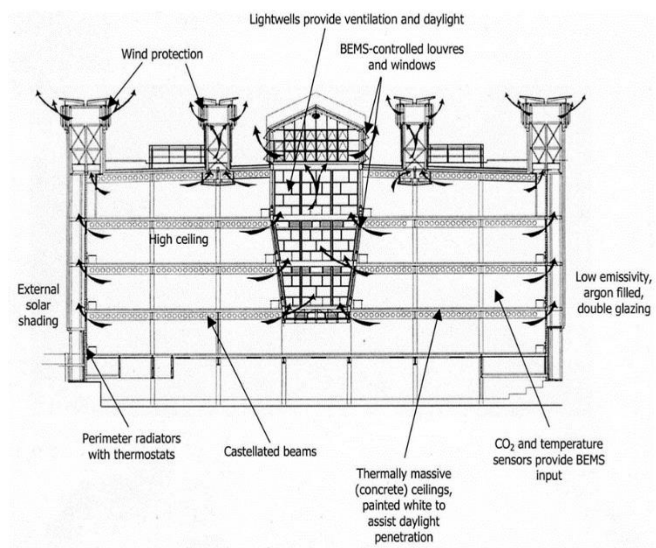


Figure 2.50: Cross section through Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

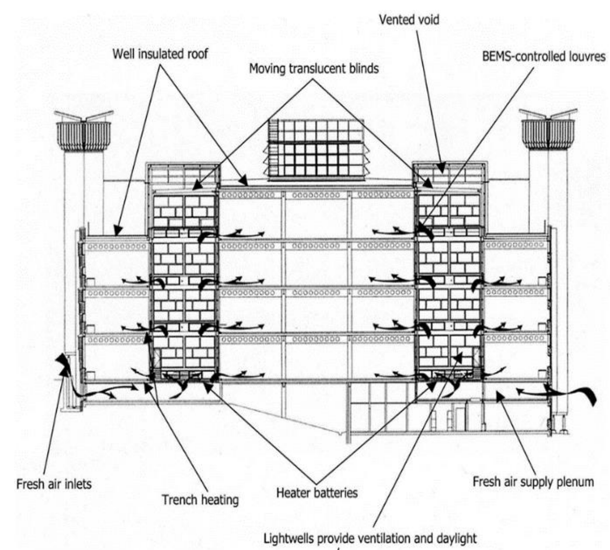


Figure 2.51: Cross section through Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

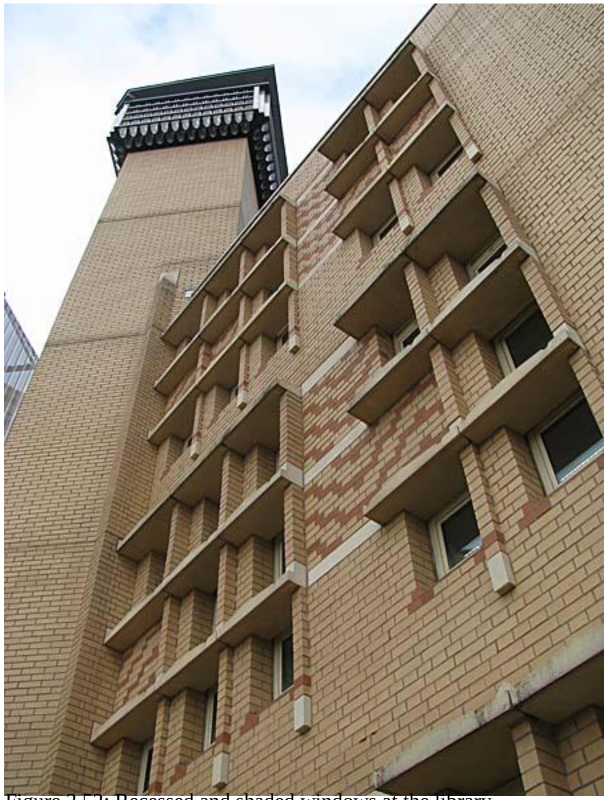


Figure 2.52: Recessed and shaded windows at the library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

Figure 2.53: Perspective of Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

The building is controlled by a Building Energy Management System (BEMS) which operates dampers and windows depending on indoor and outdoor temperatures, wind speed and direction and CO_2 concentrations inside the library. Ventilation for night time cooling is based on the BEMS self-learning algorithm to predict the likely (passive) cooling requirement for the next day. Over-cooling is prevented by monitoring the slab temperature.

Thermal control

High thermal mass walls, made of bricks have been used as well as exposed concrete ceilings. These increase the time lag, leading to better thermal performance of the building. Apart from air-conditioning for the basement, summer temperatures are controlled by a combination of internal blinds, deep set windows which are shaded form the sun, fixed screens and night cooling by ventilation. Medium temperature hot water provided by high efficiency, non-condensing boilers, supplies perimeter heating (principally radiators) during the winter and pre-heats incoming air through the natural ventilation system, using trench heaters. The heating, lighting and ventilation installations are controlled by a Building Energy Management System (BEMS) using temperature and carbon dioxide sensors for each 6 m by 6 m zone throughout the building.

Solar gains are also minimized by moveable translucent horizontal blinds at the head of the supply light wells, careful window placement and the use of overhangs and metal shading fins. This helps to reduce the risk of overheating and improves the effectiveness of the natural ventilation system.

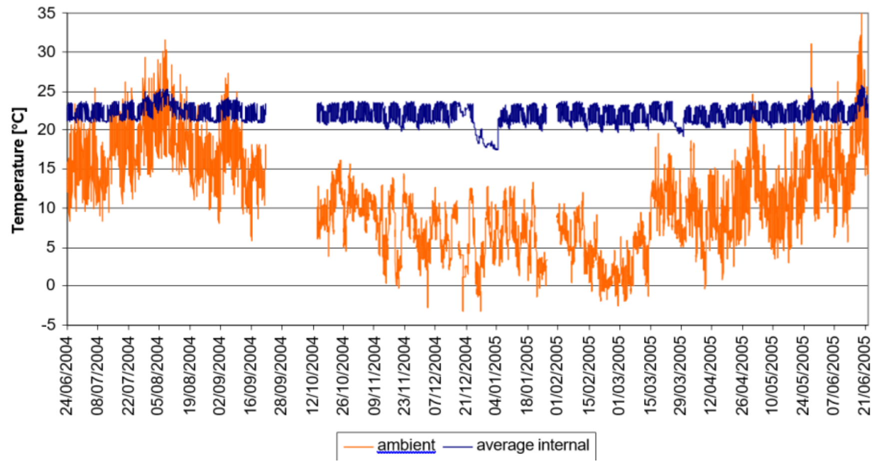
Ventilation, thermal and energy performance

Indoor air temperatures have been measured over a full year from June 2004 to June 2005. The data has been taken from 8 BEMS sensors situated at two positions on each floor, located on different walls at a height of 1.5 m. Temperatures have been measured at hourly intervals and averaged over all eight measuring locations. The data shows that the average temperature in the building remains relatively stable throughout the year. During the heating seasons the daytime indoor temperatures

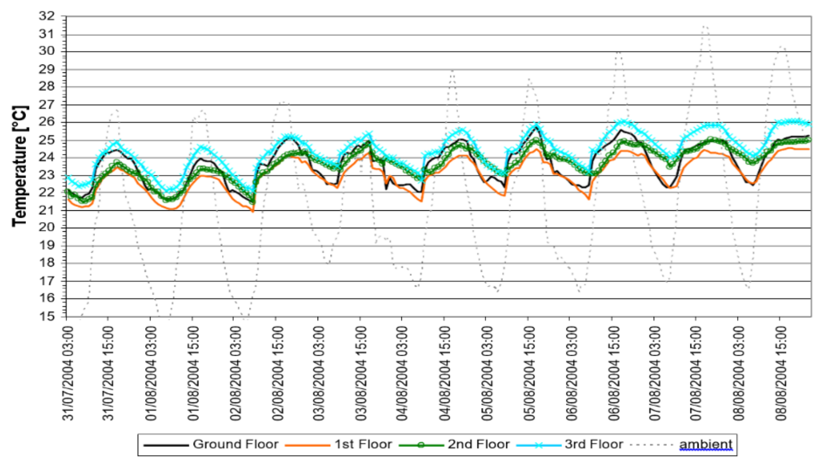
Figure 2.54: Recessed and shaded windows at the library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

Figure 2.55: Pespective of Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

are dominated by the heating schedule, heating set points and the internal heat gains. The temperatures remain below 24°C during the daytime and decrease to approximately 21°C during the night, which is the minimum mid-week temperature set by the facilities managers and the temperature set for the air supplied by the light wells. Decreases in temperature below 21°C can be observed at weekends and more obviously during the Christmas and Easter breaks - when the building is not occupied.



Graph 2.5: Ambient and average internal temperature for Frederick Lanchester Library
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html



Graph 2.6: Indoor temperature and ambient temperature for Frederick Lanchester Library
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

Figure 2.56: Pespective of Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

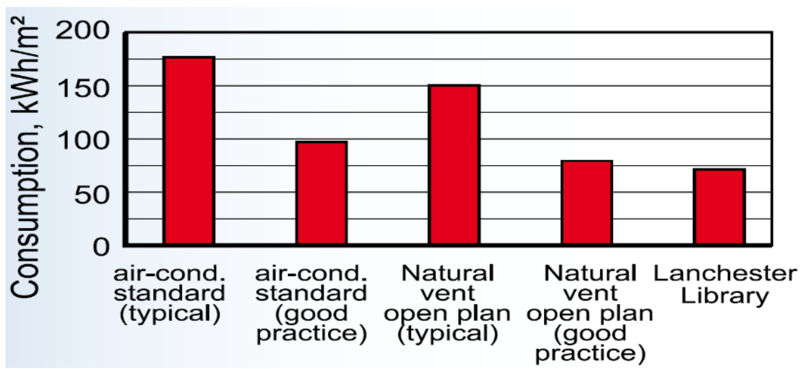
Figure 2.57: Interior perspective of Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

Figure 2.58: Interior perspective of Frederick Lanchester library
Source: https://www.researchgate.net/figure/a-The-Frederick-Lanchester-Library-Coventry-University-Coventry

The graph above shows the thermal performance of the building during a hot spell. During the day, the ambient temperatures rise to over 30 °C and the night time ambient temperatures remain below 18 °C. Despite these conditions, the internal temperatures remain relatively low, between 21^{0}C - 25.5^{0}C. The ground floor has the lowest temperatures since it benefits most from the ventilation stack height, while the third floor has the highest temperatures due to the decreased ventilation stack height at its level.

Carbon dioxide concentrations have been measured over a representative six week period at four locations on one floor. There are no specific UK standards for carbon dioxide concentration in library or office buildings, although a maximum of 1000 ppm is used for schools. In the Coventry Library carbon dioxide does not exceed 350 ppm above ambient during the measurement period, indicating that the building meets this criterion.

With an annual consumption of 0.049 kWh/m^2/hour of occupancy, the building performs significantly better than the good practice guidelines for offices. The Library uses 51 % less energy than a typical air conditioned office and 35 % less than a typical naturally ventilated open plan office. However, these energy savings are conservative as the values recorded include the supply to the 24-hour computer suite which is not part of the natural



Graph 2.7: Energy consumption data for Frederick Lanchester Library
Source: https://www.new-learn.info/packages/euleb/en/p6/index.html

Figure 2.59: Perspective of Eastgate Centre
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

Figure 2.60: Perspective of Eastgate Centre
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

2.4.3 EASTGATE CENTRE, HARARE, ZIMBABWE

Location: Harare, Zimbabwe

Primary use: Offices and shopping facilities

Architects: Mick Pearce Architects

Service Engineers: Ove Arup and Partners

Year of completion: April 1996

Number of floors: 9

Usable floor area: 31,600sqm

Parking slots: 425

Introduction

With its 26000m^2 of lettable office accommodation, 5600m^2 of retail space and covered parking for 425 cars, Eastgate is the largest commercial building in Zimbabwe. Located in the eastern portion of the Harare central business district, it occupies two city blocks alongside Meikles International Hotel. The development comprises two nine-storey parallel 146m by 16m plan blocks, linked by a 16.8m wide glass-roofed atrium, with its long axis oriented east-west. The upper seven storeys of office accommodation have double slab floors to enable overnight cooling by outside air. The two lower storeys and the two basement car parking levels have conventional mechanical supply and extract ventilation; the former can be equipped with mechanical cooling if required by their retail tenants. The atrium houses all the vertical circulation elements—stairs, escalators, elevators as well as four sets of bridges across the atrium and a skywalk along its length at Level Two.

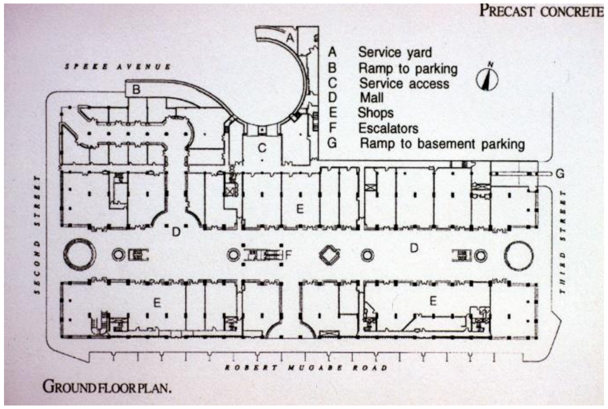


Figure 2.61: Ground floor plan of Eastgate Centre
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

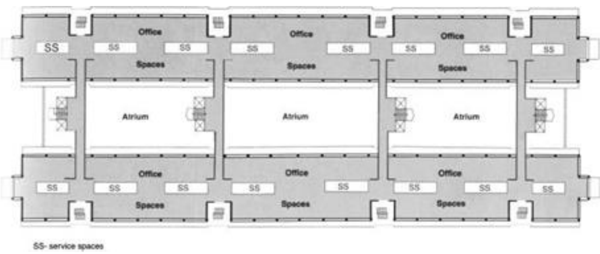


Figure 2.62: Typical floor plan of Eastgate Centre
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

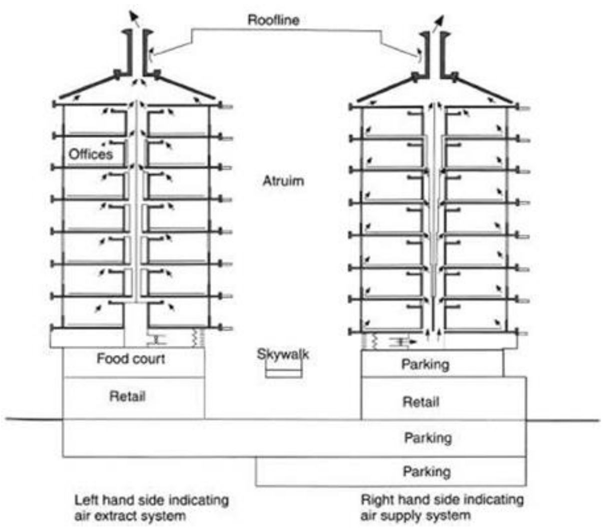


Figure 2.63: Cross section of Eastgate Centre
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

Climatic conditions

Harare, the capital city of Zimbabwe, is at a latitude of 18°S and at an altitude of 1503m. It enjoys a tropical high-altitude climate; warm, dry and clear sky conditions for up to 8 months of the year with increasing heat and humidity during the other four. The daily maximum/minimum temperatures are 29°C /19°C, 26°C /21°C and 22°C /17°C. These are virtually ideal conditions for natural ventilation combined with night cooling.

Environmental design

Having minimized external and internal heat gains, the concept is to cool the thermal mass of the building overnight by drawing outside air through the floor slabs (rather than opening windows with their potential dust, noise and security problems) using the natural stack effect. However, computer simulations carried out by Ove Arup's London office indicate that the temperature forces would be difficult to balance throughout the building all year round. The decision was taken to use simple, low power, locally made supply fans to ensure that all floors received the same quantities of cooling fresh air.

In a project of this type, there are many ways of organizing the vertical supply and exhaust ducts to and from the floor slabs and the office spaces—ranging from a few large ducts to a multiplicity of small ones, on the outside of the façade or in the core, and so on—with a requirement for compatibility with the overall design concept. The architect felt that external risers would inhibit flexibility of internal room divisions by taking up too much façade area, and devised a central core arrangement to incorporate them along the lengths of the two blocks. With supply inlets at low level in each block and extract outlets at high level, but tapering in opposite directions, it was feasible to incorporate these in the same vertical stack.

How to maximize the amount of heat exchange between air and floor slab was another key issue addressed during the design process. Rather than having a plain surface, the underside of the floor

Figure 2.64: Perspective of sun shading elements at Eastgate Centre
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

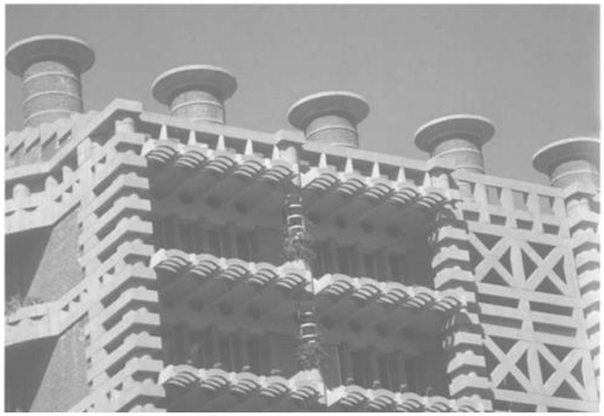


Figure 2.65: Perspective of sun shading elements at Eastgate Centre
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

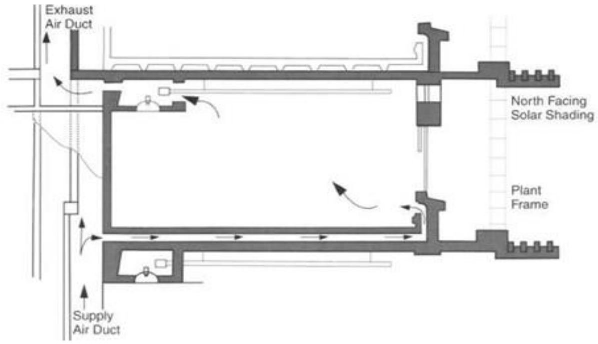


Figure 2.66: Cross section of an office indicating air supply and exhaust routes
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

slab has studs or dentillations cast into it to increase the air turbulence, the exposed surface area and hence the heat transfer. Within the occupied spaces, the exposed vaulted ceilings have a similar advantage over more conventional horizontal (frequently suspended) ceilings.

The massive protruding stone elements not only protect the small windows from sun but also increase the external surface area of the building to improve heat loss to space at night and minimize heat gain by day. These are made of precast concrete, brushed to expose the granite aggregate that matches the lichen-covered rocks in Zimbabwe's wild landscape. The horizontal protruding ledges are interrupted by columns of steel rings supporting green vines to bring nature back into the city.

At the most basic level, the means of environmental control is expressed in the overall form of the building. The orientation of the two blocks on an east-west axis to minimize solar heat gain on the main north- and south-facing façades, together with the use of a relatively narrow, rectangular plan shape, with the potential for natural ventilation and lighting, are fundamental. The relatively high proportion of solid to void on the façade, and the permanent north-south differentiated shading of both, are direct expressions of the concept; as is the (thermal) mass of the materials used in its construction. Together, these give the building façades their distinctive articulation. Last but not least, the multiple chimneys and an atrium canopy have been used to naturally ventilate the building.

Ventilation control systems

In this project, thermal environmental control is achieved through the design of appropriate air flow systems and surfaces for the transfer and storage of heat.

First, regarding the air flow systems, one of the functions of the atrium space is to serve as a fresh air intake to all of the building's ventilation systems. With its glass canopy well above the roofs of the office blocks and its ends fitted with 30° pitched fixed open louvres, both wind and stack pressures can operate freely on this space, while still providing protection from the worst excesses of rain, wind and sand.

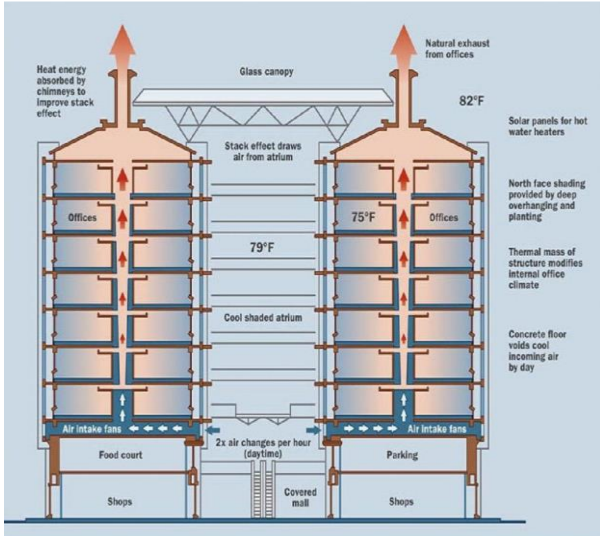


Figure 2.67: Thermal chimney ventilation system at Eastgte Centre
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

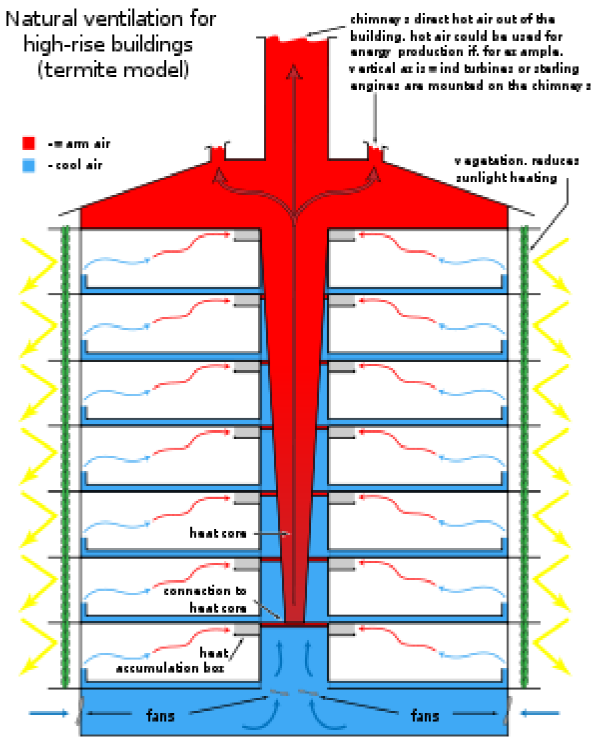


Figure 2.68: Thermal chimney ventilation system and sun shading system at Eastgte Centre
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

The louvres that provide the main intake for fresh air to the atrium and hence to the various spaces inside the building cover the full height of the east and west façades. Once in the atrium, the air intakes to the fan chambers serving the offices are expressed as cross-chevron screens running the full length of the atrium at mezzanine level; while the four intakes to the basement ventilation system take the form of open topped, 3.5m high, glass block-encased, 2.8m diameter drums at ground floor level. The chevron pattern used in the mezzanine-level air intakes carries echoes of the traditional stone architecture of Great Zimbabwe. The only other visible expression of the air distribution system inside the office blocks is the rectangular air supply grilles under the windows and the circular air-extract ports at high level in the core, the latter echoing the high-level circular windows at the perimeter.

Each of the office floors is subdivided into 16 bays. The main supply air fans are housed in a corresponding set of 16 plant rooms at mezzanine level immediately below the bays of the seven floors of offices they serve. Each plant room houses a filter bank and two pairs of single-stage, axial-flow fans, one with a capacity of ~1m^3/s designed for daytime use, the other in the 4– 5m^3/s range for night-time operation (their precise capacities depending on the requirements of the office bay being served). A pair of fans serves the north side of any given set of bays, the other pair the south side. The fans are standard sizes, locally manufactured, with spare parts available ex-stock.

The air is then distributed in vertical ducts (two per bay, 32 in all) in the core of each bay, via the void in the double-floor slab, to low-level supply grilles under the windows at the perimeter of the bay. Some of these supply grilles incorporate small-capacity (250–500W) electric heaters. It should also be noted that every other window is operable; all are single-glazed and have internal horizontal venetian blinds.

The air is then extracted at high level, via circular exhaust ports at the inner end of each section of the vaulted ceiling. These ports lead to vertical exhaust stacks in the central core of each bay, which in turn lead to the chimneys visible on the roof. In practice, the stacks from each bay are connected

Figure 2.69: Exterior view of the fixed louvres on the east façade of the atrium
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

Figure 2.70: Interior view of the fixed louvres on the east façade of the atrium
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

to a pair of chimneys via a simple offset arrangement that enables rainwater to be drained away rather than fall directly down the stacks. The stacks are also fitted with motorized dampers. This arrangement accounts for 32 of the 48 chimneys, the remainder being used for mechanical exhaust systems from the non-office levels. The office-area toilets have mechanical extract systems that discharge into the large ventilated loft space on top of each block.

Thermal control systems

As far as heat transfer/storage surfaces are concerned, thermal mass may be used for at least two main purposes—to store heat or cool for future use and to smooth out fluctuations in inside air temperature due to (say) intermittent heat gains. Both processes are employed in this building—in practice, neither is particularly easy to predict.

In this instance, the inner surfaces of the double floor slab through which the fresh air is supplied are intended as the heat storage medium. Attempts have been made to increase the exposed surface area and the air turbulence in the void which is ‘festooned with concrete teeth, the intent being to increase the rate and amount of heat stored—without, presumably, unduly increasing the resistance to airflow.

In terms of smoothing out temperature fluctuations due to the intermittent heat gains from artificial lighting, office equipment and human metabolism and so on, the principal device employed internally was to expose the concrete of the ceiling and to increase its area by use of a vaulted profile. The starting gear for the lights was placed directly in the extract air stream—thus avoiding the gain and enhancing the stack effect at the same time.

Apart from these specific effects, one would also expect the enormous overall thermal mass of the building to smooth out temperature fluctuations due to external heat gains—in this connection, the aim of the engineers was to keep the concrete heat exchanger at an average temperature of ∼20°C.

Figure 2.71: Filter bank between the fresh air inlet from the atrium (right) and the fan room (left, on the other side of the filters)
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

The initial method of control for the offices was simply one of time clock operation of the fans. The smaller of each pair of fans operated from 07.00 to 18.00 hours, providing around two air changes per hour; the larger from 21.00 to 07.00 hours (say), but at a rate of eight air changes per hour. The system operates on 100% fresh air and is thus capable of cooling the building mass overnight while minimizing heat gains due to peak daytime air temperatures.

Figure 2.73: Air supply grilles inder the perimeter windows. The grille on the left incorporates a small electric heater
Source:https://www.researchgate.net/figure/Eastgate-Center-Harare

Figure 2.75: Circular exhaust air ports in the office areas
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

Figure 2.72: Typical fan room with the day fan housed in the back wall (right) and the night fan out of its circular duct housing for repair
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

Figure 2.74: Fresh air intakes via the cross chevron screens with a parking area below and the skywalk above
Source:https://www.researchgate.net/figure/Eastgate-Center-Harare

Figure 2.76: Ventilated loft space above the office floors. The square grilles on the right hand wall are the exhausts from the toilets. The foreground piping is part of the drainage system from the chimneys
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

Figure 2.77: Perspective of thermal chimneys
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

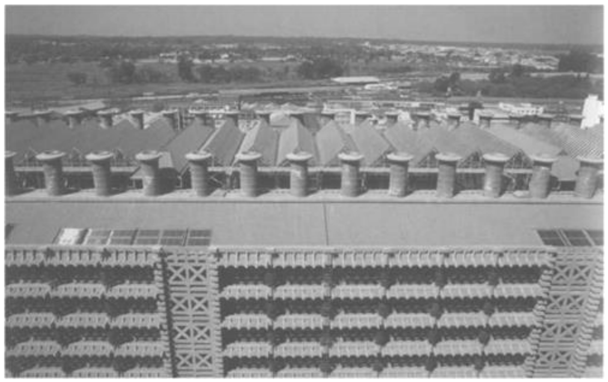


Figure 2.78: Perspective of the roof showing the chimney and canopy layout
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

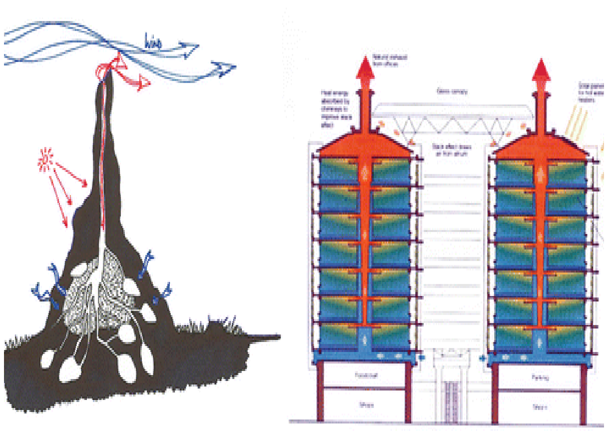
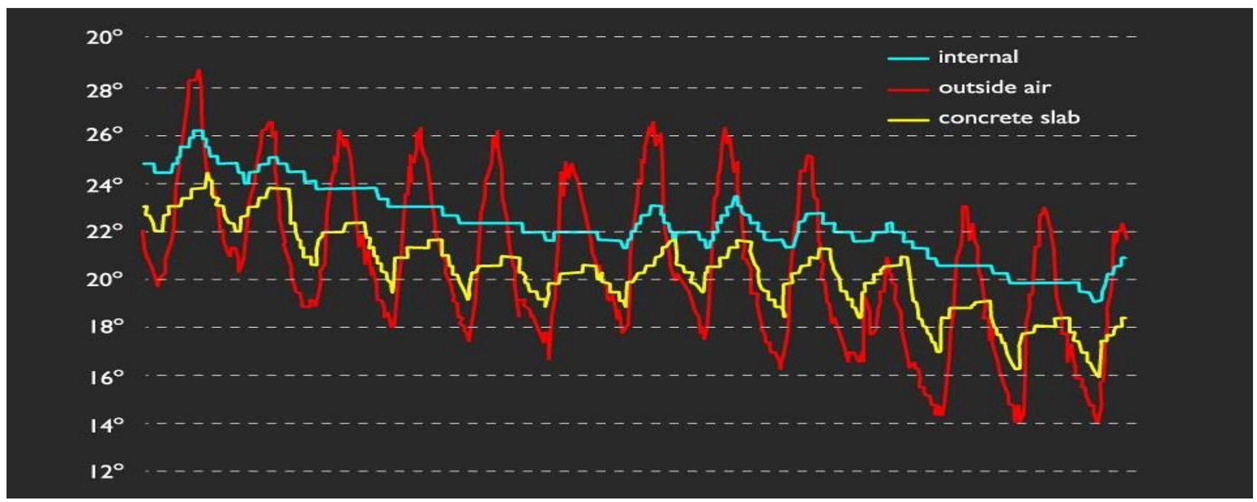


Figure 2.79: Bioclimatic design of Eastgate Centre
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

Building performance

The data logger graph shows that in average conditions covering ten months of the year 3°C of cooling between outside and inside temperature is achieved. Optimum cooling is achieved when the external night temperature falls below 20°C. When 20°C is exceeded at night; mainly due to cloud cover (which prevents efficient heat radiation back to space), and when the following day is clear especially in October or November the office temperature remains fairly warm. The peak internal temperatures recorded at 4:00pm on occasions during 2 to 3 weeks of the whole year have been up to 27 - 28°C on certain days within that period.

Usually during the rains in November onwards cloudy nights are followed by cloudy days and the internal office peak temperatures remain below 26°C. People and machines add 1.5°C to the internal temperature each day which if not flushed out each night tends to accumulate until the week ends when the building cools down sufficiently. The difference between low level and high level temperatures in the room is 1.5°C due to stratification in a 3m high room. Eastgate consumes less than 50% of the energy used in conventionally air conditioned buildings while achieving very satisfactory comfort conditions for all but 2 weeks in 52 weeks of the year.



Graph 2.8: Indoor, outdoor and concrete slab temperature of Eastgate centre
Source: https://www.researchgate.net/figure/Eastgate-Center-Harare

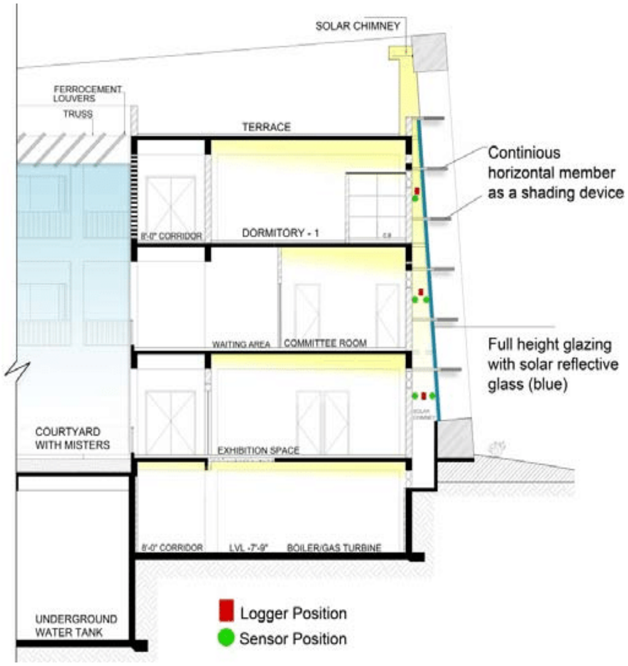
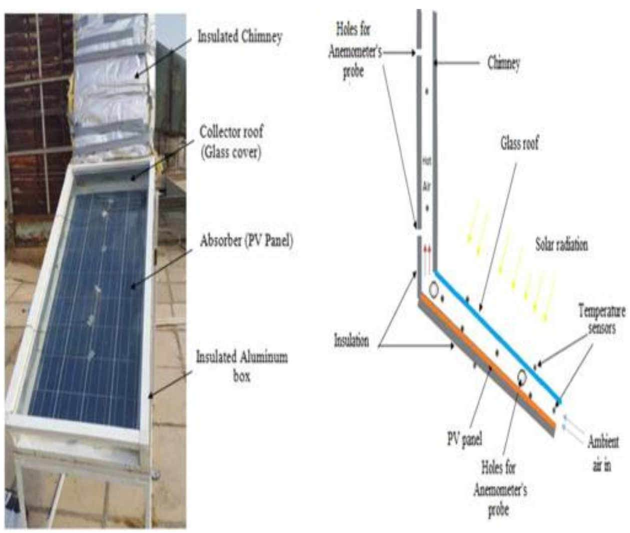


Figure 2.80: Inclined wall mounted thermal chimney with glazed surface
Source: esearchgate.net/figure/Solar-chimneys-on-the-facade-and-misters-in-the-courtyard-in-building-W2_fig1_308972008



(a) Photographic picture **(b) Schematic diagram**

Figure 2.81: Inclined roof mounted thermal chimney with a photovoltaic panel as an absorber
Source: esearchgate.net/figure/Solar-chimneys-on-the-facade-and-misters-in-the-courtyard-in-building

2.5 FACTORS INFLUENCING THE PERFORMANCE OF THERMAL CHIMNEYS

The main challenge of designing a thermal chimney is to optimize its ventilation performance with the lowest cost. In this study, the following factors have been obtained based on literature review - configuration (cavity height, cavity gap width, inlet and outlet areas, and cavity height to gap ratio), installation conditions (thermal chimney inclination angle, fenestrations within the room, and solar collector), construction materials (type of glazing, materials of solar absorber, and thermal insulation), and environmental factors (solar radiation and external wind).

2.5.1 CONFIGURATION FACTORS

i. Height

The height of a wall thermal chimney refers to the vertical height of the chimney cavity. A double ventilation flow is observed in experiments when the chimney height is doubled (Spencer, 2001). According to AboulNage and Abdrabboh (2000), the maximum airflow rate of 2.3m^3/s happens at a chimney height of 3.45 m. With a cavity gap of 0.3m and a wall height increase from 3.5m to 9.5m, the volumetric flow rate increases by approximately 73% (Lee et al., 2009). Al-Kayiem et al. (2014) numerically deduce that when the height rises from 5m to 15m, the maximum air velocity rises from 3.47m/s to 4.5m/s. Therefore, Du et al. (2011) suggest that it is advisable to select the longest vertical length as possible within the restriction of building codes to achieve the best performance.

The thermal efficiency of a thermal chimney increases with an increase in cavity height. This is the ratio between heat gained by the air in the chimney cavity and the input heat from the solar radiation (Burek et al., 2007). According to Somsila et al. (2010), the thermal efficiency increases by 5% when the cavity height increases from 1 m to 2 m under solar radiation of both 400W/m^2 and 800 W/m^2.

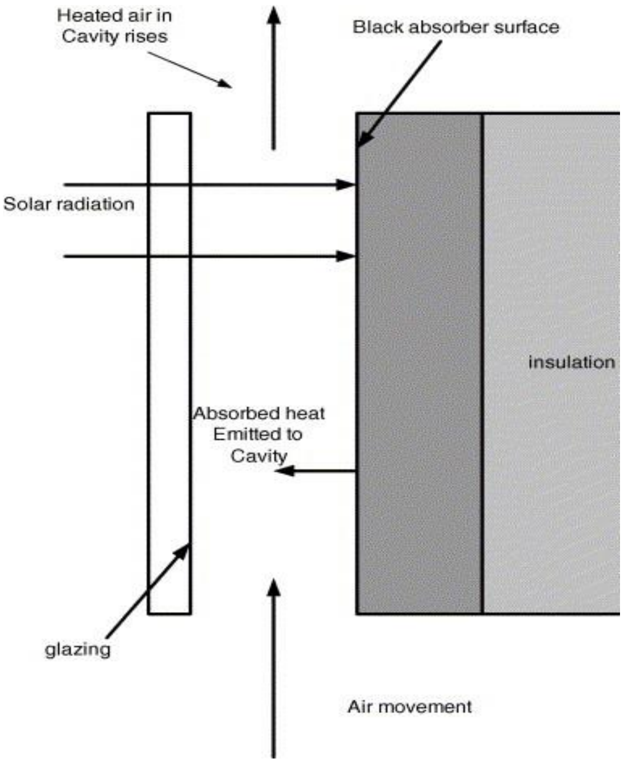


Figure 2.82: Vertical wall mounted thermal chimney with glazing and black absorber surface
Source: esearchgate.net/figure/Solar-chimneys-on-the-facade-and-misters-in-the-courtyard-in-building

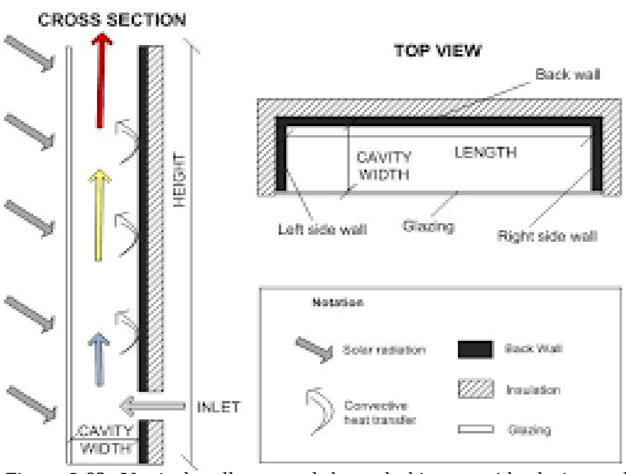


Figure 2.83: Vertical wall mounted thermal chimney with glazing and black absorber surface
Source: esearchgate.net/figure/Solar-chimneys-on-the-facade-and-misters-in-the-courtyard-in-building

Therefore, it is quite certain that a larger chimney height can result in a better performance due to the increased pressure difference (Ding et al., 2005) and increased heat gain.

ii. Cavity gap

This refers to the thermal chimney width. The performance of both roof-mounted and wall-mounted thermal chimneys is dependent on the chimney width. Numerical studies by Ong and Chow (2003) show an increase in ventilation by 56% when the cavity gap increases from 0.1m to 0.3m.

All other factors held constant, an increase of the thermal chimney cavity gap from 0.1m to 0.6m leads to an increase in the airflow rate (Halldorsson et al., 2002). Balocco (2002) deduces that when the cavity gap increases from 0.07m to 0.35m, the over-heating reduction rises from 7% to 27.5% during summer.

Bassiouny and Koura (2008) identify the cavity gap as a significant parameter on thermal chimney performance in terms of air change per hour. The airflow rate in the cavity does not always increase with a bigger cavity gap. For example, a numerical study (Lee et al., 2009) indicates that as cavity gap width increases from 0.15m to 0.75m, the airflow rate diminishes by 1.9 - 4.7% due to the occurrence of reverse flow. As the heating of the air in the cavity is dependent on convection processes, the air abutting to the hot wall gets additional chances to be heated. The convective heat transfer from the hot wall to the movable air is relatively limited in the middle of the thermal chimney with a bigger cavity gap. The temperature difference and friction between the two air layers are the two main reasons for reverse flow.

Multiple studies suggest a cavity gap of 0.2m to 0.3 m to achieve the maximum thermal chimney performance (Aboulnaga, 1998). However, the value of 0.2m to 0.3 m may not apply to all the thermal chimney configurations. This is because the optimum value is dependent factors such as the size of inlet areas ad chimney height (Spencer, 2001). A numerical study (Gan, 2006) indicates

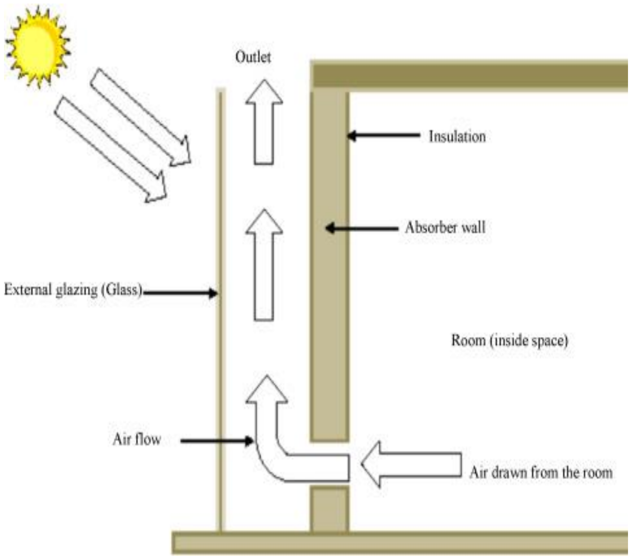


Figure 2.84: Vertical wall mounted thermal chimney with glazing and absorber wall
Source: esearchgate.net/figure/Solar-chimneys-on-the-facade-and-misters-in-the-courtyard-in-building

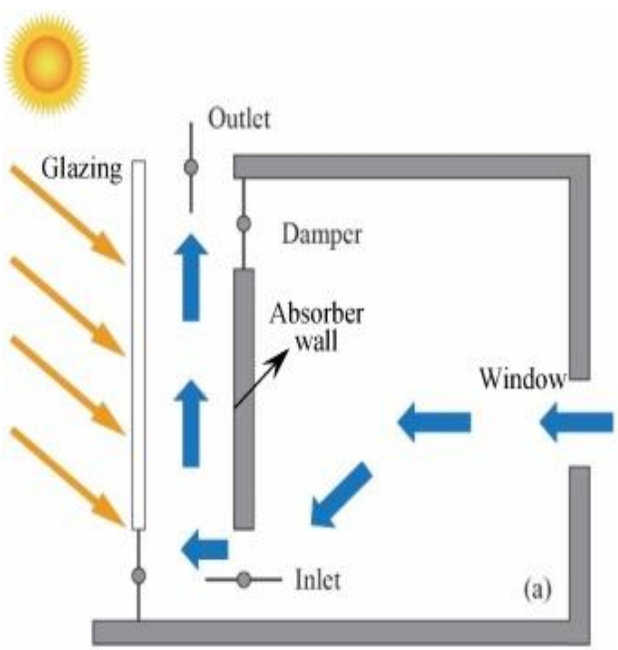


Figure 2.85: Vertical wall mounted thermal chimney used to cool the building
Source: esearchgate.net/figure/Solar-chimneys-on-the-facade-and-misters-in-the-courtyard-in-building

that there exists an optimum cavity gap to maximize buoyancy-induced flow rate, which is between 0.55-0.6 m for a 6.0 m high. According to Ahmad et al. (2014), the optimum cavity width is equal to 0.4 m for a 2 m high thermal chimney in most cases of angled thermal chimneys except the right angled chimney. Grounded on numerical modeling, Thong et al. (2007) state that for higher inclination angles, a 0.14 m air gap is optimal for natural ventilation. During the day, the optimum cavity gap depends on the radiative cooling load. For example, a gap of 2.5cm is appropriate for a radiative cooling load of 30W/m^2 (Miyazaki et al., 2007).

A wider cavity gap in thermal chimneys contributes to higher volumetric flow, which is more influential on the performance than inlet size (Zhou et al., 2016). Bassiouny et al., (2008) obtain a result that after increasing air gap thrice, the air change per hour increases by 25% while after increasing the inlet size thrice, the air change per hour increases by 11%. According to Khanal and Lei (2001), the performance of a wall-mounted thermal chimney is more sensitive to the air gap than the inlet height. However, according to Lee et al., (2009), solar absorbance, chimney height, and solar transmittance play more important roles in the ventilation improvement as compared to the air gap.

Therefore, an increase in the thermal chimney width leads to an increase in the airflow rate. However, beyond the optimum cavity width (0.2m to 0.3m), the rate of airflow diminishes due to occurrence of reverse flow.

iii. Inlet and outlet areas

Within a certain range of cavity gap, both inlet and outlet areas show positive influences on thermal chimney performance. An analytical analysis by Bassiouny and Koura (2008) indicates that increasing inlet size thrice increases the air changes per hour by approximately 11%. Another experimental study (Spencer, 2001) shows that the bigger the inlet area, the higher the ventilation rate.

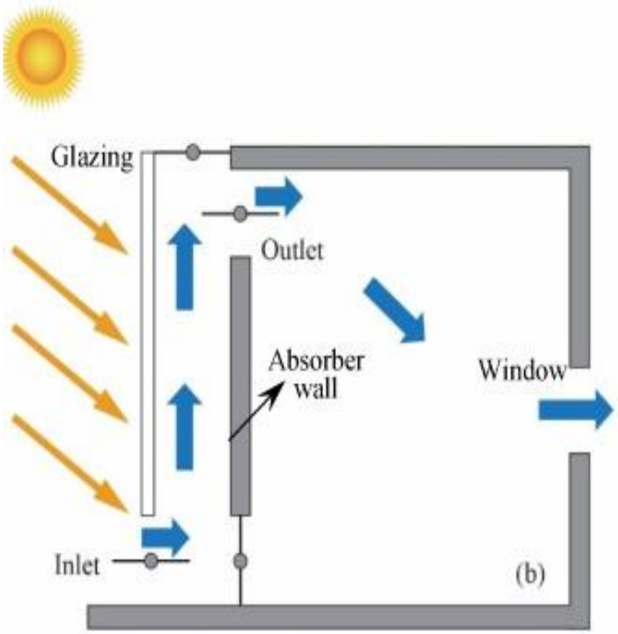


Figure 2.86: Vertical wall mounted thermal chimney used to heat the building
Source: esearchgate.net/figure/Solar-chimneys-on-the-facade-and-misters-in-the-courtyard-in-building

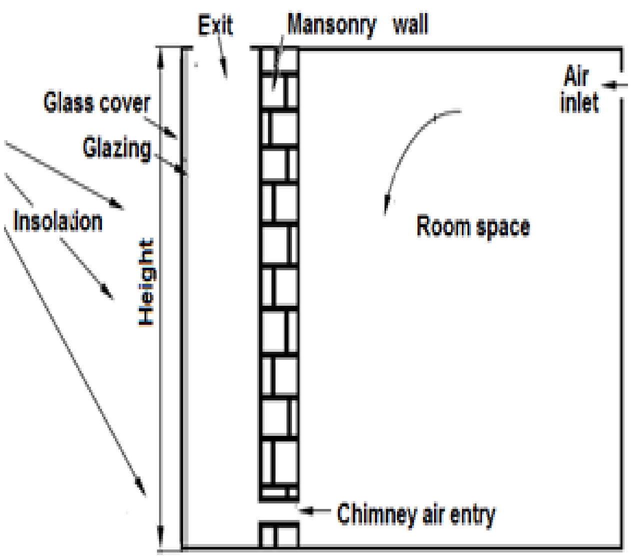


Figure 2.87: Vertical wall mounted thermal chimney with glazing and a masonry wall as an absorber wall
Source: esearchgate.net/figure/Solar-chimneys-on-the-facade-and-misters-in-the-courtyard-in-building

An equal area for both the inlet and outlet improves the performance of a thermal chimney (Li et al., 2004). For unequal openings, the outlet area has a greater effect on the performance of the thermal chimney, as compared to the inlet area (Susanti et al., 2008). Shi and Zhang (2016) obtain the following relationship between airflow rate and inlet/outlet areas based on numerical modelling:

$$V = 0.16 - 0.009A_r - 0.025A_r^{-1}, \quad A_r = A_{in}/A_{out}$$

Therefore, an equal inlet and outlet area leads to a better performance of the thermal chimney. For unequal openings, it is advisable to have a bigger outlet area and a smaller inlet area.

iv. Cavity height to gap ratio

The effects of cavity height to gap ratio on the performance of a thermal chimney are determined by the combination of the effects of cavity height and cavity gap width.

An optimum ratio of 10 is obtained from both numerical modelling by Li et al. (2004) and Bouchair, (1994). According to Wang et al. (2006), the optimum ratio of 10 is dependent on inlet design and independent of solar radiation. For the roof-mounted thermal chimney, Du et al. (2011) deduce that the optimal ratio between cavity height and cavity gap width is 12. For solar collectors above the roof, the ratio between cavity length and hydraulic diameter should be greater than 15 for a better volumetric rate flow (Tan et al., 2013).

This optimum ratio may not apply to other configurations. This is because they are obtained based on one configuration and the optimum ratio could be affected by other factors such as cavity materials, inclination angle, opening, thermal insulation, even the external wind. However, no related study has been found in the literature.

Therefore, the optimum cavity height to gap ratio for enhanced thermal chimney performance is 10.

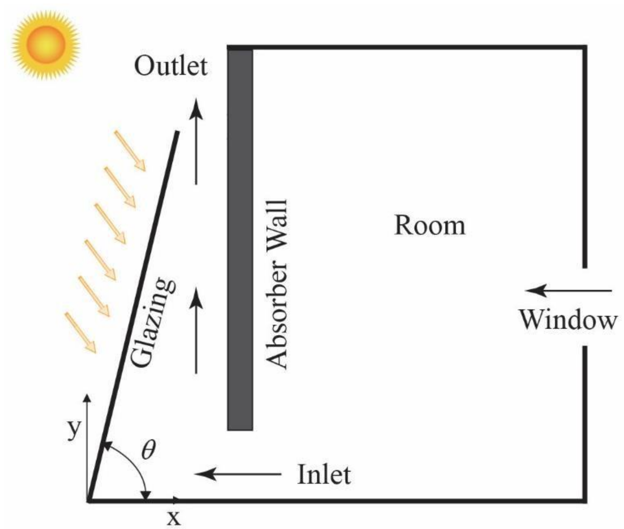


Figure 2.88: An inclined wall mounted thermal chimney
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

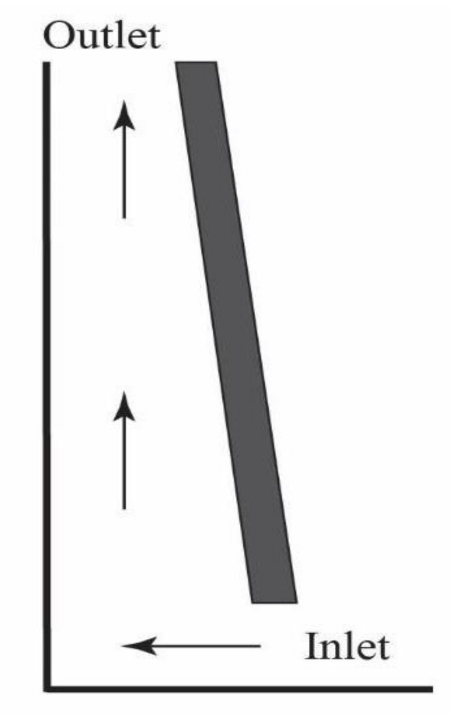


Figure 2.89: An inclined wall mounted thermal chimney
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

2.5.2 INSTALLATION FACTORS

i. Inclination angle

This refers to the angle between the thermal chimney cavity and the horizontal, which is usually applicable to a roof-mounted thermal chimney. Therefore, this inclination angle is largely dependent on the roof pitch. The inclination angle for a wall-mounted thermal chimney is considered to be 90°.

A number of the previous studies obtain an optimum inclination angle of 45^0 (Lee et al., 2015). When all other factors are held constant, the performance of a roof-mounted thermal chimney with an inclination angle around 45^0 is about 45% higher than that of a vertical thermal chimney (Chen et al., 2003). This is because a higher inclination angle causes high stack pressure inside the thermal chimney cavity, which results in decreased convective heat transfer. Therefore, an inclination angle of 45^0 is a balance between these two and allows the thermal chimney to provide maximum natural ventilation (Zhai et al., 2005).

According to Shi et al. (2016), the two optimum inclination angles are between $45^0$and 60^0since they provide a symmetric distribution of air within the thermal chimney. It is then hypothesized that the exact optimum inclination angle is not exactly 45^0 or 60^0; it could be an angle between 45^0 and 60^0.

Latitude is also an important factor related to the optimum inclination angle. Mathur et al. (2006) obtain optimum inclination angles for roof-mounted thermal chimneys for latitudes within 0^0-65^0. From previous studies, it is known that the optimum inclination angle is between 45^0-60^0, while for latitude within 20^0-30^0, the optimum inclination is 45°, and it increases a little bit as latitudes approach 0^0 or 65^0.

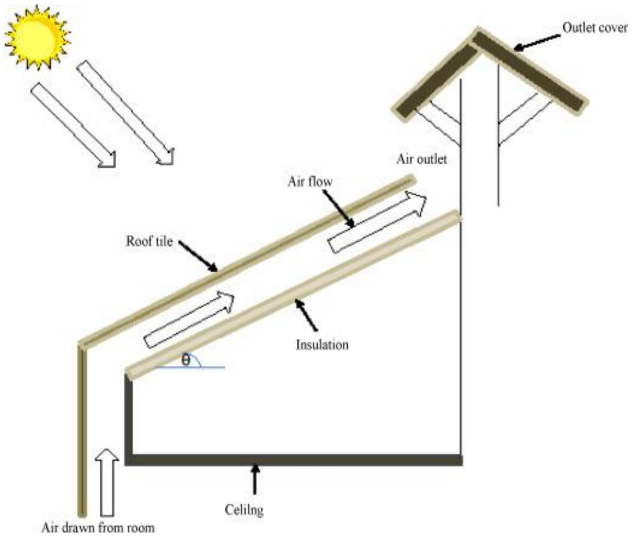


Figure 2.90: An inclined roof mounted thermal chimney
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

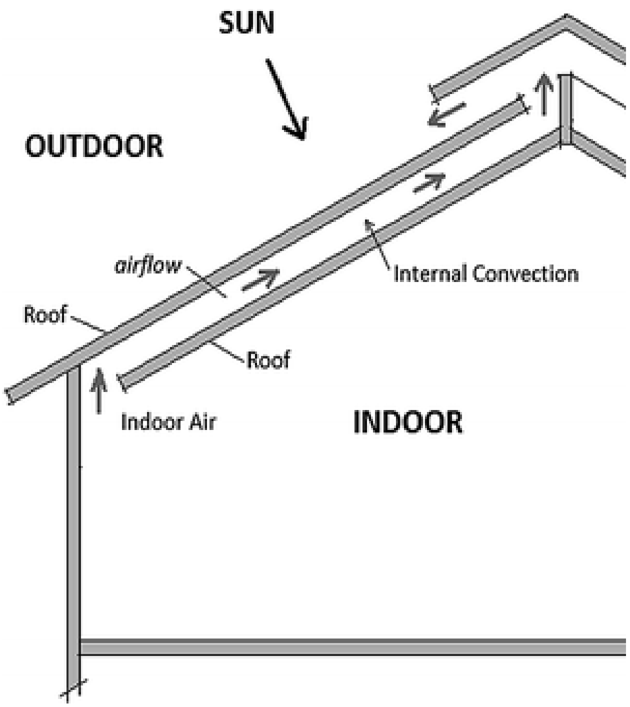


Figure 2.91: An inclined roof mounted thermal chimney
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

For wall-mounted thermal chimneys, some special configurations have also been analyzed such as having the thermal chimney cavity covered by an inclined glazing wall. According to Khanal and Lei (2015), this configuration is called inclined passive wall thermal chimney.

Inclination angles of 84^0-90^0 from the horizontal are investigated and an optimum inclination angle of 86^0 is obtained based on simulation. According to Manca et al. (2014) inclining the absorber wall as shown below does not lead to substantial differences.

Therefore, the optimum inclination angle for roof-mounted thermal chimneys ranges from 45^0 to 60^0 and is dependent on the latitude of the building. For optimum performance of wall-mounted thermal chimneys, the glazed wall should be inclined at an angle of 86^0 to the horizontal.

ii. Fenestrations within the room

Efforts have been made to optimize the design of fenestrations within the room to enhance the performance of thermal chimneys. The factors related to fenestrations within a room that affect the performance of a thermal chimney are door status, extract fan and stack size (Wong et al., 2004). In hot and dry climates, the performance of thermal chimneys can be enhanced by making minor changes to existing windows to keep away the solar heat and enhance the indoor ventilation rates (Bansal et al., 2005).

The optimum fenestration width is directly proportional to the chimney height and cavity gap; it increases with a bigger cavity gap width and chimney height (Wang et al., 2006). Priyadarsini et al. (2004) state that when the doors are closed, the airflow velocity is much higher and localized, but when the doors are open, the velocity increase is distributed more evenly.

A big fenestration area does not always favour the performance of a thermal chimney. According to Ding et al., (2005) the rate of air change rate decreases sharply with an over 16 m2 fenestration

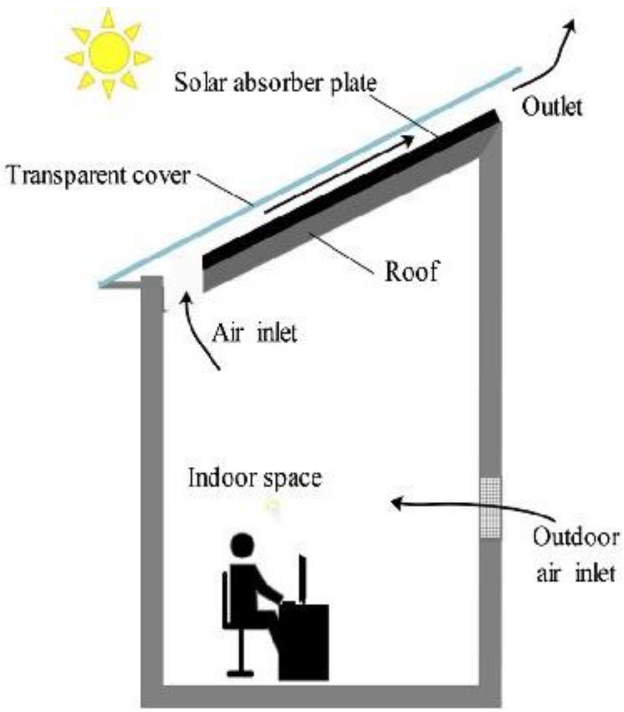


Figure 2.92: An inclined roof mounted thermal chimney
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

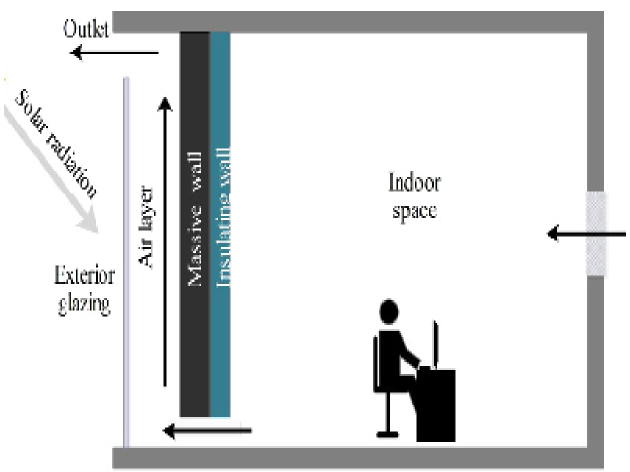


Figure 2.93: A wall mounted thermal chimney with exterior glazing, an absorber wall and an insulation wall
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

area. According to Shi and Zhang (2016), the relationship between the volumetric flow rate and opening area (A_{open}) is:

$$V = \frac{A_{open}}{0.65 + 5.2A_{open}}$$

Therefore, a bigger fenestration area within a room is not always worthwhile when it comes to enhancing the performance of a thermal chimney. The total fenestration area should not exceed $16m^2$.

iii. Solar collector

Solar collectors can have various placements such as a vertical solar collector, or a solar collector installed along the inclined roof, or a combination of these two. Both types of solar collectors should have good optical performance in order to increase the temperature of the air inside the cavity by absorbing as much heat as possible (Tian et al., 2013)

The pattern on the solar collector plate affects the performance of the thermal chimney as well. The three categories of patterns on solar collector plates are flat, v-grooved and chevron patterns. According to El-Sawi et al. (2010), the chevron pattern absorber achieves a 20% enhancement of thermal efficiency and an increase of 10 degrees Celsius in outlet temperature.

The size of a solar collector is an important factor with regard to the performance of a thermal chimney. According to Al-Kayiem et al. (2014), the average air velocity, average mass flow rate and performance increase gradually after increasing the area of the solar collector. According to Mathur et al. (2006), the ventilation rate increases with an increase in the ratio between absorber height and thermal chimney cavity gap. Al-Kayiem et al. (2015) deduce that the roof-mounted thermal chimney with an additional vertical absorber at the roof shows an enhanced performance of 1.2- 7.6%.

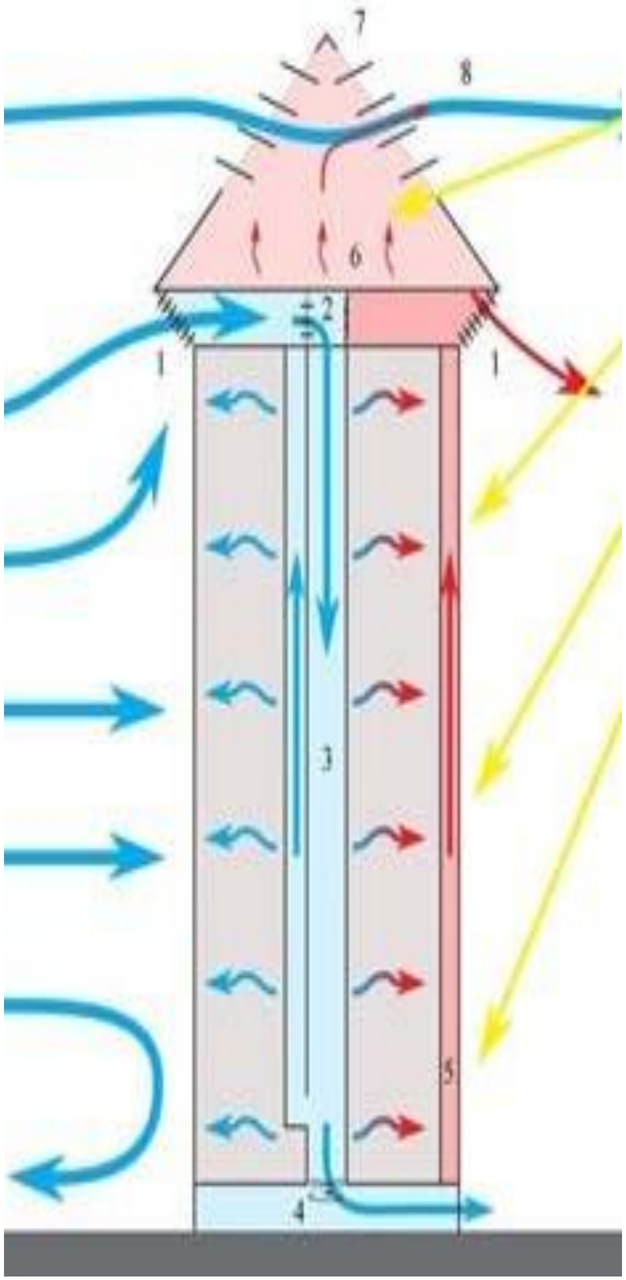


Figure 2.94: Ventilation system using a thermal chimney as an outlet system and a wind catcher as an inlet system
Source: https://www.researchgate.net/figure/Typical-solar-chimneys-used-in-building

The configuration of the solar collector also affects the performance of a thermal chimney. There are two types of configurations namely the single pass and the double-pass solar collector. According to Sawhney et al. (2002), a single-glazed solar collector with a corrugated aluminium absorber (insulated at the back) can provide an average temperature rise of 25 °C under 900 W/m2 solar radiation. On the other hand, a double-glazed collector with a flat absorber, operated in a forced convection model at a similar airflow rate of 72 m3/(h.m2), can deliver a temperature rise of about 29 °C under 915 W/m2 solar radiation (Löf, 1981).

Therefore, having a solar collector with a chevron pattern on the collector plate, with a large surface area and with a double-glazed system enhances the performance of a thermal chimney.

2.5.3 CONSTRUCTION MATERIALS

i. Type of glazing

Glazing is extensively used in both wall-mounted and roof-mounted thermal chimneys. It aims to enhance buoyancy inside the thermal chimney cavity through the heating processes. The properties of glazing that affect thermal chimney performance are transmissivity, reflectivity and absorptivity. According to Lee et al. (2015), a high value of transmissivity of glazing for a thermal chimney can increase the outlet temperature and also the performance of the chimney. The influence of the transmissivity of chimney glazing on temperature rise is more profound than those of reflectivity and absorptivity.

An analysis by Ong (2003) shows that the surface temperature of glazing is lower than the mean air temperature inside the thermal chimney cavity under solar radiation of 400 W/m2. As the radiation increases, the surface temperature of the glazing becomes higher than the mean air temperature inside the cavity. In addition to this, double glazing enhances the performance of the thermal chimney (Hatami et al., 2008).

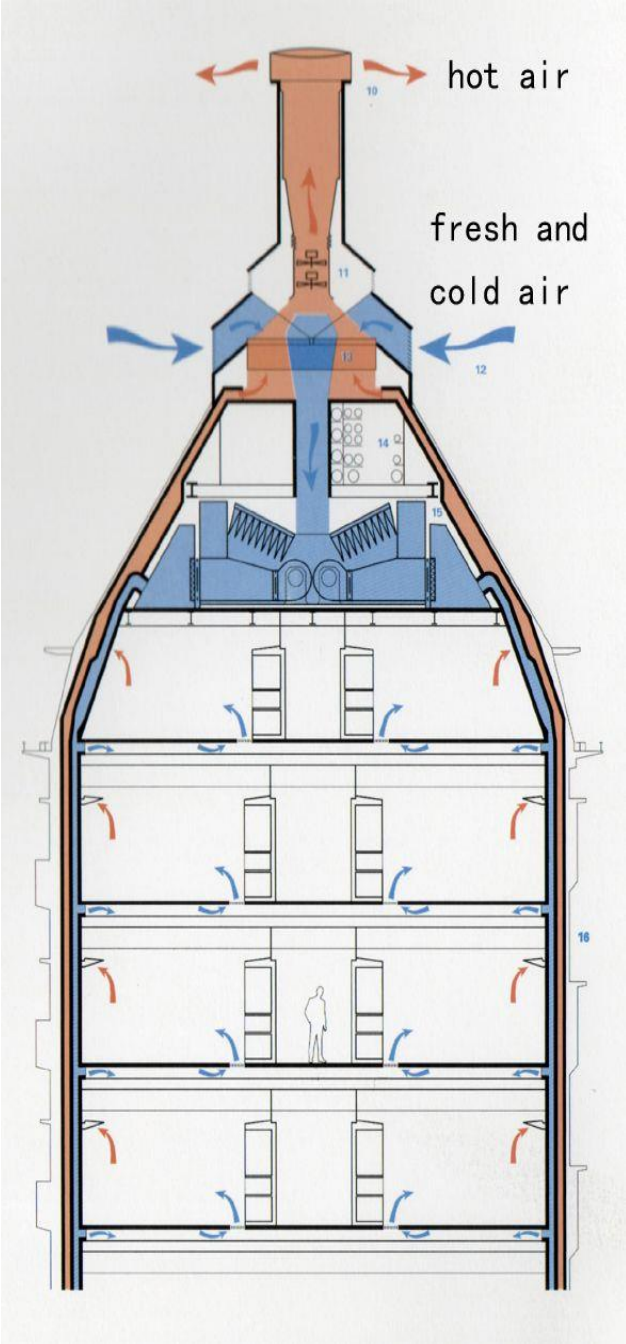


Figure 2.95: Cross section through Portcullis House in Westminster
Source: https://br.pinterest.com/pin/559642691174721243/

Therefore, the most important property of glazing is its transmissivity. The higher the transmissivity value, the better the thermal chimney performance.

ii. Solar absorber material

Thermal chimneys are designed to enhance ventilation by maximizing the heat obtained from the sun (Bansal et al. 1993). A numerical study (Lee et al., 2009) indicates an increase in volumetric flow rate by 40% after the increase of solar transmittance from 0.25 to 0.92. A longer cavity and absorber plate with a black-polished surface enhances the thermal chimney performance (Lee et al., 2015).

The absorptivity of the solar collector plays an important role for a roof-mounted thermal chimney. Lee and Strand (2009) observe a 57% increase in volumetric flow rate when the solar absorbance rises from 0.25 to 1.0.

For the thermal chimney design, it is essential to:

i. Use a small V-groove absorber for the related solar collector
ii. Maintain a narrow gap between absorber and bottom plate for the flat-plate collector
iii. Use selected coatings with very high absorbance rates
iv. Maintain no less than 0.1 kg/m2·s airflow rate
v. Enable an airflow entry with a temperature similar to the room temperature.

The emissivity of the solar absorber is also important to the performance of the thermal chimney. According to Khanal et al., (2011), the volumetric rate is enhanced with a higher surface emissivity, showing a 59% increase when it rises from 0 to 0.9.

However, when compared to emissivity, solar absorptivity seems to play a more important role. Leon and Kumar (2007) address the effects of solar radiation, thermal emissivity and solar

Figure 2.96: School of Slavonic and East European studies in London by Allan Short
Source: https://www.architectural-review.com/essays/architecture-becomes-music?tkn=1

Figure 2.97: Perspective of roof mounted thermal chimneys at Portcullis House in Westminster
Source: https://br.pinterest.com/pin/559642691174721243/

absorptivity on the performance of the solar collector. Pavlou et al. (2009) mention that the surface of a collector should be designed with the highest possible values of absorbance and emittance.

Therefore, high absorbance and emissivity values of the solar absorber material enhances thermal chimney performance.

iii. Thermal insulation

The design of the emissivity of the thermal chimney back wall should be such that it prevents heat losses through radiation processes (Harris et al., 2007). A study by Yang et al., (2012) indicates that decreasing the resistance of heat transfer in the cavity plays the most important role in thermal efficiency enhancement, as compared to parameters such as properties of glazing cover, stagnant air layer height, absorber plate surface emissivity and the conductive resistance of back plate.

The optimum thickness of the insulation wall is also suggested in previous studies. A numerical study by Afonso et al., (2000) suggests that a thickness of 5 cm insulation wall is enough and no profound enhancement can be observed with a thickness of 10 cm insulation. The study also shows that it is necessary to use external insulation on brick walls to take advantage of solar gains since thermal efficiency is reduced by more than 60% if external insulation is not used. The optimum thickness for a back wall is quite dependent on the pattern use of a building. A thin wall is enough for thermal chimney use during the day but for use during the night, a thick wall will be preferable.

Therefore, thermal insulation of the back wall enhances the performance of a thermal chimney.

2.5.4 ENVIRONMENTAL FACTORS

i. Solar radiation

Thermal energy from solar radiation is normally used to drive the air inside a thermal chimney cavity. Adequate air movement can be facilitated with the availability of solar radiation (Seytier

Figure 2.98: Perspective of Queen's Building in Leicester
Source: https://www.cam.ac.uk/research/news/back-to-the-future-of-skyscraper-design

Figure 2.99: Perspective of roof mounted thermal chimneys at Queen's Building in Leicester
Source: https://www.cam.ac.uk/research/news/back-to-the-future-of-skyscraper-design

et al., 2013). With an average radiation intensity of 850W/m^2, a roof-mounted thermal chimney induces 0.81 m^3/s volumetric flow rate while with a solar radiation up to 650 W/m^2, experimental results confirmed an obtained air velocity of 0.25-0.39 m/s (Ong et al., 2003).

According to Somsila et al., (2010) both the ventilation efficiency and volumetric flow rate increase with an increase in solar radiation. The influences of solar radiation on wall temperature, velocity and airflow rate are outlined by Manca et al., (2014). When the solar radiation is increased from 300 to 600 W/m^2, a 30% increase rate can be observed at the outlet, accompanied by a 30% increase of the maximum velocity, and approximately 10% enhancement of the maximum temperature of the heated wall. Bansal et al. (1993) obtains that 100 m^3/h and 350 m^3/h volumetric flow rates are possible for a thermal chimney with a surface area of 2.25 m^2 when it is put under solar radiation of 100 W/m^2 and 1,000 W/m^2, respectively. According to Chen et al. (2003), the ventilation flow rate rises by approximately 38% with an increase of solar radiation from 200 to 600 W/m^2.

Therefore, high solar radiation greatly improves the performance of a thermal chimney.

ii. External wind

External wind shows significant influence on the thermal chimney performance. According to Arce et al. (2009), the volumetric flow rate is significantly influenced by the pressure difference between openings caused by wind velocity and thermal gradients. In addition to the external wind velocity, the opening geometry and the angle of wind direction is significant to the ventilation rate of a building (Nikas et al., 2010). Another numerical study by Chungloo et al., (2007) shows that a thermal chimney can bring in a significant amount of natural ventilation of up to 1.13 - 2.26 air changes per hour without considering the effect from wind. These air changes increase to 7.5-15.1 per hour with the wind effect (Khedari et al., 2000)

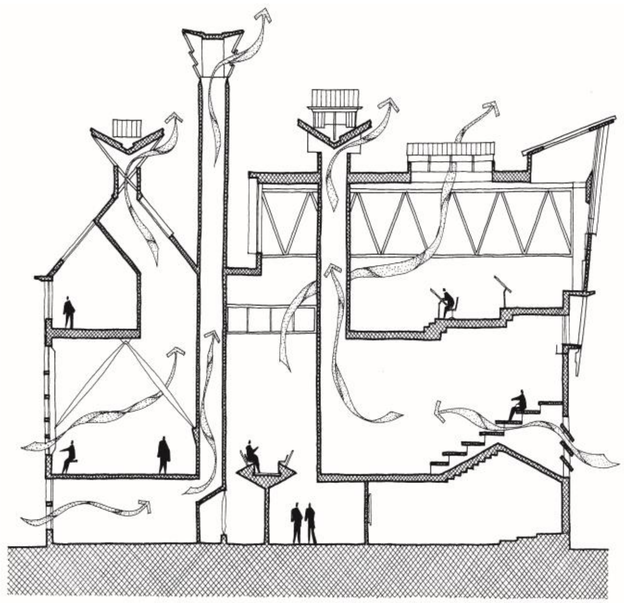


Figure 2.100: Cross section through Queen's Building in Leicester
Source: https://www.cam.ac.uk/research/news/back-to-the-future-of-skyscraper-design

Figure 2.101: Perspective of Queen's Building in Leicester
Source: https://www.cam.ac.uk/research/news/back-to-the-future-of-skyscraper-design

For a naturally ventilated building, external wind is one of the most critical factors to determine the performance of a thermal chimney (Wong et al., 2004). An experimental study by Tan and Wong (2014) shows that at least 2 m/s wind speed can improve the volumetric flow rate within the chimney cavity. However, with a solar radiation higher than 700 W/m^2, the importance of the external wind speed is negligible.

Due to unpredictable wind profiles, thermal chimney design can be taken without considering the effects from external wind (Afonso et al., 2000).A theoretical study by Dai et al. (2003) indicates that airflow rate can simply be designed considering solar radiation, ambient temperature as well as the cavity configuration.

Therefore, high wind speeds improve the performance of a thermal chimney. However, with solar radiation levels above 700Wm^2, the importance of external wind is negligible.

2.6 DESIGN PARAMETERS FOR THERMAL CHIMNEYS

i. Configuration factors

The design recommendations based on configuration factors are:

i. A large cavity height is beneficial to enhance passive ventilation via a thermal chimney, which is due to the increased pressure difference and heat gain.

ii. An appropriate cavity gap width is significant to the performance of a thermal chimney. This is because the airflow rate does not always increase with a bigger cavity gap due to reverse flow under uneven heating of air inside the cavity. An optimum cavity gap of 0.2 - 0.3 m is appropriate.

iii. An equal area for the inlet and outlet is a good way to improve the performance of a thermal chimney. For unequal openings, it is advisable to have a bigger outlet area and a smaller inlet area.

iv. A cavity height to cavity gap (width) ratio of 10 is appropriate.

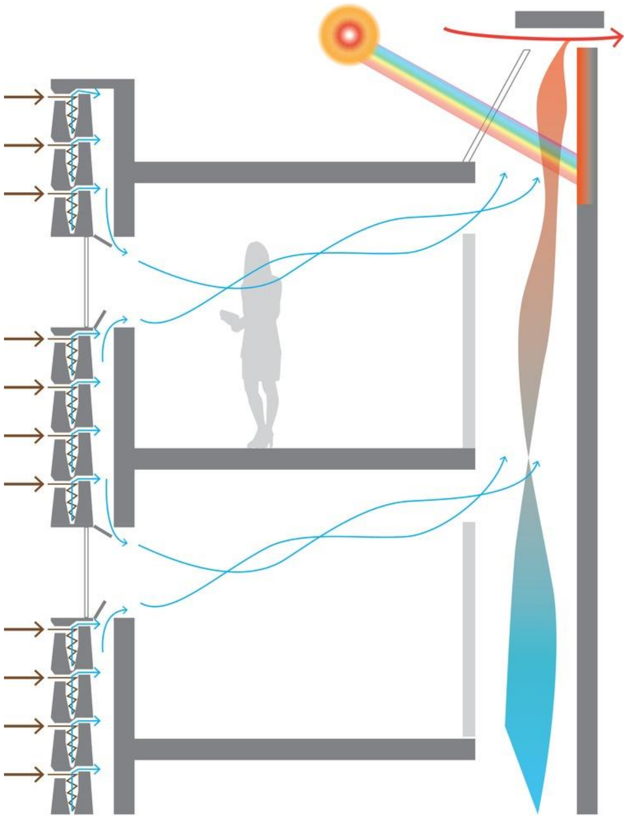


Figure 2.102: Section through a building showing air movement into the building through windows and out through a thermal chimney
Source: https://www.pinterest.co.uk/hannahmarguerit/thermal-chimney/

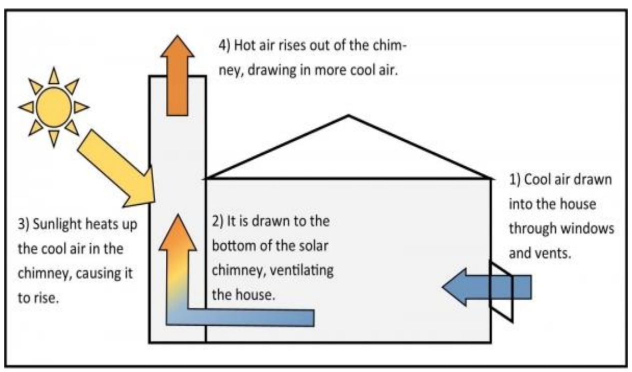


Figure 2.103: Section through a building showing ventilation system through a thermal chimney
Source: https://www.pinterest.co.uk/hannahmarguerit/thermal-chimney/

ii. Installation factors

The design recommendations based on installation factors are:

i. For a roof mounted thermal chimney, the optimum inclination angle is 45^0 to 60^0, which is dependent on the latitude of the building. For optimum performance of wall-mounted thermal chimneys, the glazed wall should be inclined at an angle of 86^0 to the horizontal.

ii. A bigger fenestration area within a room is not always worthwhile when it comes to enhancing the performance of a thermal chimney. The total fenestration area should not exceed $16m^2$.

iii. With regards to a solar collector, a design that favours heat gain can improve the performance, such as increasing the area of the collector plate, using a plate with the chevron pattern, using a collector with a double glazed system and using materials with high absorptivity and low thermal conductivity.

iii. Construction materials

The design recommendations based on construction materials are:

i. Regarding the selection of glazing, properties of transmissivity are more important than those of reflectivity and absorptivity. The higher the transmissivity, the better the performance of the thermal chimney.

ii. The solar collector material should have high absorptivity and emissivity rates for better thermal chimney performance. A thermal storage layer and absorber plate with black-polished surface should be incorporated.

iii. Thermal insulation of the cavity wall should have a thickness of at least 5 cm.

iv. Environmental factors

The design recommendations based on environmental factors are:

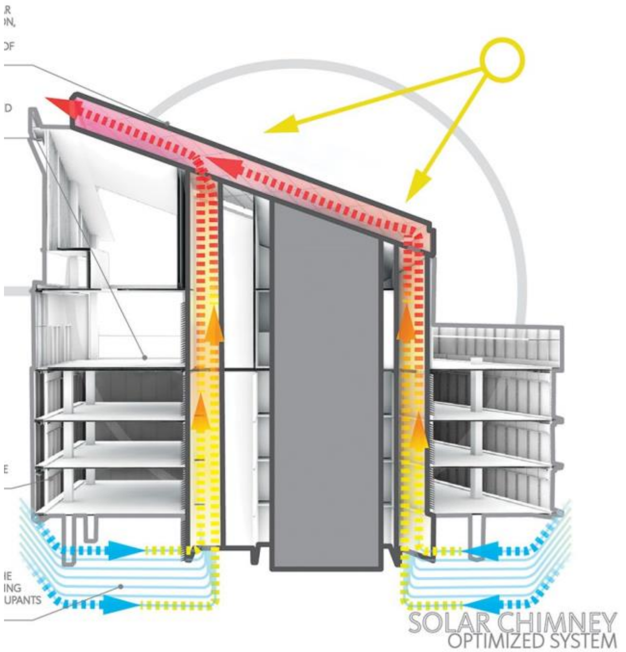


Figure 2.104: Section through a building showing ventilation system through a combined thermal chimney
Source: https://www.pinterest.co.uk/hannahmarguerit/thermal-chimney/

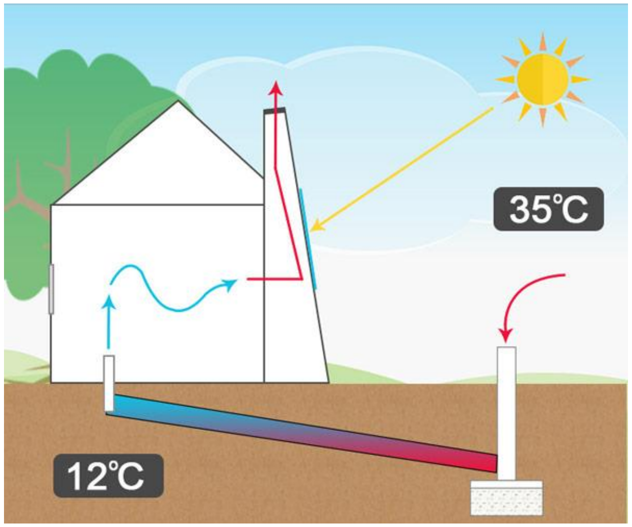


Figure 2.105: Section through a building showing ventilation system through a combined thermal chimney
Source: https://gharpedia.com/blog/solar-chimney-sustainable-solution-for-homes/

i. High solar radiation enhances the performance of a thermal chimney. Measures should be taken to absorb as much solar radiation as possible.

ii. The design of a thermal chimney can be taken without considering the effects from external wind because of its unpredictable profile.

2.7 SUMMARY OF LITERATURE REVIEW

In this chapter, the characteristics of the tropical uplands climate have been documented as well as the various categories of ventilation and the ventilation rate requirements for buildings. In addition to this, the various types of thermal chimneys have been discussed and their respective mathematical models have been documented. Relevant case studies have been included in this chapter for an in-depth understanding of the working mechanism of thermal chimneys. The factors influencing the performance of thermal chimneys such as configuration factors, installation factors, construction materials and environmental factors have been analysed. Based on this analysis the design parameters for optimum performance of thermal chimneys have been generated and documented. These form the basis of the parameters that will be used during the field work study.

Based on the literature review design parameters, the basic thermal chimney prototype that will be used for this study is as illustrated below:

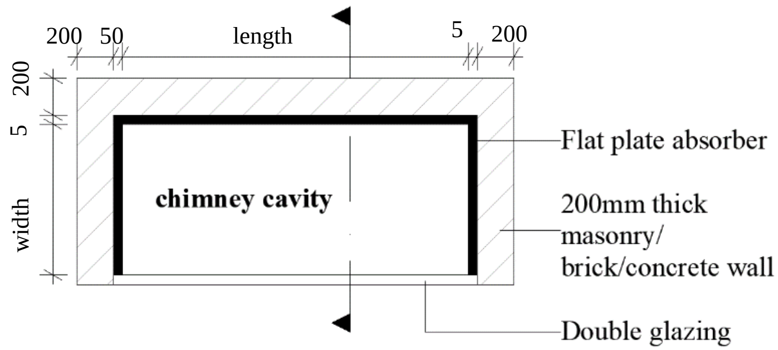


Figure 2.106: Plan of thermal chimney prototype
Source: Author

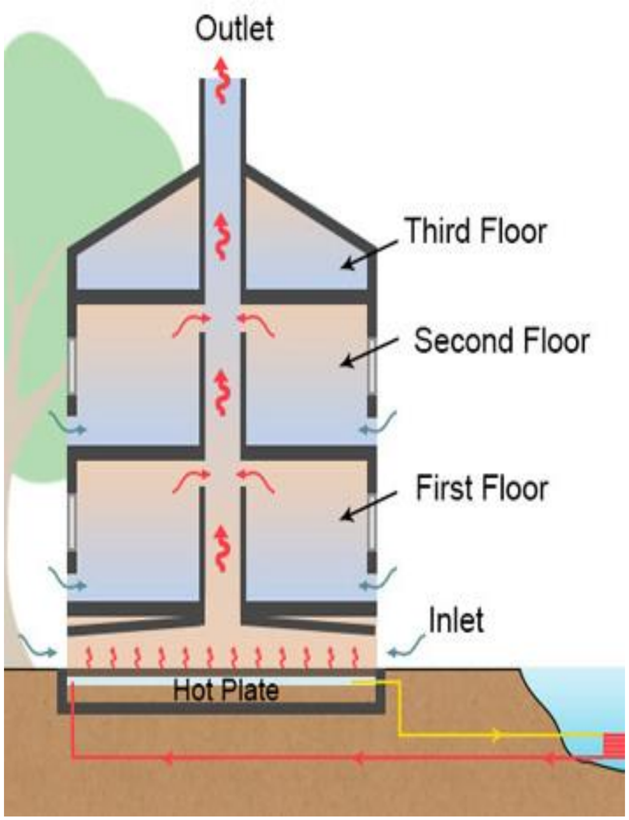


Figure 2.107: Section through a building showing ventilation system through a combined thermal chimney
Source: https://gharpedia.com/blog/solar-chimney-sustainable-solution-for-homes/

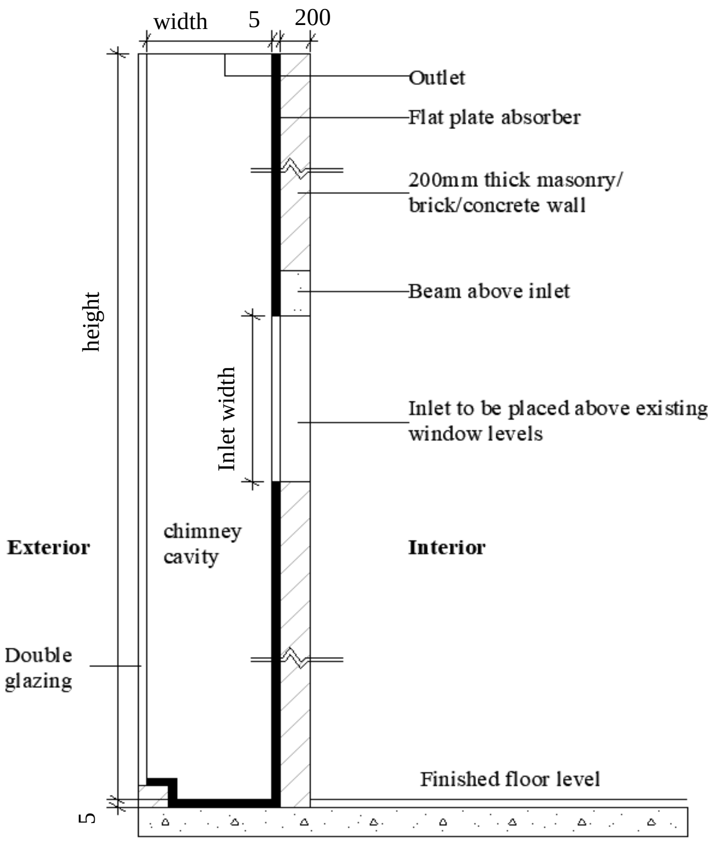


Figure 2.108: Section through thermal chimney prototype
Source: Author

CHAPTER THREE: RESEARCH METHODS

Figure 3.1: Aerial view of Nairobi CBD
Source: https://ubmnews.com/umuji-wa-nairobi-washizwe-k-urutonde-rw-imiji-yo-kw-isi-igoye-kubamwo/kk/

Figure 3.2: Night view of the Hilton Hotel and Kencom building
Source: https://ubmnews.com/umuji-wa-nairobi-washizwe-k-urutonde-rw-imiji-yo-kw-isi-igoye-kubamwo/kk/

Figure 3.3: Perspective of the Hilton Hotel and International House
Source: https://ubmnews.com/umuji-wa-nairobi-washizwe-k-urutonde-rw-imiji-yo-kw-isi-igoye-kubamwo/kk/

3.0 INTRODUCTION

This chapter focuses on the research design and the methods employed in the study to achieve the goals and objectives stated in chapter 1. A prior look at the specific research purpose puts into perspective the research approach used. The methods used for data collection, data recording, data analysis and eventually the methods used for presentation of the study are clearly outlined. It is the purpose of this chapter to comprehensively structure the research design for purposes of answering posed research questions:

i. What are the configurations, installation parameters and materials used in the design of thermal chimneys?
i. What are the air changes per hour in the office buildings in Nairobi?
ii. What are the design strategies for thermal chimneys in the tropical uplands climate?

3.1 RESEARCH DESIGN

This research is explanatory as it purposes to investigate the design of thermal chimneys in the tropical uplands climatic regions in order to enhance air change rates. With the findings of the study, it intends to create design recommendations for thermal chimney design in the tropical uplands climate, specifically Nairobi.

Being quantitative type of research, it is objective and singular, free from author bias, augmenting the deductive process to depict the cause-and-effect phenomenon prevalent in the design of thermal chimneys.

3.2 RESEARCH STRATEGY

The research uses case studies as the strategy for comprehensive coverage of the topic of study. According to Kothari (1985), case study is a form of qualitative analysis where careful and complete observations of an individual or a situation or an institution is done; efforts are made to


Figure 3.4: Aerial view of KICC building
Source: https://ubmnews.com/umuji-wa-nairobi-washizwe-k-urutonde-rw-imiji-yo-kw-isi-igoye-kubamwo/kk/


Figure 3.5: Perspective of recent developments in Upperhill
Source: https://ubmnews.com/umuji-wa-nairobi-washizwe-k-urutonde-rw-imiji-yo-kw-isi-igoye-kubamwo/kk/


Figure 3.6: Perspective of recent developments in Westlands
Source: https://ubmnews.com/umuji-wa-nairobi-washizwe-k-urutonde-rw-imiji-yo-kw-isi-igoye-kubamwo/kk/

study each and every aspect of the concerning unit(s) in minute details and then from case data generalizations and inferences are drawn.

The case study strategy has been applied at two levels:

i) In Nairobi, fieldwork was undertaken within Westlands area; a survey of the regions in Westlands was done and a particular study area was selected.

ii) Within the field study area, a number of office buildings with various forms and façade treatments were selected, studied in detail and experimented on to determine how to design thermal chimneys for such buildings.

3.2.1 SAMPLING CRITERIA

Due to the broad nature of the subject under investigation on coupled with limited time to carry out the research, use of stratified random sampling was used to select a manageable area of investigation in Westlands from which buildings studied were selected. To effectively understand how to design thermal chimneys for the tropical uplands region, there was need to investigate an area that has had and is still experiencing a construction boom bringing into perspective trends of the construction industry over the years. These trends over the years will help demonstrate how to effectively design thermal chimneys for Nairobi.

Sampling procedure:

First, stratification of areas in Nairobi that have recently experienced and are still experiencing a construction boom of structures shaping Nairobi's skyline was done. The Westlands area stands out as it has experienced a remarkable growth and development especially from the early 2000's.

Due to the vastness of Westlands area, stratifying the area in zones based on office building forms and densities saw the area bordered by GTC Towers, Westlands Road, Waiyaki way, Rhaphta

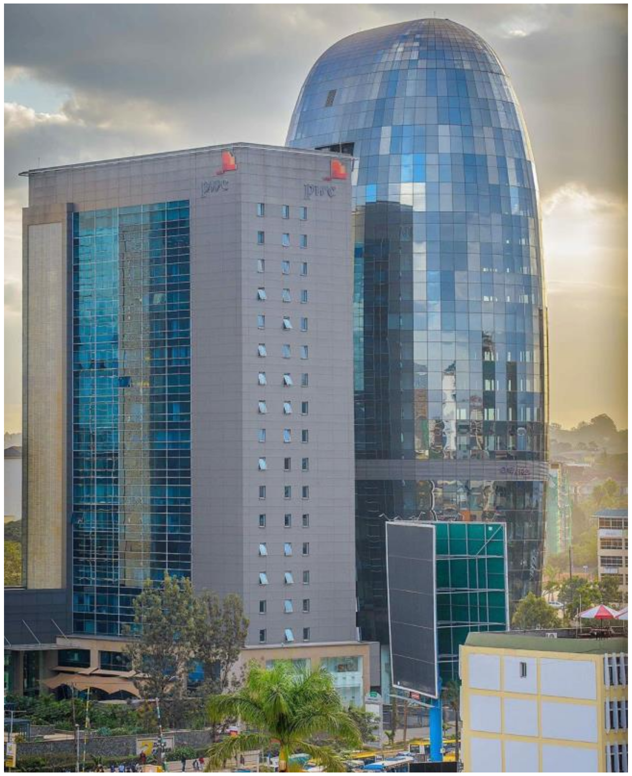


Figure 3.7: Perspective of Delta Corner Tower and One Africa Place
Source: https://www.skyscrapercity.com/threads/one-africa-place-westlands-21-fl.1797589/page-27

Figure 3.8: Perspective of the Global Trade Centre development
Source: https://www.skyscrapercity.com/threads/one-africa-place-westlands-21-fl.1797589/page-27

Road, Ring Road Westlands Lane, Nairobi River and Riverside Drive (as illustrated in the map below) being chosen as the area of study. This area has a variety of office building forms, façade treatments, building heights and densities all which affect wind flow patterns into the building and will thus affect the design of their thermal chimneys.

Figure 3.9: Map showing study area and selected case studies
Source: Google earth pro

Five office buildings were chosen using stratified random sampling method from the above identified zone of study. Their selection was based on the following factors that influence natural ventilation in buildings, as explained in chapter two:

Figure 3.10: Perspective of recent developments in Westlands with Park Inn by Radisson at the foreground
Source: Author

i. Building orientation with regards to prevailing wind direction
ii. Building form
iii. External elements/ obstructions
iv. Opening location and size
v. Opening control

Therefore, the buildings to be analysed are:

i. Global Trade Centre (GTC) office tower
ii. Riverfront Offices
iii. ICEA Lion Group Head Office (One block)
iv. One Africa Place
v. Delta Corner Towers

The parameters to be assessed at the macro scale are:

PARAMETER	
CLIMATIC DATA	Wind speed Temperature
URBAN PLANNING	Site planning Street networks Street geometry Street orientation Building densities Building heights Building forms


Figure 3.11: Perspective of GTC office tower
Source: https://nairobi-exposed.com/lifestyle/villa-rosa-kempinski-has-been-dwarfed/

	Open spaces

Table 3.1: Parameters to be assessed at the macro scale during the field study
Source: Author

The parameters to be assessed at the micro scale are:

PARAMETER	
MORPHOLOGY	Site planning External elements/obstructions Building orientation Building form
SPATIAL DESIGN	Construction materials Surface finishes Floor layout Opening location and size Opening control Wall thicknesses Floor to ceiling height Room sizes and spatial use Sun shading devices
VENTILATION PERFORMANCE	Internal air changes per hour

Table 3.2: Parameters to be assessed at the micro scale during the field study
Source: Author

Figure 3.12: Perspective of GTC development
Source: https://nairobi-exposed.com/lifestyle/villa-rosa-kempinski-has-been-dwarfed/

Figure 3.13: Perspective of GTC development
Source: https://nairobi-exposed.com/lifestyle/villa-rosa-kempinski-has-been-dwarfed/

3.2.2 AIMS AND OBJECTIVES

i. Document the configurations, installation parameters and materials used in the design of thermal chimneys.
ii. Analyze the air changes per hour in the office buildings in Nairobi.
iii. Develop design strategies for thermal chimneys in the tropical uplands climate.

3.2.3 OVERALL DEMOGRAPHICS OF THE STUDY

As stated by Mugenda & Mugenda (2012), the population frame is a complete listing of all the units of the target population to enable the researcher determine the sample size and the appropriate method of sampling.

In this research, the area of study is Westlands area. It represents the sample size of the population to be studied, which is office buildings. The elements are the buildings within Westlands area.

The following are the considerations taken in the study:

Population; the study focuses on the design of thermal chimneys for office buildings in Westlands area. The region has a high concentration of various forms of office buildings.

Population frame; In Westlands, the following make up the built environment- residential buildings, office buildings, commercial buildings, institutional buildings, recreational buildings and religious buildings.

Sample size; despite the type of buildings present in this area, five office buildings were selected for the study.

3.3 DATA SOURCES

These include the following:

Figure 3.14: Perspective of Mirage Towers
Source: https://coralpi.com/properties/office-space-to-let-in-westlands-mt/

Figure 3.15: Perspective of Mirage Towers
Source: https://coralpi.com/properties/office-space-to-let-in-westlands-mt/

I. SECONDARY DATA

i) Literature Review

This is majorly covered in chapters 2 and 3. It highlights the tropical uplands climate characteristics, types of ventilation, design parameters of thermal chimneys and various case studies that have successfully used thermal chimneys. It also gives a brief discussion of the historical architectural development of the Nairobi area and consequently the area of study, Westlands. This aims to ground the research on proper philosophical starting points.

It constitutes:

i. Literature Review of published books

ii. Literature Review of published journals/ research papers/ reports

iii. Literature Review of unpublished material- Internet sources

iv. Images and tables collected from the field

II. PRIMARY DATA (FIELD STUDY)

i) Observation

The observation method is approached in two ways; i.e participant and non-participant observation. However, this study employs participant observation as a major research strategy in order to gain a close and intimate familiarity with a given area of study. Observation techniques used include free hand sketching, photography and taking notes.

Figure 3.16: Perspective of Mirage Towers
Source: https://coralpi.com/properties/office-space-to-let-in-westlands-mt/

Figure 3.17: Perspective of GTC development
Source:https://www.standardmedia.co.ke/business/adblock?u=https://www.standardmedia.co.ke/business/home-away/article/2001403042/westlands-takes-lead-in-race-to-the-skies

Figure 3.18: Perspective of GTC development
Source:https://www.standardmedia.co.ke/business/adblock?u=https://www.standardmedia.co.ke/business/home-away/article/2001403042/westlands-takes-lead-in-race-to-the-skies

ii) Sketches, photographs and measured drawings

Photographs were used to capture the existing built forms as they are, how they respond to their immediate context, how the spaces are used, the materials used among others. Free hand sketches were also used to document built forms.

iii) Interviews

This study employs unstructured interviews, which were used to ask questions that did not reflect the research objectives and issues that were realized on site visit.

iv) Modified 3D images and visualizations

Modified three dimensional images and visualizations from CFD simulations have been used to analyze form and structure, as well as selected environmental aspects. Computerized models that have been generated using Archicad 22 have been presented as well.

3.4 FIELD WORK (RESEARCH STUDY)

4.4.1 RESEARCH INSTRUMENTS

I) Primary Data Sources

i. Interviews: Discussions concerning the office buildings and inquiries into the perceived ventilation rates were made. The informants involved included:

i) Architects

ii) Planners

ii) Building users. Random sampling was used to choose the interviewees.

Figure 3.19: Perspective of One Africa Place
Source: https://baa-architects.com/office-corporate-projects/one-africa-place-nairobi-kenya/

These were conducted with the help of an interview guide/ unstructured questionnaire. The interview guide used to generate users' perceptions was as follows:

i. How many people visit the office per day?
ii. Do users exhibit symptoms of sick building syndrome?
iii. What improvements have been made to this building since it was built?
iv. How many hours in a day is the building in use?
v. Do you feel the need to acquire or use a fan?
vi. Which rooms/ spaces are used most during daytime?
vii. Which rooms/ spaces are used most during the night?
viii. Do you ever open the windows, if any? If so, when?

ii. Observation: This is structured using static checklists to record visual observations of the spatial layouts and distinct architectural elements in form of analytical sketches, notes and photographic images.

iii. Physical measurements: These were used to generate sketches, ARCHICAD drawings (plans, sections, and elevations) and three dimensional drawings of the buildings.

iv. Scientific measurements: Scientific thermal anemometers were used to measure the volume flow, air speed, humidity and temperature levels in the buildings.

3.5 DATA ANALYSIS

3.5.1 CAUSAL- EXPLANATORY ANALYSIS

This analysis probes relations between variables and identify their correlations. Independent variables (building orientation, building shape, external obstructions, spatial layout, layout arrangement, opening control of windows, window sizes and position, room sizes & spatial use)

Figure 3.20: Perspective of GTC development
Source: https://www.pinterest.com/mcallans_louis/gtc/

impact the dependent variable (air changes per hour) which represents the indoor environment and human comfort levels with regards to ventilation.

The data collected from the indoor and outdoor environment is used to recreate a three dimensional model of the building which is used for geo-referenced computational fluid dynamics simulations. In order to improve air change rates within the building, an initial thermal chimney (based on the recommendations from chapter two) is modelled for the building and computational fluid dynamics simulations are done to determine the air change rates in the interiors.

CFD simulation tool: Designbuilder has been chosen as the CFD simulation software in this study, incorporating the EnergyPlus calculation engine which has been validated under the Evaluation of Building Energy Analysis Computer Programs test. Natural ventilation studies have been performed through CFD simulation of indoor airflow for the lettable space in the case-study using the weather files from Dagoretti Meteorological Station for accurate results.

CFD boundary conditions and assumptions:

i. The study areas/ volumes have no interior partitions.
ii. The calculated module has been preferred over scheduled module where the calculation engine uses information about building fabric & openings in conjunction with weather data and internal gains to calculate the pressure difference and air flow through each zone.
iii. The system is at steady state.
iv. The working air behaves like an ideal gas.
v. The air at the entrance in the thermal chimney to the outlet is without friction or leakages
vi. The thermal chimney walls are used as heat flux sources
vii. Properties (pressures, temperatures and density) are assumed at standard with the standard atmospheric conditions.
viii. The flow is assumed to be laminar.

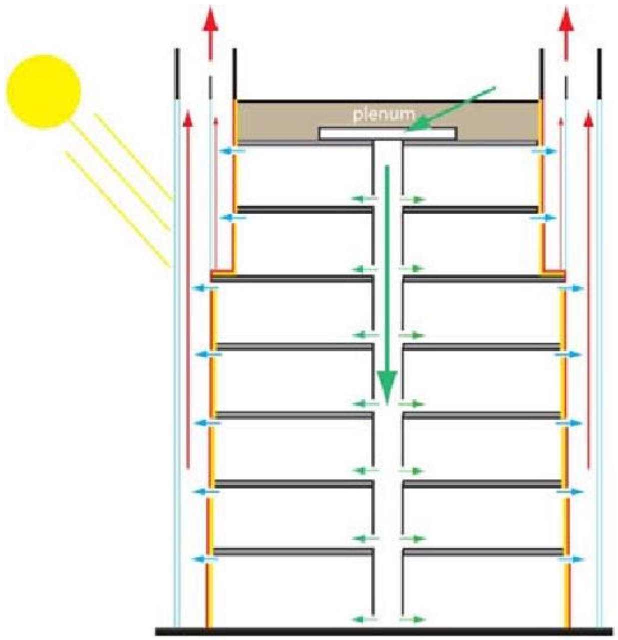


Figure 3.21: Ventilation through a wall mounted thermal chimney
Source: https://www.semanticscholar.org/paper/A-naturally-ventilated-office-building-through-and-Kemperman/60f616ff03da57ca3cb94c11fb50002731f60fdf

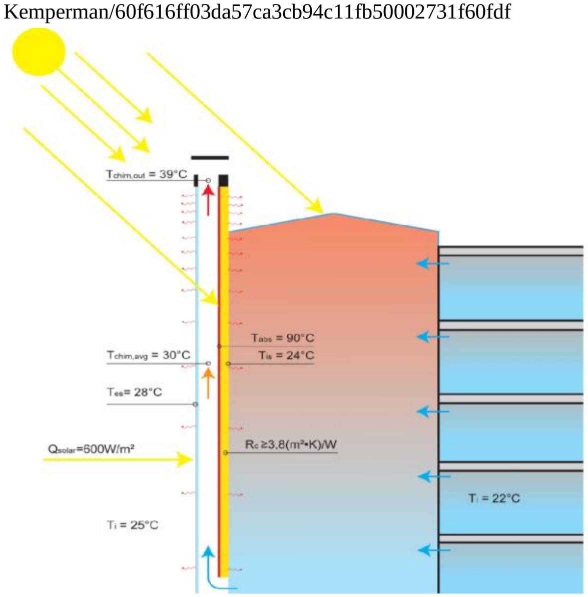


Figure 3.22: Ventilation through a wall mounted thermal chimney
Source: https://www.semanticscholar.org/paper/A-naturally-ventilated-office-building-through-and-Kemperman/60f616ff03da57ca3cb94c11fb50002731f60fdf

Simulation modelling parameters:

i. **Thermal chimney cavity height:** The thermal chimney's cavity height is bound by the height of the office space (including the thickness of the roof slab). The cavity height increases by a height of 2 m for each consecutive trial.

ii. **Thermal chimney cavity width:** The thermal chimney's cavity width is bound by 0.2m and 0.6m with an increment of 0.2m for each trial. Widths lower than 0.2m give fairly low air speeds while widths higher than 0.6m may be physically too large relative to the building.

iii. **Thermal chimney cavity length:** The length of the thermal chimney cavity is a parameter commonly overlooked since airflow within the thermal chimney is generally a two-dimensional flow, based on the cavity width and height. For this study, the length is based on the widths of the existing vertical elements (for example in the GTC Office Tower) or the distance between windows on the facades. The thermal chimney's cavity length increases by approximately 0.5m for each trial.

iv. **Thermal chimney outlet and inlet areas:** The thermal chimneys have outlets at the top of the stack. This means that this area will be determined by the cavity width and length. As recommended in the literature review, the inlets and outlets have the same areas.

With the examination of the influences of the input parameters, their combined effects on the indoor air speed are determined in order to design and optimize the thermal chimney. Although there are over 100 possible cases according to the limits from the table above, a first set of 20 cases (the lower and upper limits of the five input parameters) is modeled and simulated, after which the second set of 25 cases (chosen randomly) and the third set of 20 cases (chosen randomly) follow. The combined 65 cases are sufficient in developing a performance trend of the chimneys, which makes it possible to narrow down on the number of cases that have been presented for this study.

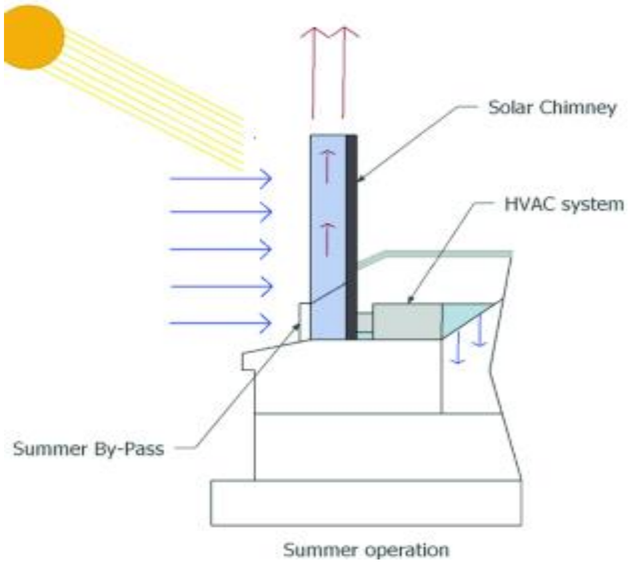


Figure 3.23: Ventilation through a wall and roof mounted thermal chimney
Source: https://www.semanticscholar.org/paper/A-naturally-ventilated-office-building-through-and-Kemperman/60f616ff03da57ca3cb94c11fb50002731f60fdf

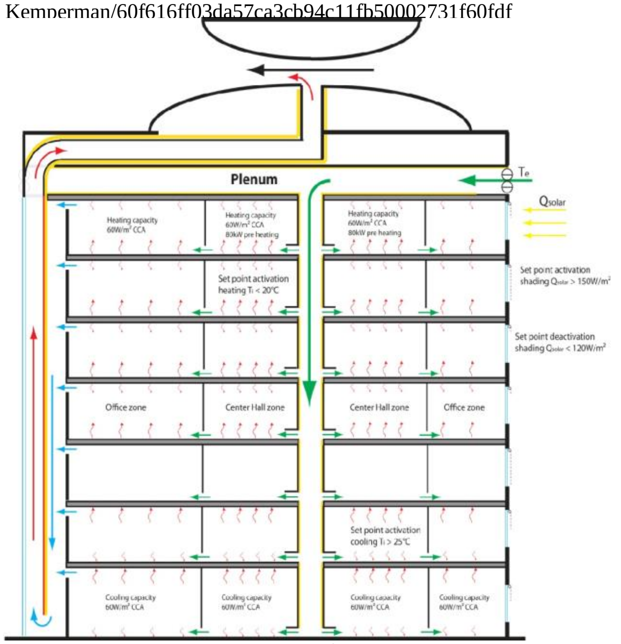


Figure 3.24: Ventilation through a roof mounted thermal chimney
Source: https://www.semanticscholar.org/paper/A-naturally-ventilated-office-building-through-and-Kemperman/60f616ff03da57ca3cb94c11fb50002731f60fdf

Simulation modelling constants:

i. **Thermal chimney inclination angle:** The study is limited to wall mounted thermal chimneys. Therefore, for all trials, the inclination angle is set at 90^0.

ii. **Location:** The thermal chimneys have been placed on the South Western end of the offices as shown in the simulation models. This location has made it possible for the chimneys to increase air flow rates into the office while still receiving maximum solar radiation.

iii. **Thermal chimney construction materials:** The chimneys have double glazing and are made of brick walls with a flat copper plate absorber.

The thermal chimney design parameters (configuration factors, installation factors and construction materials) are tweaked until the recommended air change rates per hour are achieved, as confirmed by the simulations. The thermal chimney design parameters are derived from the final chimney model. These design parameters are dependent on the building characteristics and make it possible to form generalizations for future use. The table below summarizes the the thermal chimney design parameters:

PARAMETER	VARIABLES
MATERIALS	Type of glazing Materials of thermal absorber
CONFIGURATION	Chimney height Cavity gap Inlet area Outlet area Chimney height/cavity gap ratio

Figure 3.25: Perspective of One Africa Place and Delta Corner Towers
Source: https://baa-architects.com/office-corporate-projects/one-africa-place-nairobi-kenya/

Figure 3.26: Perspective of Delta Corner Towers
Source: https://baa-architects.com/office-corporate-projects/one-africa-place-nairobi-kenya/

INSTALLATION	Inclination angle Thermal collector plate pattern

Table 3.3: Thermal chimney design parameters
Source: Author

3.5.2 COMPARATIVE ANALYSIS

A macro scale analysis of the case study area in Westlands has been done at a town planning level. The variables that identify this area as well as any impact of the planning on wind flow patterns within the area has been analysed and documented.

The author selected a physical environment (tropical uplands climate) and collected data based on a variety of relevant variables (different physical building characteristics). The purpose of selecting these comparable examples is to isolate the factor (parameters) that cause significant differences in the levels of variables measured (air changes per hour).

The variations of thermal chimney design parameters for each building type have been compared in order to understand how the parameters change as building characteristics change.

By being explanatory in nature, this research inquiry culminates in an explanatory conceptual system with use beyond the confines of one place and time, and hence can apply to other regions experiencing the tropical uplands climate. Armed with tangible evidence; this experimental study enables generalizations to be deduced hence satisfying the aims of this research.

Figure 3.27: Aerial view of Westlands area
Source: https://kenyannews.co.ke/news/county-news/waiguru-and-joho-among-governors-evicted-from-their-nairobi-office/

Figure 3.28: Perspective of upcoming developments in Westlands
Source: Author

3.6 DATA PRESENTATION

The data collected in the course of fieldwork for this dissertation has been presented in the form of:

i) Maps

ii) Architectural drawings i.e. plans, sections, elevations.

iii) Graphs

iv) Photographs

v) Tables

vi) Sketches

vii) Notes

viii) Charts

3.7 TIME & LIMITATIONS OF STUDY

The field work has been undertaken in a time frame of four weeks. The study is limited to office buildings in Westlands area, Nairobi. Due to the limitation of time, data logging equipment and financial resources, a comprehensive field study has been conducted in Westlands area only. The study scope is limited to thermal chimneys only. Thermal chimneys coupled with other systems have not been included in the study.

3.8 SUMMARY OF RESEARCH METHODS

This chapter spells out how this study is undertaken and further describes the research design, research strategy, data collection techniques, data analysis methods and presentation. The primary sources of data have been identified as interviews, observations, physical measurements and scientific measurements. These have been presented in the documentation of the case studies in the next chapter in the form of photographs, analytical notes, tables, charts and architectural sketches.

CHAPTER FOUR: URBAN ENVIRONMENTAL ANALYSIS OF WESTLANDS

4.0 Introduction

4.1 Climate of Nairobi

4.2 The built environment in Nairobi

4.2.1 Transformation of buildings in Nairobi

4.2.2 Environmental concerns in Nairobi

4.2.3 Urban contexts in Nairobi

4.3 Westlands

4.3.1 Urban history of Westlands

4.3.2 Urban functions of Westlands

4.3.3 Westlands study area

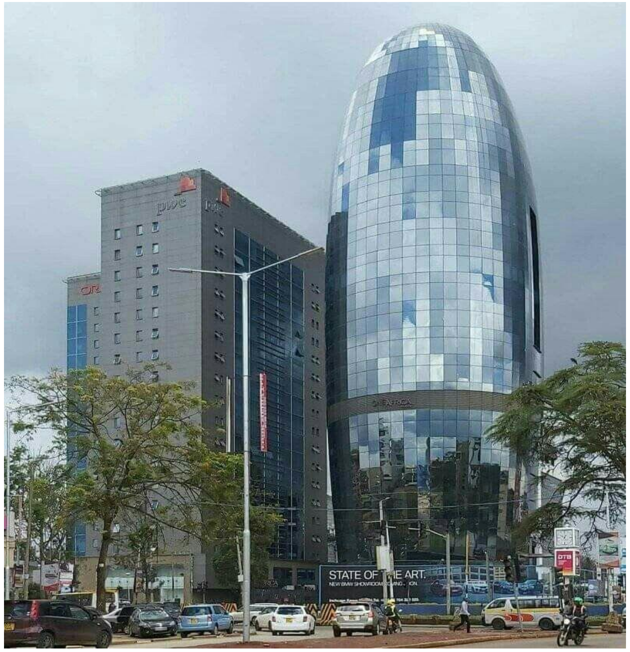


Figure 4.1: Perspective of Delta Corner Towers and One Africa Place
Source: Author's archive

Figure 4.2: Perspective of Delta Corner Towers and One Africa Place
Source: Author's archive

4.0 INTRODUCTION

This chapter analyses the environmental concerns of the built environment in Nairobi. A historical development of buildings in Nairobi is undertaken by analyzing their evolution over the years. A brief introduction of Westlands area, Nairobi, investigating its urban history in terms of its built density, circulation and land use is done, followed by an environmental analysis of the specific area of study within the larger Westlands area by analyzing its urban climatology and building form analysis. In addition, a historical study of the evolution of the area's building typologies and forms over the years is undertaken which in turn introduces the five buildings being investigated for thermal chimney design parameters in Chapter 5.

4.1 CLIMATE OF NAIROBI

Nairobi's climate is classified as tropical uplands. Nairobi is 1669m above sea level. Nairobi has a significant amount of rainfall during the year. The temperature here averages 18.8 °C. The annual rainfall is approximately 674 mm and the average hourly wind speed is 3m/s.

4.1.1 WIND

The wind experienced at any given location is highly dependent on local topography and other factors, and instantaneous wind speed and direction vary more widely than hourly averages. The average hourly wind speed in Nairobi experiences significant seasonal variation over the course of the year.

The windier part of the year lasts for 7.6 months, from September 8th to April 26th, with average wind speeds of more than 4m/s. The windiest month of the year in Nairobi is December, with an average hourly wind speed of 5m/s. The calmer time of year lasts for 4.4 months, from April 26th to September 8th. The calmest month of the year in Nairobi is June, with an average hourly

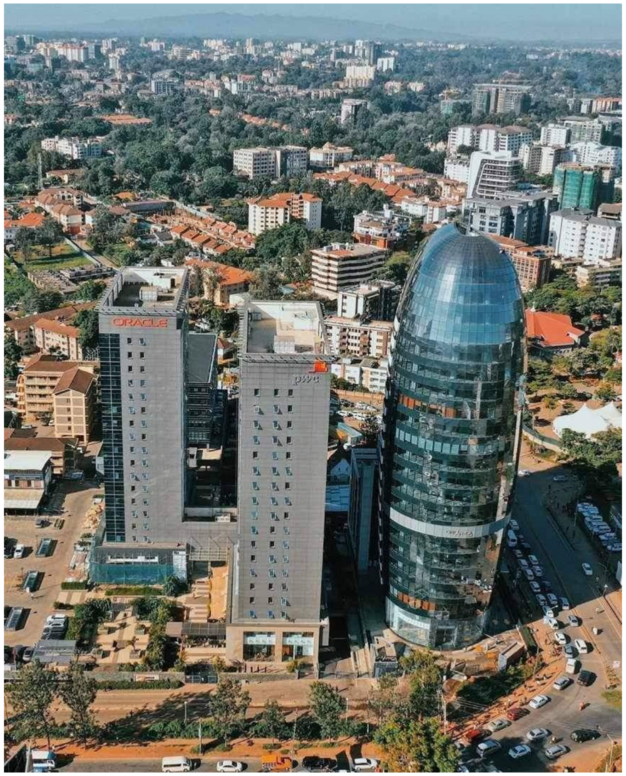
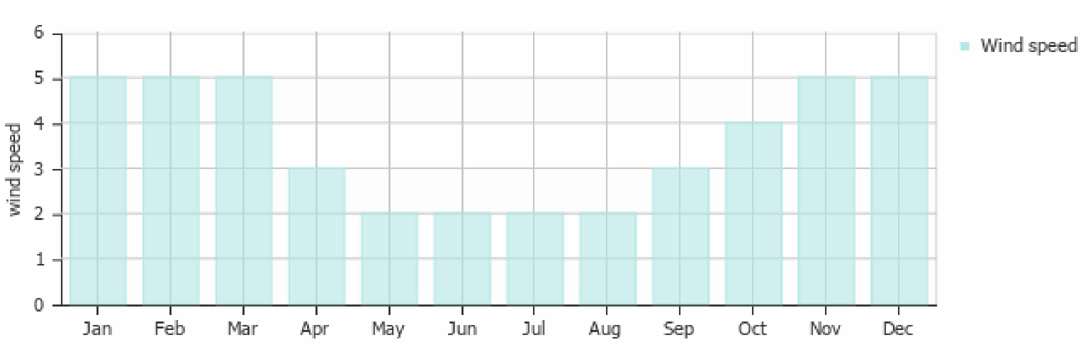


Figure 4.3: Perspective of Delta Corner Towers and One Africa Place
Source: Author's archive

Figure 4.4: Perspective of Koinange Street
Source: Author's archive

wind speed of 3m/s. The predominant wind direction in Nairobi is from the North East throughout the year.

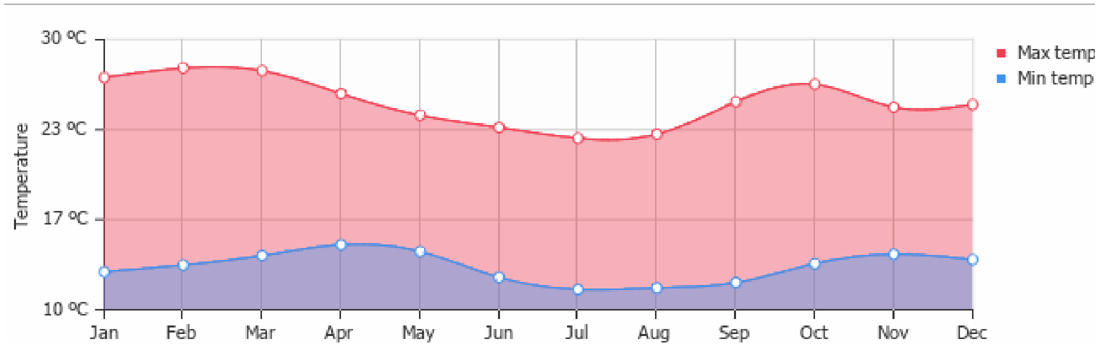


Graph 4.1: Average wind speeds in Nairobi
Source: https://weatherspark.com/

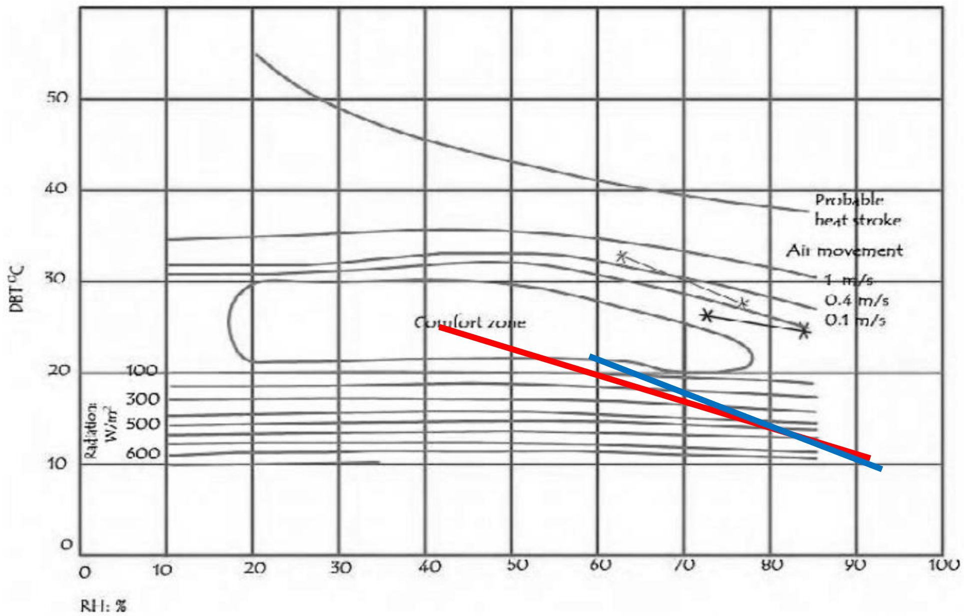
4.1.2 TEMPERATURE

The warm season lasts for 2.1 months, from January 24th to March 27th, with an average daily high temperature above 26°C. The hottest month of the year in Nairobi is March, with an average high of 27°C and low of 16°C.

The cool season lasts for 2.6 months, from June 5 to August 25, with an average daily high temperature below 22°C. The coldest month of the year in Nairobi is July, with an average low of 12°C and high of 21°C.



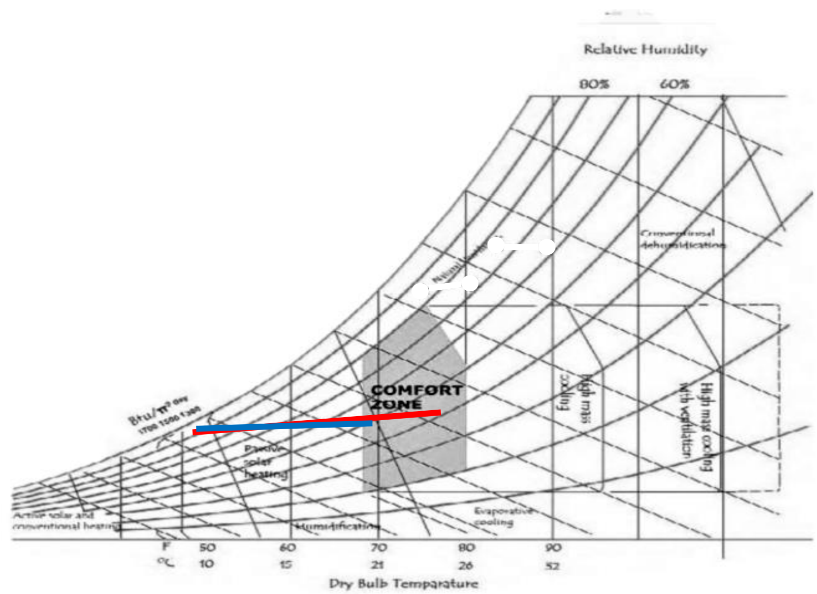
Graph 4.2: Average temperature in Nairobi
Source: https://weatherspark.com/



COLDEST MONTH (JULY)

HOTTEST MONTH (FEBRUARY)

Figure 4.5: Bioclimatic chart for Nairobi
Source: Author



COLDEST MONTH (JULY)

HOTTEST MONTH (FEBRUARY)

Figure 4.6: Psychrometric chart for Nairobi
Source: Author

Figure 4.7: Perspective of Global Trade Centre Development
Source: Author's archive

As seen above, the range between the hottest and coldest months partially lies in the comfort zone, and below the comfort zone, necessitating the provision of radiation of up to 800 W/m^2 especially in the cold season (bioclimatic chart) and provision of passive solar heating (Psychrometric chart to achieve human comfort.

4.1.3 RAINFALL

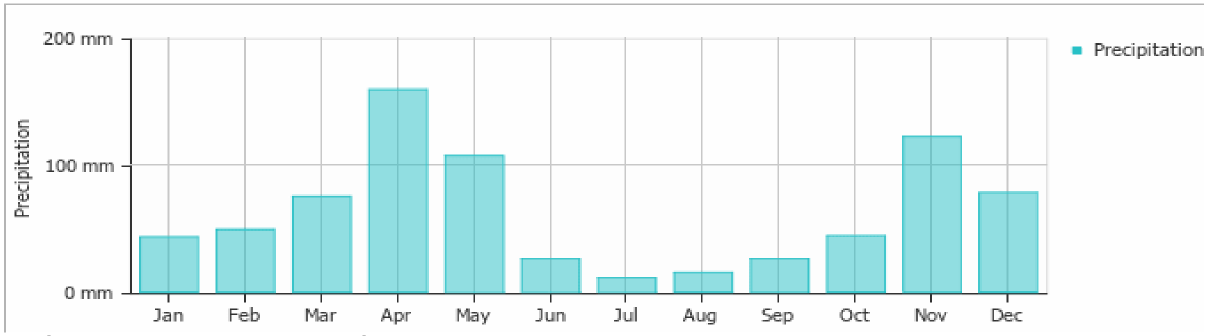
The rainy period of the year lasts for 8.2 months, from October 1 to June 8, with a sliding 31-day rainfall of at least 12.7 inches. The month with the most rain in Nairobi is April, with an average rainfall of 84mm.

Figure 4.8: Perspective of developments in Nairobi
Source: Author's archive

Figure 4.9: Perspective of ICEA LION Group Head Office
Source: Author

Figure 4.10: Perspective of One Africa Place and Delta Corner Towers
Source: Author's archive

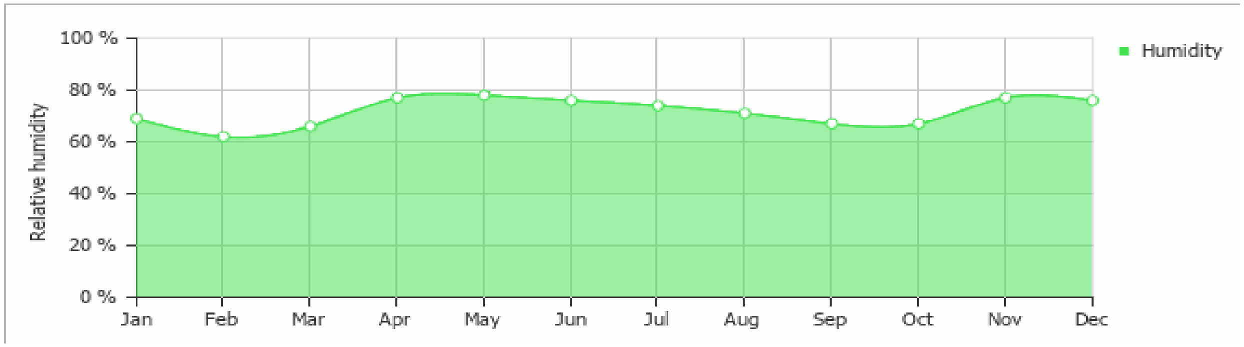
The drier period of the year lasts for 3.8 months, from June 8 to October 1. The month with the least rain in Nairobi is July, with an average rainfall of 3mm.



Graph 4.3: Average precipitation in Nairobi
Source: https://weatherspark.com/

4.1.4 HUMIDITY

The average relative humidity in Nairobi is 75%, with April and November having the highest humidity levels and February having the lowest humidity levels.



Graph 4.4: Average relative humidity in Nairobi
Source: https://weatherspark.com/

4.1.5 CLOUD COVER

In Nairobi, the average percentage of the sky covered by clouds experiences significant seasonal variation over the course of the year. The clearer part of the year in Nairobi begins around June 26th and lasts for 3.5 months, ending around October 10th. The clearest month of the year in Nairobi is August, during which on average the sky is clear, mostly clear, or partly cloudy 52% of the time.

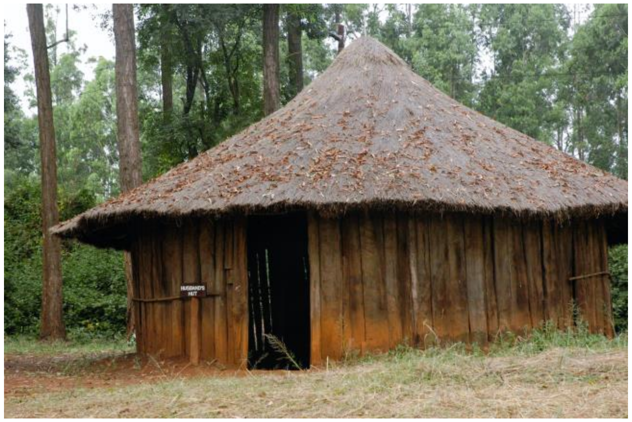


Figure 4.11: Perspective of a traditional hut
Source: https://www.makeheritagefun.com/

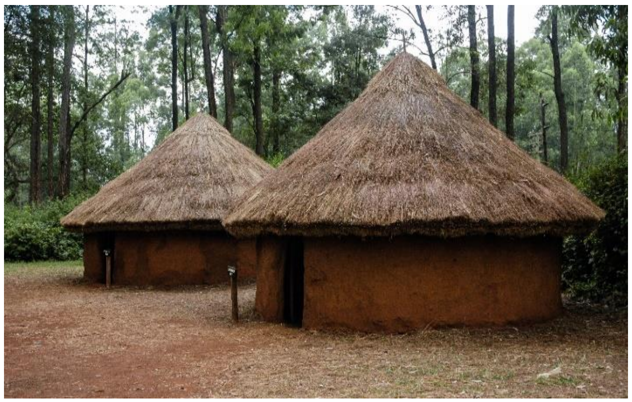
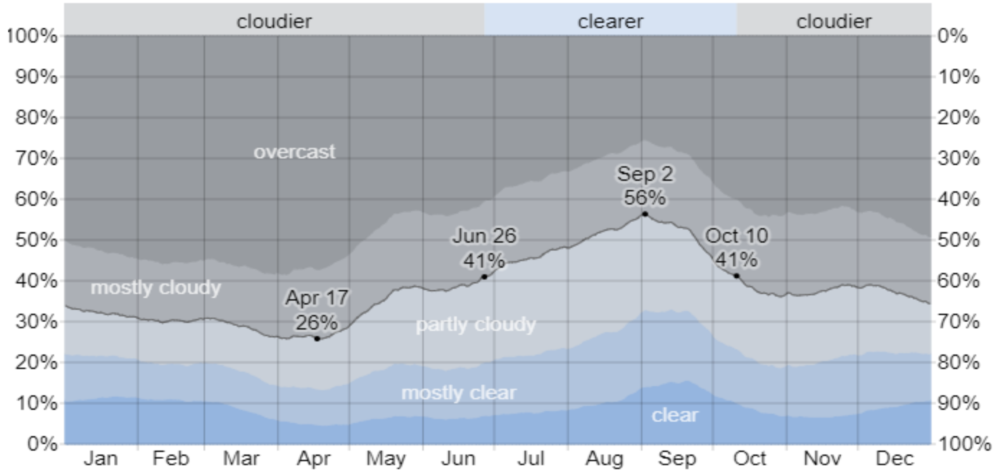


Figure 4.12: Perspective of a traditional huts
Source: https://www.makeheritagefun.com/

Figure 4.13: Perspective of a traditional hut
Source: https://www.makeheritagefun.com/

The cloudier part of the year begins around October 10th and lasts for 8.5 months, ending around June 26th. The cloudiest month of the year in Nairobi is April, during which on average the sky is overcast or mostly cloudy 73% of the time.



Graph 4.5: Average relative cloud cover in Nairobi
Source: https://weatherspark.com/

4.2 THE BUILT ENVIRONMENT IN NAIROBI

4.2.1 TRANSFORMATION OF BUILDINGS

Traditionally, basic shelter was provided using simple buildings constructed using materials that were locally available and employed basic construction techniques with natural systems of lighting, ventilation, heating and cooling. Vernacular buildings have transformed over time to make the best use of local materials and conditions to provide adequate and luxurious shelter for the people. An overview of Nairobi's architecture over time, shows a clear transformation of building typologies over the years. The Nairobi region was originally inhabited by the Maasai, Kikuyu and Kamba communities but today, its skyline is dotted by many modern sky scrapers as illustrated in the images, which use mechanical systems for ventilation, heating, cooling and lighting.

Figure 4.14: Perspective of I &M Towers
Source: Author's archives

The vernacular buildings had fenestrations and made use of natural ventilation while the modern buildings gravitate towards the use of glass facades with fixed window panes, thus necessitating the use of artificial means of ventilation.

This increase in the complexities and capacities of developments in Nairobi has led to an increase in the demand for building systems to provide sufficient air change rates for the occupants. This has consequently led to employment of mechanical ventilation systems which are expensive to install, maintain and often do not deliver the recommended minimum air changes per hour. Users of such buildings eventually exhibit symptoms of sick building syndrome, respiratory disease, allergic symptoms, and sensory irritation as had been mentioned in chapter 1.

Figure 4.16: Buildings in Nairobi before 1899
Source:
https://www.makeheritagefun.com/

Figure 4.18: Buildings in Nairobi in the 1920s (Kenya Railways headquarters)
Source:
https://www.makeheritagefun.com/

Figure 4.20: Buildings in Nairobi in the 1980s (ICEA building)
Source: Author's archive

Figure 4.15: Perspective of View Park Towers
Source: Author's archives

Figure 4.17: Buildings in Nairobi in the early 2000s (I & M building)
Source: Author's archive

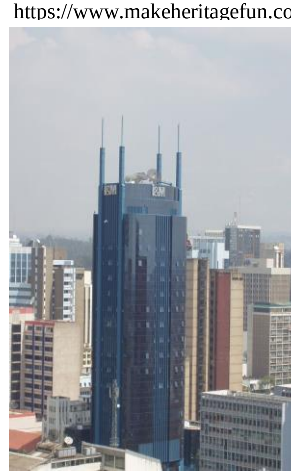


Figure 4.19: Buildings in Nairobi in 2019 (One Africa Place and Delta Corner)
Source: Author's archive

Figure 4.21: Buildings in Nairobi in 2021 (GTC Office Tower)
Source: Author's archive

Figure 4.22: Future buildings in Nairobi (Proposed Upper Hill Square)
Source: https://www.skyscrapercity.com/

4.2.2 ENVIRONMENTAL CONCERNS

A number of buildings coming up in Nairobi are replicas of buildings designed in the cold and temperate climates. This does not take into consideration the differences in climate and has led to the creation of buildings that are not environmentally friendly. As a result, most buildings heavily rely on artificial means for ventilation, cooling, heating and lighting leading to increased prevalence of sick building syndrome symptoms, respiratory disease, allergic symptoms, and sensory irritation. Furthermore, this can increase the transmission risk for certain communicable diseases such as the Coronavirus disease. These eventually affect occupant health and productivity, contributing to increased health care cost, productivity loss, and absenteeism

Figure 4.23: Kenyatta Avenue in the 1900s
Source: https://www.ma3route.com/

Figure 4.25: Kenyatta Avenue in the 2000s
Source: https://www.ma3route.com/

Figure 4.24: Moi Avenue in the 1900s
Source: https://www.ma3route.com/

Figure 4.26: Moi Avenue in the 2000s
Source: https://www.ma3route.com/

4.2.3 URBAN CONTEXTS IN NAIROBI

AREAS COVERED	GROUND COVERAGE %	PLOT RATIO %	TYPES OF DEVELOPMENTS
Central Business District (CBD)			Commercial/Residential/LightIndustry
Core CBD	80	600	
Peri-CBD	80	500	
West of Tom Mboya Street	60	600	
East Of Tom Mboya Street	80	350	
Uhuru Highway/ UniversityWay/Kipande Rd	80	500	
Upper Hill Area			Commercial/Offices/ Residential
Block 1 – Commercial /Office	60	250	
Block 2 - Offices	60	300	
Block 3 - Residential	35	150	
Block 4 - (Mixed)	60	200	
Westlands			Commercial/Offices/Residential
Westlands CBD	80	240	
Block 1- Commercial	80	200	
Block 2&3- Offices & High rise Residential	35	80	
Block 4- Offices	80	200	
Block 5- Commercial/ResidentialHotels			
Upper Spring Valley, Loresho and Kyuna	25	25	Low-density residential developments

Table 4.1: Urban contexts in Nairobi
Source: Author

Due to the high ground coverage percentages and high plot ratios in Westlands, the urban ventilation of the area is hampered by the upcoming relatively dense and high rise developments. The microclimate and air quality of the urban built environment have drastically declined due to the high rates of construction as well as the introduction of the expressway. In addition to this, the increasing urban heat island effect leads to higher daytime temperatures. Higher outdoor temperatures result in higher indoor temperatures, which leads to a greater demand for buildings in this area to provide sufficient ventilation and cooling. These circumstances led to the selection of Westlands as the study area.

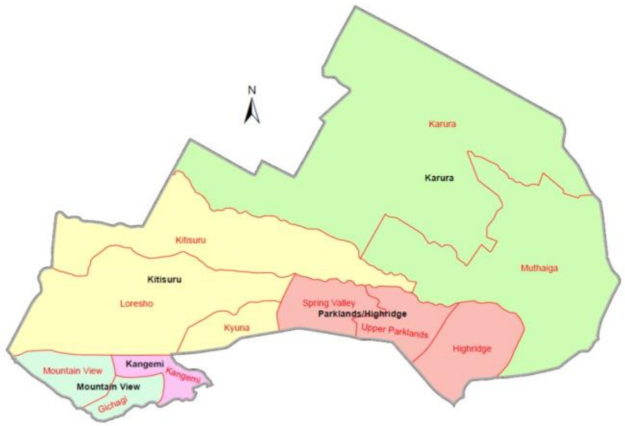


Figure 4.27: Map of Westlands Constituency
Source: https://www.ma3route.com/

4.3 WESTLANDS

Approximately 3.2 km from Nairobi C.B.D., Westlands area is known for its many company headquarters' buildings. The area used to be a low density residential area but since the 1990's the character of the area has been changing rapidly from the low density residential development to high-rise office blocks. Westlands was a residential neighborhood of Nairobi during the colonial period which ended in 1963. During the 1990s and early 2000s, as land and office space became scarce and exorbitantly priced in the central business district, more businesses relocated to Westlands and Upper Hill, where land and office space was more readily available and less expensive. Westlands was initially considered part of the Parklands area and straddled what is now Waiyaki Way, originally the Kenya Uganda Railway.

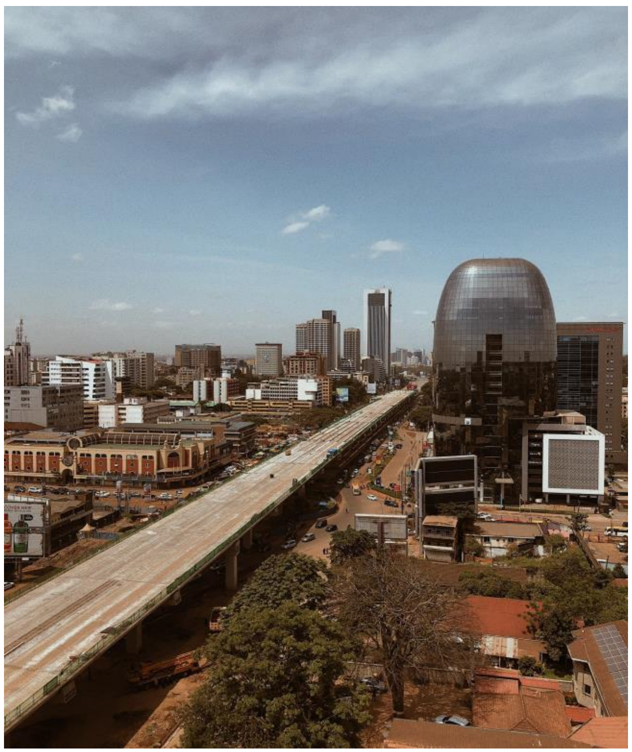


Figure 4.28: Developments in Westlands
Source: Author's archive

Figure 4.29: Map illustrating various zones in Westlands constituency. Study area has been highlighted in red
Source: Google Earth Pro- Author modified

Figure 4.30: Perspective of Delta Corner Towers and One Africa Place
Source: Author's archive

Figure 4.31: Perspective of Developments in Nairobi
Source: Author's archive

4.3.1 URBAN HISTORY OF WESTLANDS AREA

Land use patterns: Over the years, the area has been transformed from a residential area to an area with high-rise officeblocks and commercial buildings and residential apartments.

Built Density: Peeling back the layers of history reveals the change in built density in this area of study brought about by changes in by-laws, people population, concentric growth of the CBD, which has resulted in the increase of plot ratio over the years hence increase in built density. With increase in plot ratio, the building density in the area has increased. At the moment, the minimum plot area is 0.05 Ha with a ground coverage of 60% and a plot ratio of 300%.

Circulation: Although in the early 1900's there were no cars, the plan did lay out roads. The roads clearly indicated boundaries between different residential areas. Initially, the railway road was the major means of circulation infrastructure with a series of dusty roads that made the above stated boundaries between the residential areas and their accesses. These accesses have been made elaborate with time by giving them a tarmac finish. Owing to the fact that development in Westlands area has taken place on the basis of the existing surveyed plots whose use was originally residential, the road circulation orientation has not changed much.

4.3.2 URBAN FUNCTIONS OF WESTLANDS

Westlands area has developed over years from an exclusive residential area for the Kenya-Uganda railway officers to what is now a business economic centre. Below are some of theactivities housed in the many buildings in Westlands area today.

Residential: Residential areas include W Place furnished apartments, Capital M Apartments, Matinga Court, Sitara Apartments, Diplomatic Apartments, Kiya furnished rooms, Taarifa suites among others.

Figure 4.32: Perspective of Developments in Westlands
Source: Author's archive

Figure 4.33: Perspective of Developments in Nairobi
Source: Author's archive

Entertainment: There are several entertainment and fast food establishments found in the area. These include The Node, Urban eatery, Clay oven restaurant, Mama Rocks restaurant, Havana Bar and Restaurant among others.

Banks: Banks in the area include Ecobank, Equity bank, NCBA bank, Sidian Bank, SBM bank, First Community Bank, Fidelity bank and Fina Bank

Office blocks: Office blocks in the area include One Africa Place, ICEA Lion Head Offices, Delta Offices, PWC Offices, GTC Office Tower, Kofisi flexible working space, Fortis Tower, Eden Park Offices, Chiromo Business Park and Universal Towers among others.

Hospitals: Hospitals in the area include Menorah hospital, Muthithi medical centre, Chiromo lane medical centre and International health centre.

Schools: Learning institutions found in the area are Graffins College and Citech Institute

4.3.3 WESTLANDS STUDY AREA

Due to the vastness of Westlands area, stratifying the area in zones based on office building forms and densities saw the area along the expressway being chosen as the area of study. The study was limited to the stretch between Rhapta Road / Ring Road round about and Riverside Drive/ Waiyaki Way Junction. This area has a variety of office building forms, façade treatments, building heights and densities all which affect wind flow patterns into the building and will thus affect the design of their thermal chimneys.

The following buildings were selected for the study:

i. Global Trade Centre Office Tower
ii. The Riverfront Offices
iii. ICEA LION Group Head Office

Figure 4.34: Perspective of Developments in Nairobi
Source: Author's archive

iv. Delta Corner Towers

v. One Africa Place

The selection of five case studies gives an adequate study sample. This makes it possible to carry out a thorough analysis and make conclusive recommendations for design of thermal chimneys in the tropical uplands climate.

CHAPTER FIVE: FIELDWORK

5.0 Introduction

5.1 Global Trade Centre Office Tower

5.2 The Riverfront Offices

5.3 ICEA LION Group Head Office

5.4 Delta Corner Towers

5.5 One Africa Place

5.6 Comparative analysis of case studies

5.7 Summary

5.0 INTRODUCTION

The previous chapters of this thesis grounded the study on a theoretical basis. This chapter focuses on the fieldwork findings carried out in Westlands, Kenya. The findings are based on the identified broad parameters of climatic analysis, morphology, spatial design and ventilation performance analysis of the case studies.

Five buildings of interest were selected and an in-depth study was carried out from 20th March to 16th April, 2022. The data collected from the digital data loggers for each office building was analysed with respect to the building orientation, building shape, external obstructions, spatial layout, layout arrangement, opening control of windows, window sizes and position, room sizes and spatial use.

The data collected from the indoor and outdoor environment was used to recreate a three dimensional model of the building which was used for geo-referenced CFD simulations. In order to improve air change rates within the building, an initial thermal chimney (based on the recommendations from chapter two) was modelled for the building and computational fluid dynamics simulations were done to determine the air change rates in the interiors.

The thermal chimney design parameters (configuration factors, installation factors and construction materials) were tweaked until the recommended air change rates per hour are achieved, as confirmed by the simulations.

The thermal chimney design parameters were derived from the final chimney model. These design parameters are dependent on the building characteristics and make it possible to form generalizations for future use.

The variations of thermal chimney design parameters for each building type have been compared in order to understand how the parameters change as building characteristics change.

Figure 5.1: Map showing selected case studies
Source: Google Earth Pro

Figure 5.2: Case study 1- Global Trade Centre Office tower
Source: Author's archives

Figure 5.3: Case study 2- The Riverfront Offices
Source: Author's archives

Figure 5.4: Case study 3- ICEA LION Head Offices
Source: Author's archives

Figure 5.5: Case study 4- Delta Corner Towers
Source: Author's archives

Figure 5.6: Case study 5- One Africa Place
Source: Author's archives

5.1 GLOBAL TRADE CENTRE OFFICE TOWER

5.1.1 INTRODUCTION

Client: AVIC International

Location: Westlands, Nairobi

Completion: 2022

Architect: Triad Architects and GMP Architects

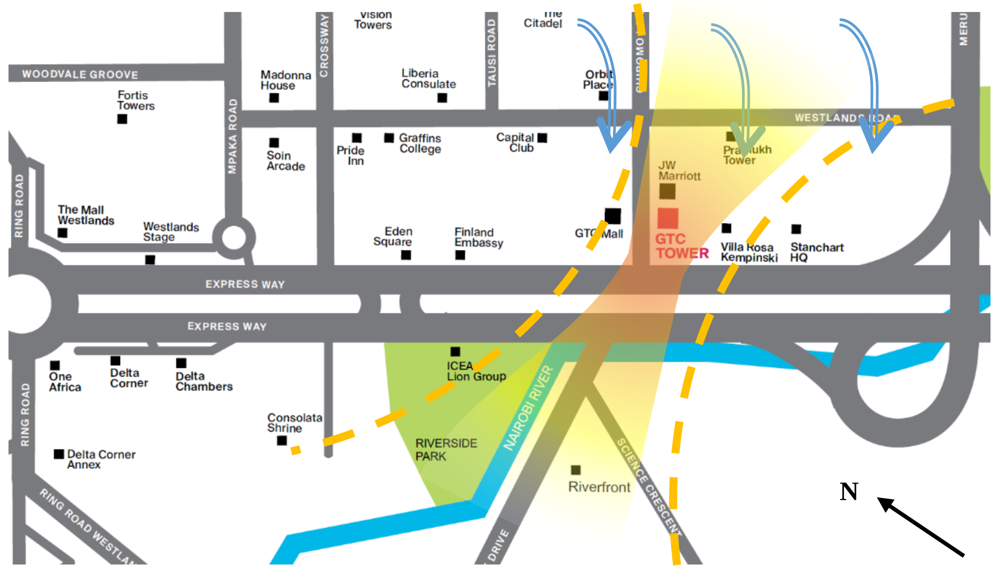


Figure 5.7: Location plan highlighting GTC Office tower
Source: https://www.knightfrank.co.ke/ Author modified

The Global Trade Centre development is one sophisticatedly built cluster of six high rise buildings that form a unique mixed use development. The development comprises four residential towers, a mall, the JW Marriott Hotel and an office tower.

The GTC Office Tower is an iconic forty-two-storey commercial office development with an approximate total gross lettable area of 57,000m^2. The building will be ready for occupation in July 2022.

5.1.2 MORPHOLOGY

i) Site planning: The tower is strategically positioned in an excellent location at the intersection of Chiromo Road, Chiromo Lane and Westlands Road in Westlands, Nairobi.

ii) External elements/ obstructions: The building is bordered by the Expressway to the South West, by Villa Rosa Kempinski to the East, by JW Marriott Hotel to the North East and by GTC Mall and Chiromo Lane to the West.

iii) Orientation: The building is oriented with the longer axis along the North East/ South West axis.

The North Easterly prevailing winds are perpendicular to the shorter side of the building façade instead of the longer façade, which would have been more advantageous for providing natural ventilation.

iv) Building form: The office tower is 184m high with a rectangular floor plate (43m by 44m) and a cuboidal form. It has 800mm deep vertical fins projecting on all four sides of the building facades.

The roof is a flat concrete slab. The ground floor is raised by 5.85m in order to create ample space for basement parking.

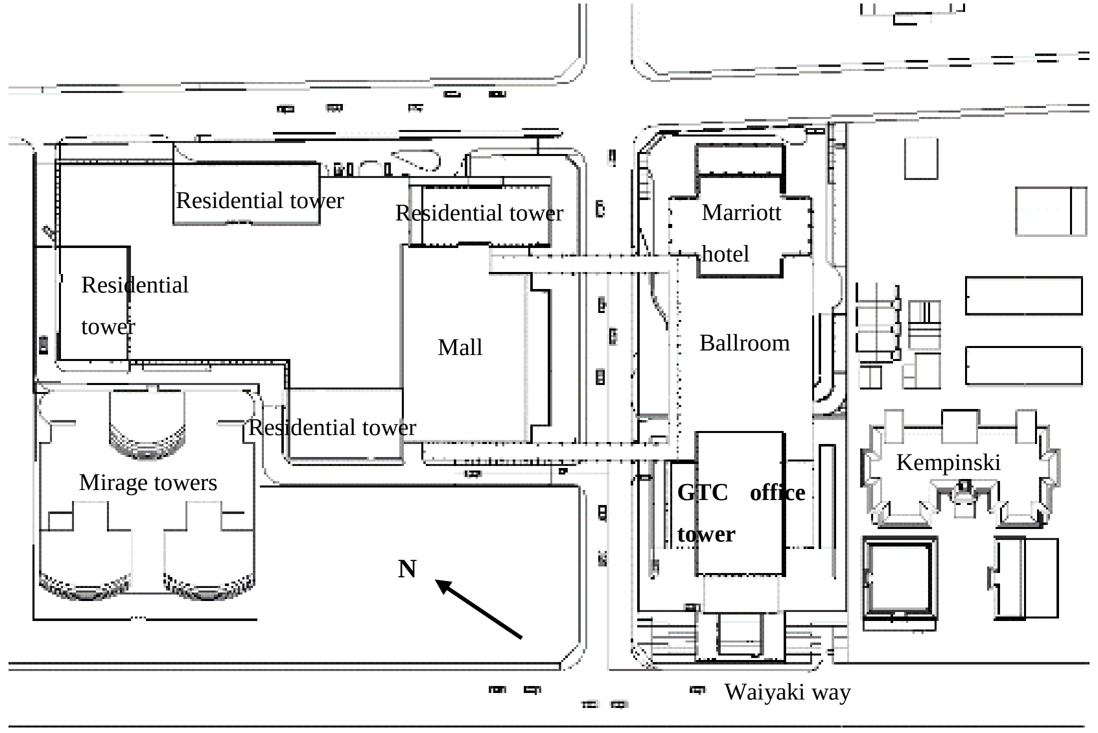


Figure 5.8: Site plan of GTC Development
Source: Author

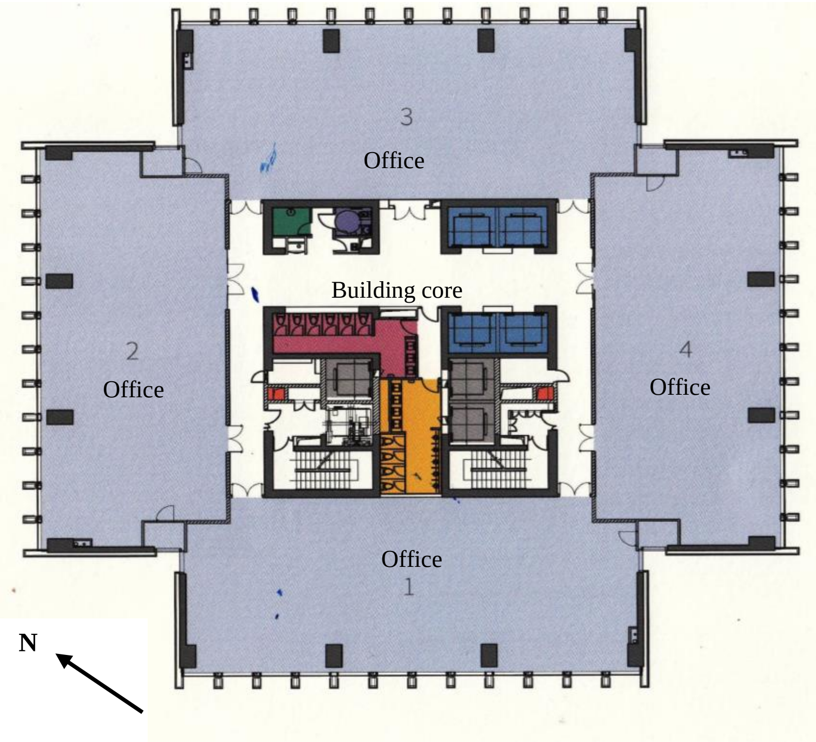


Figure 5.9: Floor plan of GTC office tower
Source: Author's archives

Figure 5.9: Model of GTC Development
Source: Author

Figure 5.10: Sky bridge connecting the office tower to the mall
Source: Author

5.1.3 SPATIAL DESIGN

The parameters that have been analysed under spatial design include:

i) Construction materials
ii) Surface finishes
iii) Floor layout
iv) Opening location and size
v) Opening control
vi) Wall thicknesses
vii) Floor to ceiling height
viii) Room sizes and spatial use
ix) Sun shading devices

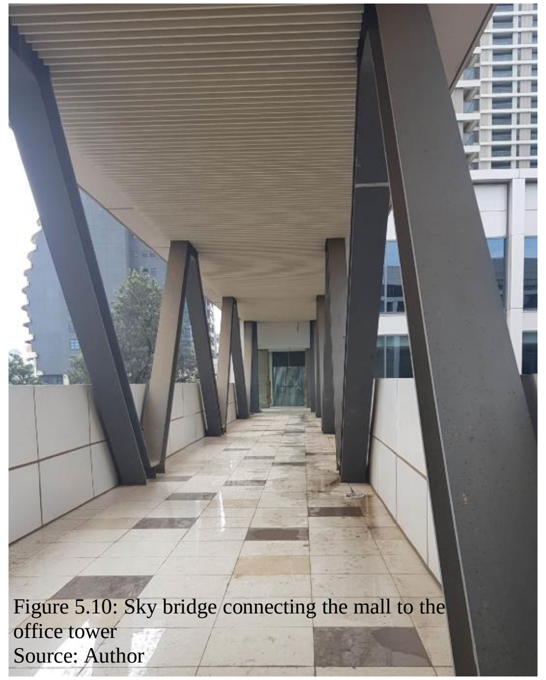
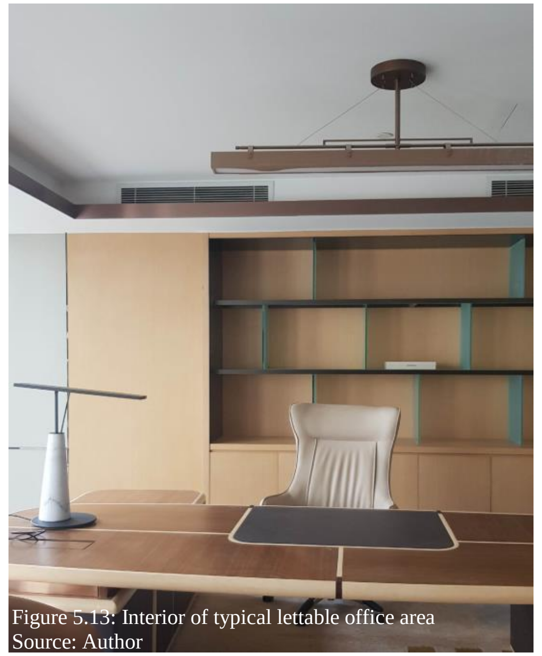
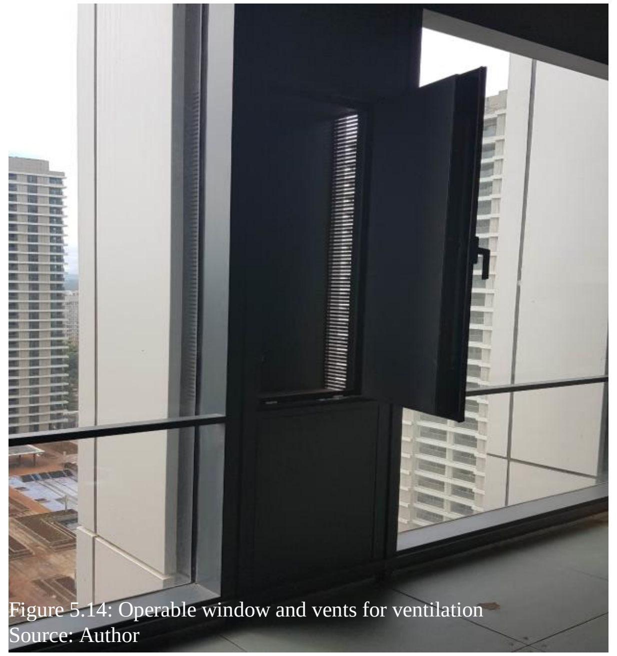
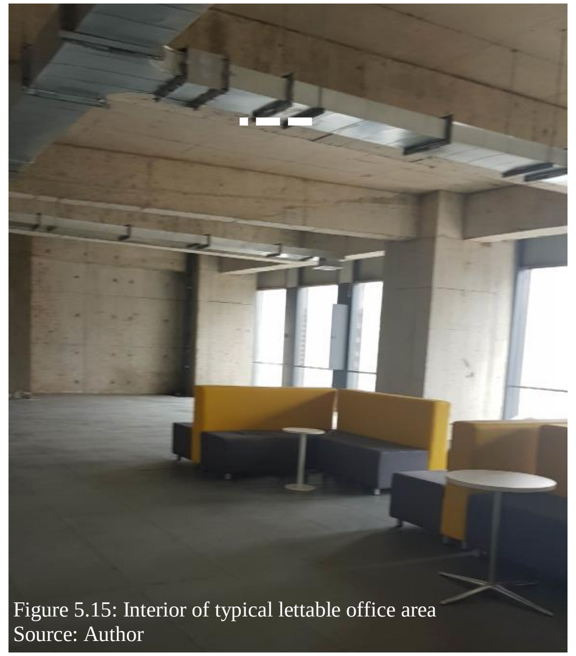


Figure 5.10: Sky bridge connecting the mall to the office tower
Source: Author

i. Construction materials	ii. Surface finishes	iii. Floor layout	iv. Opening location and size	v. Opening control
The structure is made of 1500mm by 1200mm reinforced concrete columns and 830mm deep reinforced concrete beams. Some external wall panels are made of reinforced concrete for structural purposes. The rest of the external walls are made of low – E coated curtain glass walling to ensure optimal natural lighting and blocking of indoor infrared penetration to ensure temperature balance and energy conservation of the air conditioning system. The core walls are made of reinforced concrete.	The lettable spaces have no surface finishes. The concrete floors, walls and ceilings are left bare so that the users can customize the space. In the common areas, the ceilings are made of gypsum which is a good heat insulator. The wet areas have non slip porcelain tile floor finish. The external wall panels and vertical fins that are made of reinforced concrete have been cladded with white composite aluminium panels that measure 1680mm wide by 3980mm long. The light colour helps to reflect away excess heat.	The building has 42 floors. On each floor, the core and services are located at the centre and the open plan office spaces surround the core as illustrated in the floor plans. The rectangular floor plate with no columns in the interiors creates extremely functional and flexible spaces. The office spaces have narrow widths of approximately 11m-13m which are almost sufficiently naturally lit by the 4m high external wall glass panels.	The exterior breathable curtain wall glass is divided into fixed panels that measure 1750mm wide by 5100mm high. There are fixed louvres on the sides of the vertical fins, which can be accessed by side hung aluminium panels that measure 1400mm high by 440mm wide. The area with the fixed louvres measures 180mm wide by 1400mm high. The four doors at the main entrance area are side hung double doors and measure 2150mm wide by 3080mm high.	The exterior low – E coated curtain wall glass is fixed. It lacks operable panes. The doors at the entrance area are side hung double doors and have a maximum opening angle of 90^0. The fixed external louvres that ventilate the air conditioning rooms are angled at 30^0. This allows for air movement into and out of the building while preventing rain water from getting into the room.
 Figure 5.11: Aluminium composite panels on the office tower Source: Author	 Figure 5.12: Interior of typical lettable office area Source: Author	 Figure 5.13: Interior of typical lettable office area Source: Author	 Figure 5.14: Operable window and vents for ventilation Source: Author	 Figure 5.15: Interior of typical lettable office area Source: Author

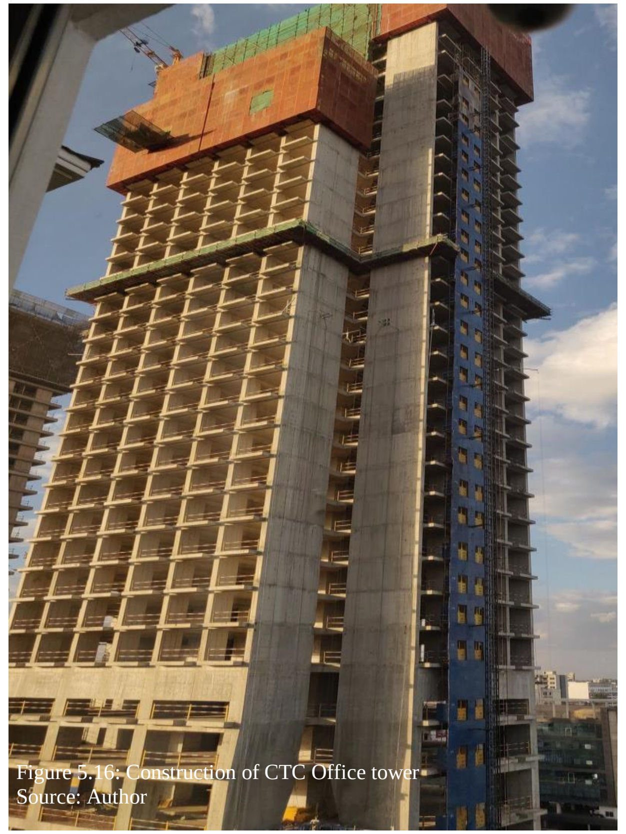
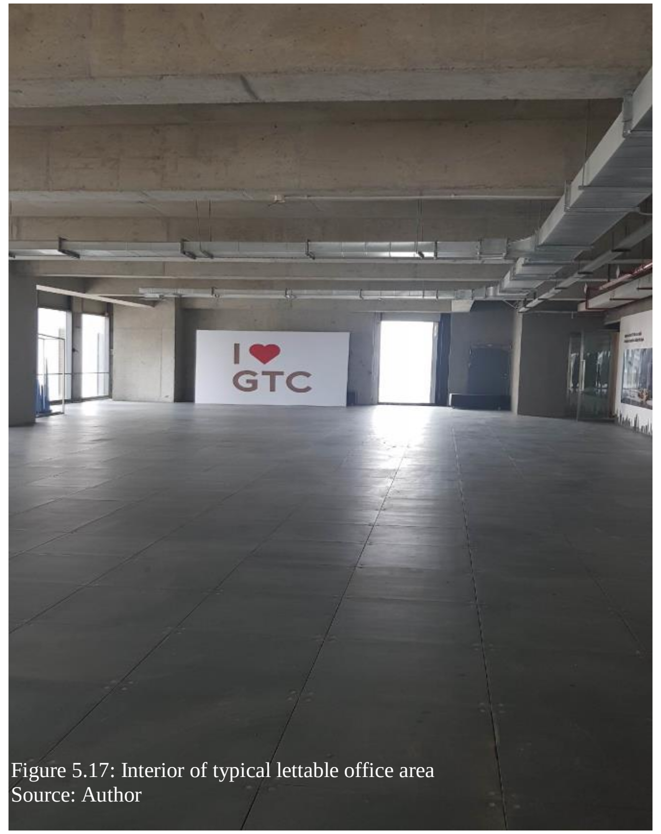
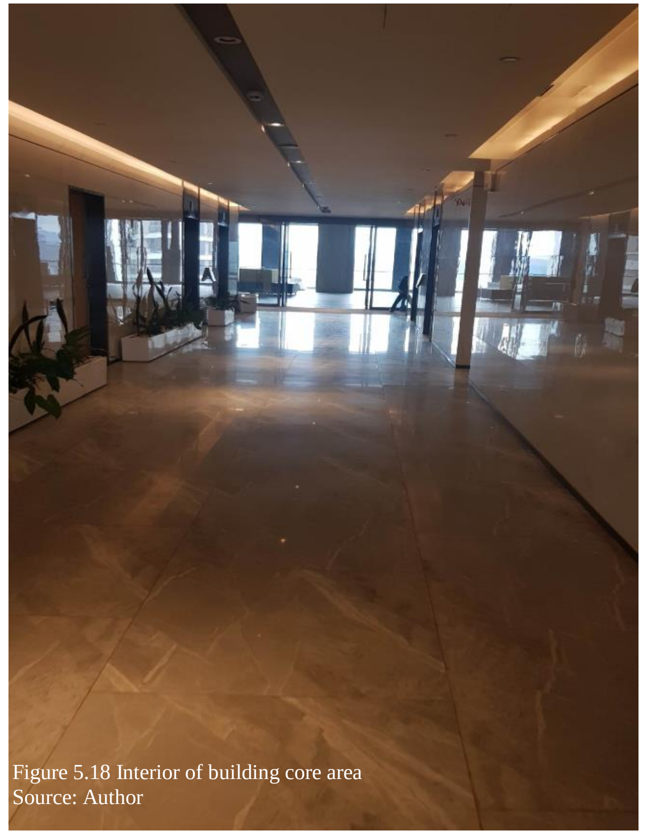
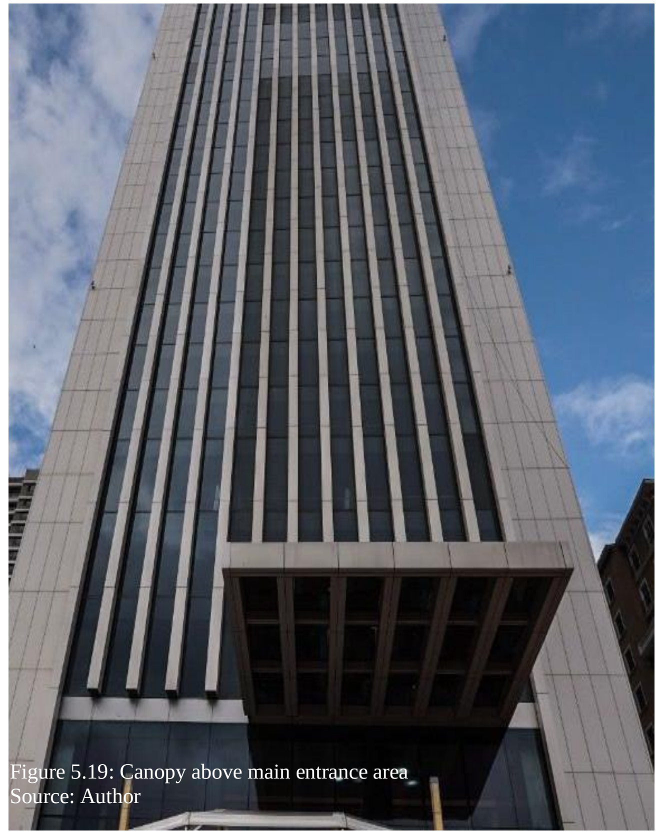
vi. Wall thicknesses	vii. Floor to ceiling height	viii. Room sizes and spatial use	ix. Sun shading devices	Interview questions
The external walls have a thickness of 500mm for structural purposes as well as provision of high thermal mass. The internal core walls have a thickness of 600mm for structural purposes.  Figure 5.16: Construction of CTC Office tower Source: Author	The gross room height is 4000mm (top of slab to bottom of slab). The ground floor lobby has a floor to ceiling height of 11000mm, highlighting the grand scale of the development.  Figure 5.17: Interior of typical lettable office area Source: Author	The office spaces have narrow widths of approximately 10m which are almost sufficiently naturally lit by the 4m high external wall glass panels. Each office floor has a core which has 12 high speed lifts, two staircases, a fire duct, washrooms and a pantry.  Figure 5.18 Interior of building core area Source: Author	The building has 800mm deep vertical fins projecting on all four sides of the building facades. These do not adequately shade the interior spaces from direct sunlight. The entrance area is defined by a canopy that measures 23000mm long by 12000mm deep and it adequately shades the interior lobby from direct sunlight.  Figure 5.19: Canopy above main entrance area Source: Author	i. How many people visit the building per day? Approximately 20 to 30 people visit the show office per day. ii. Do users exhibit symptoms of sick building syndrome? Not yet so far. iii. What improvements have been made to this building since it was built? None so far. iv. How many hours in a day is the building in use? Currently, the building is in use from 8am to 5pm. In July 2022, it will be functional for 24 hours. v. Do you feel the need to acquire or use a fan? Yes, during the hot months like February vi. Which rooms/ spaces are used most during daytime? The offices vii. Which rooms/ spaces are used most during the night? The offices (as from July 2022). viii. Do you ever open the windows, if any? If so, when? Yes. During the day from around 11am

Figure 5.20: Perspective of GTC Office Tower
Source: Author

5.1.4 VENTILATION PERFORMANCE ANALYSIS

i) External wind effects generated by GTC Office Tower

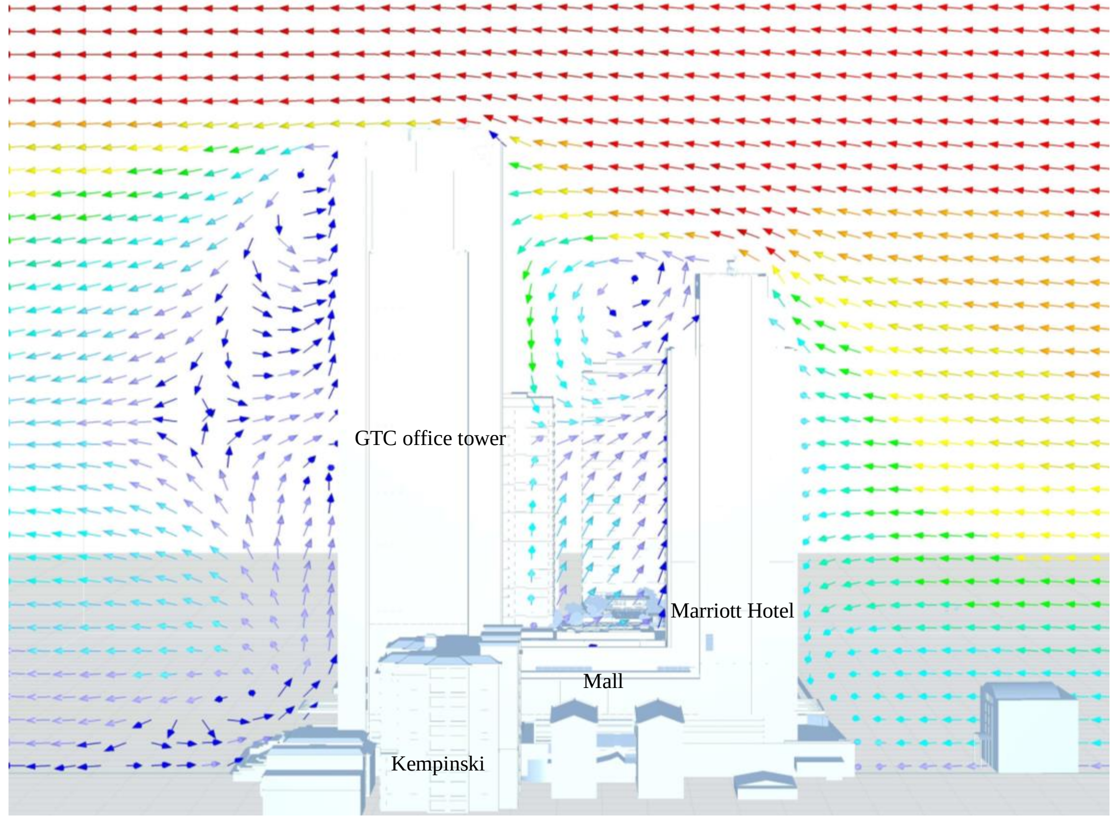
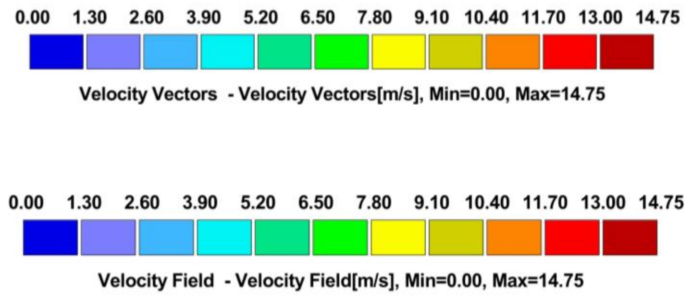


Fig.5.21: Side elevation of GTC Office tower illustrating the velocity vectors around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

KEY



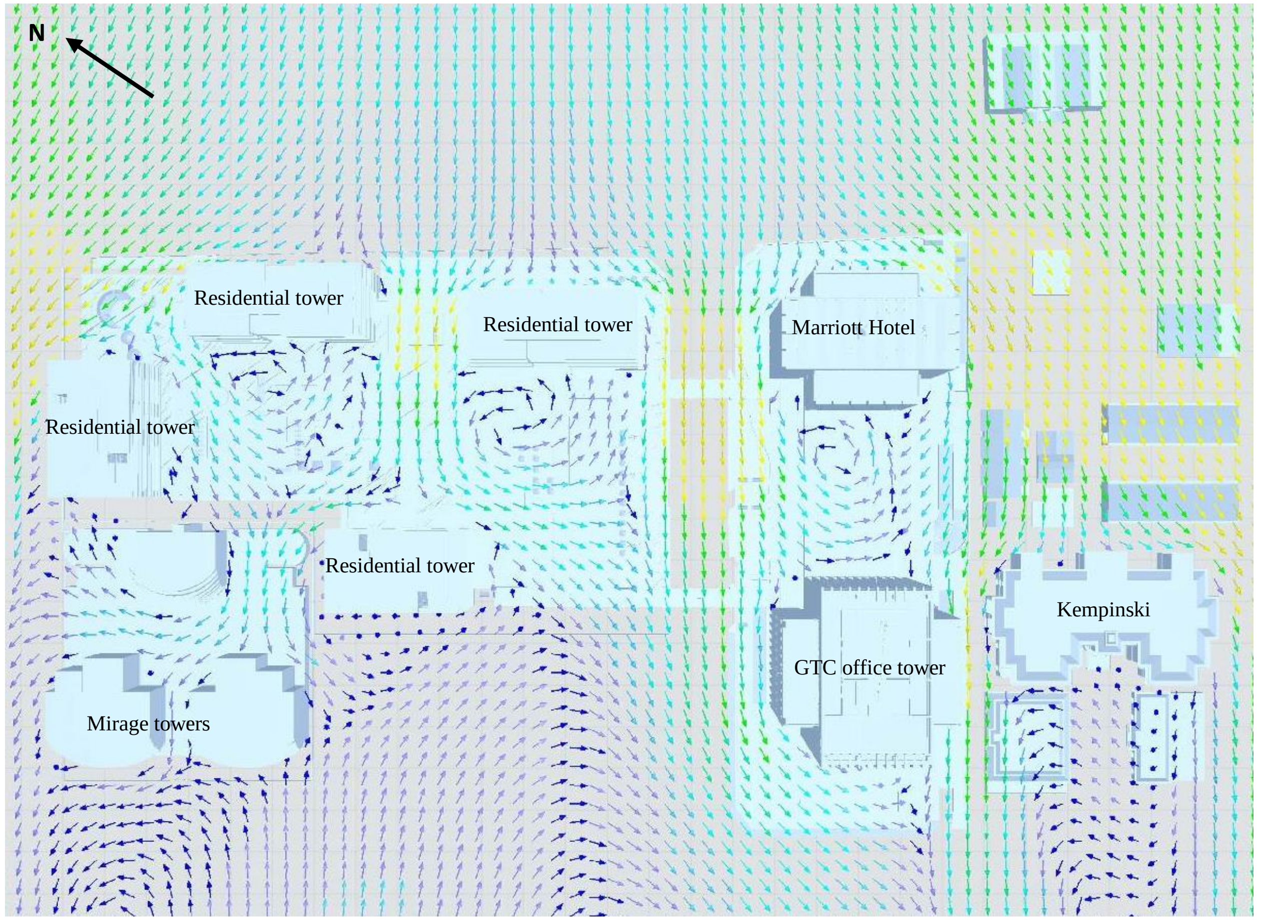


Fig. 5.22: Plan view of GTC Office tower illustrating the velocity vectors around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

The GTC office tower is surrounded by both short and tall buildings. This urban environment creates the following wind effects:

Downdraught effect: This happens when there is a tall building surrounded by lower buildings. The tall building captures the wind at higher levels and then redirects it towards the ground, causing a three-dimensional flow moving downwards. In turn, this effect often creates a large recirculation at the ground level, causing greater wind activity. This is experienced at the back side of the JW Marriott Hotel.

Channeling: This happens due to the Venturi effect and is experienced when buildings are located in close proximity to one another, with the wind flow direction being parallel to the street or canyon. The effect is perpetuated by a reduction of wind pressure, resulting in wind acceleration through the tight channel created between the buildings. This is experienced in the canyon between the GTC office tower and Kempinski hotel, which is has an aspect ratio of 7.1.

Vertically rotating wind flow: This is experienced when the wind flow direction is perpendicular to the canyon. A vertically rotating wind flow is created with a centered primary vortex inside the canyon. This is experienced in the canyon between the GTC office tower and the JW Marriott Hotel, which has an aspect ratio of 3.55.

Corner acceleration: This happens when the wind reaches the vertical edge of a tall building. This effect is mainly created from sharp building shapes, causing acceleration around the corners. This is experienced along the sharp vertical edges of the GTC office tower.

This analysis of wind velocities and movement patterns around the GTC office tower has been used to inform the placement of the air inlets and air outlets within the building's proposed thermal chimney ventilation system. It is advisable to ensure that the air inlets face the North Eastern and South Western direction while the outlets should face the South Eastern or North Western direction.

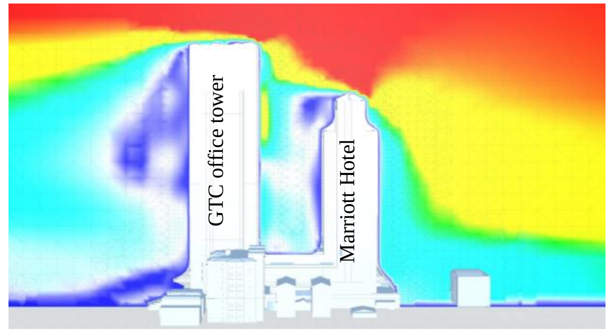


Fig. 5.23: Side elevation of GTC Office tower illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

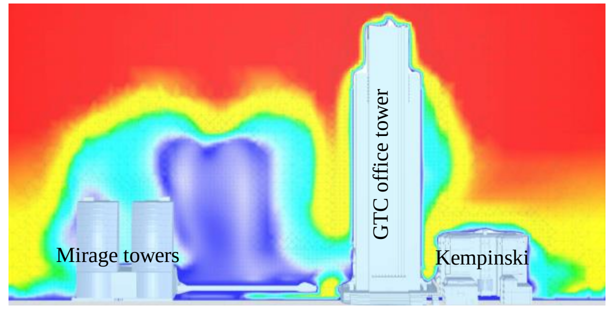


Fig. 5.24:Front elevation of GTC Office tower illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

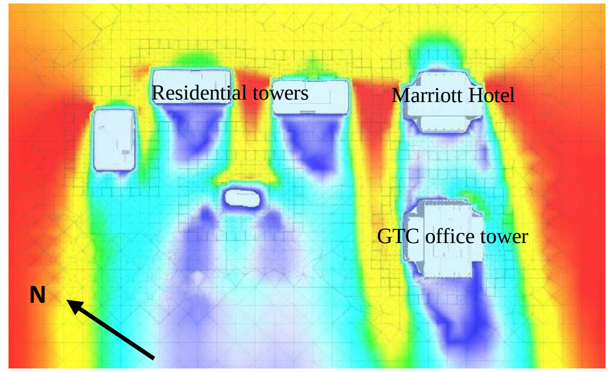


Fig. 5.25: Plan view of GTC Office tower illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

ii) Internal ventilation performance analysis

The rotating vane anemometer was placed in an office on the 3rd floor. The anemometer has a single rotating vane that was used to capture air speeds through the fixed louvres. The readings were taken between the dates 20th March and 16th April 2020.

Air speed:

Readings from the graph indicate that the highest outdoor air speeds were experienced between 12 noon and 6pm, while the lowest speeds were experienced between 12 midnight and 6 am.

Readings from the graph indicate that the velocity through the fenestrations (indoor air apeed) is fairly low, with the lowest values being recorded at 12 midnight. The average velocity through the fenestrations is 0.08m/s.

Air changes per hour:

Since the building is naturally ventilated, the air changes per hour vary depending on the air velocity through the fenestrations. In sich cases, the air changes per hour are obtained as explained below:

ACH= Q/Vol

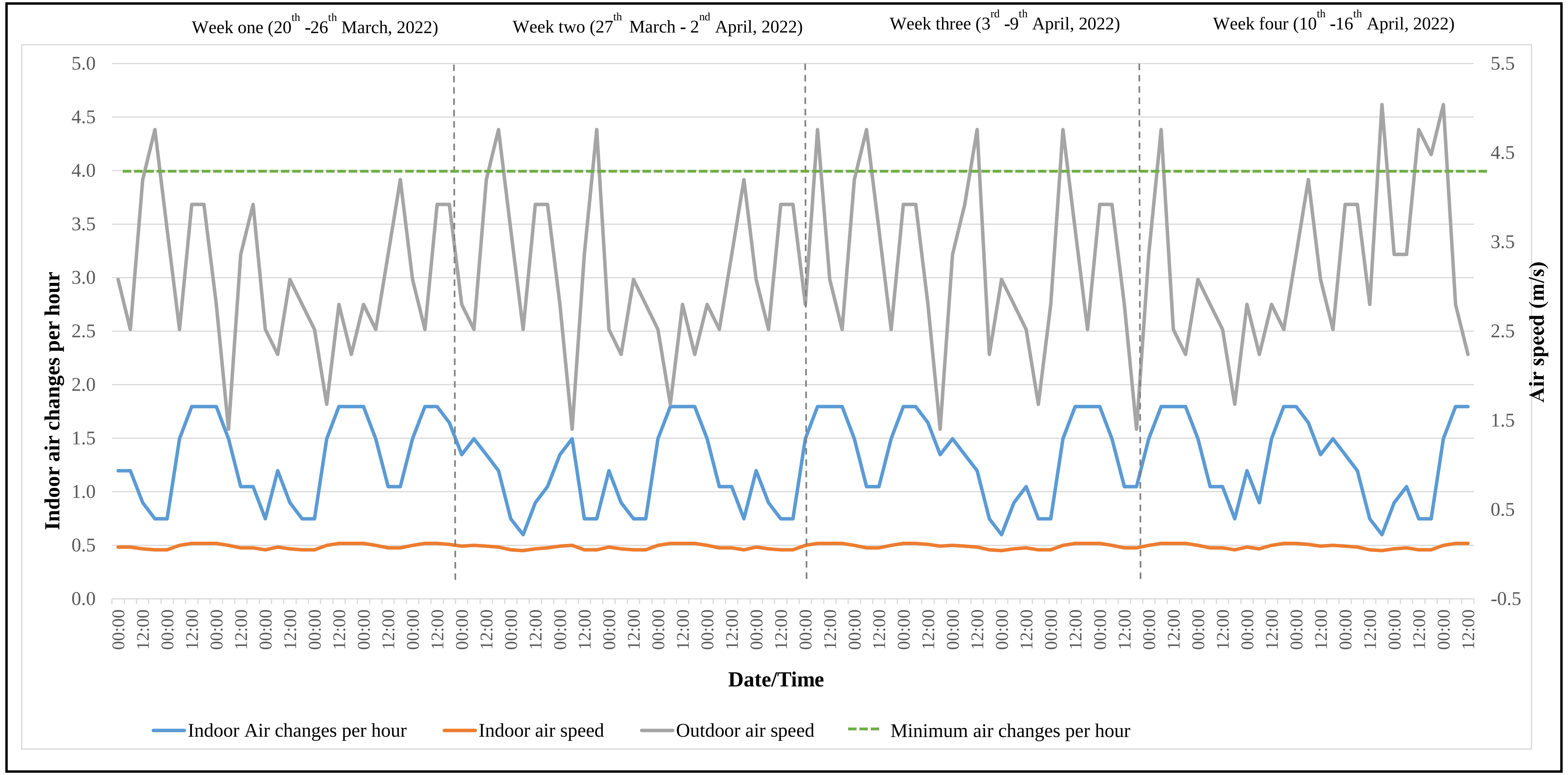
Where;

Q= Volumetric flow rate of air in m^3/hr (Velocity of air through the fenestrations in m/s x area of fenestration in m^2 x 3600)

Vol= Volume of room in m^3 ($278m^2$ x 4m)

Average ACH = 1.2 air changes per hour

This is significantly below the recommended figure of 4 air changes per hour, meaning that the office is not being sufficiently ventilated. The office needs ventilation systems that will provide more air changes.



Graph 5.1: Graph showing the indoor air changes per hour, indoor air speed and outdoor air speed for an office space in GTC Office tower
Source: Author

5.1.5 VENTILATION PERFORMANCE ANALYSIS WITH PROPOSED THERMAL CHIMNEY

CFD simulation tool: Designbuilder was chosen as the CFD simulation software in this study, incorporating the EnergyPlus calculation engine which has been validated under the Evaluation of Building Energy Analysis Computer Programs test. Natural ventilation studies were performed through CFD simulation of indoor airflow for the lettable space in the case-study using the weather files from Dagoretti Meteorological Station for accurate results.

CFD boundary conditions:

i. The calculated module was preferred over scheduled module where the calculation engine uses information about building fabric & openings in conjunction with weather data and internal gains to calculate the pressure difference and air flow through each zone.
ii. The system is at steady state.
iii. The working air behaves like an ideal gas.
iv. The air at the entrance in the thermal chimney to the outlet is without friction or leakages
v. The thermal chimney walls are used as heat flux sources
vi. Properties (pressures, temperatures and density) are assumed at standard with the standard atmospheric conditions.
vii. The flow is assumed to be laminar.

Model description: The study area as highlighted on the floor plan has a floor area of 278m^2 and a floor to ceiling height of 4m. A typical lettable area on the third floor was selected for the study. There are fixed louvres on the sides of the vertical fins, which measure 180mm wide by 1400mm high. Only the louvres have been featured in the simulation model.

Thermal chimney cavity height: The thermal chimney's cavity height is bound by the height of the office space (including the thickness of the roof slab). The cavity height increases by a height of 2 m for each consecutive trial. The cavity heights of the first and last trials are 6.15m and 10.15m respectively.

Thermal chimney inclination angle: The study is limited to wall mounted thermal chimneys. Therefore, for all trials, the inclination angle is set at 90^0.

Thermal chimney cavity width: The thermal chimney's cavity width is bound by 0.2m and 0.6m with an increment of 0.2m for each trial. Widths lower than 0.2m give fairly low air speeds while widths higher than 0.6m may be physically too large relative to the building.

Thermal chimney cavity length: The length of the thermal chimney cavity is a parameter commonly overlooked since airflow within the thermal chimney is generally a two-dimensional flow, based on the cavity width and height. For this study, the length is based on the widths of the existing vertical sun shading elements in order to match the existing facade. The thermal chimney's cavity length is bound by 0.5m and 1.5m with an increment of 0.5m for each trial.

Location: Four thermal chimneys have been placed on the South Western end of the office as shown in the models. This location has made it possible for the chimneys to increase air flow rates into the office while still receiving maximum solar radiation.

Thermal chimney outlet and inlet areas: The thermal chimneys have outlets at the top of the stack. This means that this area will be determined by the cavity width and length. As recommended in the literature review, the inlets and outlets have the same areas.

Thermal chimney construction materials: The chimneys have double glazing and are made of brick walls with a flat copper plate absorber.

Input parameters	Lower bound	Upper bound	Increment	No. of values
Cavity height	6.15m	10.15m	2m	3
Cavity gap width	0.2m	0.6m	0.2m	3
Cavity gap length	0.5m	1.5m	0.5m	3
Inlet area	0.1m^2	0.9m^2	-	3
Outlet area	0.1m^2	0.9m^2	-	3

Table 5.1: Input parameters used to model the various thermal chimney trials
Source: Author

With the examination of the influences of the input parameters, their combined effects on the indoor air speed are determined in order to design and optimize the thermal chimney. Although there are over 100 possible cases according to the limits from the table above, a first set of 20 cases (the lower and upper limits of the five input parameters) is modeled and simulated, after which the second set of 25 cases (chosen randomly) and the third set of 20 cases (chosen randomly) follow. The combined 65 cases are sufficient in developing a performance trend of the chimneys, which makes it possible to narrow down on the number of cases that will be presented for this study.

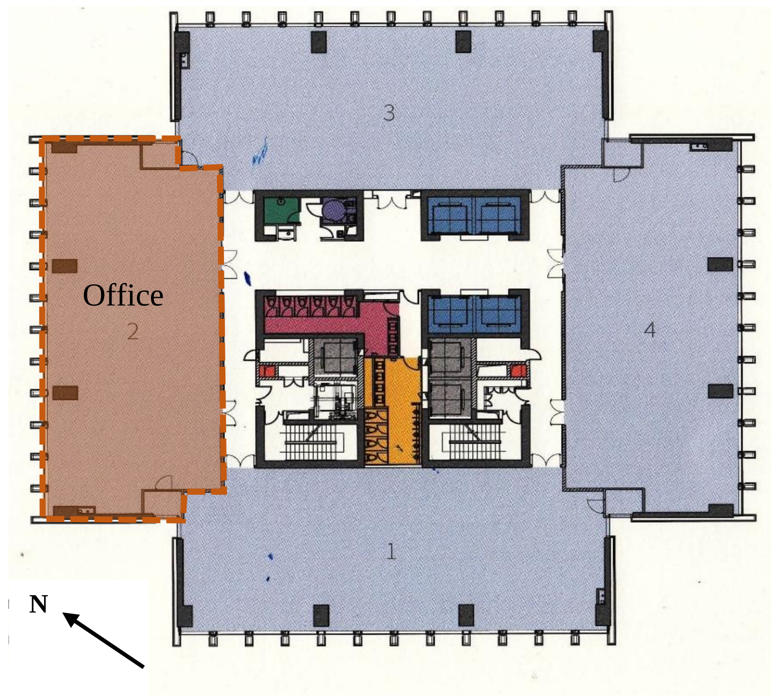


Figure 5.26: Floor plan highlighting the study area
Source: Author

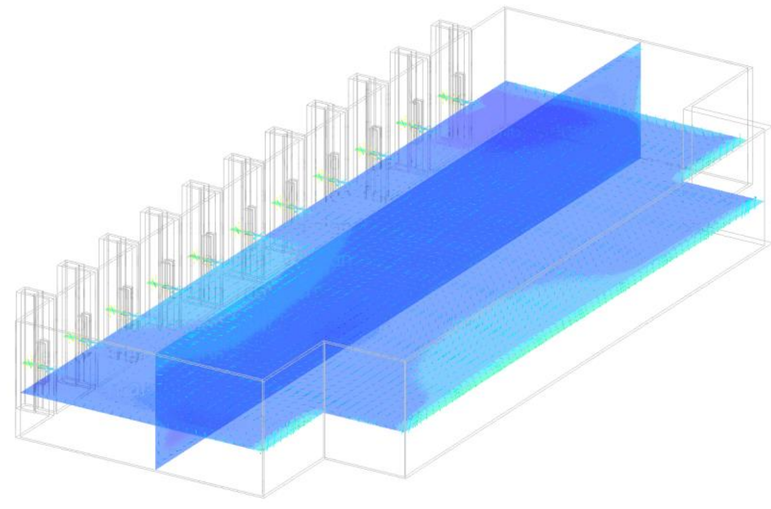


Figure 5.27: Existing ventilation conditions in the office. Average air speed is 0.08m/s with an average of 1.2 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

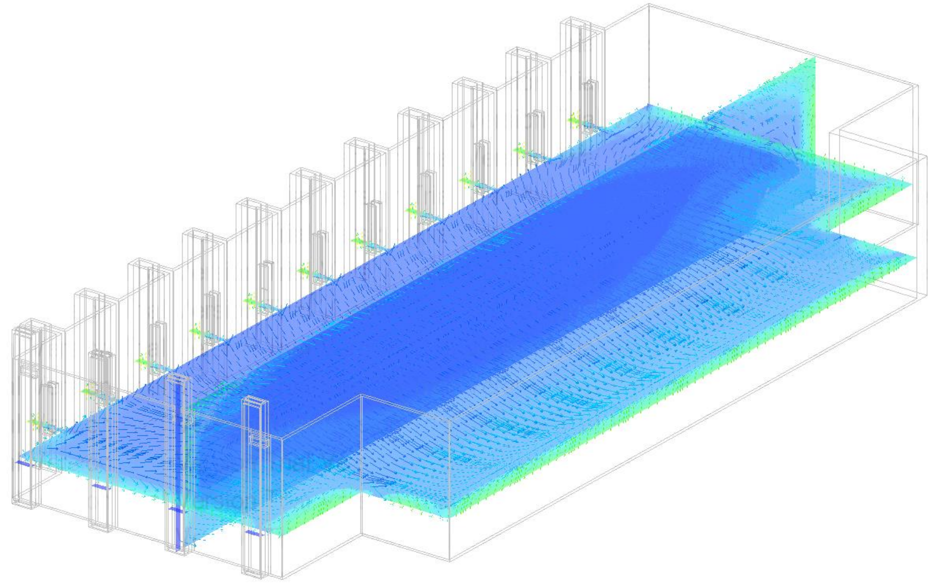


Figure 5.28: Ventilation conditions in the office with the first trial of the thermal chimney. Average air speed is 0.1m/s with an average of 1.5 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

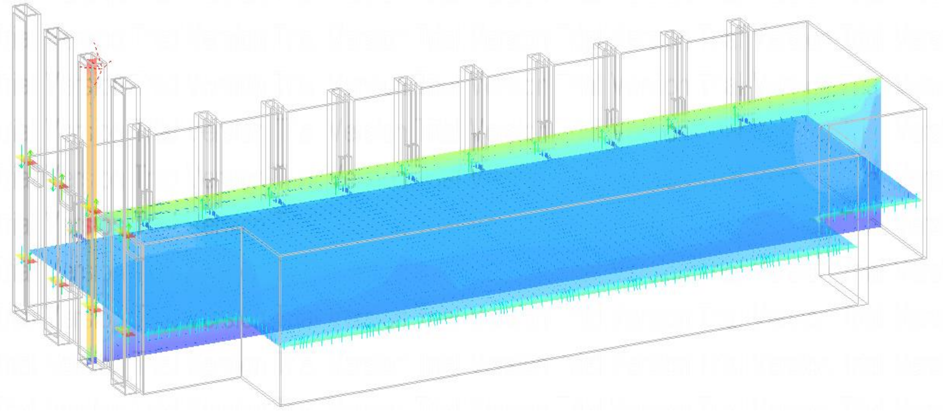


Figure 5.29: Ventilation conditions in the office with the second trial of the thermal chimney. Average air speed is 0.35m/s with an average of 5.3 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

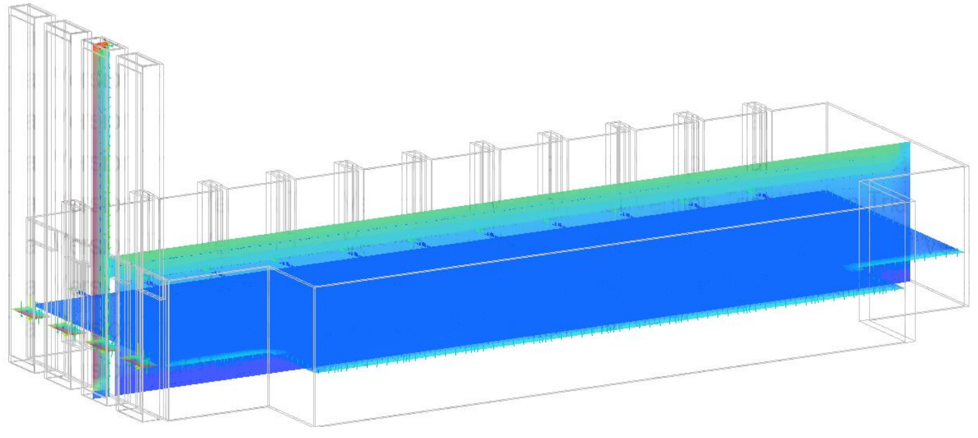


Figure 5.30: Ventilation conditions in the office with the third trial of the thermal chimney. Average air speed is 0.25m/s with an average of 3.8 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

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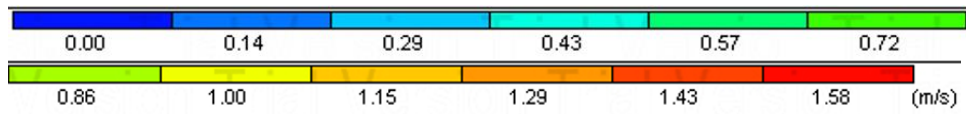


Analysis: The office majorly has a single-flow directional ventilation system due to the location of its vents. The existing conditions indicate that the office has an average of 0.7 air changes per hour, which is below the recommended minimum of 4 air changes per hour.

The thermal chimneys in the first trial give the lowest number of air changes per hour (1.5) as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.2m wide, the cavity heights are 6.15m and the cavity lengths are 0.5m. The narrow cavity widths result in friction losses which leads to a decrease in air speed.

The thermal chimneys in the second trial give the highest number of air changes per hour (5.3) as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.4m wide, the cavity heights are 8.15m and the cavity lengths are 1m. This combination gives the optimum number of air changes per hour for the office space.

The thermal chimneys in the third trial give 3.8 air changes per hour as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.6m wide, the cavity heights are 10.15m and the cavity lengths are 1.5m. The wide cavity widths and high cavity heights result in lower heat transfers within the chimney, which creates reverse flows in the stack resulting in decreased air speeds.

5.1.6 THERMAL CHIMNEY DESIGN RECOMMENDATIONS

The following are the design recommendations for four thermal chimneys for an office space with a floor area of 278m^2 and a floor to ceiling height of 4m:

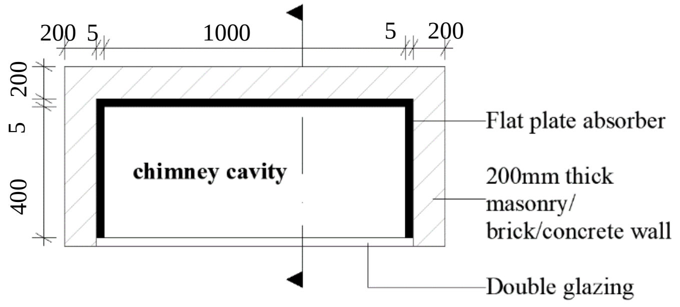


Figure 5.31: Plan of recommended thermal chimney
Source: Author

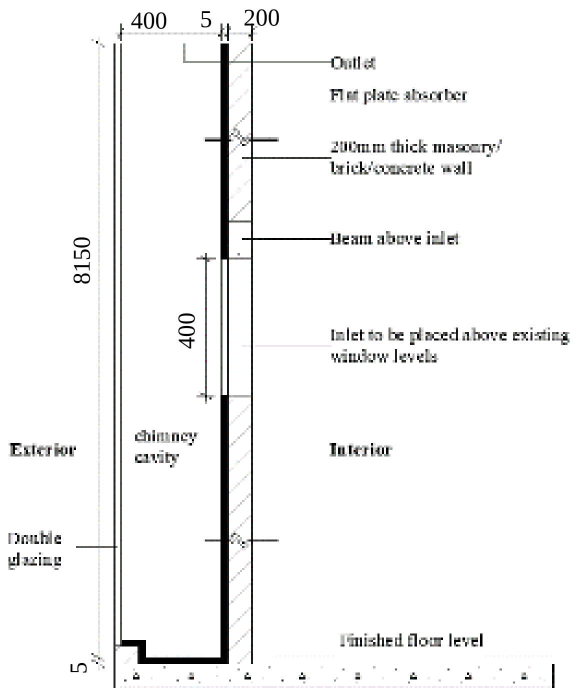


Figure 5.32: Cross section through recommended thermal chimney
Source: Author

Parameters	Variables	Description
Materials	Type of glazing	Double glazing
	Thermal absorber type	Flat copper plate absorber
Configuration	Cavity height	8.15
	Cavity gap width	0.4m
	Cavity gap length	1m
	Inlet area	0.4m^2
	Outlet area	0.4m^2
	Cavity height to gap width ratio	20.4
Installation	Inclination angle	90^0
No. of chimneys	Quantity	4

Table 5.2: Thermal chimney design recommendations
Source: Author

5.2 THE RIVERFRONT

5.2.1 INTRODUCTION

Location: Westlands, Nairobi

Completion: 2015

Architect: BAA Architects

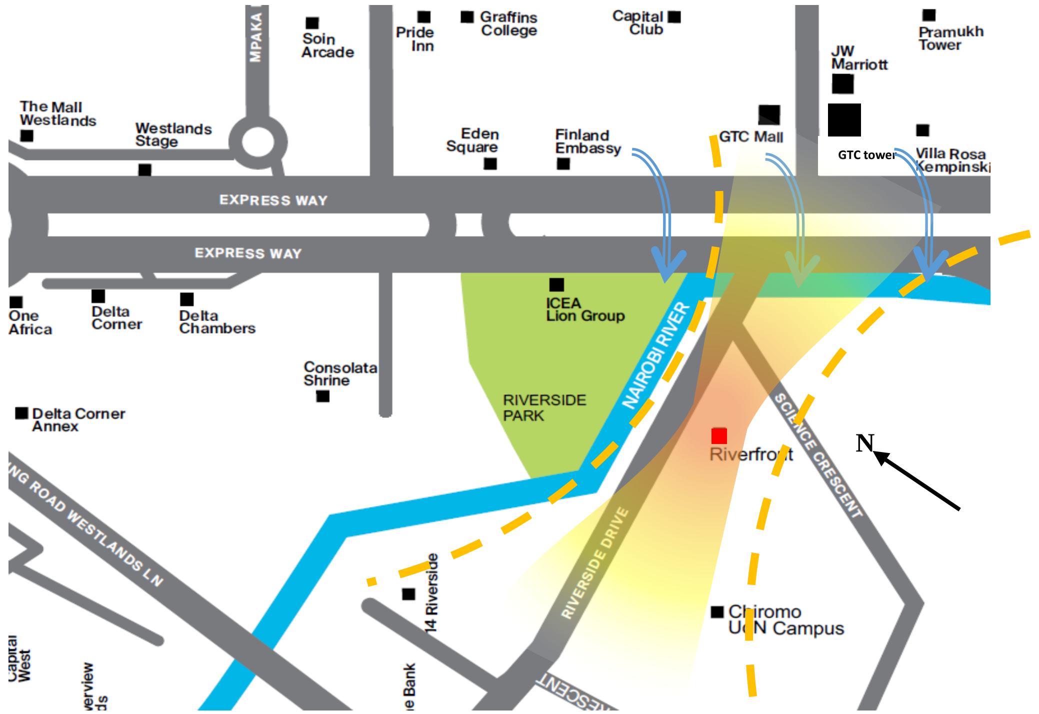


Figure 5.33: Location plan highlighting The Riverfront Offices
Source: https://www.knightfrank.co.ke/ Author modified

The Riverfront is an office development located at the junction of Riverside Drive and Science Crescent Road. The building houses offices and a restaurant. The development has two levels of basement parking for the builidng users.

The Riverfront development has an approximate total gross lettable area of 5,110m^2 spread across 5 floors.

5.2.2 MORPHOLOGY

i) Site planning: The office building is at the junction of Riverside Drive and Science Crescent Road. The area between the buildings is used as a parking lot. The Riverside park buildings are located behind these office buildings.

ii) External elements/ obstructions: The building is bordered by the Expressway to the North East, by ICEA Lion Group head Office 1 to the South East and by Riverside Park to the South West. The first head office is 41m away from the second head office. Both forms are identical.

iii) Orientation: The building is oriented with the longer axis along the South East/ North West axis. The North Easterly prevailing winds are perpendicular to the longer side of the building façade.

This ensures that the building receives sufficient natural ventilation.

iv) Building form: The office tower is 20m high with a U-shaped floor plate (32m by 37m) and a cuboidal form. Each floor has terraces that are 750mm deep, which partly shade the interior spaces from direct sunlight.

The building has two types of roofs - is a flat concrete slab and a hipped roof. The ground floor is raised by 0.9m in order to create ample space for basement parking.

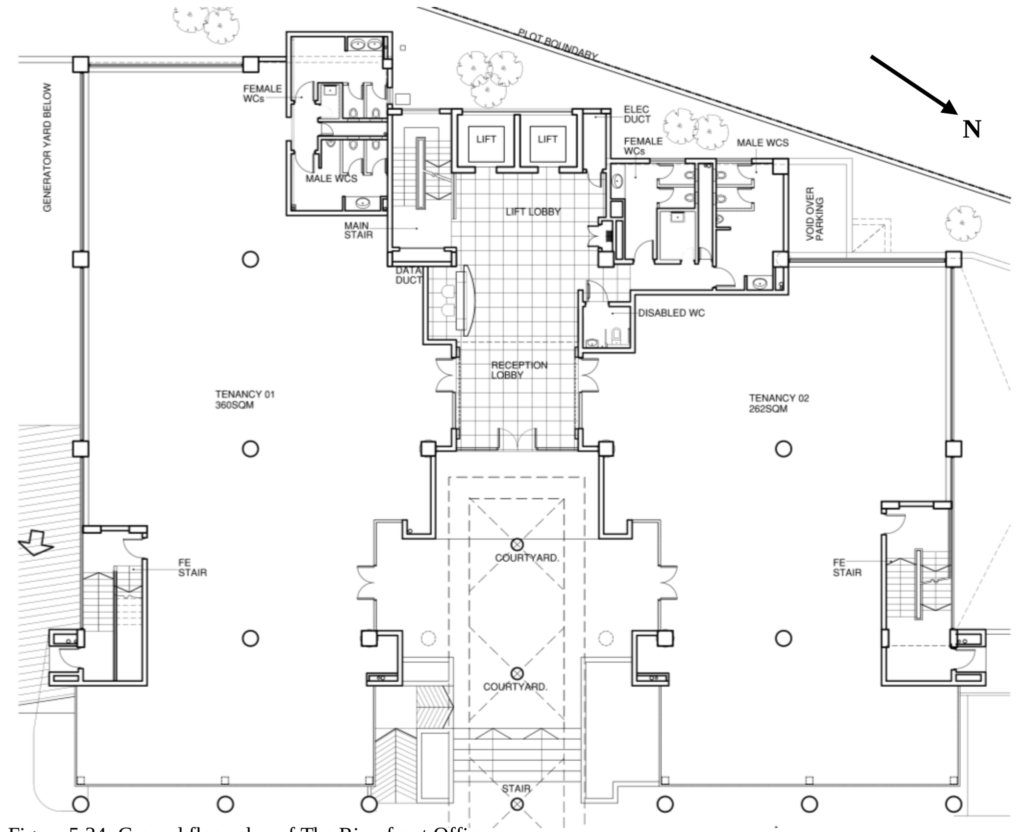


Figure 5.34: Ground floor plan of The Riverfront Offices
Source: Author

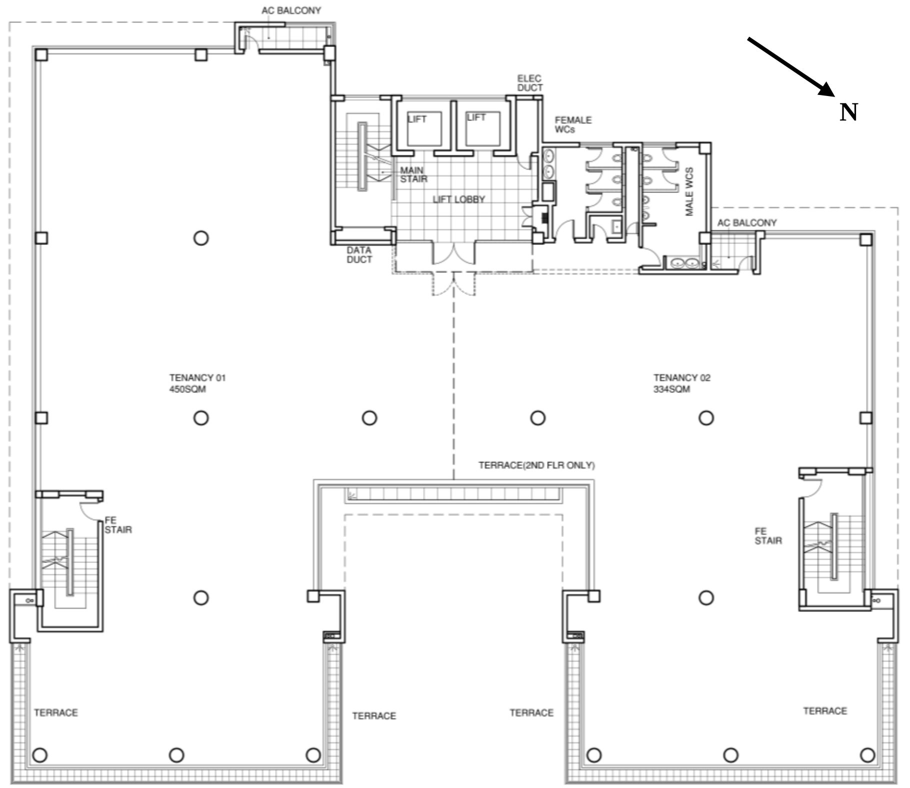


Figure 5.35: Typical floor plan of The Riverfront Offices
Source: Author

Figure 5.36: Aerial view of The Riverfront Offices
Source: Author

Figure 5.37: Aerial view of The Riverfront Offices
Source: Author

5.2.3 SPATIAL DESIGN

The parameters that have been analysed under spatial design include:

i. Construction materials
ii. Surface finishes
iii. Floor layout
iv. Opening location and size
v. Opening control
vi. Wall thicknesses
vii. Floor to ceiling height
viii. Room sizes and spatial use
ix. Sun shading devices

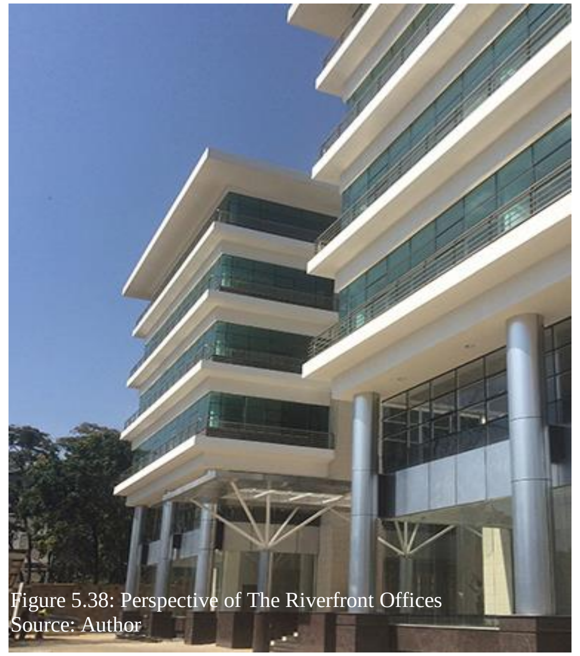
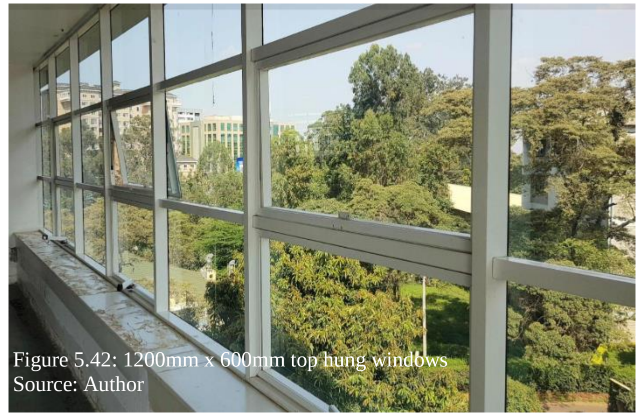


Figure 5.38: Perspective of The Riverfront Offices
Source: Author

i. Construction materials	ii. Surface finishes	iii. Floor layout	iv. Opening location and size	v. Opening control
The structure is made of circular reinforced concrete columns with a diameter of 500mm and reinforced concrete square columns that are 650mm wide. The building has beams that are 600mm deep. The floor slabs are 150mm thick and are made of reinforced concrete. The lift core walls are made of reinforced concrete, the external and internal walls are made of masonry blocks. The glazing on the windows and curtain walls is double glazed solar efficient glass panels.	The office floors have cement screed floor finish, the walls and columns have been plastered and finished with white paint. In the common areas, the ceilings are made of gypsum which is a good heat insulator. The floors of the common areas are finished with porcelain tiles. The external walls are finished with plaster and white coloured paint in order to reflect heat away. The glazing on the window and curtain walls is double glazed solar efficient glass panels.	The building has 5 floors. On each floor, the core and services are located at the rear end of the building. The columns within the U-shaped floor plate provide guidance on how to partition the spaces. There is one core on each floor. Each core has two passenger lifts, a staircase and washrooms. There are two additional fire escape staircases provided in each wing of the floor. The floors narrow, with widths of 12m, which ensures that the offices are almost sufficiently naturally lit by the 1.8m high windows.	The building has top hung steel casement windows which measure 600mm by 1200mm. These windows are located on all facades of the building. The doors at the entrance area are side hung double doors that are 1,5000mm wide.  Figure 5.42: 1200mm x 600mm top hung windows Source: Author	Parts of the external walls external walls are made of double glazed solar efficient glass panels which are fixed. The building also has top hung steel casement windows which measure 600mm by 1200mm.  Figure 5.44: Typical lettable office area Source: Author
 Figure 5.39: Perspective of The Riverfront Offices Source: Author	 Figure 5.40: Typical lettable office area Source: Author	 Figure 5.41: Typical lettable office area Source: Author	 Figure 5.42: 1200mm x 600mm top hung windows Source: Author	 Figure 5.45: Perspective of The Riverfront Offices Source: Author

vi. Wall thicknesses	vii. Floor to ceiling height	viii. Room sizes and spatial use	ix. Sun shading devices	Interview questions
Some of the external walls are made of double glazed solar efficient glass while the rest are made of 200mm thick masonry blocks. The interior walls have a thickness of 200mm and the lift core walls have a thickness of 300mm for structural purposes.	The gross room height is 3200mm (top of slab to bottom of slab). Some offices have false gypsum ceilings used to conceal the deep beams and air conditioning systems. The entrance lobby at the ground floor has a double volume, highlighting the grand scale of the development.	The as- built open plan offices are of the same area, which is approximately 800m^2. The floors narrow, with widths of 12m. The building houses offices and a restaurant. There is one core on each floor. Each core has two passenger lifts, a staircase and washrooms. There are two additional fire escape staircases provided in each wing of the floor.	The building has 750mm deep terraces projecting on four sides of the building facades. These do not sufficiently shade the interiors from direct sunlight. The entrance area is shaded by a canopy that measures 16500mm long by 5700mm wide.	i. How many people visit the building per day? Over 70 people visit the building per day ii. Do users exhibit symptoms of sick building syndrome? No iii. What improvements have been made to this building since it was built? None so far iv. How many hours in a day is the building in use? From 8am to 6 or 7pm v. Do you feel the need to acquire or use a fan? Yes, during the hot months like February and March vi. Which rooms/ spaces are used most during daytime? The offices and restaurant vii. Which rooms/ spaces are used most during the night? None viii. Do you ever open the windows, if any? If so, when? Yes, during the day from around 10am

Figure 5.46: Perspective of The Riverfront Offices
Source: Author

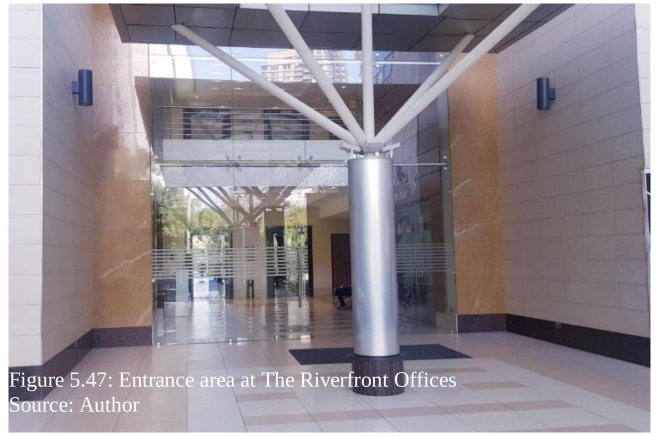


Figure 5.47: Entrance area at The Riverfront Offices
Source: Author


Figure 5.48: Typical lettable office area
Source: Author

Figure 5.49: Lifts area at The Riverfront Offices
Source: Author

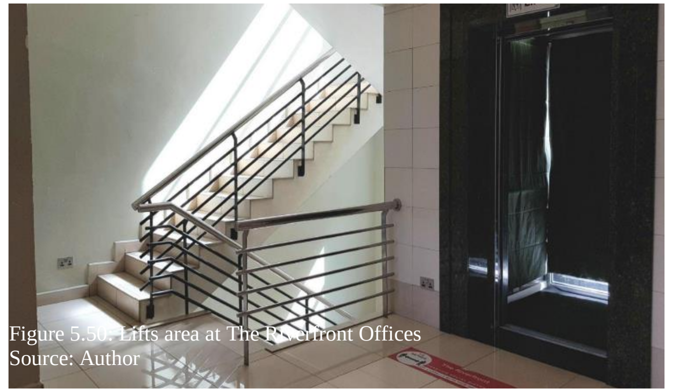


Figure 5.50: Lifts area at The Riverfront Offices
Source: Author


Figure 5.51: Entrance area at The Riverfront Offices
Source: Author

Figure 5.52: Perspective of The Riverfront Offices
Source: Author


Figure 5.53: Aerial view of The Riverfront Offices
Source: Author

5.2.4 VENTILATION PERFORMANCE ANALYSIS

i) External wind effects generated by the Riverfront

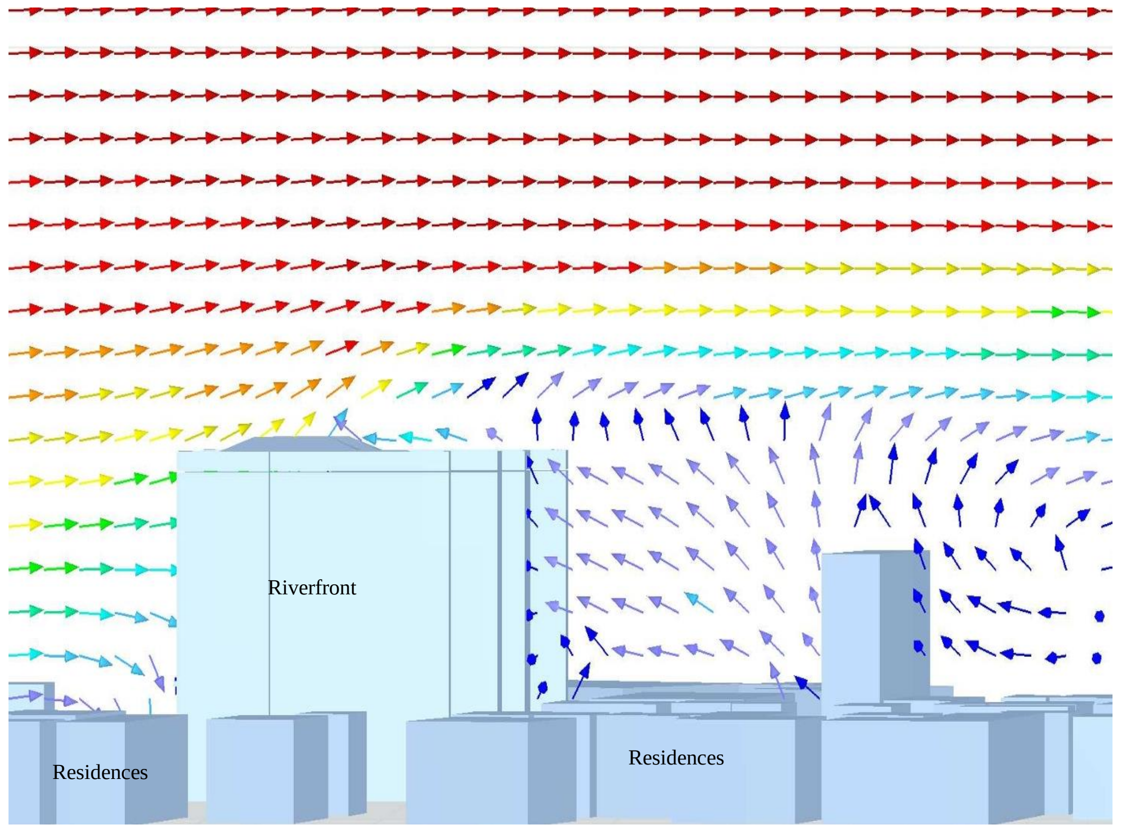
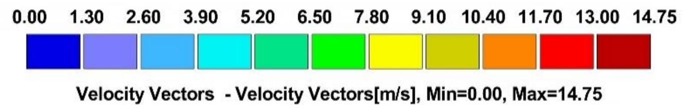
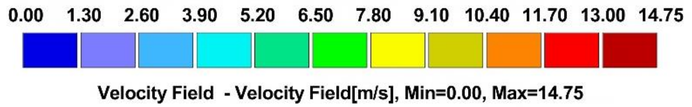


Fig.5.54: Side elevation of Riverfront development illustrating the velocity vectors around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

KEY





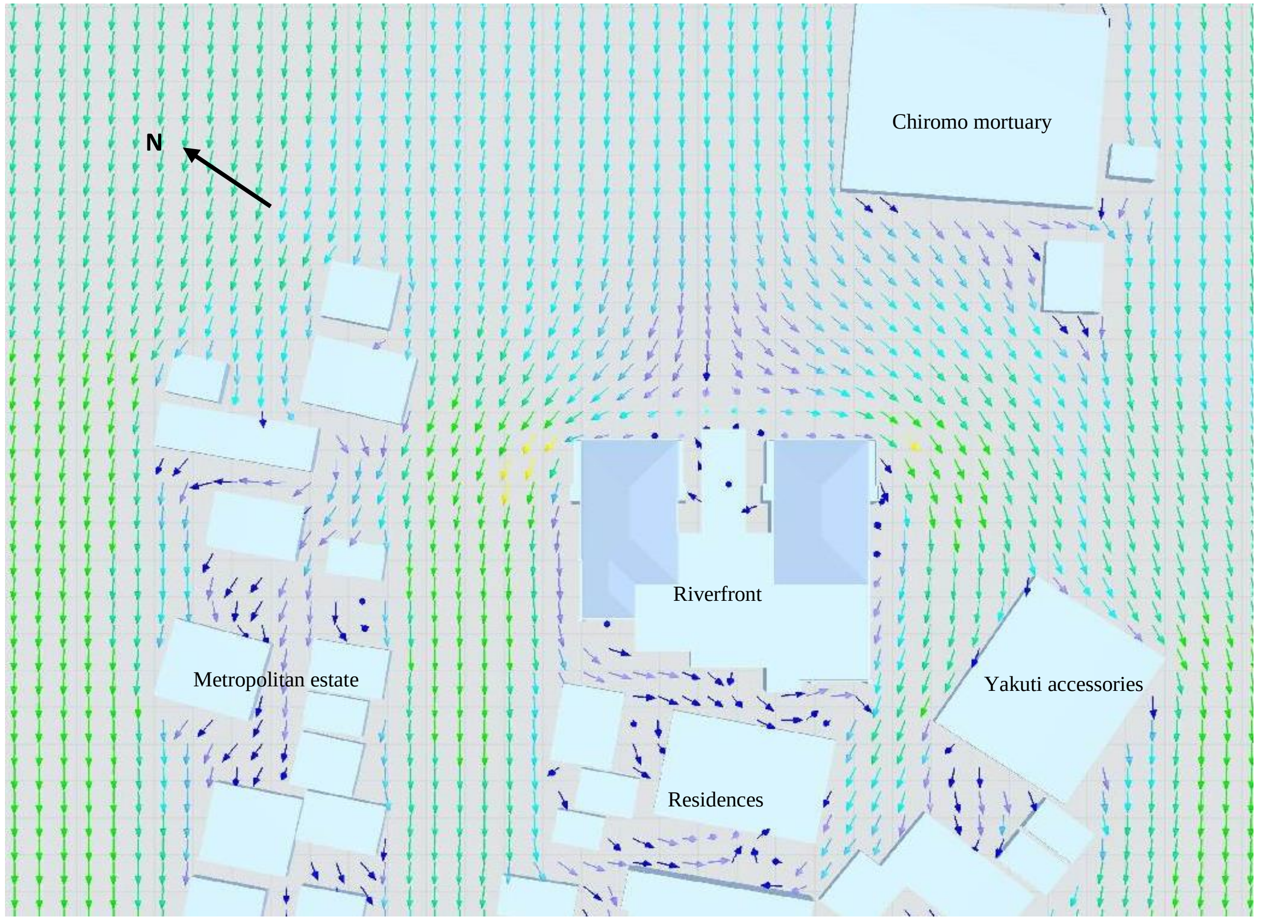


Fig.5.55: Plan view of Riverfront development illustrating the velocity vectors around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

Riverfront development is bordered by low rise buildings on all sides. This urban environment creates the following wind effects:

Downdraught effect: This happens when a tall building captures the wind at higher levels and then redirects it towards the ground, causing a three-dimensional flow moving downwards. In turn, this effect often creates a large recirculation at the ground level, causing greater wind activity. This is experienced at the front side of the building as shown in the simulation images.

Channeling: This happens due to the Venturi effect and is experienced when buildings are located in close proximity to one another, with the wind flow direction being parallel to the street or canyon. The effect is perpetuated by a reduction of wind pressure, resulting in wind acceleration through the tight channel created between the buildings. This is experienced in the canyon between Riverfront development and Yakuti accessories, which is has an aspect ratio of 4.

Vertically rotating wind flow: This is experienced when the wind flow direction is perpendicular to the canyon and also on the leeward side of the building. This is also referred to as to leeward recirculation and is eaperienced within the courtyard.

Corner acceleration: This happens when the wind reaches the vertical edge of a tall building. This effect is mainly created from sharp building shapes, causing acceleration around the corners. This is experienced on the corners of the building as shown in the front elevation, and is absent along the curved edge of the building.

This analysis of wind velocities and movement pattenrs around Riverfront development has been used to inform the placement of the air inlets and air outlets within the building's proposed thermal chimney ventilation system.

It is advisable to ensure that the air inlets face the North Eastern direction while the outlets should face the South Eastern direction.

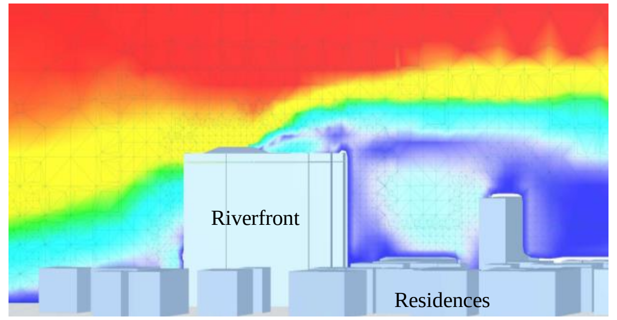


Fig.5.56: Side elevation of Riverfront development illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

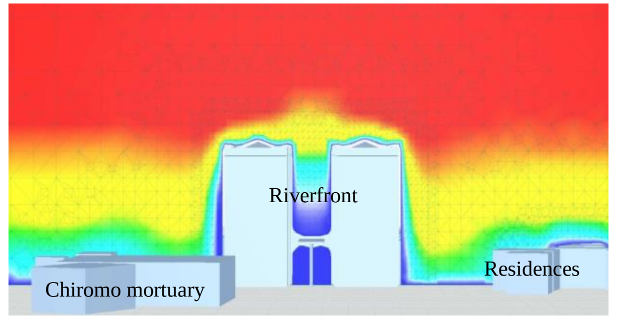


Fig.5.57: Front elevation of Riverfront development illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

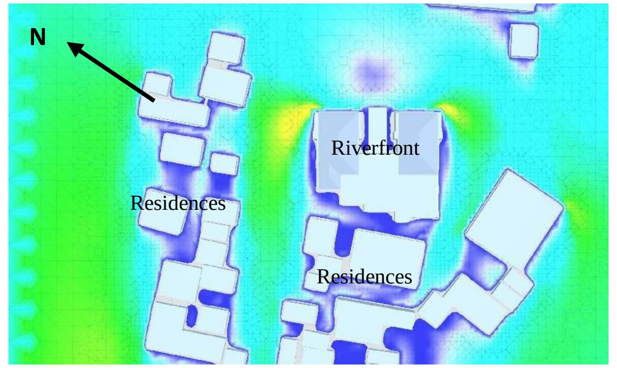


Fig.5.58: Plan view of Riverfront development illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

ii) Internal ventilation performance analysis

The rotating vane anemometer was placed in the open plan office on the 4th floor. It was placed on a table in the office. The anemometer had a single rotating vane that was used to capture air speeds through the fenestrations. The readings were taken between the dates 20th March and 16th April 2020.

Air speed:

Readings from the graph indicate that the highest outdoor air speeds were experienced between 12 noon and 6pm, while the lowest speeds were experienced between 12 midnight and 6 am.

Readings from the graph indicate that the velocity through the fenestrations (indoor air apeed) is fairly low, with the lowest values being recorded at 12 midnight. The average velocity through the fenestrations is 0.18m/s.

Air changes per hour:

Since the building is naturally ventilated, the air changes per hour vary depending on the air velocity through the fenestrations. In sich cases, the air changes per hour are obtained as explained below:

ACH= Q/Vol

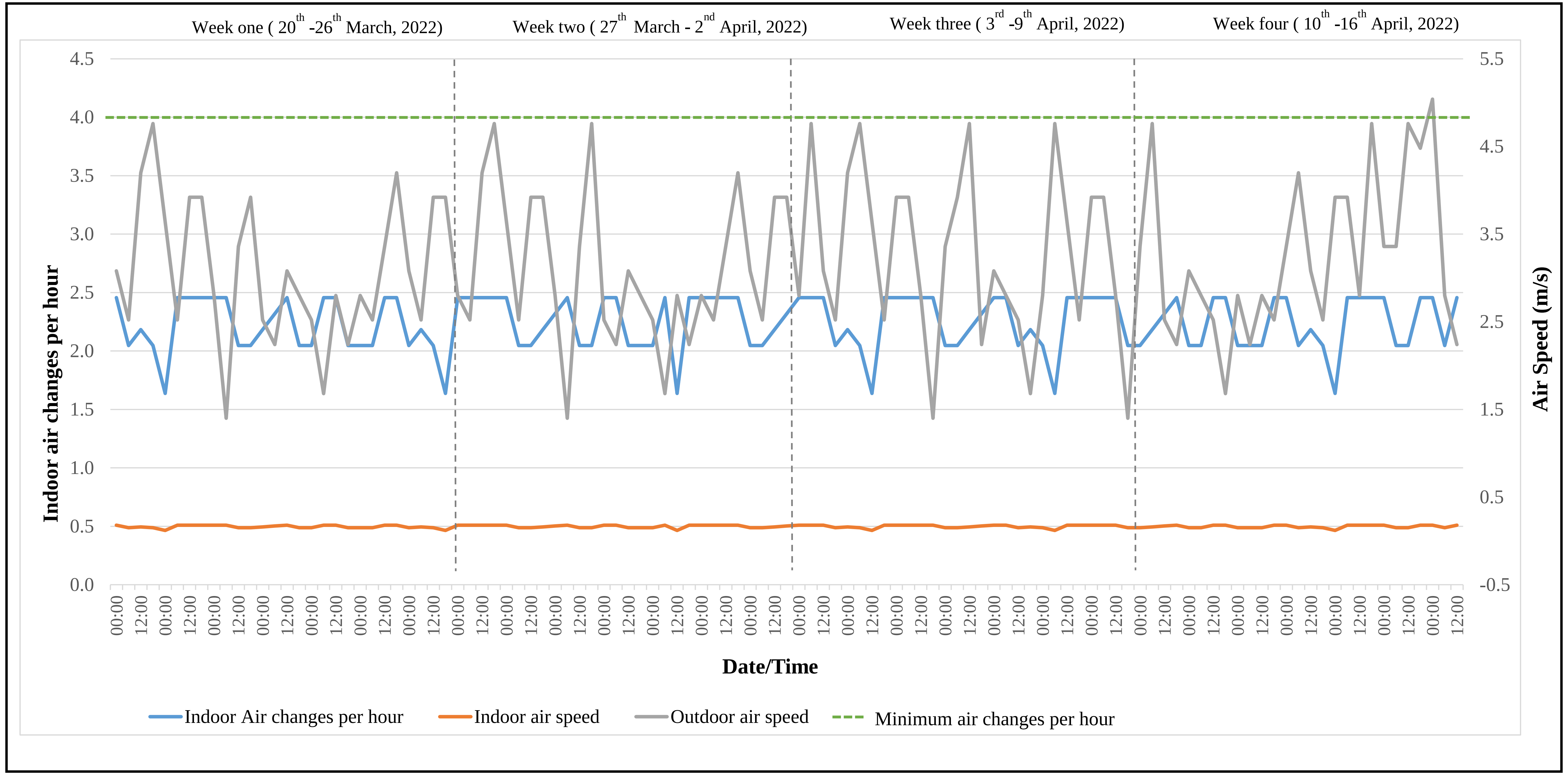
Where;

Q= Volumetric flow rate of air in m^3/hr (Velocity of air through the fenestrations in m/s x area of fenestration in m^2 x 3600)

Vol= Volume of room in m^3 (950m^2 x 3.2m)

Average ACH = 2.5 air changes per hour

This is significantly below the recommended figure of 4 air changes per hour, meaning that the office is not being sufficiently ventilated. The office needs ventilation systems that will provide more air changes.



Graph 5.2: Graph showing the indoor air changes per hour, indoor air speed and outdoor air speed for an office space in The Riverfront Office
Source: Author

5.2.5 VENTILATION PERFORMANCE ANALYSIS WITH PROPOSED THERMAL CHIMNEY

CFD simulation tool: Designbuilder was chosen as the CFD simulation software in this study, incorporating the EnergyPlus calculation engine which has been validated under the Evaluation of Building Energy Analysis Computer Programs test. Natural ventilation studies were performed through CFD simulation of indoor airflow for the lettable space in the case-study using the weather files from Dagoretti Meteorological Station for accurate results.

CFD boundary conditions:

i. The calculated module was preferred over scheduled module where the calculation engine uses information about building fabric & openings in conjunction with weather data and internal gains to calculate the pressure difference and air flow through each zone.
ii. The system is at steady state.
iii. The working air behaves like an ideal gas.
iv. The air at the entrance in the thermal chimney to the outlet is without friction or leakages
v. The thermal chimney walls are used as heat flux sources
vi. Properties (pressures, temperatures and density) are assumed at standard with the standard atmospheric conditions.
vii. The flow is assumed to be laminar.

Model description: The study area as highlighted on the floor plan has a floor area of 471m2 and a floor to ceiling height of 3.2m. A typical lettable area on the fourth floor was selected for the study. The office space has top hung steel casement windows which measure 600mm by 1200mm. The rest of the glazed panels are fixed. Only the operable panes have been featured in the simulation model.

Thermal chimney cavity height: The thermal chimney's cavity height is bound by the height of the office space (including the thickness of the roof slab). The cavity height increases by a height of 2 m for each consecutive trial. The cavity heights of the first and last trials are 5.35m and 9.35m respectively.

Thermal chimney inclination angle: The study is limited to wall mounted thermal chimneys. Therefore, for all trials, the inclination angle is set at 90^0.

Thermal chimney cavity width: The thermal chimney's cavity width is bound by 0.2m and 0.6m with an increment of 0.2m for each trial. Widths lower than 0.2m give fairly low air speeds while widths higher than 0.6m may be physically too large relative to the building.

Thermal chimney cavity length: The length of the thermal chimney cavity is a parameter commonly overlooked since airflow within the thermal chimney is generally a two-dimensional flow, based on the cavity width and height. For this study, the length is based on the distance between the windows, since this is where the chimneys have been placed. The thermal chimney's cavity length is bound by 1m and 2m with an increment of 0.5m for each trial.

Location: Three thermal chimneys have been placed on the opposite side of the main air inlets as shown in the models. This location has made it possible for the chimneys to increase air flow rates into the office while still receiving maximum solar radiation.

Thermal chimney outlet and inlet areas: The thermal chimneys have outlets at the top of the stack. This means that this area will be determined by the cavity width and length. As recommended in the literature review, the inlets and outlets have the same areas.

Thermal chimney construction materials: The chimneys have double glazing and are made of brick walls with a flat copper plate absorber.

Input parameters	Lower bound	Upper bound	Increment	No. of values
Cavity height	5.35m	9.35m	2m	3
Cavity gap width	0.2m	0.6m	0.2m	3
Cavity gap length	1m	2m	0.5m	3
Inlet area	0.2m^2	1.2m^2	-	3
Outlet area	0.2m^2	1.2m^2	-	3

Table 5.3: Input parameters used to model the various thermal chimney trials
Source: Author

With the examination of the influences of the input parameters, their combined effects on the indoor air speed are determined in order to design and optimize the thermal chimney. Although there are over 100 possible cases according to the limits from the table above, a first set of 20 cases (the lower and upper limits of the five input parameters) is modeled and simulated, after which the second set of 25 cases (chosen randomly) and the third set of 20 cases (chosen randomly) follow. The combined 65 cases are sufficient in developing a performance trend of the chimneys, which makes it possible to narrow down on the number of cases that will be presented for this study.

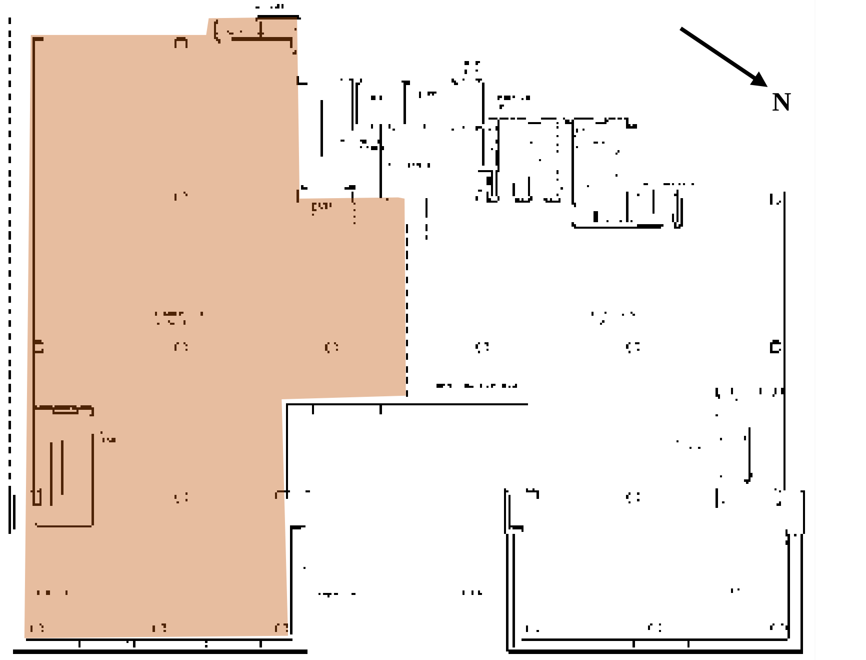


Figure 5.59: Floor plan highlighting the study area
Source: Author

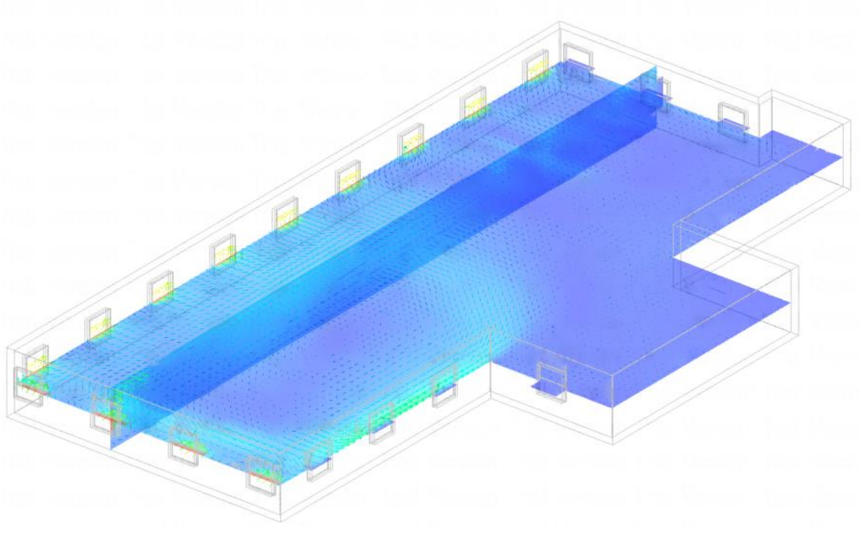


Figure 5.60: Existing ventilation conditions in the office. Average air speed is 0.18m/s with an average of 2.5 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

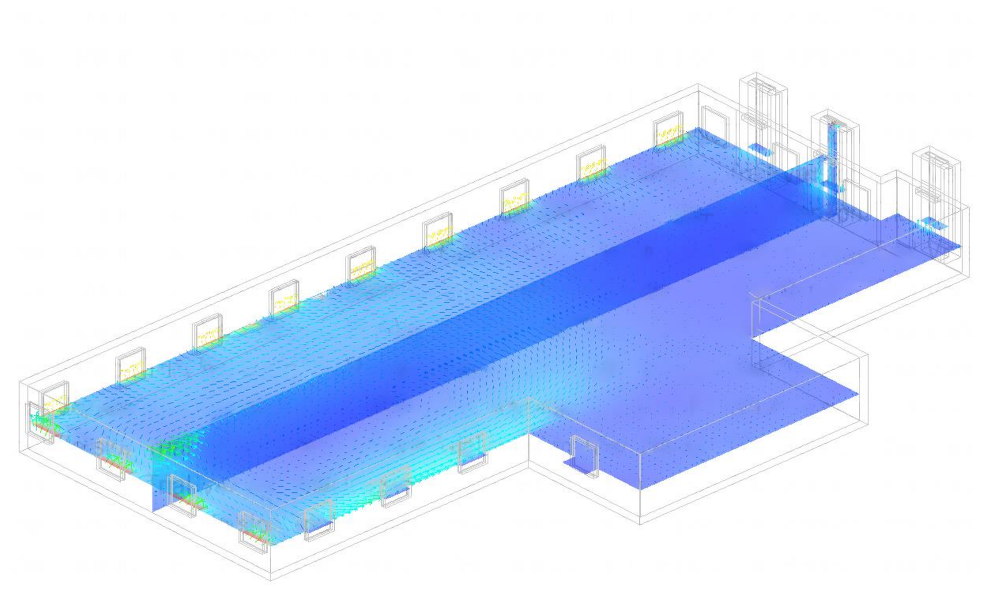


Figure 5.61: Ventilation conditions in the office with the first trial of the thermal chimney. Average air speed is 0.21m/s with an average of 2.9 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

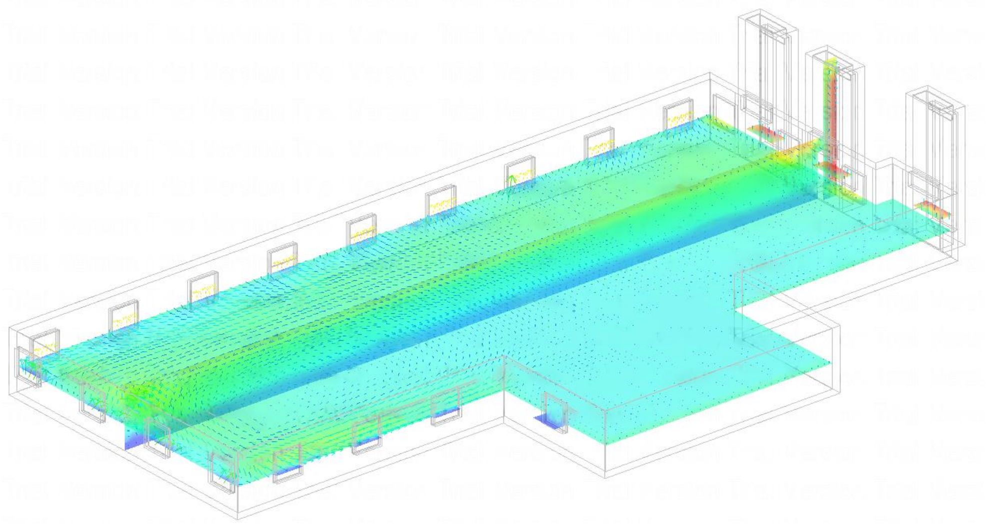


Figure 5.62: Ventilation conditions in the office with the second trial of the thermal chimney. Average air speed is 0.40m/s with an average of 5.5 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

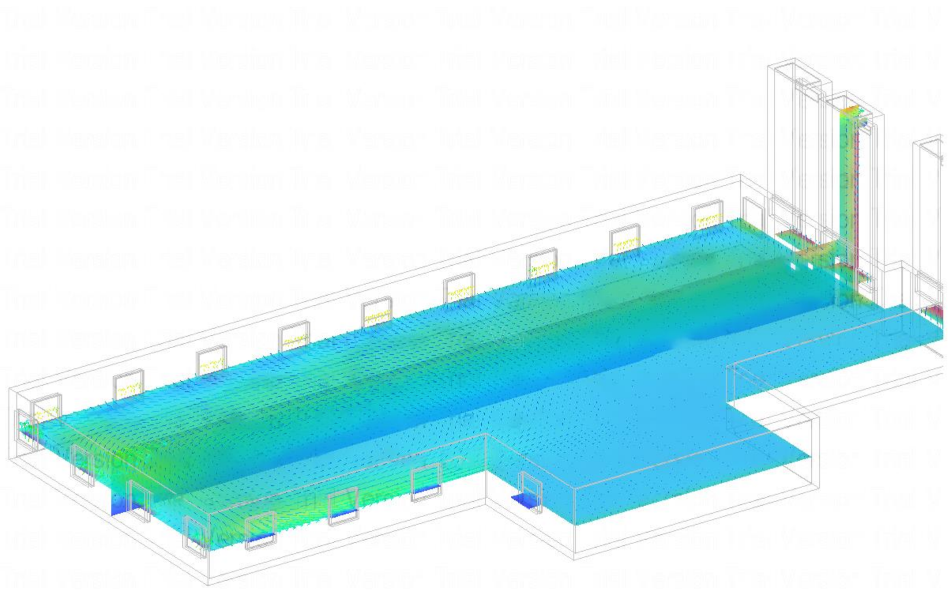


Figure 5.63: Ventilation conditions in the office with the third trial of the thermal chimney. Average air speed is 0.27m/s with an average of 3.7 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

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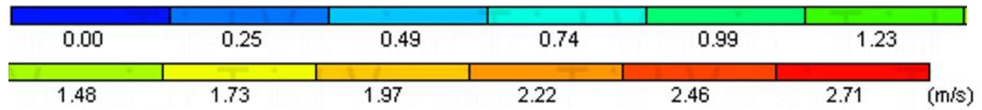


Analysis: The office majorly has a single-flow directional ventilation system due to its orientation with regards to the prevailing wind direction. The existing conditions indicate that the office has an average of 2.5 air changes per hour, which is below the recommended minimum of 4 air changes per hour.

The thermal chimneys in the first trial give the lowest number of air changes per hour (2.9) as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.2m wide, the cavity heights are 5.35m and the cavity lengths are 1m. The narrow cavity widths result in friction losses which leads to a decrease in air speed.

The thermal chimneys in the second trial give the highest number of air changes per hour (5.5) as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.4m wide, the cavity heights are 7.35m and the cavity lengths are 1.5m. This combination gives the optimum number of air changes per hour for the office space.

The thermal chimneys in the third trial give 3.7 air changes per hour as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.6m wide, the cavity heights are 9.35m and the cavity lengths are 2m. The wide cavity widths and high cavity heights result in lower heat transfers within the chimney, which creates reverse flows in the stack resulting in decreased air speeds.

5.2.6 THERMAL CHIMNEY DESIGN RECOMMENDATIONS

The following are the design recommendations for three thermal chimneys for an office space with a floor area of $471m^2$ and a floor to ceiling height of 3.2m:

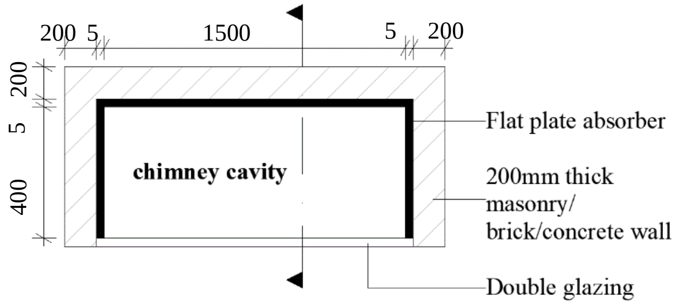


Figure 5.64: Plan of recommended thermal chimney
Source: Author

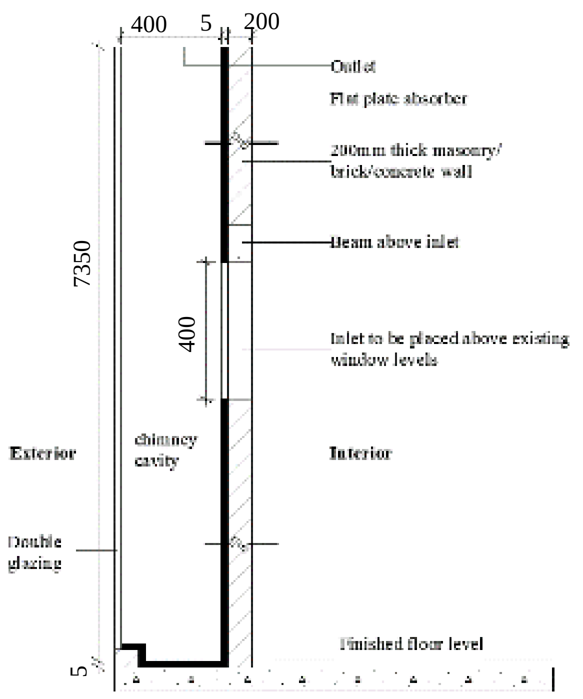


Figure 5.65: Cross section through recommended thermal chimney
Source: Author

Parameters	Variables	Description
Materials	Type of glazing	Double glazing
	Thermal absorber type	Flat copper plate absorber
Configuration	Cavity height	7.35m
	Cavity gap width	0.4m
	Cavity gap length	1.5m
	Inlet area	$0.6m^2$
	Outlet area	$0.6m^2$
	Cavity height to gap width ratio	18
Installation	Inclination angle	90^0
No. of chimneys	Quantity	3

Table 5.4: Thermal chimney design recommendations
Source: Author

5.3 ICEA LION GROUP HEAD OFFICE 2

5.3.1 INTRODUCTION

Location: Westlands, Nairobi

Completion: 2014

Architect: BAA Architects

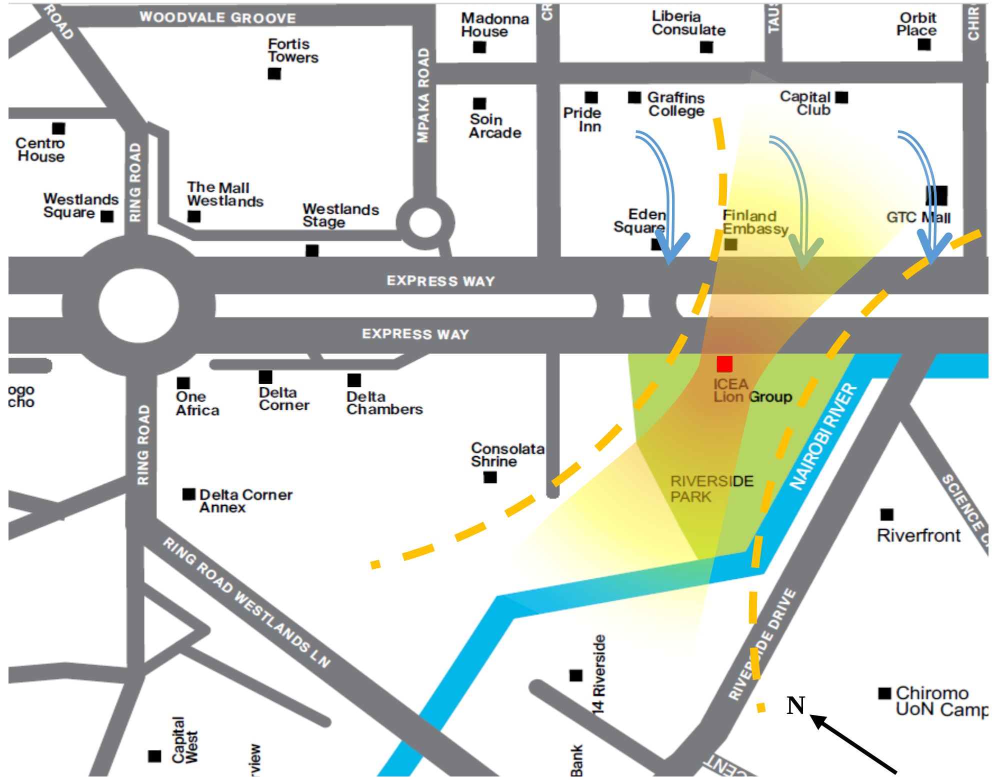


Figure 5.66: Location plan highlighting ICEA LION Group Head Offices
Source: https://www.knightfrank.co.ke/ Author modified

ICEA Park is an office development located along Waiyaki Way, between Riverside Drive and Ring Road in Westlands. The building houses offices, a bank and cafeterias. The development offers both above ground and below ground parking facilities.

The ICEA Lion group Head Offices are two iconic office block developments with five storeys each. The approximate total gross lettable area is 10,000m^2.

5.3.2 MORPHOLOGY

i) Site planning: The office building is located along Waiyaki Way. There are two identical office buildings that are 41m apart. The area between the buildings is used as a parking lot. The Riverside park buildings are located behind these office buildings.

ii) External elements/ obstructions: The building is bordered by the Expressway to the North East, by ICEA Lion Group head Office 1 to the South East and by Riverside Park to the South West. The first head office is 41m away from the second head office. Both forms are identical.

iii) Orientation: The building is oriented with the longer axis along the South East/ North West axis. The North Easterly prevailing winds are perpendicular to the longer side of the building façade.

This ensures that the building receives sufficient natural ventilation.

iv) Building form: The office tower is 19m high with a U-shaped floor plate and a cuboidal form with one curved edge. It has 1000mm deep horizontal fins projecting on three sides of the building facades.

These fins are used to shade the interiors from direct sunlight. The roof is a flat concrete slab with a slope of 5^0. The ground floor is raised by 1.5m in order to create ample space for basement parking.

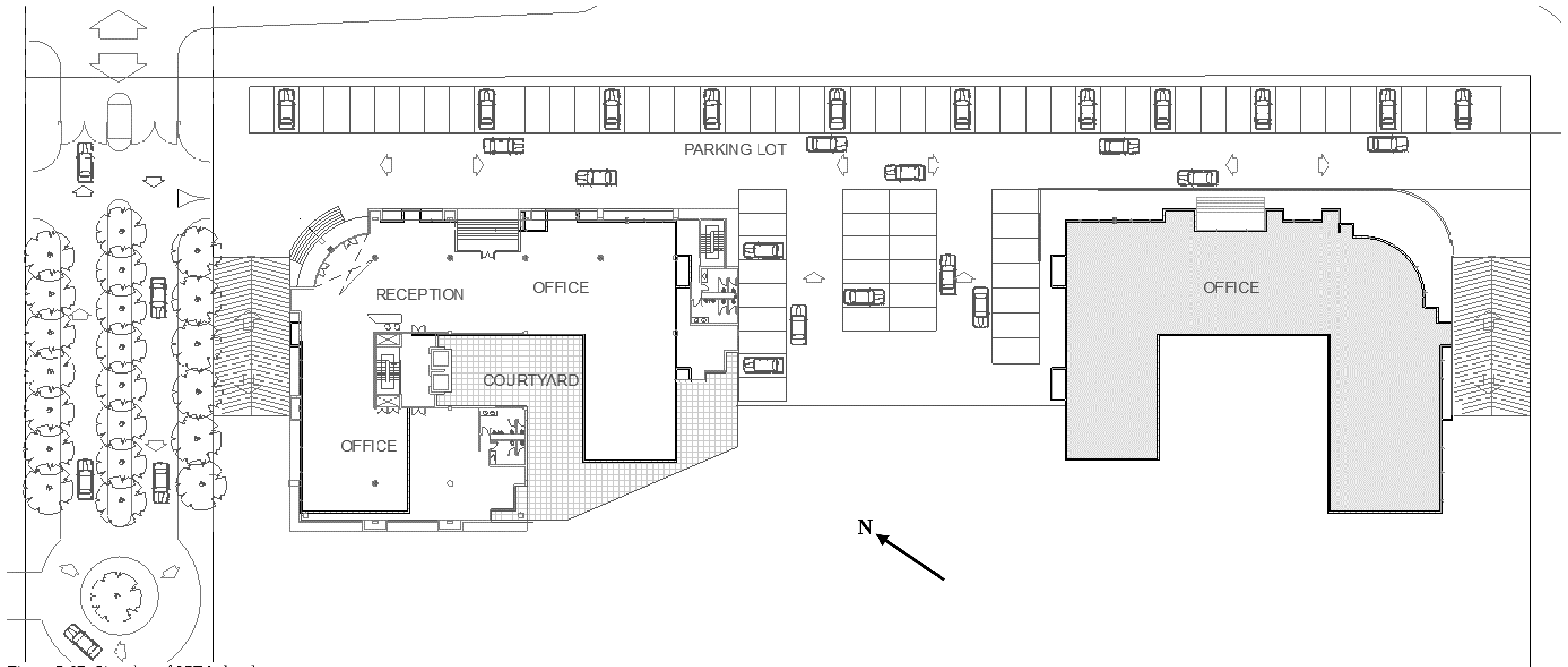


Figure 5.67: Site plan of ICEA development
Source: Author

Figure 5.68: Interior perspective of ICEA head office
Source: Author

Figure 5.69: Interior perspective of ICEA Head Office
Source: Author

5.3.3 SPATIAL DESIGN

The parameters that have been analysed under spatial design include:

i. Construction materials
ii. Surface finishes
iii. Floor layout
iv. Opening location and size
v. Opening control
vi. Wall thicknesses
vii. Floor to ceiling height
viii. Room sizes and spatial use
ix. Sun shading devices

Figure 5.70: Perspective of ICEA development
Source: Author

i. Construction materials	ii. Surface finishes	iii. Floor layout	iv. Opening location and size	v. Opening control
The structure is made of circular reinforced concrete columns with a diameter of 600mm and reinforced concrete square columns that are 400mm wide. The building has beams that are 600mm deep. The floor slabs are 150mm thick and are made of reinforced concrete. The lift core walls are made of reinforced concrete, the external and internal walls are made of masonry blocks. The glazing on the windows and curtain walls is double glazed solar efficient glass panels. The vertical sun shading elements are made of steel.	The office floors are finished with porcelain tiles which are easy to clean and maintain. The wet areas have non slip porcelain tile floor finish. The office walls are finished with light coloured paint in order to reflect heat away. The ceilings are made of gypsum which is a good heat insulator. Some office ceilings have been finished with plaster and paint. The interior surface finishes can be customized in order to suit the client's preferences. The external walls are finished with plaster and light coloured paint in order to reflect heat away. The glazing on the window and curtain walls is double glazed solar efficient glass panels.	The building has 5 floors. On each floor, the core and services are located at the edges of the building. The columns within the U-shaped floor plate provide guidance on how to partition the spaces, if need be. There are two cores on each floor. One core has two passenger lifts, a staircase and washrooms while the other core has a staircase and washrooms. The floors narrow, with widths of 11m, which ensures that the offices are almost sufficiently naturally lit by the 1.8m high windows.	The building has top hung steel casement windows which measure 600mm by 1200mm. These windows are located on the front and side facades of the building. The doors at the entrance area are side hung double doors that are 1,5000mm wide. The doors leading to the court at the back side of the building are side hung double doors that are 1,5000mm wide.	Parts of the external walls external walls are made of double glazed solar efficient glass panels which are fixed. The building also has top hung steel casement windows which measure 600mm by 1200mm. The doors at the entrance area and at the back of the building are side hung double doors.

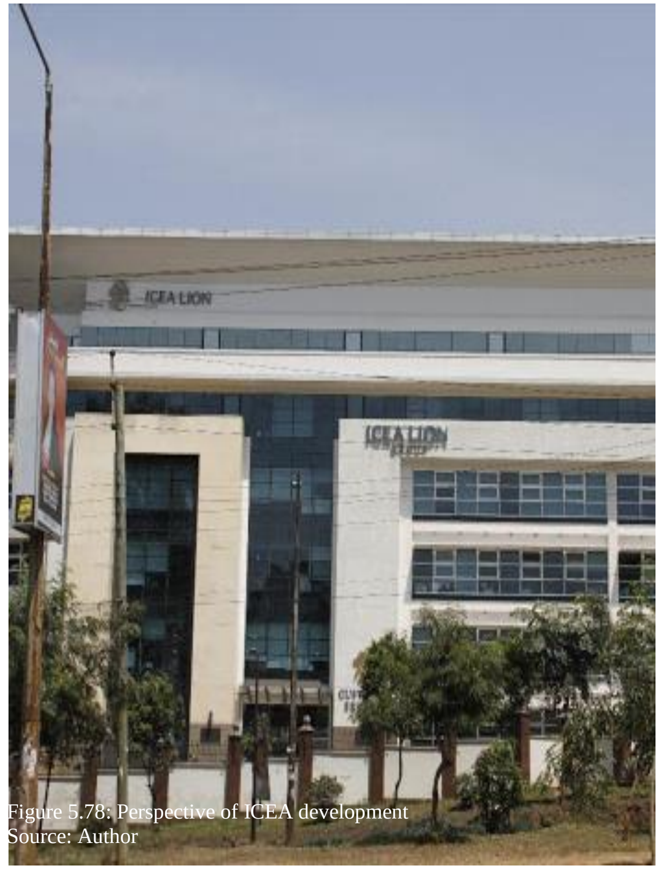
Figure 5.71: Perspective of ICEA development
Source: Author

Figure 5.72: Interior perspective of ICEA development
Source: Author

Figure 5.73: Perspective of ICEA development
Source: Author

Figure 5.74: Perspective of ICEA development
Source: Author

Figure 5.75: Perspective of ICEA development
Source: Author

vi. Wall thicknesses	**vii. Floor to ceiling height**	**viii. Room sizes and spatial use**	**ix. Sun shading devices**	**Interview questions**
Some of the external walls are made of double glazed solar efficient glass while the rest are made of 200mm thick masonry blocks. The interior walls have a thickness of 200mm and the lift core walls have a thickness of 300mm for structural purposes.	The gross room height is 3200mm (top of slab to bottom of slab). Some offices have false gypsum ceilings used to conceal the deep beams and air conditioning systems. The entrance lobby at the ground floor has a double volume, highlighting the grand scale of the development.	The as- built open plan offices are of the same area, which is approximately 780m^2. The floors narrow, with widths of 11m. The building houses a office spaces, cafeterias and a bank. Each floor has two cores. One core has two passenger lifts, a staircase and washrooms while the other core has a staircase and washrooms.	The building has 1000mm deep horizontal fins projecting on three sides of the building facades. These fins do not sufficiently shade the interiors from direct sunlight.	i. How many people visit the building per day? Approximately 55 people visit the building per day ii. Do users exhibit symptoms of sick building syndrome? No iii. What improvements have been made to this building since it was built? None so far iv. How many hours in a day is the building in use? From 8am to 6 or 7pm v. Do you feel the need to acquire or use a fan? Yes, during the hot months like February and March vi. Which rooms/ spaces are used most during daytime? The offices, the bank and the cafeterias vii. Which rooms/ spaces are used most during the night? None viii. Do you ever open the windows, if any? If so, when? Yes, during the day from around 10am
 Figure 5.76: Perspective of ICEA development Source: Author	 Figure 5.77: Entrance area of ICEA development Source: Author	 Figure 5.78: Perspective of ICEA development Source: Author	 Figure 5.79: Perspective of ICEA development Source: Author	

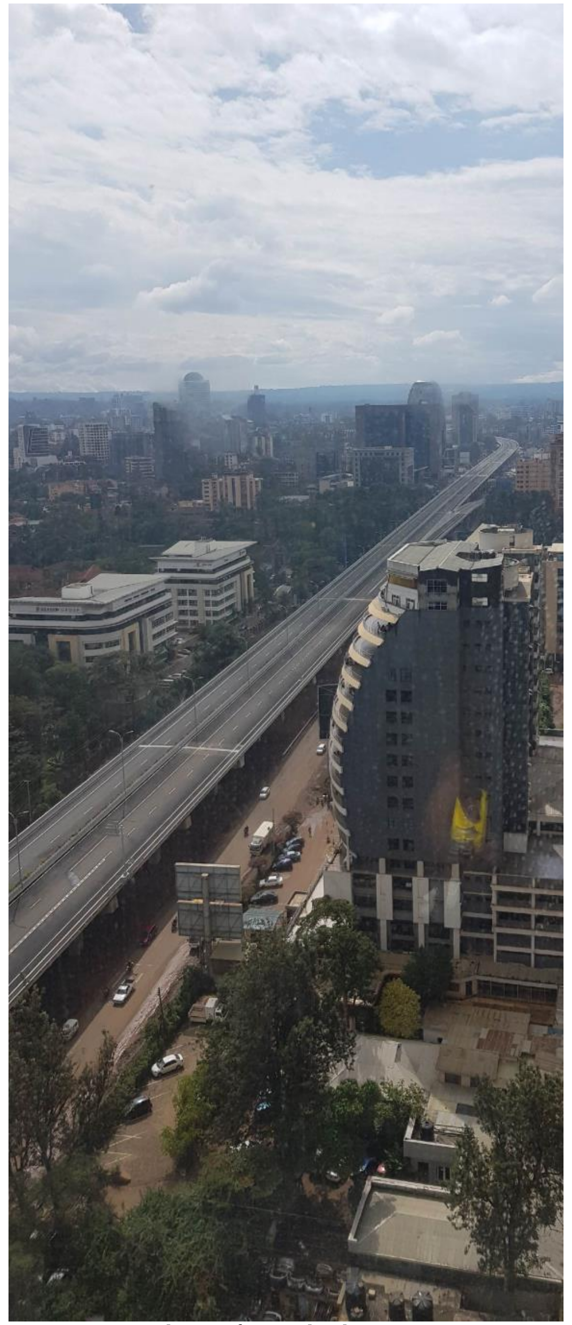


Figure 5.75: Aerial view of ICEA development
Source: Author

5.3.4 VENTILATION PERFORMANCE ANALYSIS

i) External wind effects generated by ICEA Lion Group Head Office

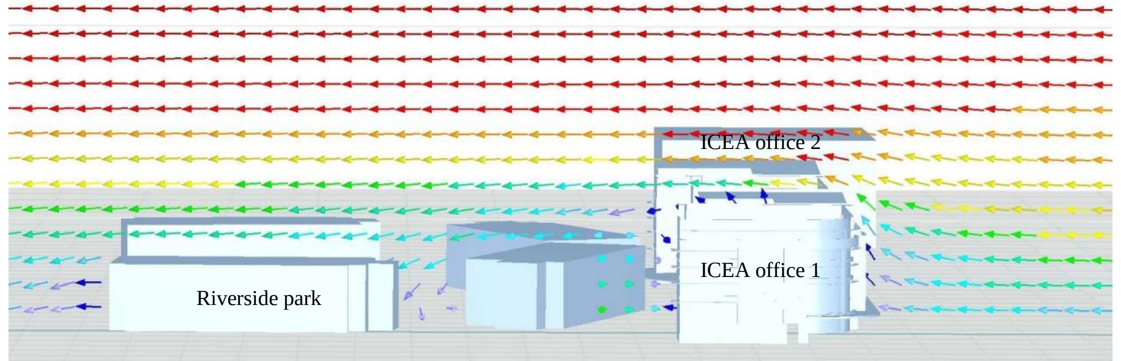


Fig.5.76: Side elevation of ICEA Park development illustrating the velocity vectors around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

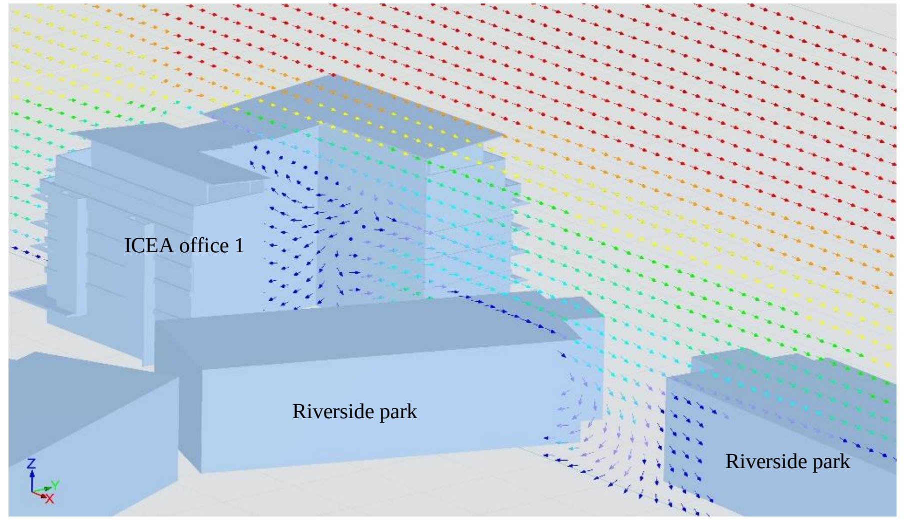


Fig.5.77: Perspective of ICEA Park illustrating the velocity vectors around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

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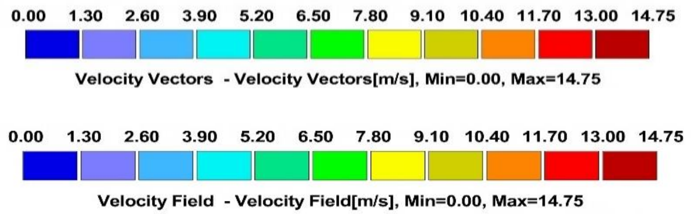


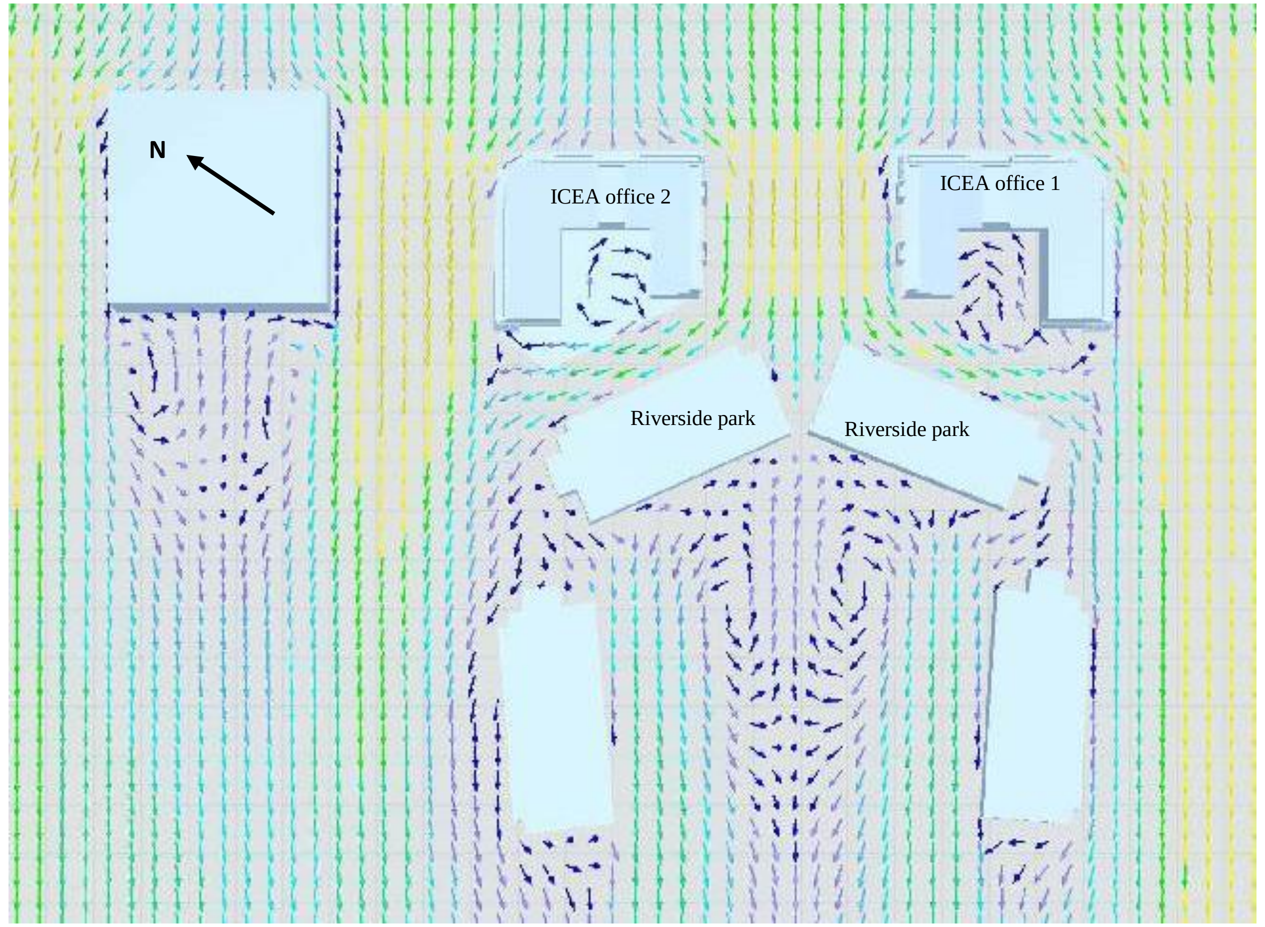


Fig.5.78: Plan view of ICEA park development illustrating the velocity vectors around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

ICEA head office 2 is bordered by low rise buildings on all sides. This urban environment creates the following wind effects:

Downdraught effect: This happens when a tall building captures the wind at higher levels and then redirects it towards the ground, causing a three-dimensional flow moving downwards. In turn, this effect often creates a large recirculation at the ground level, causing greater wind activity. This is experienced at the front side of the building as shown in the simulation images.

Channeling: This happens due to the Venturi effect and is experienced when buildings are located in close proximity to one another, with the wind flow direction being parallel to the street or canyon. The effect is perpetuated by a reduction of wind pressure, resulting in wind acceleration through the tight channel created between the buildings. This is experienced in the canyon between ICEA office 1 and ICEA office two, which is has an aspect ratio of 0.41.

Vertically rotating wind flow: This is experienced when the wind flow direction is perpendicular to the canyon and also on the leeward side of the building. This is also referred to as to leeward recirculation and is experienced within the courtyard.

Corner acceleration: This happens when the wind reaches the vertical edge of a tall building. This effect is mainly created from sharp building shapes, causing acceleration around the corners. This is experienced on the corners of the building as shown in the front elevation, and is absent along the curved edge of the building.

This analysis of wind velocities and movement patterns around ICEA park has been used to inform the placement of the air inlets and air outlets within the building's proposed thermal chimney ventilation system.

It is advisable to ensure that the air inlets face the North Eastern direction while the outlets should face the South Eastern direction.

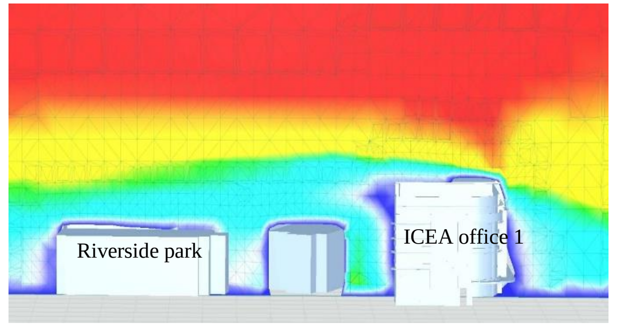


Fig.5.79: Side elevation of ICEA park illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

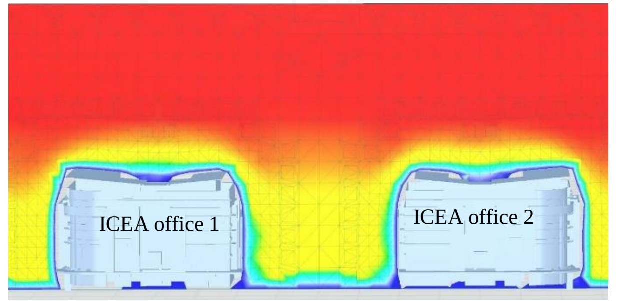


Fig.5.80: Front elevation of ICEA park development illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

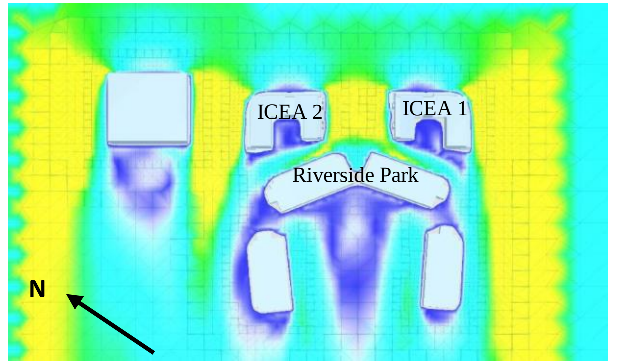


Fig.5.81: Plan view of ICEA park illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

ii) Internal ventilation performance analysis

The rotating vane anemometer was placed in the open plan office on the 4th floor. It was placed on a desk in the officel. The anemometer had a single rotating vane that was used to capture air speeds through the fenestrations. The readings were taken between the dates 20th March and 16th April 2020.

Air speed:

Readings from the graph indicate that the highest outdoor air speeds were experienced between 12 noon and 6pm, while the lowest speeds were experienced between 12 midnight and 6 am.

Readings from the graph indicate that the velocity through the fenestrations (indoor air apeed) is fairly low, with the lowest values being recorded at 12 noon. The average velocity through the fenestrations is 0.12m/s.

Air changes per hour:

Since the building is naturally ventilated, the air changes per hour vary depending on the air velocity through the fenestrations. In sich cases, the air changes per hour are obtained as explained below:

ACH= Q/Vol

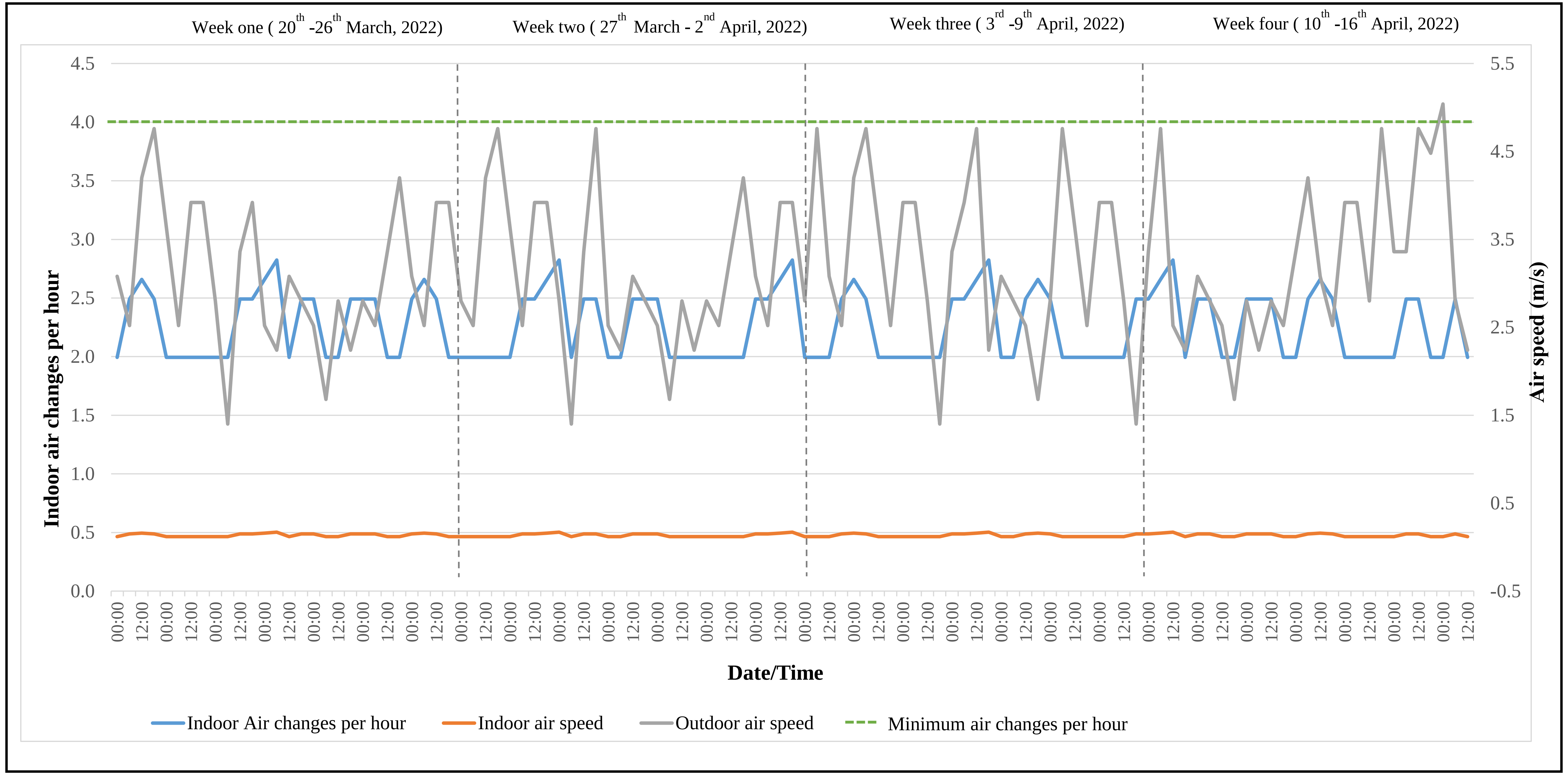
Where;

Q= Volumetric flow rate of air in m^3*/hr (Velocity of air through thefenestrations in m/s x area of fenestration in* m^2 *x 3600)*

Vol= Volume of room in m^3 *(780*m^2 *x 3.2m)*

Average ACH = 2.3 air changes per hour

This is significantly below the recommended figure of 4 air changes per hour, meaning that the office is not being sufficiently ventilated. The office needs ventilation systems that will provide more air changes.



Graph 5.3: Graph showing the indoor air changes per hour, indoor air speed and outdoor air speed for an office space in ICEA
Source: Author

5.3.5 VENTILATION PERFORMANCE ANALYSIS WITH PROPOSED THERMAL CHIMNEY

CFD simulation tool: Designbuilder was chosen as the CFD simulation software in this study, incorporating the EnergyPlus calculation engine which has been validated under the Evaluation of Building Energy Analysis Computer Programs.

Natural ventilation studies were performed through CFD simulation of indoor airflow for the lettable space in the case-study using the weather files from Dagoretti Meteorological Station for accurate results.

CFD boundary conditions:

i. The calculated module was preferred over scheduled module where the calculation engine uses information about building fabric & openings in conjunction with weather data and internal gains to calculate the pressure difference and air flow through each zone.
ii. The system is at steady state.
iii. The working air behaves like an ideal gas.
iv. The air at the entrance in the thermal chimney to the outlet is without friction or leakages
v. The thermal chimney walls are used as heat flux sources
vi. Properties (pressures, temperatures and density) are assumed at standard with the standard atmospheric conditions.
vii. The flow is assumed to be laminar.

Model description: The study area as highlighted on the floor plan has a floor area of 274m^2 and a floor to ceiling height of 3.2m. A typical lettable area on the fourth floor was selected for the study. The office space has top hung steel casement windows which measure 600mm by 1200mm. The rest of the glazed panels are fixed. Only the operable panes have been featured in the simulation model.

Thermal chimney cavity height: The thermal chimney's cavity height is bound by the height of the office space (including the thickness of the roof slab). The cavity height increases by a height of 2 m for each consecutive trial. The cavity heights of the first and last trials are 5.35m and 9.35m respectively.

Thermal chimney inclination angle: The study is limited to wall mounted thermal chimneys. Therefore, for all trials, the inclination angle is set at 90^0.

Thermal chimney cavity width: The thermal chimney's cavity width is bound by 0.2m and 0.6m with an increment of 0.2m for each trial. Widths lower than 0.2m give fairly low air speeds while widths higher than 0.6m may be physically too large relative to the building.

Thermal chimney cavity length: The length of the thermal chimney cavity is a parameter commonly overlooked since airflow within the thermal chimney is generally a two-dimensional flow, based on the cavity width and height. For this study, the length is based on the distance between the windows, since this is where the chimneys have been placed. The thermal chimney's cavity length is bound by 1m and 1.2m with an increment of 0.1m for each trial.

Location: Three thermal chimneys have been placed on the opposite side of the main air inlets as shown in the models. This location has made it possible for the chimneys to increase air flow rates into the office while still receiving maximum solar radiation.

Thermal chimney outlet and inlet areas: The thermal chimneys have outlets at the top of the stack. This means that this area will be determined by the cavity width and length. As recommended in the literatur review, the inlets and outlets have the same areas.

Thermal chimney construction materials: The chimneys have double glazing and are made of brick walls with a flat copper plate absorber.

Input parameters	Lower bound	Upper bound	Increment	No. of values
Cavity height	5.35m	9.35m	2m	3
Cavity gap width	0.2m	0.6m	0.2m	3
Cavity gap length	1m	1.2m	0.1m	3
Inlet area	0.2m^2	0.72m^2	-	3
Outlet area	0.2m^2	0.72m^2	-	3

Table 5.5: Input parameters used to model the various thermal chimney trials
Source: Author

With the examination of the influences of the input parameters, their combined effects on the indoor air speed are determined in order to design and optimize the thermal chimney. Although there are over 100 possible cases according to the limits from the table above, a first set of 20 cases (the lower and upper limits of the five input parameters) is modeled and simulated, after which the second set of 25 cases (chosen randomly) and the third set of 20 cases (chosen randomly) follow. The combined 65 cases are sufficient in developing a performance trend of the chimneys, which makes it possible to narrow down on the number of cases that will be presented for this study.

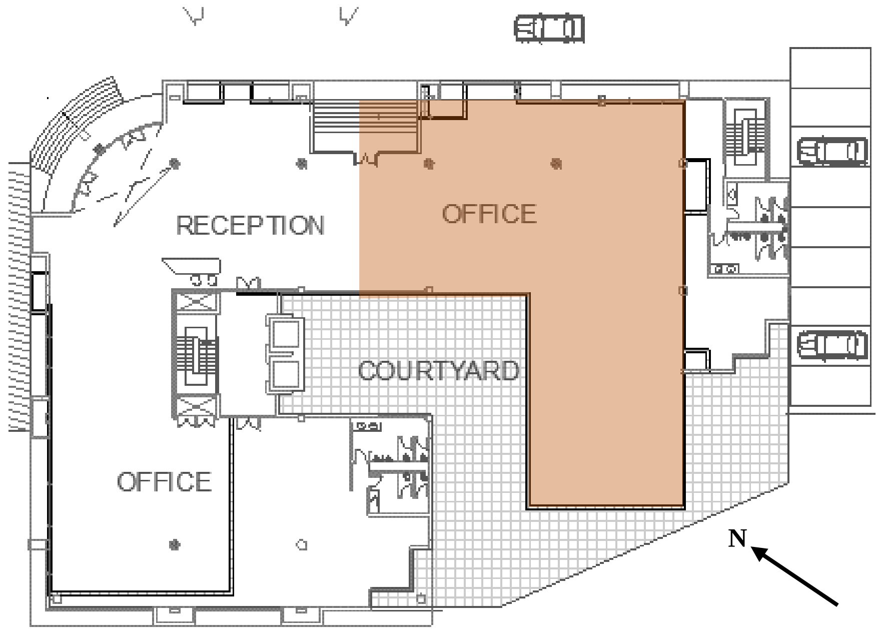


Fig.5.82: Layout plan higlighting study area
Source: Author

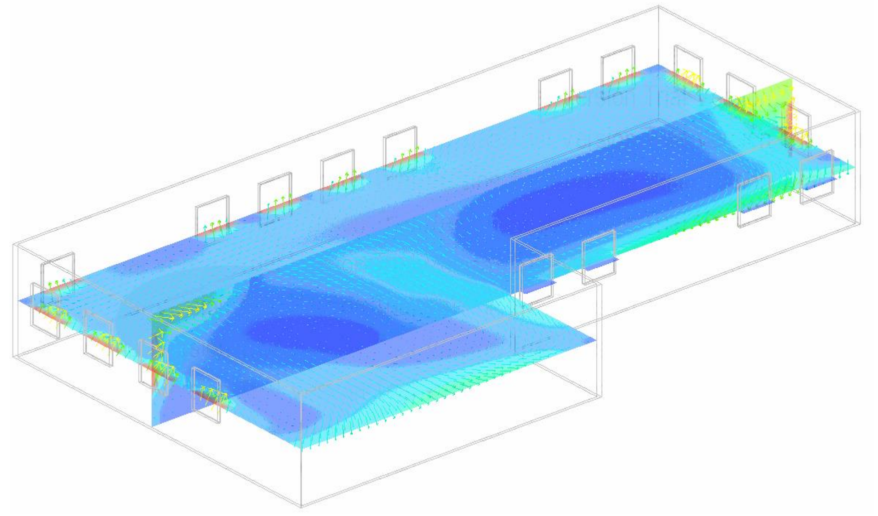


Fig.5.83: Existing ventilation conditions in the office. Average air speed is 0.12m/s with an average of 2.8 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

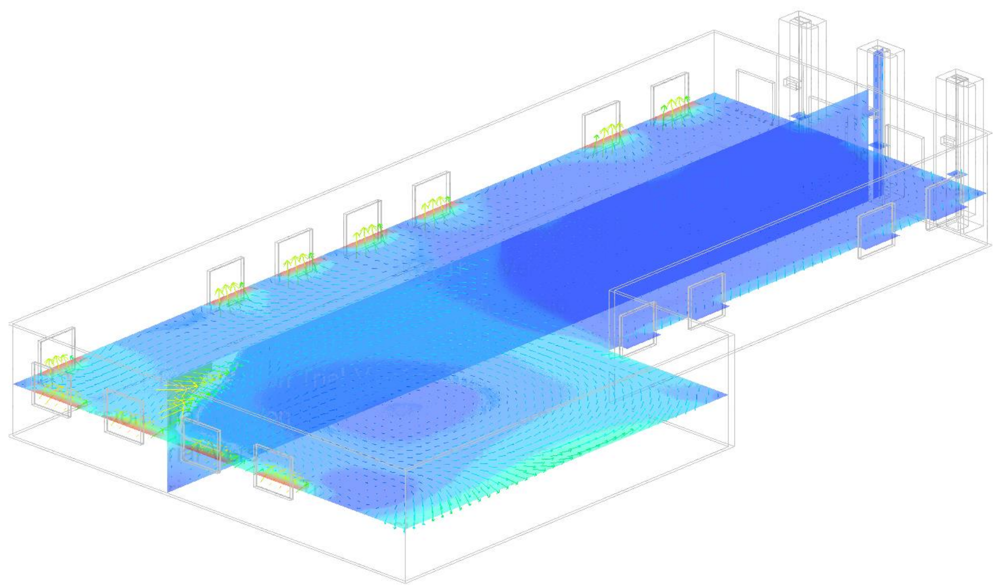


Fig.5.84: Ventilation conditions in the office with the first trial of the thermal chimney. Average air speed is 0.14m/s with an average of 3.3 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

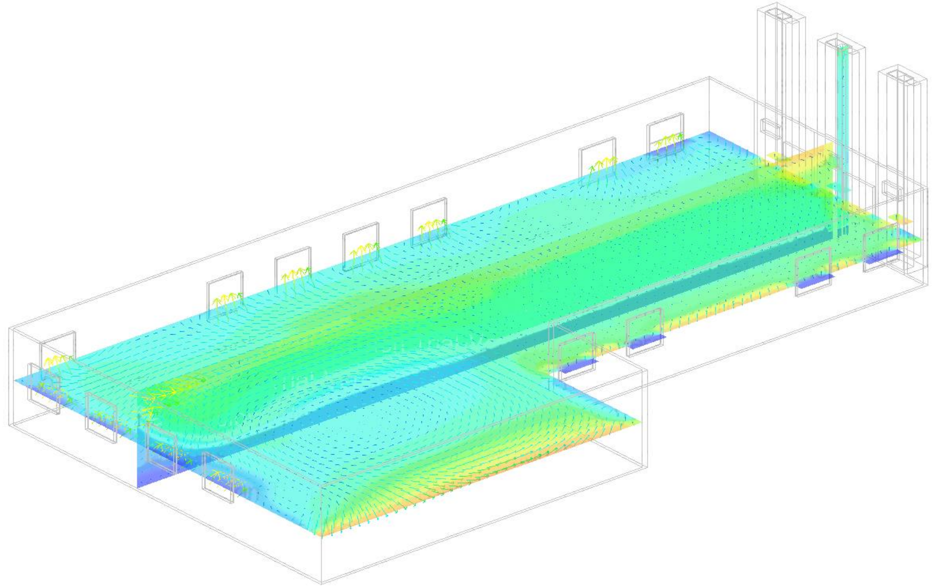


Fig.5.85: Ventilation conditions in the office with the second trial of the thermal chimney. Average air speed is 0.21m/s with an average of 4.9 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

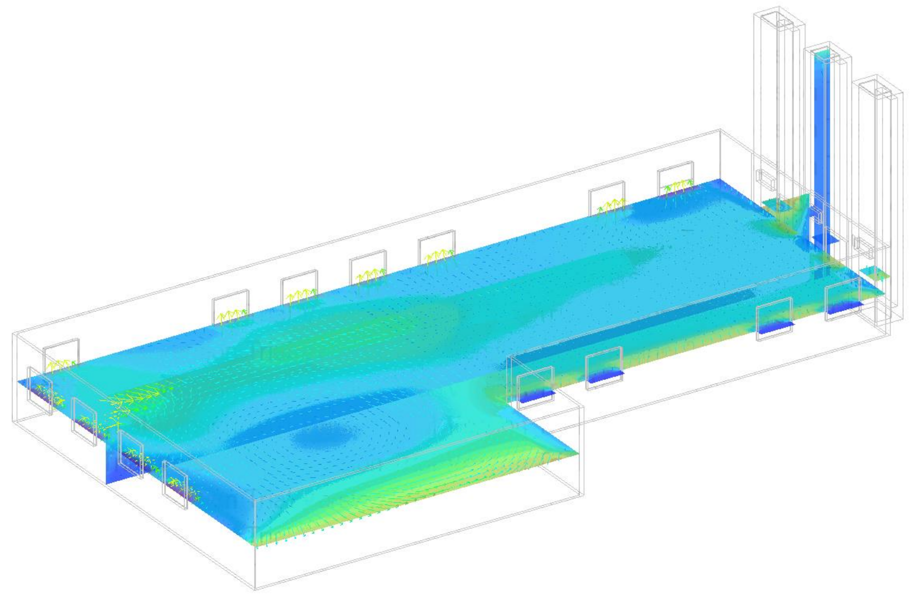
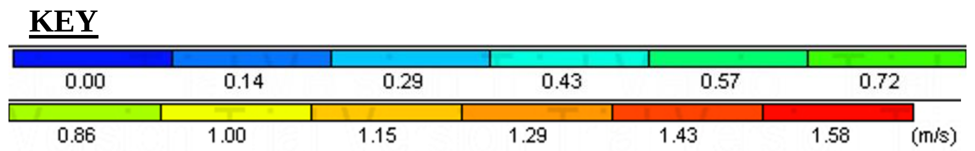


Fig.5.86: Ventilation conditions in the office with the third trial of the thermal chimney. Average air speed is 0.17m/s with an average of 4 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station



Analysis: The office majorly has a single-flow directional ventilation system due to its orientation with regards to the prevailing wind direction. The existing conditions indicate that the office has an average of 2.8 air changes per hour, which is below the recommended minimum of 4 air changes per hour.

The thermal chimneys in the first trial give the lowest number of air changes per hour (3.3) as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.2m wide, the cavity heights are 5.35m and the cavity lengths are 1m. The narrow cavity widths result in friction losses which leads to a decrease in air speed.

The thermal chimneys in the second trial give the highest number of air changes per hour (4.9) as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.4m wide, the cavity heights are 7.35m and the cavity lengths are 1.1m. This combination gives the optimum number of air changes per hour for the office space.

The thermal chimneys in the third trial give 4 air changes per hour as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.6m wide, the cavity heights are 9.35m and the cavity lengths are 1.2m. The wide cavity widths and high cavity heights result in lower heat transfers within the chimney, which creates reverse flows in the stack resulting in decreased air speeds.

5.3.6 THERMAL CHIMNEY DESIGN RECOMMENDATIONS

The following are the design recommendations for three thermal chimneys for an office space with a floor area of 274m^2 and a floor to ceiling height of 3.2m:

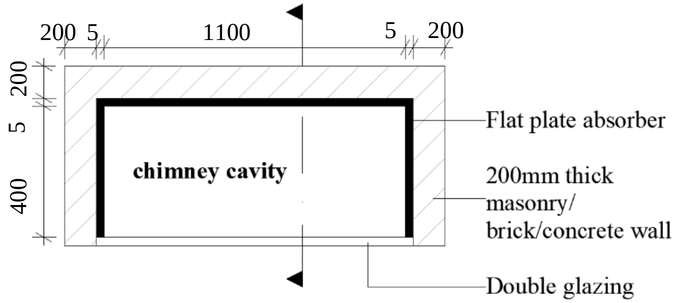


Figure 5.87: Plan of recommended thermal chimney
Source: Author

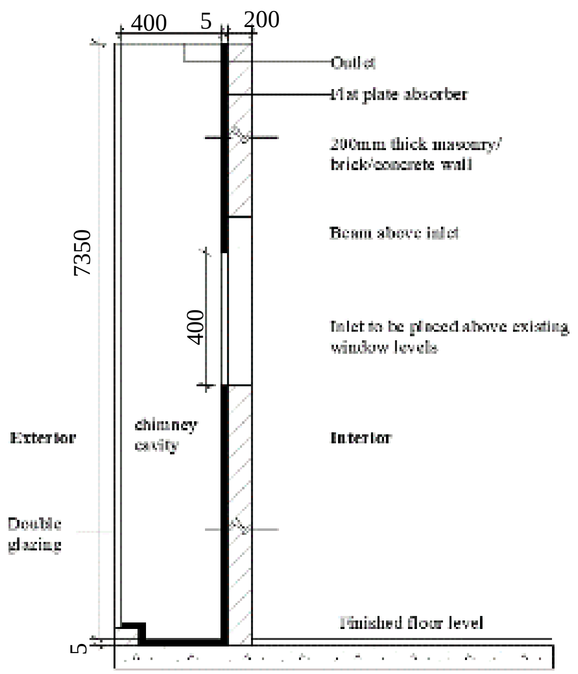


Figure 5.88: Cross section through recommended thermal chimney
Source: Author

Parameters	Variables	Description
Materials	Type of glazing	Double glazing
	Thermal absorber type	Flat copper plate absorber
Configuration	Cavity height	7.35m
	Cavity gap width	0.4m
	Cavity gap length	1.1m
	Inlet area	0.44m^2
	Outlet area	0.44m^2
	Cavity height to gap width ratio	18
Installation	Inclination angle	90^0
No. of chimneys	Quantity	3

Table 5.6: Thermal chimney design recommendations
Source: Author

5.4 DELTA CORNER TOWERS

5.4.1 INTRODUCTION

Location: Westlands, Nairobi

Completion: 2012

Architect: TMS Consulting Group

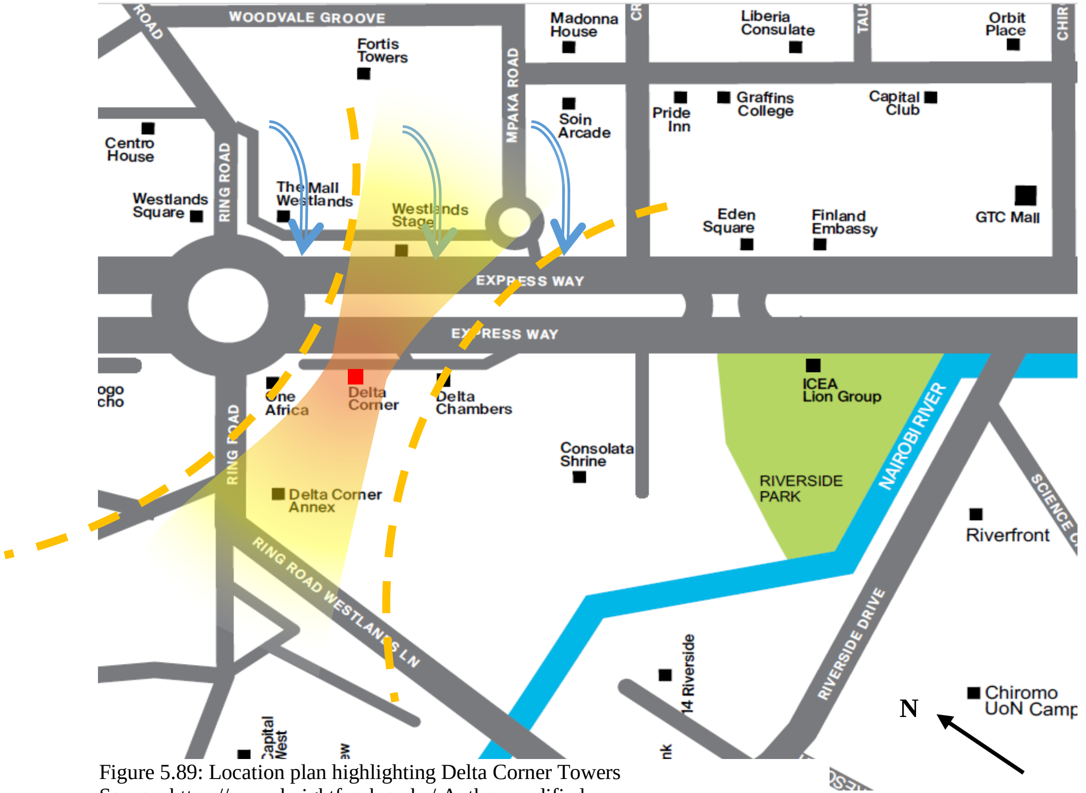


Figure 5.89: Location plan highlighting Delta Corner Towers
Source: https://www.knightfrank.co.ke/ Author modified

Delta Corner Tower is an office development located at the junction of Waiyaki Way and Ring Road in Westlands. The building houses a club house, offices, a car showroom and a restaurant. Two levels of basement parking have been provided for the users of the building.

Delta Corner development is an office block that comprises two towers, each with 19 floors. It has an approximate total gross lettable area of approximately 23,225m^2.

5.4.2 MORPHOLOGY

i) Site planning: The tower is strategically positioned in an excellent location at the intersection of Waiyaki expressway and Ring Road in Westlands.

ii) External elements/ obstructions: The building is bordered by the Expressway to the North East, by Delta Chambers to the South East, by Delta Corner Annex to the South West and by One Africa Place to the North West.

iii) Orientation: The building is oriented with the longer axis along the North East/ South West axis. The North Easterly prevailing winds are perpendicular to the shorter side of the building façade instead of the longer façade, which would have been more advantageous for providing natural ventilation.

iv) Building form: The two office towers are 61m high with rectangular plates (41m by 16.6m) and a cuboidal forms. They have smooth glazed and aluminium cladded façades with no projections. The two towers are connected by a lobby area that is approximately 12m high and measures 15m by 12m on plan.

The entire development is raised above the ground by 1650mm in order to provide adequate space for basement parking.

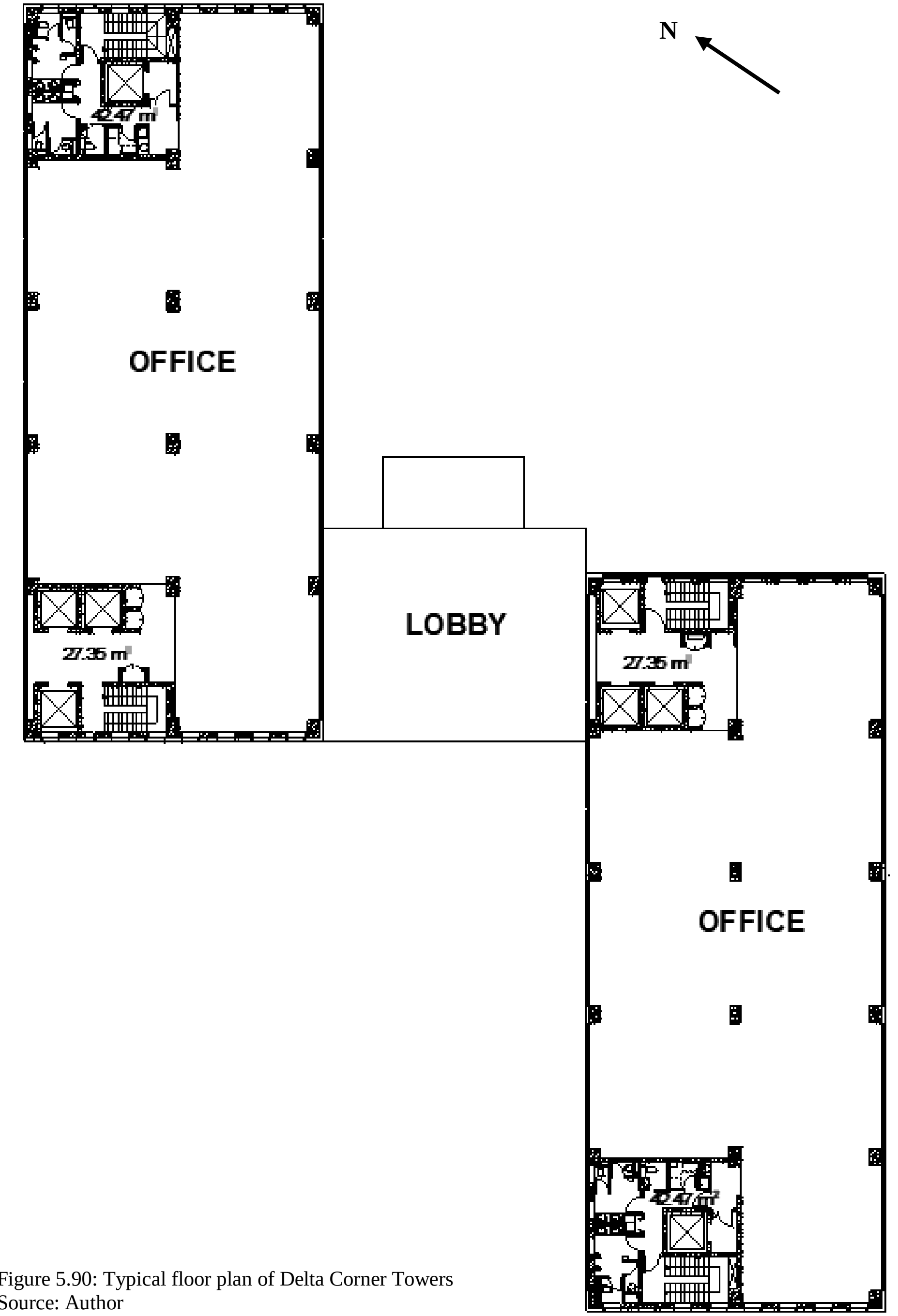


Figure 5.90: Typical floor plan of Delta Corner Towers
Source: Author

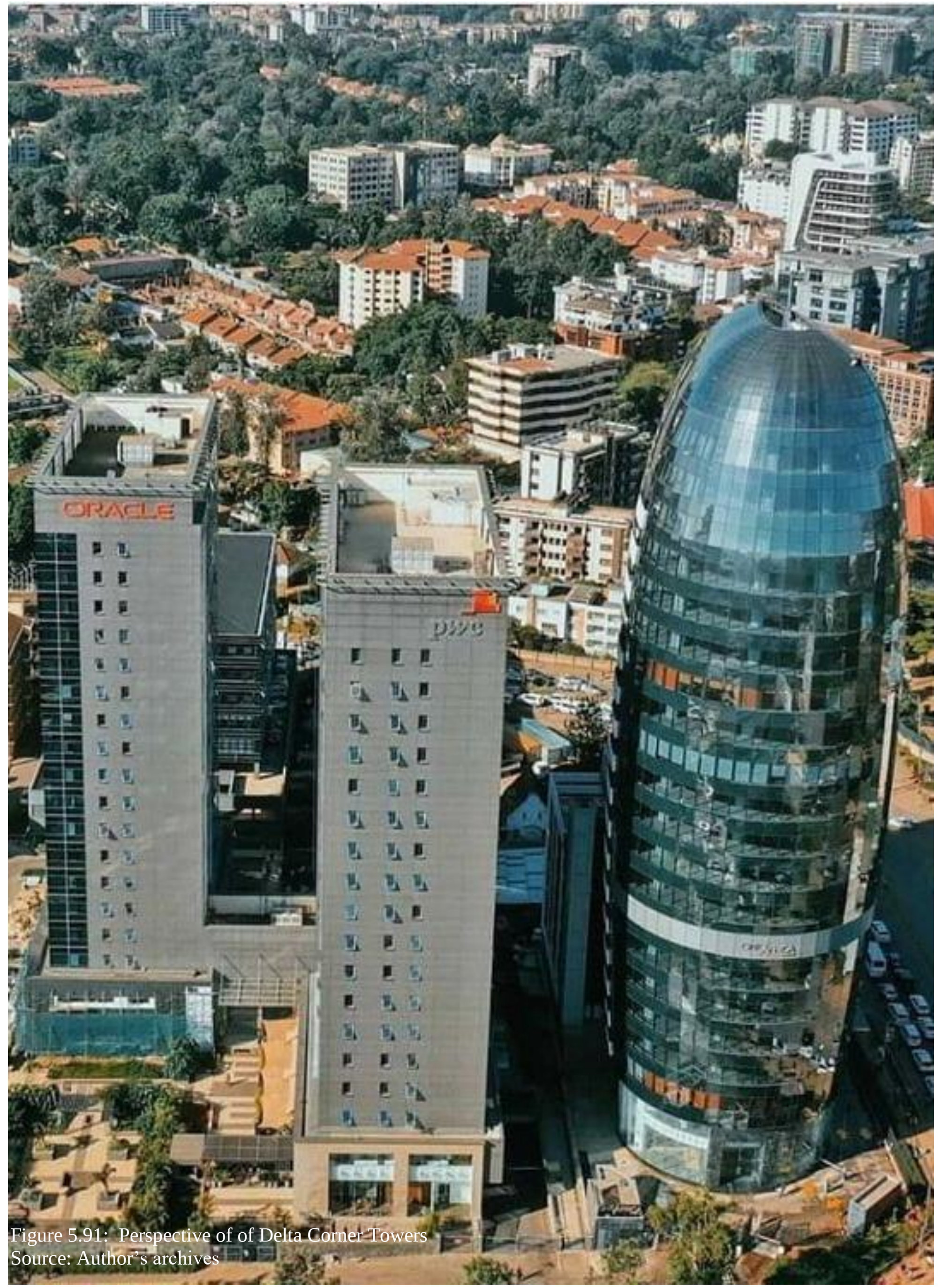


Figure 5.91: Perspective of of Delta Corner Towers
Source: Author's archives

5.4.3 SPATIAL DESIGN

The parameters that have been analysed under spatial design include:

i. Construction materials
ii. Surface finishes
iii. Floor layout
iv. Opening location and size
v. Opening control
vi. Wall thicknesses
vii. Floor to ceiling height
viii. Room sizes and spatial use
ix. Sun shading devices

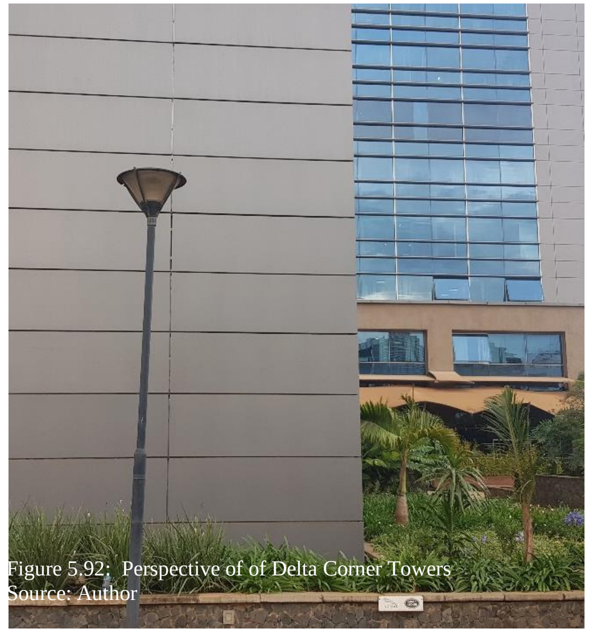
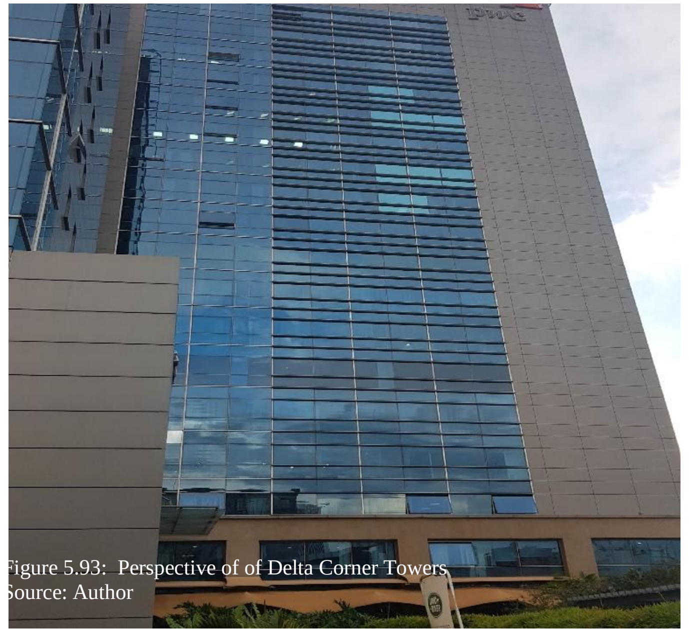
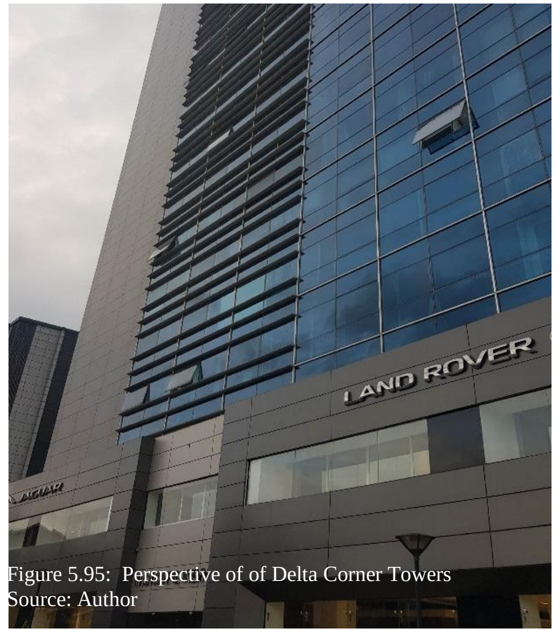
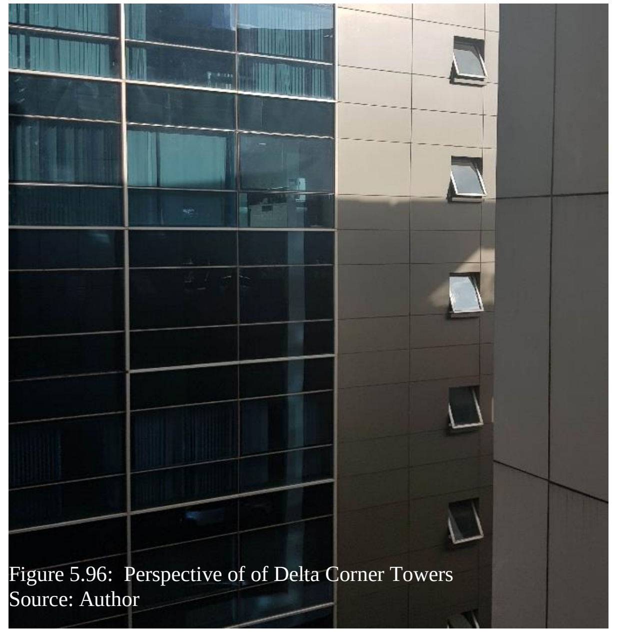
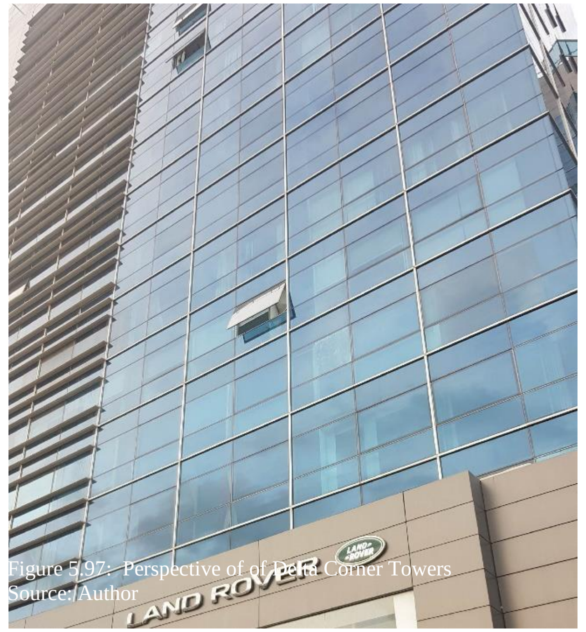
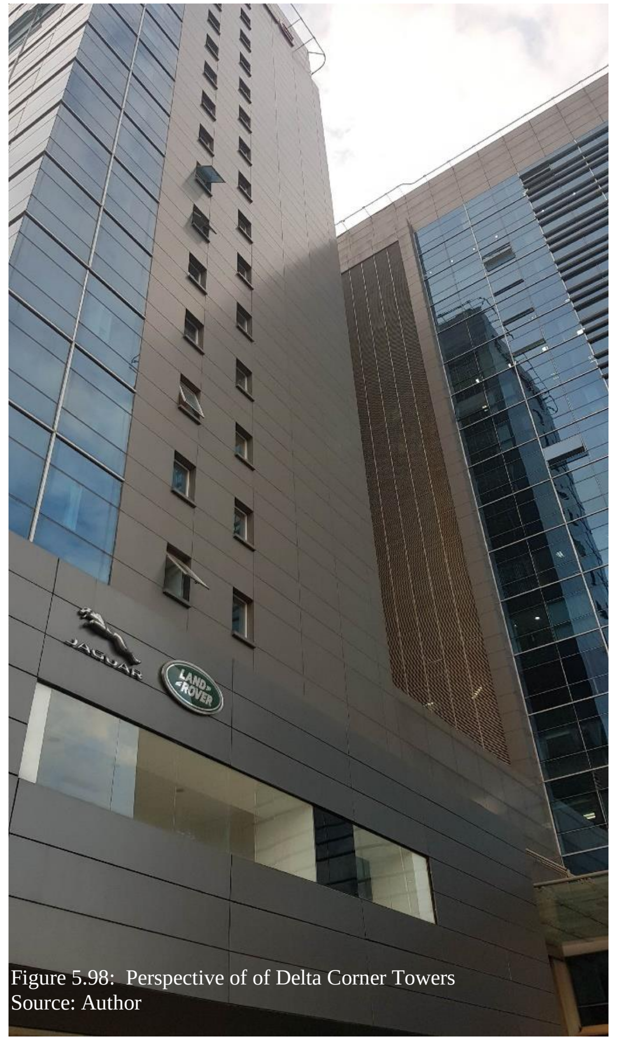
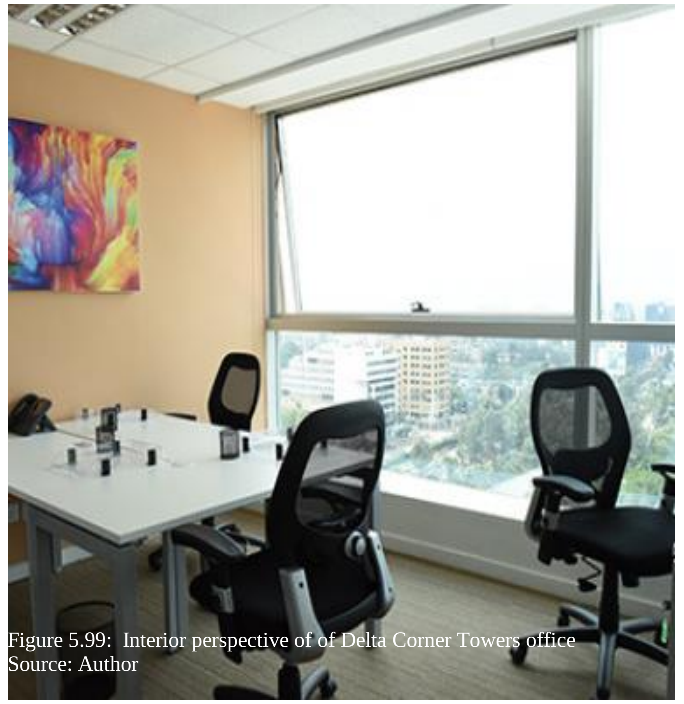
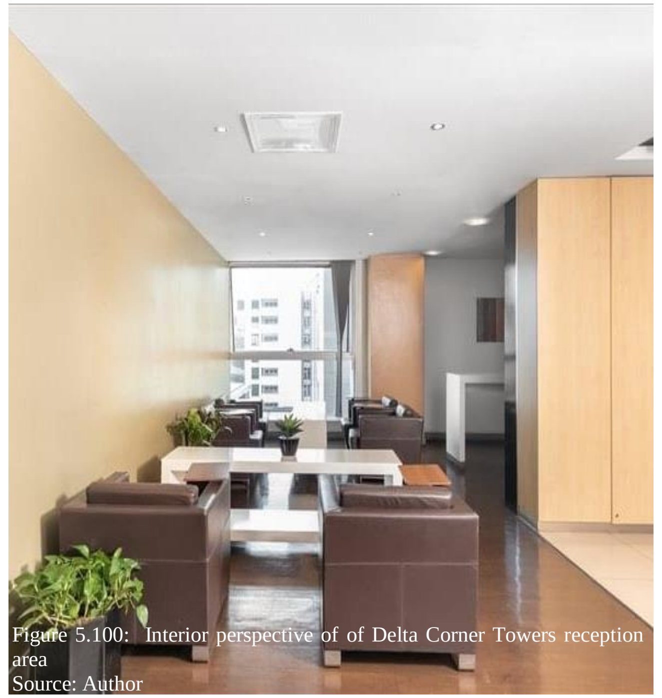
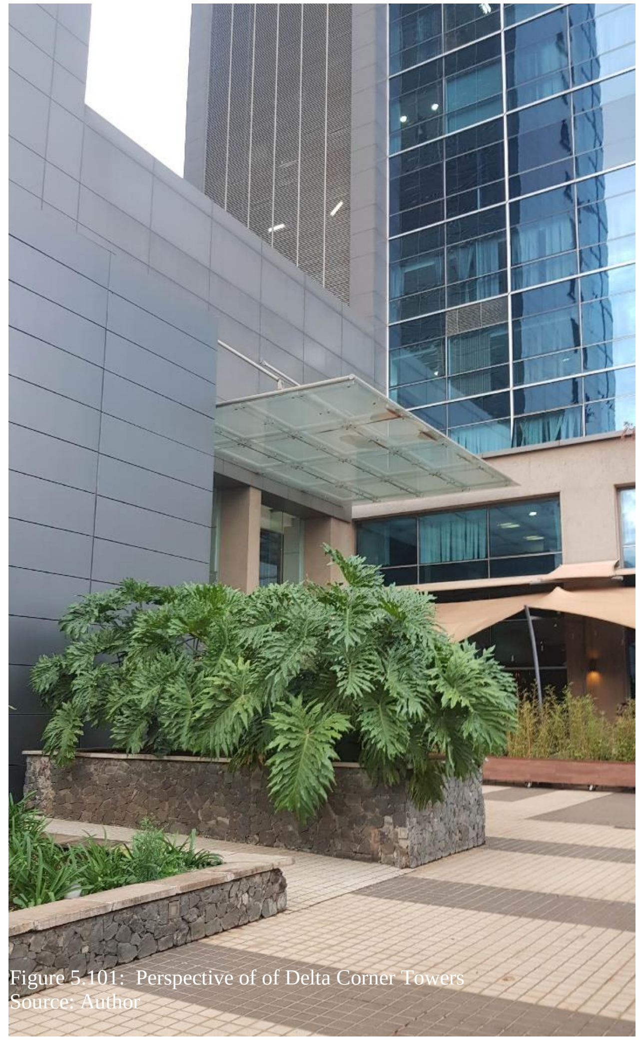


Figure 5.92: Perspective of of Delta Corner Towers
Source: Author

i. Construction materials	ii. Surface finishes	iii. Floor layout	iv. Opening location and size	v. Opening control
The structure is made of rectangular reinforced concrete columns that measure 1125mm by 725mm. The floor slabs are 150mm thick and are made of reinforced concrete. The external walls and lift core walls are made of reinforced concrete while the external and internal walls are made of masonry blocks. The glazing on the operable and fixed windows has a light blue tint.	The office floors are finished with porcelain tiles which are easy to clean and maintain. The wet areas have non slip porcelain tile floor finish. The office walls are finished with light coloured paint in order to reflect heat away. The ceilings are made of gypsum which is a good heat insulator. At the ground floor level, the external walls are finished with textured brown plaster. From the 1st floor till the 19th floor, the walls are cladded with grey aluminium composite panels. The glazing on the operable and fixed windows has a light blue tint.	The towers have 19 floors. On each floor, the core and services are located at the corners of the building. The columns within the rectangular shaped floor plate provide guidance on how to partition the spaces, if need be. There are two cores on each floor. One core has three passenger lifts, and a staircase while the other core has a fire escape staircase, a lift and washrooms. The floors are narrow, with widths of 16.6m, which ensures that the offices are sufficiently naturally lit by the floor to ceiling glazed areas.	The building has top hung steel casement windows which measure 2100mm wide by 1500mm high. The top hung service area windows measure 1000mm wide by 1500mm high. The doors at the entrance area are side hung double doors that are 1,8000mm wide. The doors leading to the court at the back side of the building are side hung double doors that are 1,8000mm wide.	Parts of the external walls are tinted glass panels which are fixed. The building also has two types of top hung aluminium casement windows which measure 2100mm wide by 1500mm high and 1000mm wide by 1500mm high. The doors at the entrance area and at the back of the building are side hung double doors.
 Figure 5.93: Perspective of of Delta Corner Towers Source: Author	 Figure 5.94: Interior perspective of of Delta Corner Towers reception area Source: Author	 Figure 5.95: Perspective of of Delta Corner Towers Source: Author	 Figure 5.96: Perspective of of Delta Corner Towers Source: Author	 Figure 5.97: Perspective of of Delta Corner Towers Source: Author

vi. Wall thicknesses	vii. Floor to ceiling height	viii. Room sizes and spatial use	ix. Sun shading devices	Interview questions
The reinforced concrete external and core walls are 280mm thick. The masonry block interior walls are 150mm thick.  Figure 5.98: Perspective of of Delta Corner Towers Source: Author	The gross room height is 3300mm (top of slab to bottom of slab). Some offices have false gypsum ceilings used to conceal the deep beams and air conditioning systems. The entrance lobby at the ground floor has a floor to ceiling height of 12000mm, highlighting the grand scale of the development.  Figure 5.99: Interior perspective of of Delta Corner Towers office Source: Author	The as built open plan offices are of the same area, which is 527m^2. The floors have widths of approximately 16.6m. The building houses a club house, offices, a car showroom and a restaurant. Two levels of basement parking have been provided for the users of the building. There are two cores on each floor with a total area of 70m^2. One core has three passenger lifts, and a staircase while the other core has a fire escape staircase, a lift and washrooms.  Figure 5.100: Interior perspective of of Delta Corner Towers reception area Source: Author	The towers lack sun shading devices. The entrance lobby has a canopy that measures 4000mm deep by 4000mm wide. This sufficiently shades the lobby area.  Figure 5.101: Perspective of of Delta Corner Towers Source: Author	i. How many people visit the building per day? Over 100 people visit the building per day ii. Do users exhibit symptoms of sick building syndrome? No iii. What improvements have been made to this building since it was built? None so far iv. How many hours in a day is the building in use? From 8am to 6 or 7pm, sometimes 24hours v. Do you feel the need to acquire or use a fan? Yes, during the hot months like February and March vi. Which rooms/ spaces are used most during daytime? The offices, restaurant and car show room. vii. Which rooms/ spaces are used most during the night? The offices and restaurant. viii. Do you ever open the windows, if any? If so, when? Yes, during the day from around 10am

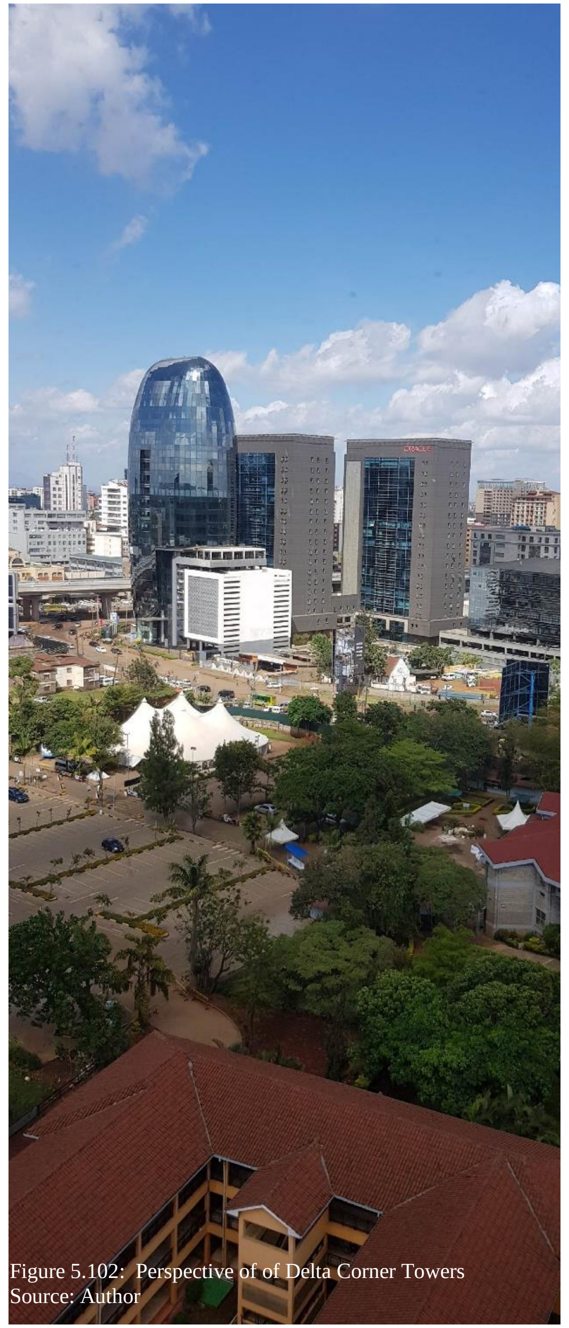


Figure 5.102: Perspective of of Delta Corner Towers
Source: Author

5.4.4 VENTILATION PERFORMANCE ANALYSIS

i) External wind effects generated by Delta Corner Towers

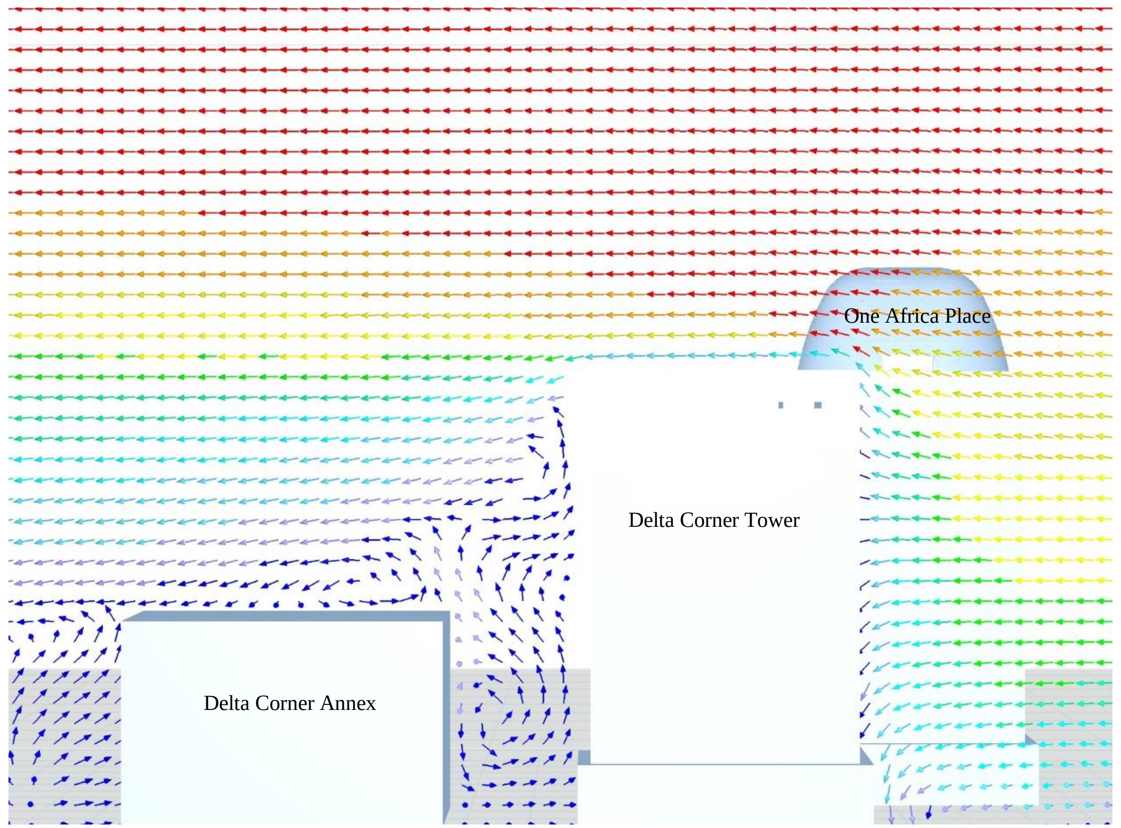
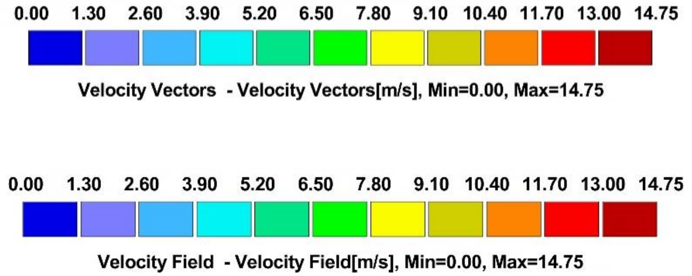


Fig.5.103: Side elevation of Delta Corner Towers illustrating the velocity vectors around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

KEY



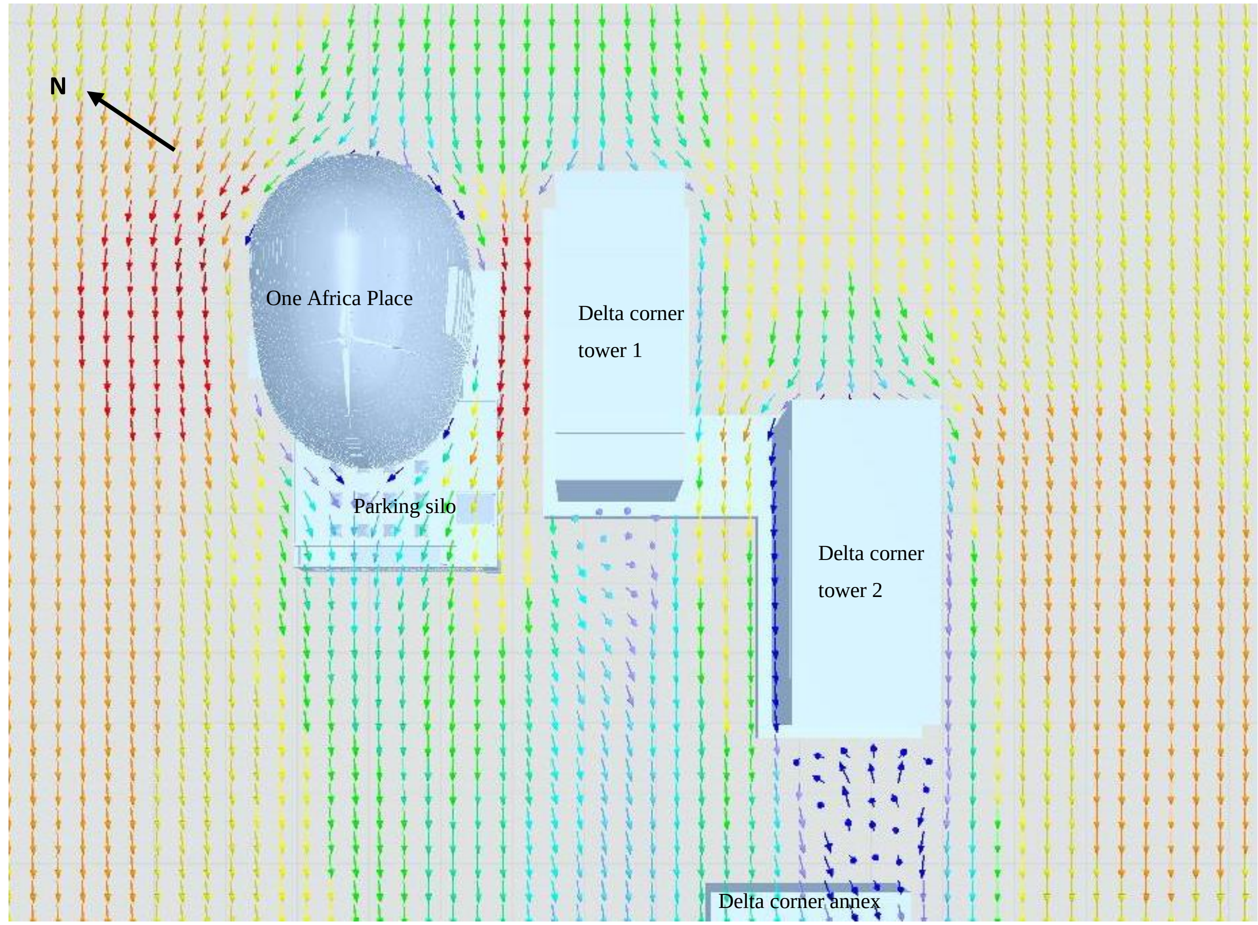


Fig.5.104: Plan view of Delta Corner Towers illustrating the velocity vectors around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

Delta Corner development is bordered by high rise builidngs on the North West and on the South West and by low rise buildings on the South East. This urban environment creates the following wind effects:

Downdraught effect: This happens when a tall building captures the wind at higher levels and then redirects it towards the ground, causing a three-dimensional flow moving downwards. In turn, this effect often creates a large recirculation at the ground level, causing greater wind activity. This is experienced at the front side of the development

Channeling: This happens due to the Venturi effect and is experienced when buildings are located in close proximity to one another, with the wind flow direction being parallel to the street or canyon. The effect is perpetuated by a reduction of wind pressure, resulting in wind acceleration through the tight channel created between the buildings. This is experienced in the canyon between the two towers, which is has an aspect ratio of 4.7. It is also experienced in the canyon between one tower and One Africa Place, which has an aspect ratio of 5.8.

Vertically rotating wind flow: This is experienced when the wind flow direction is perpendicular to the canyon. A vertically rotating wind flow is created with a centered primary vortex inside the canyon. This is experienced in the canyon between the Delta Corner towers and Delta Corner Annex, which has an aspect ratio of 2.02.

Corner acceleration: This happens when the wind reaches the vertical edge of a tall building. This effect is mainly created from sharp building shapes, causing acceleration around the corners. This is experienced along the sharp vertical edges of the Delta Corner Towers.

This analysis of wind velocities and movement patterns around the Delta Corner Towers has been used to inform the placement of the air inlets and air outlets within the building's proposed thermal chimney ventilation system. It is advisable to ensure that the air inlets face the North Eastern and South Western direction while the outlets should face the South Eastern or North Western direction.

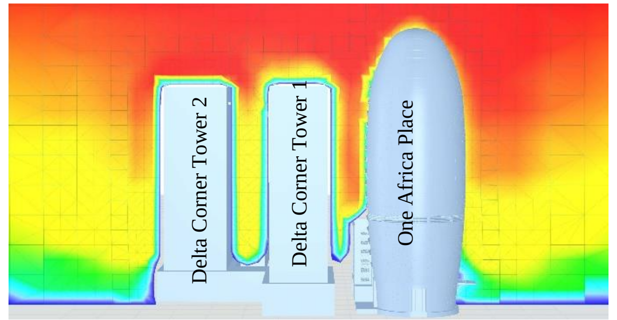


Fig.5.105: Side elevation of Delta Corner Towers illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

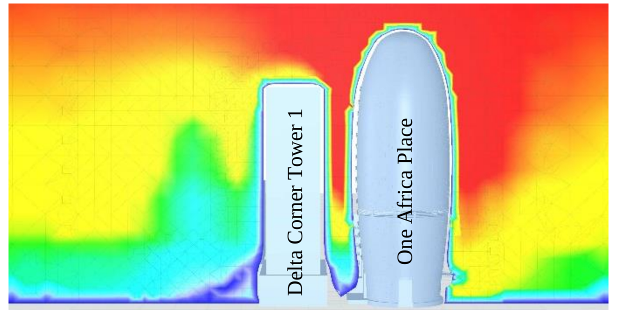


Fig.5.106: Front elevation of Delta Corner Towers illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

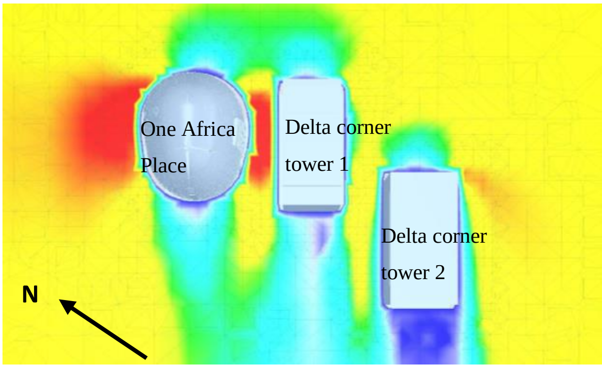


Fig.5.107: Plan view of Delta Corner Towers illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

ii) Internal ventilation performance analysis

The rotating vane anemometer was placed in the open plan office on the 3rd floor. It was placed at the window sill. The anemometer had a single rotating vane that was used to capture air speeds through the fenestrations. The readings were taken between the dates 20th March and 16th April 2020.

Air speed:

Readings from the graph indicate that the highest outdoor air speeds were experienced between 12 noon and 6pm, while the lowest speeds were experienced between 12 midnight and 6 am.

Readings from the graph indicate that the velocity through the fenestrations (indoor air apeed) is fairly low, with the lowest values being recorded at 12 midnight. The average velocity through the fenestrations is 0.18m/s.

Air changes per hour:

Since the building is naturally ventilated, the air changes per hour vary depending on the air velocity through the fenestrations. In such cases, the air changes per hour are obtained as explained below:

ACH= Q/Vol

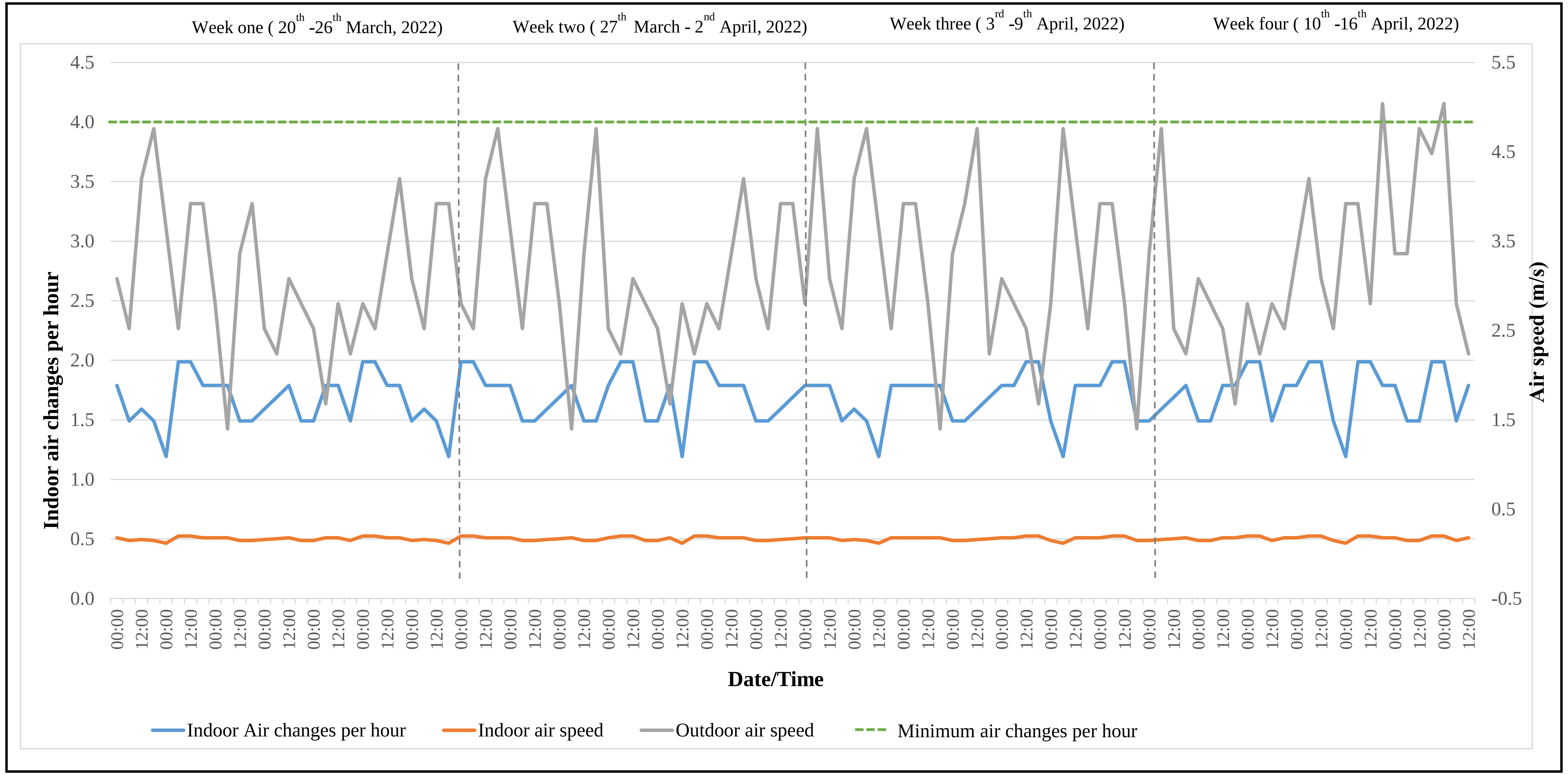
Where;

Q= Volumetric flow rate of air in m^3/hr (Velocity of air through thefenestrations in m/s x area of fenestration in m^2 x 3600)

Vol= Volume of room in m^2 (527 m^2 x 3.3m)

Average ACH = 2.2 air changes per hour

This is significantly below the recommended figure of 4 air changes per hour, meaning that the office is not being sufficiently ventilated. The office needs ventilation systems that will provide more air changes.



Graph 5.4: Graph showing the indoor air changes per hour, indoor air speed and outdoor air speed for an office space in Delta Corner towers
Source: Author

5.4.5 VENTILATION PERFORMANCE ANALYSIS WITH PROPOSED THERMAL CHIMNEY

CFD simulation tool: Designbuilder was chosen as the CFD simulation software in this study, incorporating the EnergyPlus calculation engine which has been validated under the Evaluation of Building Energy Analysis Computer Programs.

Natural ventilation studies were performed through CFD simulation of indoor airflow for the lettable space in the case-study using the weather files from Dagoretti Meteorological Station for accurate results.

CFD boundary conditions:

i. The calculated module was preferred over scheduled module where the calculation engine uses information about building fabric & openings in conjunction with weather data and internal gains to calculate the pressure difference and air flow through each zone.
ii. The system is at steady state.
iii. The working air behaves like an ideal gas.
iv. The air at the entrance in the thermal chimney to the outlet is without friction or leakages
v. The thermal chimney walls are used as heat flux sources
vi. Properties (pressures, temperatures and density) are assumed at standard with the standard atmospheric conditions.
vii. The flow is assumed to be laminar.

Model description: The study area as highlighted on the floor plan has a floor area of 527m^2 and a floor to ceiling height of 3.6m. A typical lettable area on the third floor was selected for the study. The office space has top hung steel casement windows which measure 2100mm by 1500mm and 1000mm by 1500mm. The rest of the glazed panels are fixed. Only the operable panes have been featured in the simulation model.

Thermal chimney cavity height: The thermal chimney's cavity height is bound by the height of the office space (including the thickness of the roof slab). The cavity height increases by a height of 2 m for each consecutive trial. The cavity heights of the first and last trials are 5.45m and 9.45m respectively.

Thermal chimney inclination angle: The study is limited to wall mounted thermal chimneys. Therefore, for all trials, the inclination angle is set at 90^0.

Thermal chimney cavity width: The thermal chimney's cavity width is bound by 0.2m and 0.6m with an increment of 0.2m for each trial. Widths lower than 0.2m give fairly low air speeds while widths higher than 0.6m may be physically too large relative to the building.

Thermal chimney cavity length: The length of the thermal chimney cavity is a parameter commonly overlooked since airflow within the thermal chimney is generally a two-dimensional flow, based on the cavity width and height. For this study, the length is based on the distance between the windows, since this is where the chimneys have been placed. The thermal chimney's cavity length is bound by 1m and 2.6m with an increment of 0.8m for each trial.

Location: Two thermal chimneys have been placed on the opposite side of the main air inlets as shown in the models. This location has made it possible for the chimneys to increase air flow rates into the office while still receiving maximum solar radiation.

Thermal chimney outlet and inlet areas: The thermal chimneys have outlets at the top of the stack. This means that this area will be determined by the cavity width and length. As recommended in the literatur review, the inlets and outlets have the same areas.

Thermal chimney construction materials: The chimneys have double glazing and are made of brick walls with a flat copper plate absorber.

Input parameters	Lower bound	Upper bound	Increment	No. of values
Cavity height	5.45m	9.45m	2m	3
Cavity gap width	0.2m	0.6m	0.2m	3
Cavity gap length	1m	2.6m	0.8m	3
Inlet area	0.2m^2	1.56m^2	-	3
Outlet area	0.2m^2	1.56m^2	-	3

Table 5.7: Input parameters used to model the various thermal chimney trials
Source: Author

With the examination of the influences of the input parameters, their combined effects on the indoor air speed are determined in order to design and optimize the thermal chimney. Although there are over 100 possible cases according to the limits from the table above, a first set of 20 cases (the lower and upper limits of the five input parameters) is modeled and simulated, after which the second set of 25 cases (chosen randomly) and the third set of 20 cases (chosen randomly) follow. The combined 65 cases are sufficient in developing a performance trend of the chimneys, which makes it possible to narrow down on the number of cases that will be presented for this study.

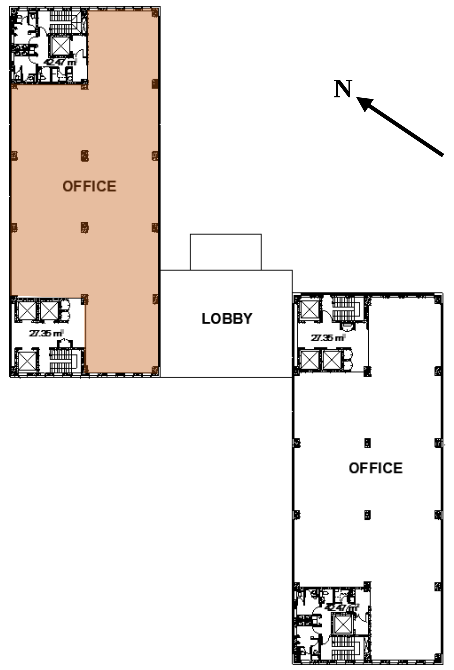


Fig.5.108: Layout plan highlighting study area
Source: Author

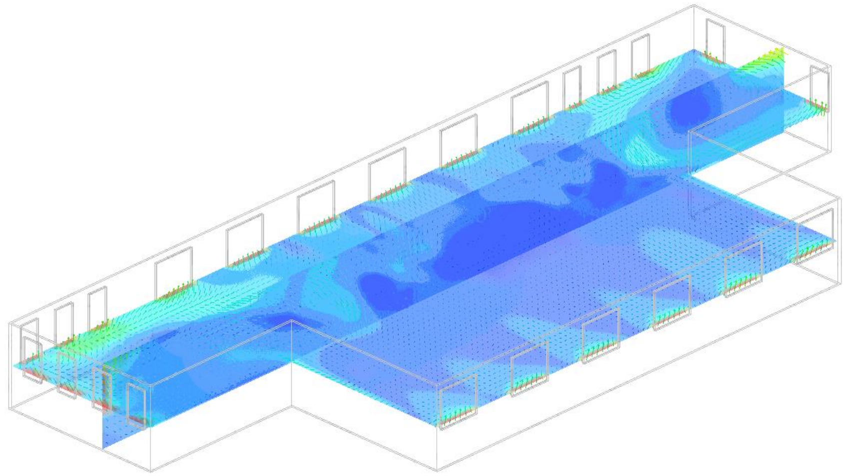


Fig.5.109: Existing ventilation conditions in the office. Average air speed is 0.18m/s with an average of 2.2 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

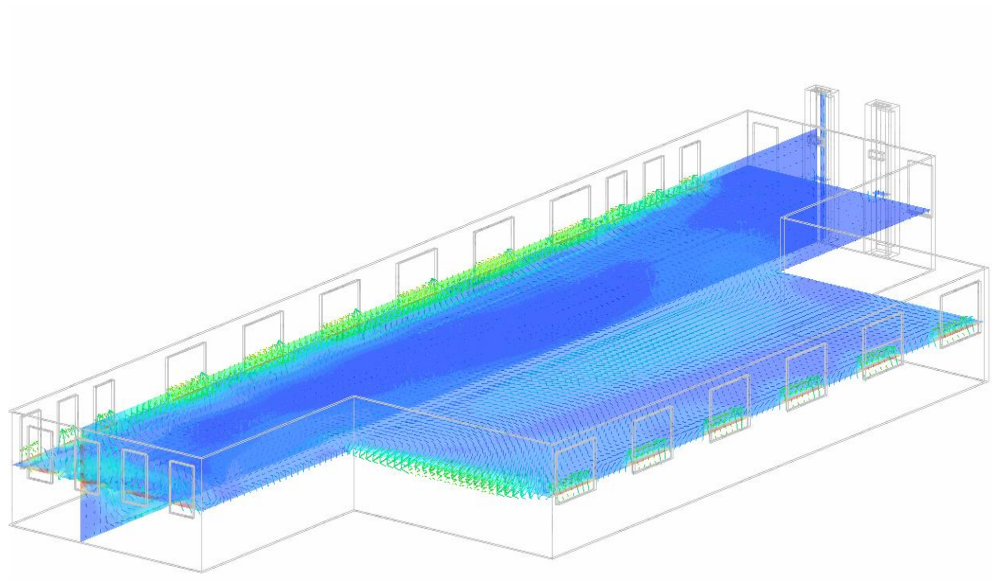


Fig.5.110: Ventilation conditions in the office with the first trial of the thermal chimney. Average air speed is 0.25m/s with an average of 3.1 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

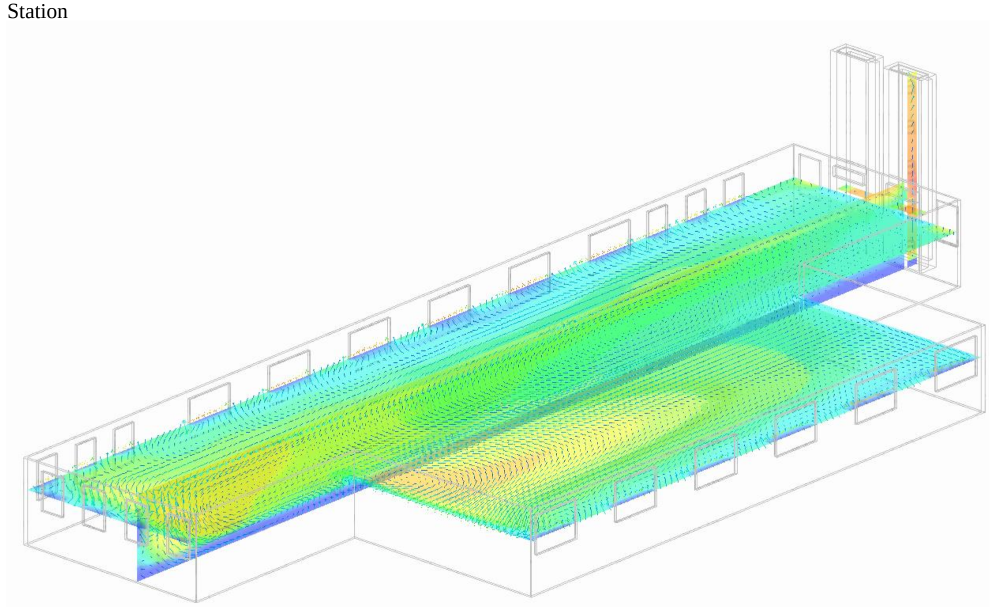


Fig.5.111: Ventilation conditions in the office with the second trial of the thermal chimney. Average air speed is 0.5m/s with an average of 6.2 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

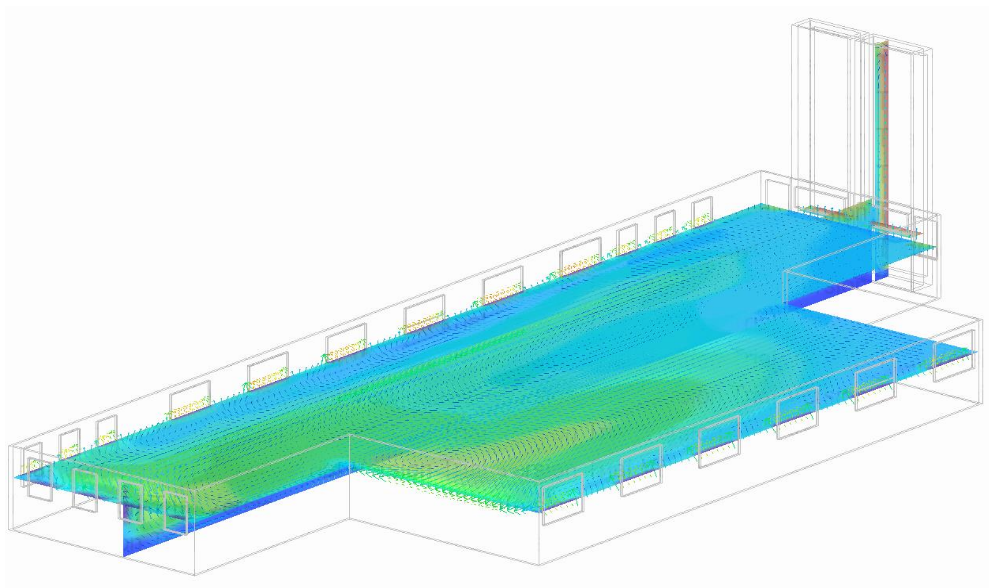
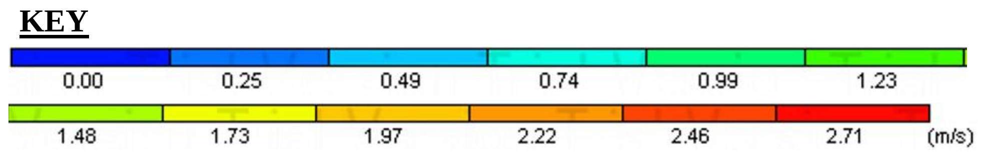


Fig.5.112: Ventilation conditions in the office with the third trial of the thermal chimney. Average air speed is 0.3m/s with an average of 3.7 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station



Analysis: The office majorly has a single-flow directional ventilation system due to its orientation with regards to the prevailing wind direction. The existing conditions indicate that the office has an average of 2.8 air changes per hour, which is below the recommended minimum of 4 air changes per hour.

The thermal chimneys in the first trial give the lowest number of air changes per hour (3.1) as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.2m wide, the cavity heights are 5.35m and the cavity lengths are 1m. The narrow cavity widths result in friction losses which leads to a decrease in air speed.

The thermal chimneys in the second trial give the highest number of air changes per hour (6.2) as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.4m wide, the cavity heights are 7.35m and the cavity lengths are 1.8m. This combination gives the optimum number of air changes per hour for the office space.

The thermal chimneys in the third trial give 3.7 air changes per hour as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.6m wide, the cavity heights are 9.35m and the cavity lengths are 2.6m. The wide cavity widths and high cavity heights result in lower heat transfers within the chimney, which creates reverse flows in the stack resulting in decreased air speeds.

5.4.6 THERMAL CHIMNEY DESIGN RECOMMENDATIONS

The following are the design recommendations for two thermal chimneys for an office space with a floor area of 527m^2 and a floor to ceiling height of 3.3m:

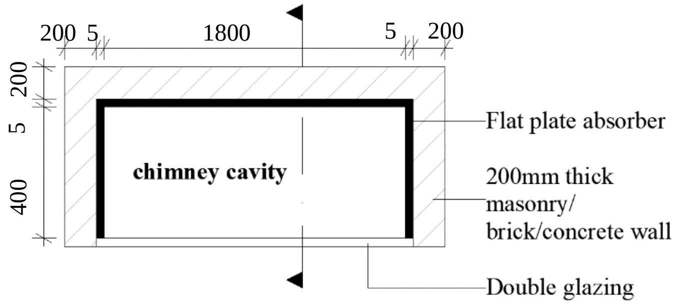


Fig.5.113: Plan of recommended thermal chimney
Source: Author

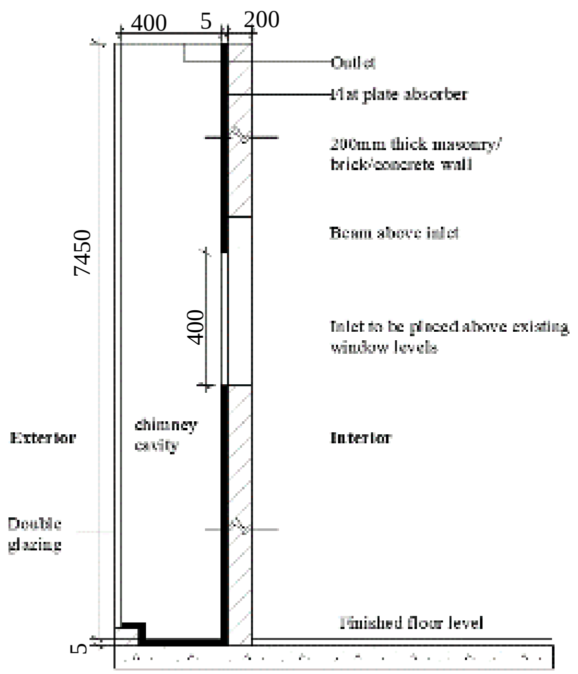


Fig.5.114: Cross section through recommended thermal chimney
Source: Author

Parameters	Variables	Description
Materials	Type of glazing	Double glazing
	Thermal absorber type	Flat copper plate absorber
Configuration	Cavity height	7.45m
	Cavity gap width	0.4m
	Cavity gap length	1.8m
	Inlet area	0.72m^2
	Outlet area	0.72m^2
	Cavity height to gap width ratio	18.6
Installation	Inclination angle	90^0
No. of chimneys	Quantity	2

Table 5.8: Thermal chimney design recommendations
Source: Author

5.5 ONE AFRICA PLACE

5.5.1 INTRODUCTION

Location: Westlands, Nairobi

Completion: 2019

Architect: BAA Architects

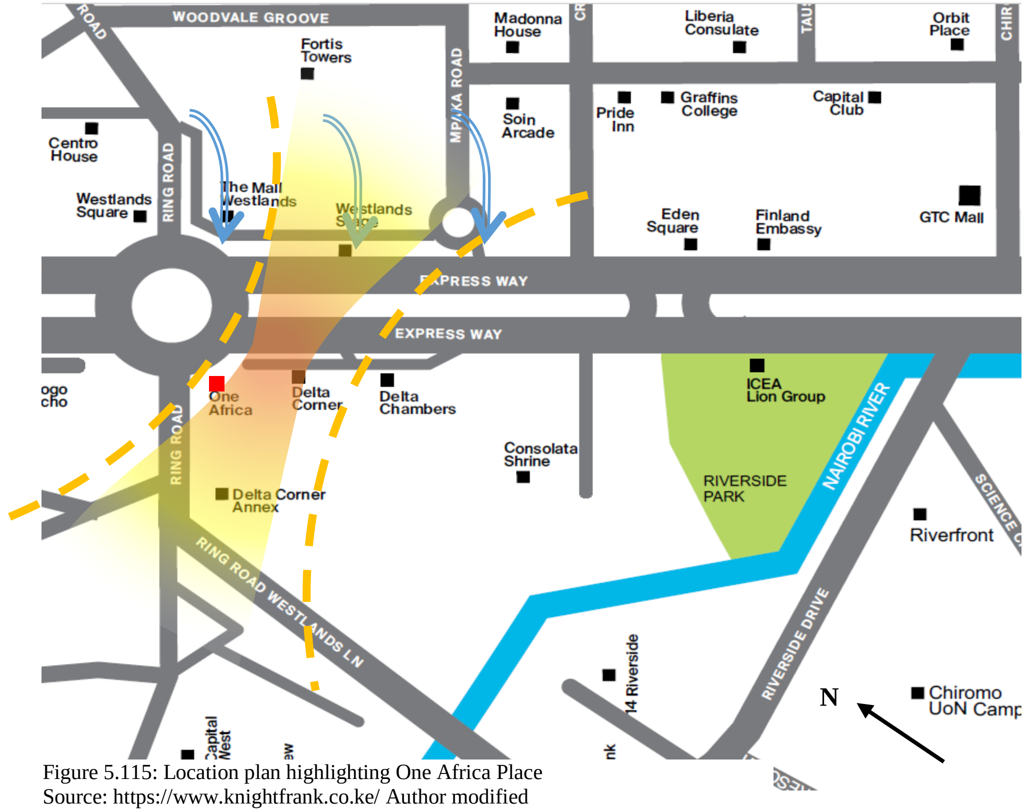


Figure 5.115: Location plan highlighting One Africa Place
Source: https://www.knightfrank.co.ke/ Author modified

One Africa Place is an office development located at the junction of Waiyaki Way and Ring Road in Westlands. The building houses offices, a gym, a car showroom and restaurants. A parking silo has been availed to provide parking spaces for the users of the building.

One Africa Place is an iconic twenty one storey commercial office development with an approximate total gross lettable area of approximately 12,820m^2.

5.5.2 MORPHOLOGY

i) Site planning: The tower is strategically positioned in an excellent location at the intersection of Waiyaki expressway and Ring Road in Westlands.

ii) External elements/ obstructions: The building is bordered by the Expressway to the North East, by Delta Corner towers to the South East, by Delta Corner Annex to the South West and by Ring Road to the North West.

iii) Orientation: The building is oriented with the longer axis along the North East/ South West axis. The North Easterly prevailing winds are perpendicular to the shorter side of the building façade instead of the longer façade, which would have been more advantageous for providing natural ventilation. However, the building does not rely on natural ventilation. All spaces are artificially ventilated by an optimally controlled HVAC system.

iv) Building form: The office tower is 90m high with an oval floor plate and an elliptical form. It has a smooth glazed façade with no projections. On the north western façade from the 10th to the 14th floor, the building has recessed balconies. The parking silo is 28m high with a rectangular floor plate (27m x 23m) and a cuboidal form. It is covered with a concrete screeen on all facades which ensures that the parking areas receive natural ventilation.

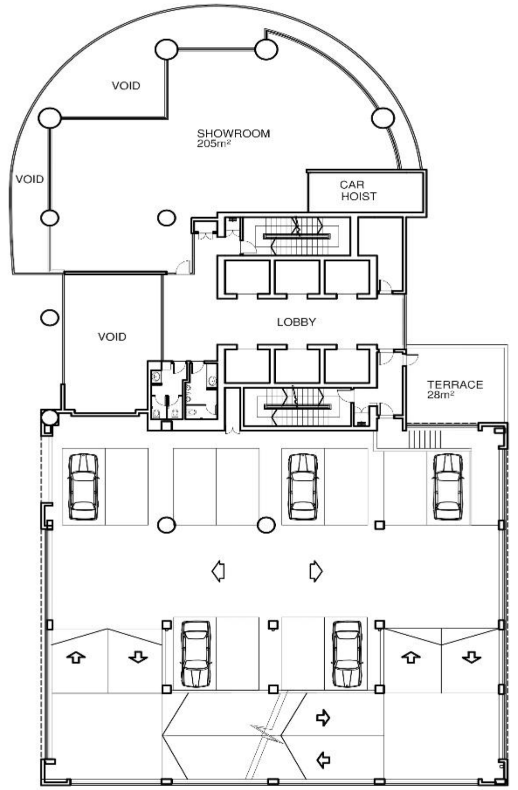


Fig.5.116: Ground floor plan of One Africa Place
Source: Author

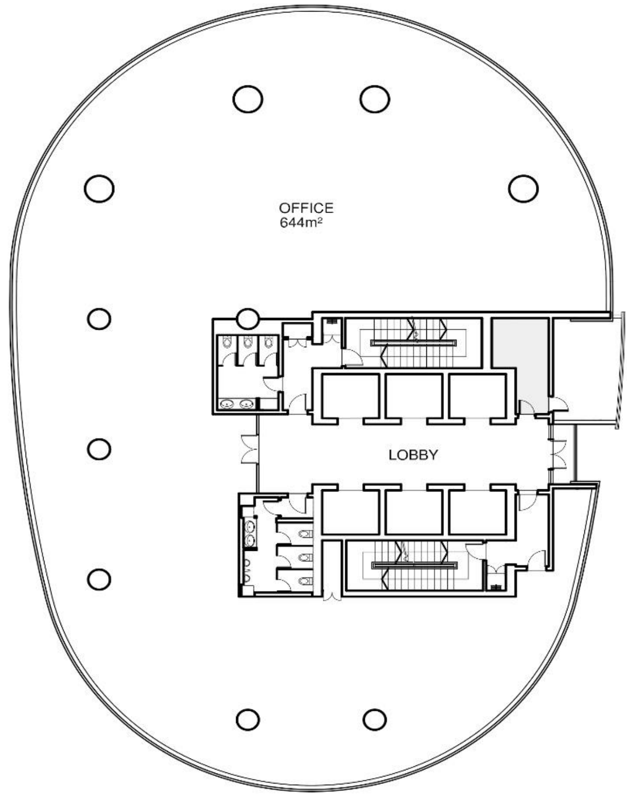


Fig.5.117: Typical floor plan of One Africa Place
Source: Author

Fig.5.118: Perspective of One Africa Place
Source: Author

Fig.5.119: Perspective of One Africa Place
Source: Author

5.5.3 SPATIAL DESIGN

The parameters that have been analysed under spatial design include:

i. Construction materials
ii. Surface finishes
iii. Floor layout
iv. Opening location and size
v. Opening control
vi. Wall thicknesses
vii. Floor to ceiling height
viii. Room sizes and spatial use
ix. Sun shading devices

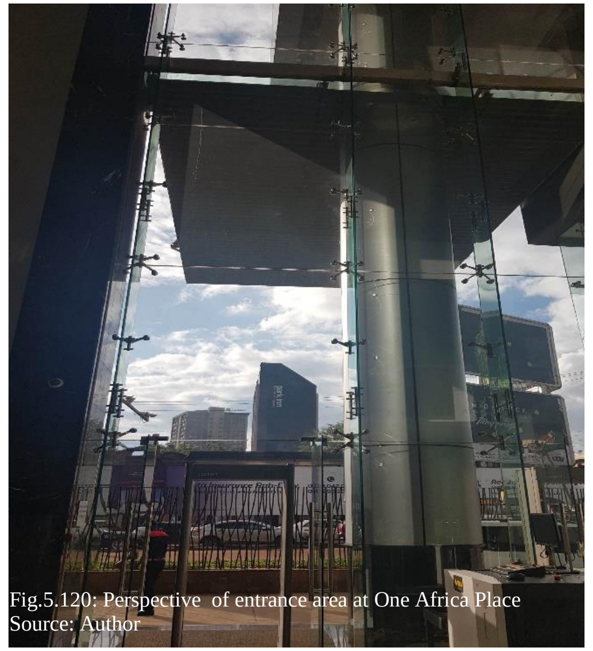
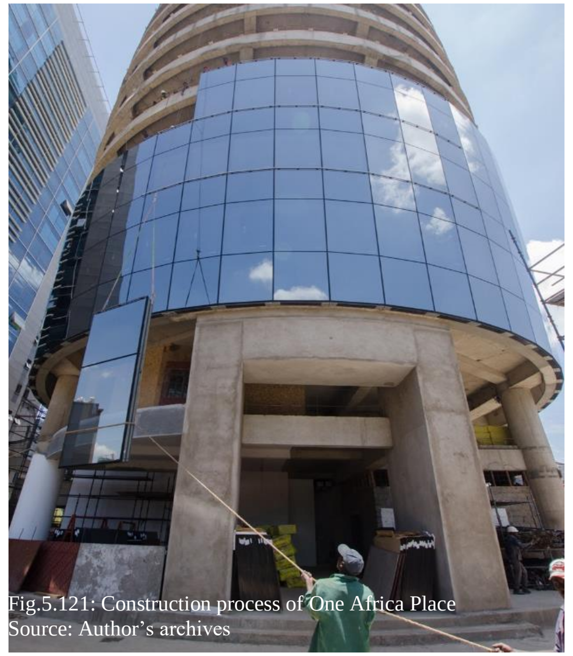
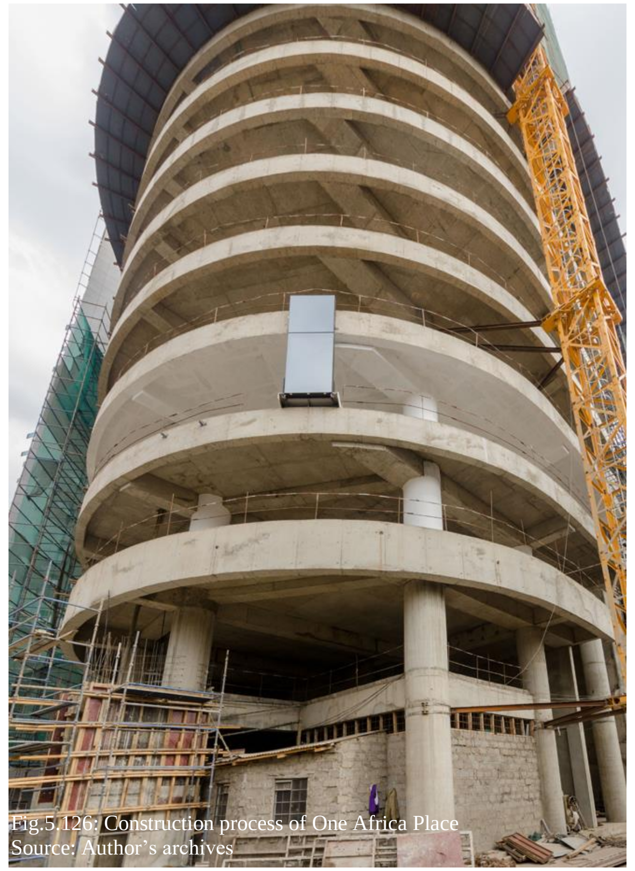
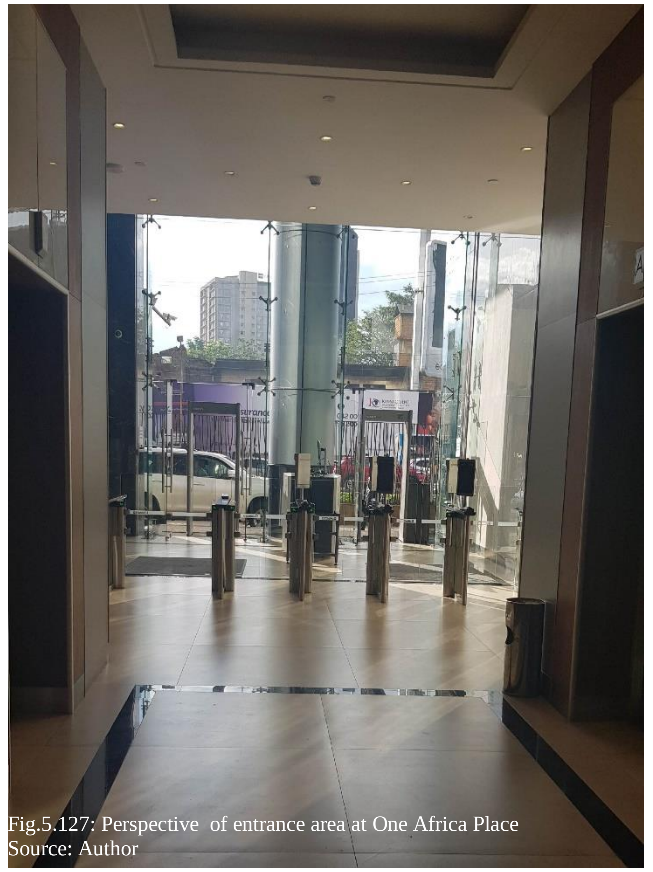
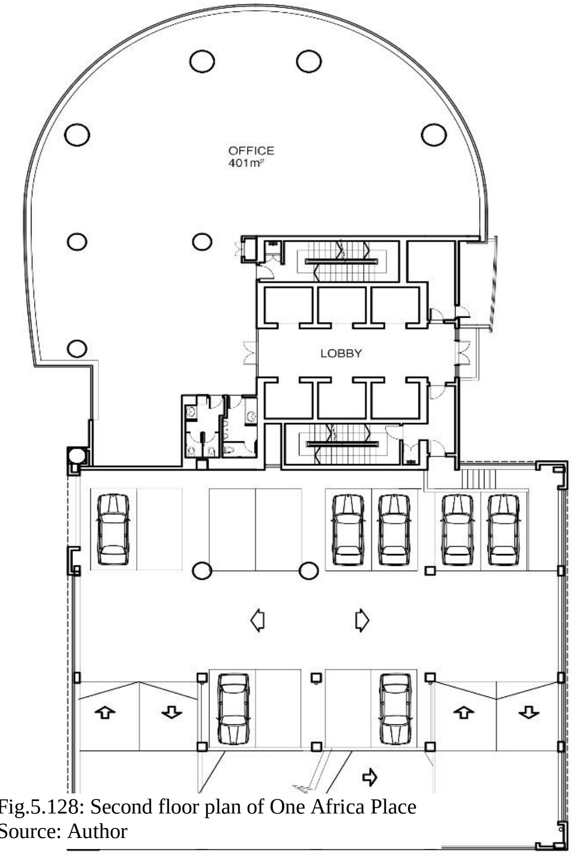


Fig.5.120: Perspective of entrance area at One Africa Place
Source: Author

i. Construction materials	ii. Surface finishes	iii. Floor layout	iv. Opening location and size	v. Opening control
The elliptical structure is made of circular reinforced concrete columns with a diameter of 1000mm. The parking silo has reinforced concrete square columns that are 450mm wide. The floor slabs are 150mm thick and are made of reinforced concrete. The lift core walls are made of reinforced concrete and the internal walls are made of masonry blocks. The external walls are made of double glazed solar efficient glass panels.	The office floors are finished with cement screed and the walls have been plastered and finished with white paint. The wet areas have non slip porcelain tile floor finish. The ceilings are made of gypsum which is a good heat insulator. The interior surface finishes can be customized in order to suit the client's preferences. The external walls are made of double glazed solar efficient glass panels. The balcony railings are made of stainless steel.	The building has 21 floors. On each floor, the core and services are located at the centre and the open plan office spaces surround the core as illustrated in the floor plans. The columns within the oval floor plate provide guidance on how to partition the spaces, if need be. The core has 6- high speed passenger lifts to boost efficient circulation and lessen waiting time. The average floor size is approximately 26m wide by 28m long. Since all facades are fully glazed, the interior spaces are sufficiently naturally lit.	The exterior curtain wall glass is divided into fixed panels that measure 950mm wide by 1250mm high. The two doors at the entrance area are side hung double doors that are 2,000mm wide. The doors leading to the terraces are 900mm wide. The service floor is located on the seventh floor. It has 5 continuous openings on the front façade that are 200mm high. This is to ensure that the service floor is sufficiently naturally ventilated.	The external walls are made of double glazed solar efficient glass panels is fixed. It lacks operable panes. The doors at the entrance area and at the balconies are side hung double doors and have a maximum opening angle of 90^0.  Fig.5.124: Glazing in lettable office Source: Author
 Fig.5.121: Construction process of One Africa Place Source: Author's archives	 Fig.5.122: Perspective of typical lettable office area Source: Author	 Fig.5.122: Perspective of lift lobby at One Africa Place Source: Author	 Fig.5.123: Perspective of typical lettable office area Source: Author	 Fig.5.125: Glazing in lettable office Source: Author

vi. Wall thicknesses	vii. Floor to ceiling height	viii. Room sizes and spatial use	ix. Sun shading devices	Interview questions
The external walls are made of double glazed solar efficient glass. The interior walls have a thickness of 200mm and the lift core walls have a thickness of 300mm for structural purposes.  Fig.5.126: Construction process of One Africa Place Source: Author's archives	The gross room height is 3450mm (top of slab to bottom of slab). The show room at the ground floor has a floor to ceiling height of 4700mm, while the entrance lobby area has a floor to ceiling height of 15950mm, highlighting the grand scale of the development.  Fig.5.127: Perspective of entrance area at One Africa Place Source: Author	The room sizes vary due to the elliptical form of the building. The average floor size is approximately 26m wide by 28m long. Each office floor has a core which has 6 high speed lifts, two staircases, a fire duct, washrooms and a pantry. The building houses a car show room, restaurant, offices and a gym.  Fig.5.128: Second floor plan of One Africa Place Source: Author	The office tower has a smooth glazed façade with no projections. On the north western façade from the 10th to the 14th floor, the building has balconies which have been recessed by 2.8m. The entrance area is defined by a canopy that measures 6000mm long by 8190mm deep and it adequately shades the interior lobby from direct sunlight.  Fig.5.129: Perspective of One Africa Place Source: Author	i. How many people visit the building per day? Approximately 60 people visit the building per day ii. Do users exhibit symptoms of sick building syndrome? Yes, at the top most floor where the restaurant is located iii. What improvements have been made to this building since it was built? None so far iv. How many hours in a day is the building in use? From 8am to 12 midnight v. Do you feel the need to acquire or use a fan? Yes vi. Which rooms/ spaces are used most during daytime? The offices vii. Which rooms/ spaces are used most during the night? The offices and restaurant viii. Do you ever open the windows, if any? If so, when? No windows are ever opened.

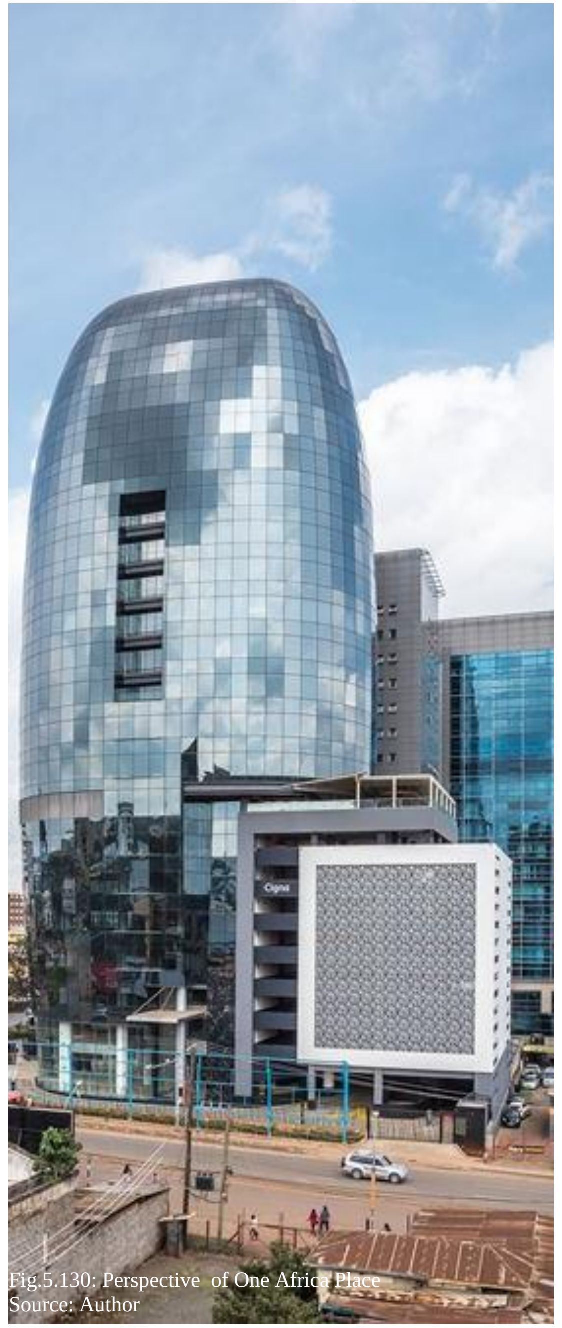


Fig.5.130: Perspective of One Africa Place
Source: Author

5.5.4 VENTILATION PERFORMANCE ANALYSIS

i) External wind effects generated by One Africa Place

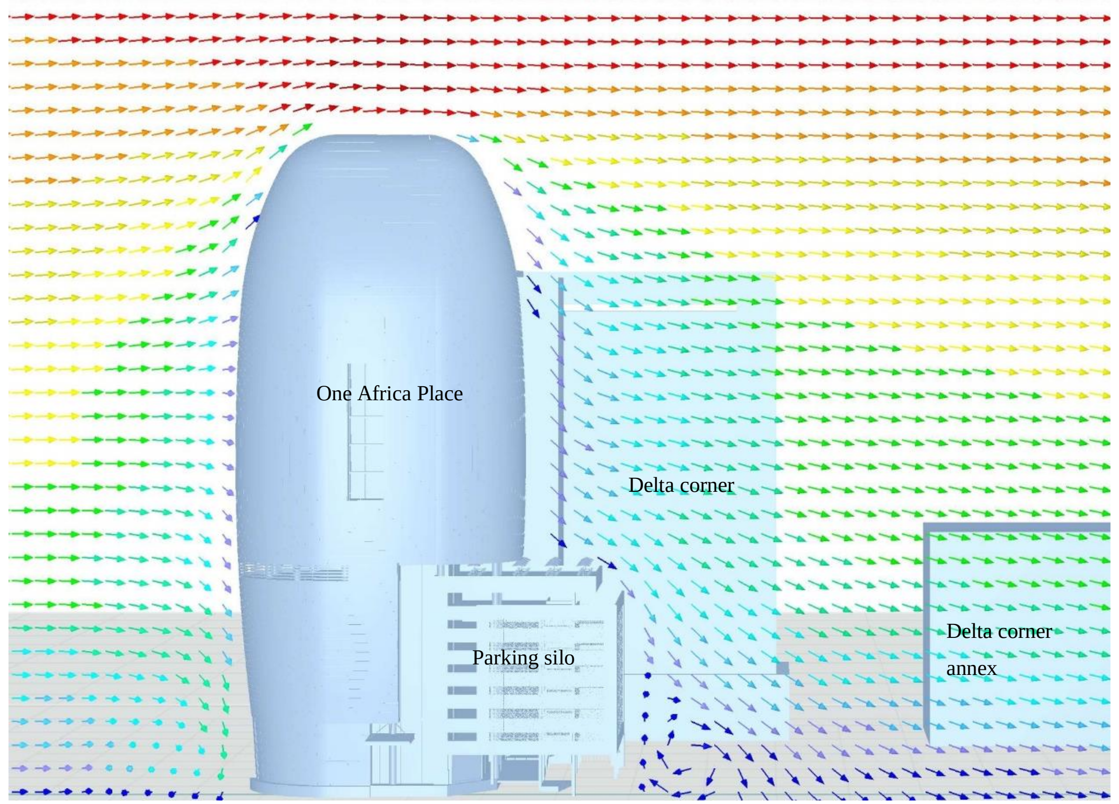


Fig.5.131: Side elevation of One Africa Place illustrating the velocity vectors around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

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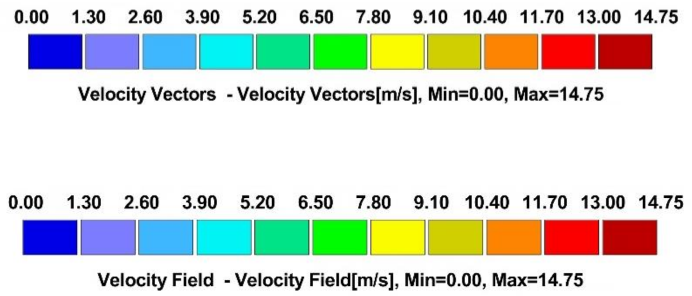
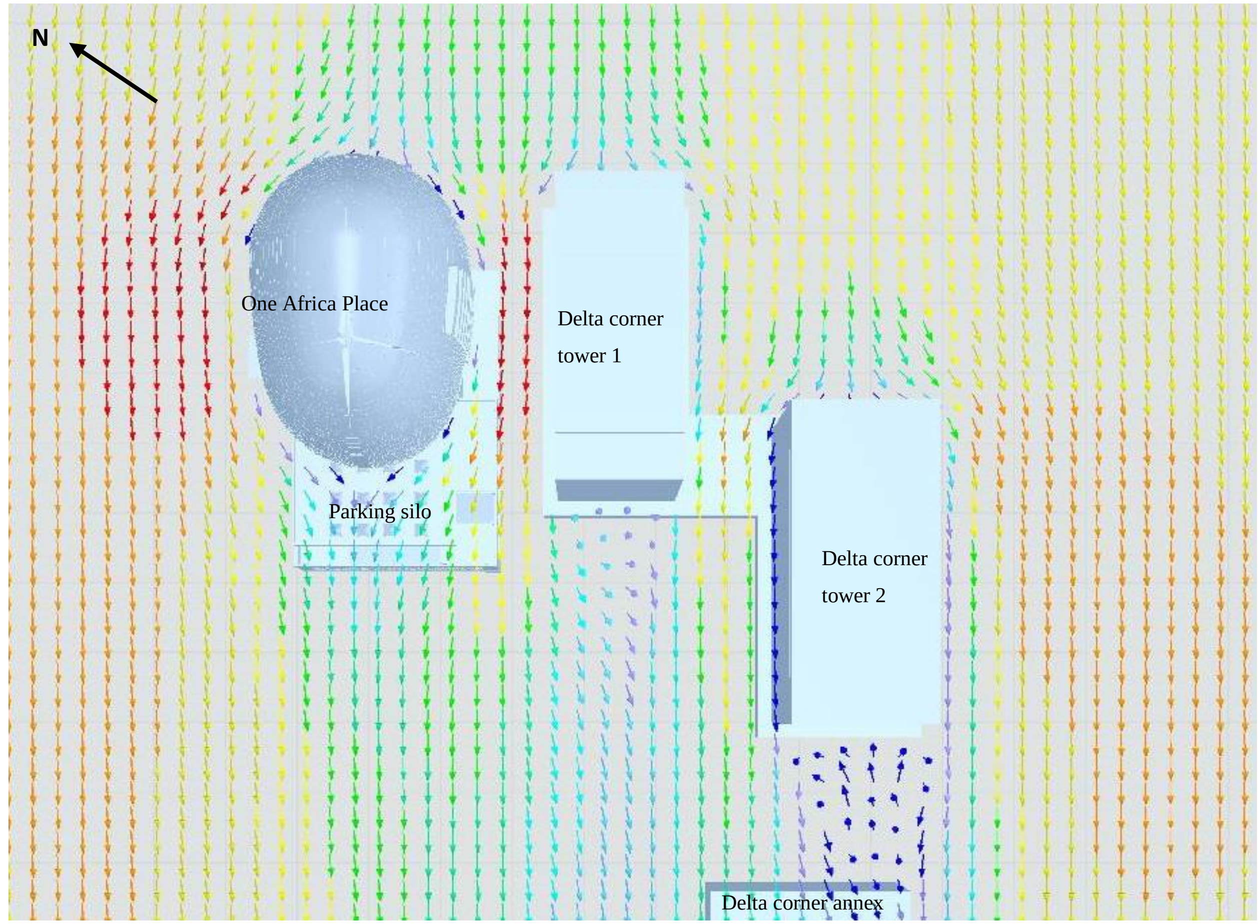




`Fig.5.132: Plan view of One Africa Place illustrating the velocity vectors around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

One Africa Place is bordered by tall builidngs on one side only. This urban environment creates the following wind effects:

Downdraught effect: This happens when a tall building captures the wind at higher levels and then redirects it towards the ground, causing a three-dimensional flow moving downwards. In turn, this effect often creates a large recirculation at the ground level, causing greater wind activity. This is experienced at the front side of the building as shown in the simulation images.

Channeling: This happens due to the Venturi effect and is experienced when buildings are located in close proximity to one another, with the wind flow direction being parallel to the street or canyon. The effect is perpetuated by a reduction of wind pressure, resulting in wind acceleration through the tight channel created between the buildings. This is experienced in the canyon between One Africa Place and Delta Corner tower 1, which is has an aspect ratio of 7.2.

Vertically rotating wind flow: This is experienced when the wind flow direction is perpendicular to the canyon. This is not experienced in this region since there is no canyon that is perpendicular to the wind flow.

Corner acceleration: This happens when the wind reaches the vertical edge of a tall building. This effect is mainly created from sharp building shapes, causing acceleration around the corners. The elliptical shape of One Africa Placeallows wind to glide around the building without causing corner acceleration.

This analysis of wind velocities and movement pattenrs around One Africa Place has been used to inform the placement of the air inlets and air outlets within the building's proposed thermal chimney ventilation system.

It is advisable to ensure that the air inlets face the North Eastern direction while the outlets should face the South Eastern direction.

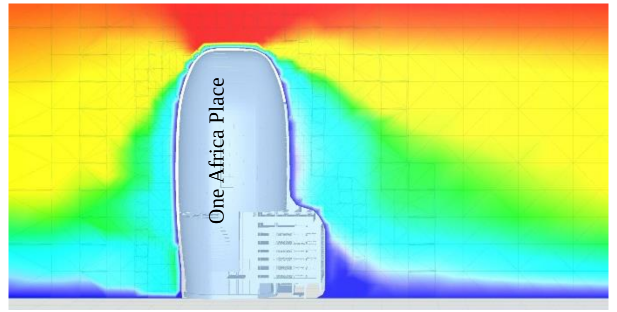


Fig.5.133: Side elevation of One Africa Place illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

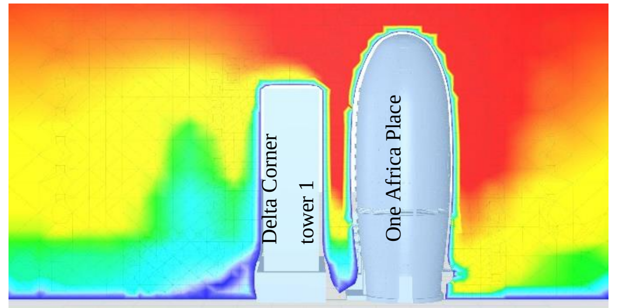


Fig.5.134: Front elevation of One Africa Place illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

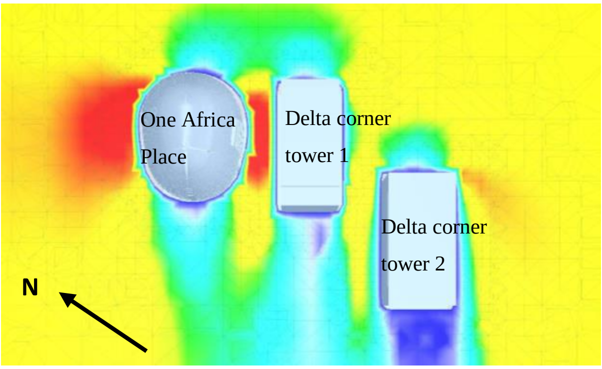


Fig.5.135: Plan view of One Africa Place illustrating the velocity fields around the building and its context
Source: Author- simulated using RWIND software and weather statistics from Dagoretti Meteorological Station

ii) Internal ventilation performance analysis

The rotating vane anemometer was placed in the open plan office on the 4th floor. It was placed on a table in the office. The anemometer had a single rotating vane that was used to capture air speeds from the air conditioning systems. The readings were taken between the dates 20th March and 16th April 2020.

Air speed:

Readings from the graph indicate that the highest outdoor air speeds were experienced between 12 noon and 6pm, while the lowest speeds were experienced between 12 midnight and 6 am. Since the indoor ventilation system is controlled, the air speeds were relatively constant, with an average of 0.11m/s.

Air changes per hour:

Since the building is mechanically ventilated, the air changes per hour are fixed due to the air conditioning system's fixed CFM rate. In sich cases, the air changes per hour are obtained as explained below:

ACH= (CFM x 60)/ V

Where;

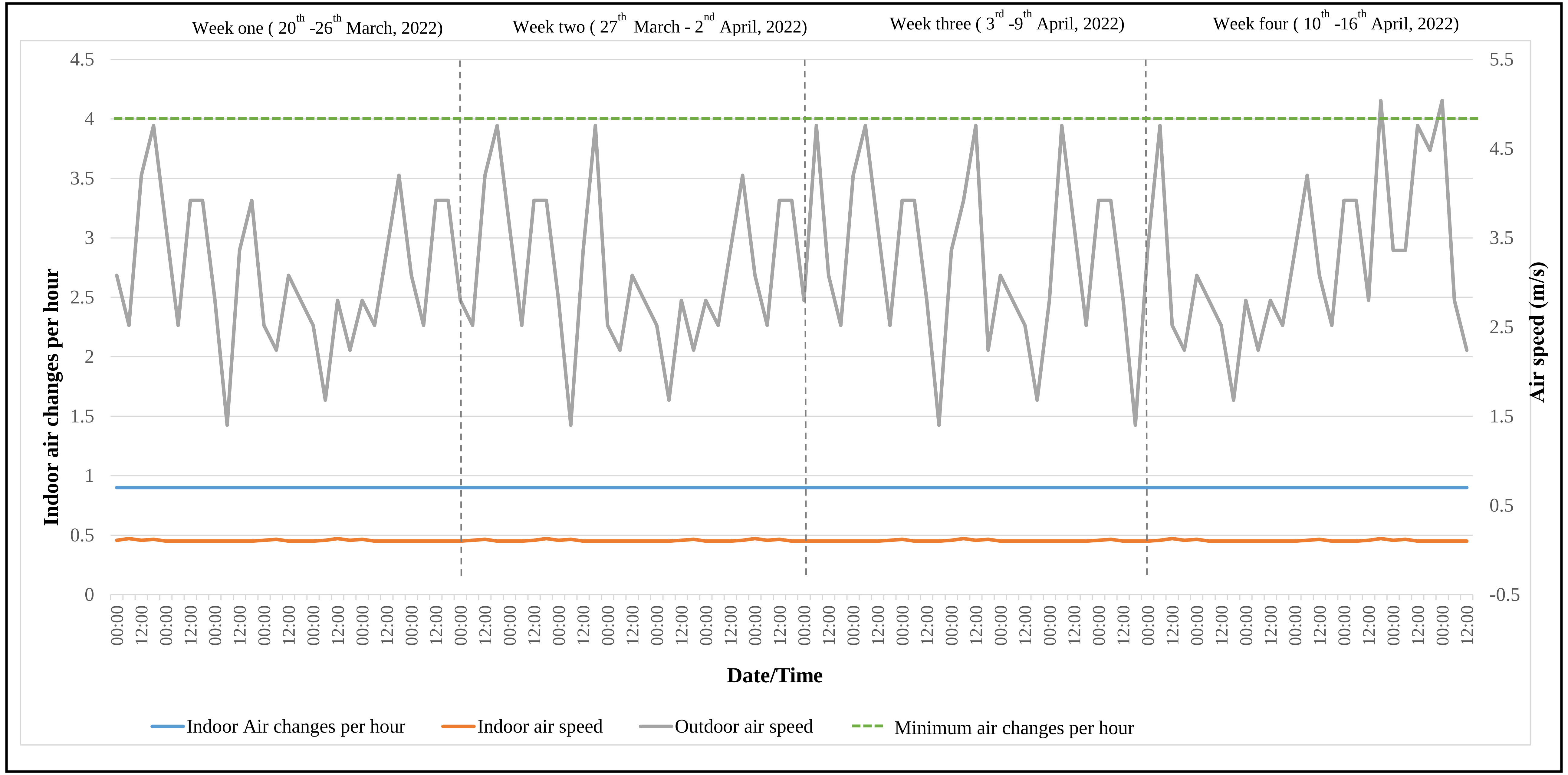
CFM= cubic feet per minute; (the figure is multiplied by 60 to convert it to cubic feet per hour)

V= Volume of room in ft^3 *(*$6889ft^2$ *x 11.3ft)*

Therefore, ACH= (1200 x 60)/ (77846 ft^3*)*

=0.9 air changes per hour.

This is significantly below the recommended figure of 4 air changes per hour, meaning that the office is not being sufficiently ventilated. The office needs ventilation systems that will provide more air changes.



Graph 5.5: Graph showing the indoor air changes per hour, indoor air speed and outdoor air speed for an office space in One Africa Place
Source: Author

5.5.5 VENTILATION PERFORMANCE ANALYSIS WITH PROPOSED THERMAL CHIMNEY

CFD simulation tool: Designbuilder was chosen as the CFD simulation software in this study, incorporating the EnergyPlus calculation engine which has been validated under the Evaluation of Building Energy Analysis Computer Programs.

Natural ventilation studies were performed through CFD simulation of indoor airflow for the lettable space in the case-study using the weather files from Dagoretti Meteorological Station for accurate results.

CFD boundary conditions:

i. The calculated module was preferred over scheduled module where the calculation engine uses information about building fabric & openings in conjunction with weather data and internal gains to calculate the pressure difference and air flow through each zone.
ii. The system is at steady state.
iii. The working air behaves like an ideal gas.
iv. The air at the entrance in the thermal chimney to the outlet is without friction or leakages
v. The thermal chimney walls are used as heat flux sources
vi. The flow is assumed to be laminar.

Model description: The study area as highlighted on the floor plan has a floor area of 640m^2 and a floor to ceiling height of 3.45m. A typical lettable area on the fourth floor was selected for the study. The office space lacks operable windows. Therefore, for this study, permananent vents have been introduced at the top and bottom frames of the glazed panels (refer to figure 5.124 and 5.125). The vents have a total area of 13m^2 and have been used as air inlets for this simulation. These vents provide natural ventilation while still ensuring that visually, the external building façade remains the same.

Thermal chimney cavity height: The thermal chimney's cavity height is bound by the height of the office space (including the thickness of the roof slab). The cavity height increases by a height of 2 m for each consecutive trial. The cavity heights of the first and last trials are 5.6m and 9.6m respectively.

Thermal chimney inclination angle: The study is limited to wall mounted thermal chimneys. Therefore, for all trials, the inclination angle is set at 90^0.

Thermal chimney cavity width: The thermal chimney's cavity width is bound by 0.2m and 0.6m with an increment of 0.2m for each trial. Widths lower than 0.2m give fairly low air speeds while widths higher than 0.6m may be physically too large relative to the building.

Thermal chimney cavity length: The length of the thermal chimney cavity is a parameter commonly overlooked since airflow within the thermal chimney is generally a two-dimensional flow, based on the cavity width and height. For this study, the length is based on the distance between the windows, since this is where the chimneys have been placed. The thermal chimney's cavity length is bound by 1m and 2.6m with an increment of 0.8m for each trial.

Location: Three thermal chimneys have been placed on the north western and south western ends of the building as shown in the models. This is the most suitable locations for the chimneys in this building since they are able to increase air flow rates into the office while still receiving maximum solar radiation.

Thermal chimney outlet and inlet areas: The thermal chimneys have outlets at the top of the stack. This means that this area will be determined by the cavity width and length. As recommended in the literatur review, the inlets and outlets have the same areas.

Thermal chimney construction materials: The chimneys have double glazing and are made of brick walls with a flat copper plate absorber.

Input parameters	Lower bound	Upper bound	Increment	No. of values
Cavity height	5.6m	9.6m	2m	3
Cavity gap width	0.2m	0.6m	0.2m	3
Cavity gap length	1m	2m	0.8m	3
Inlet area	0.2m^2	1.2m^2	-	3
Outlet area	0.2m^2	1.2m^2	-	3

Table 5.9: Input parameters used to model the various thermal chimney trials
Source: Author

With the examination of the influences of the input parameters, their combined effects on the indoor air speed are determined in order to design and optimize the thermal chimney. Although there are over 100 possible cases according to the limits from the table above, a first set of 20 cases (the lower and upper limits of the five input parameters) is modeled and simulated, after which the second set of 25 cases (chosen randomly) and the third set of 20 cases (chosen randomly) follow. The combined 65 cases are sufficient in developing a performance trend of the chimneys, which makes it possible to narrow down on the number of cases that will be presented for this study.

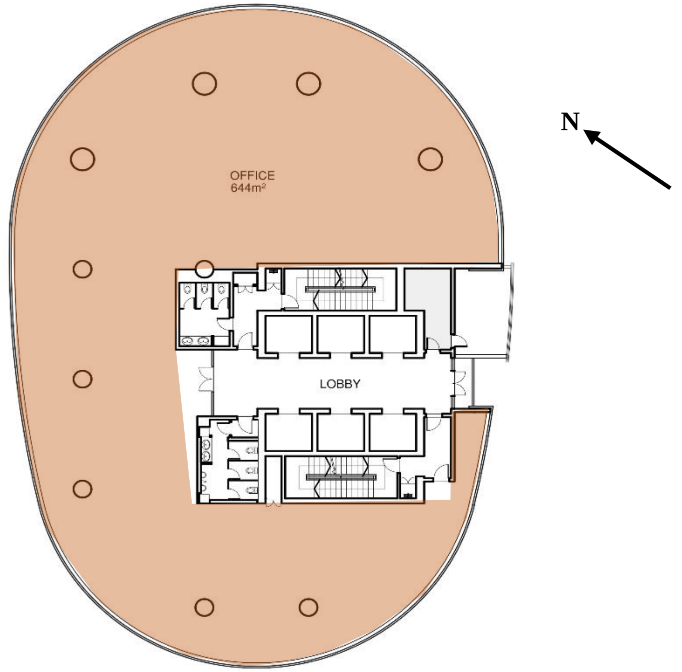


Fig.5.136: Floor plan highlighting the study area
Source: Author

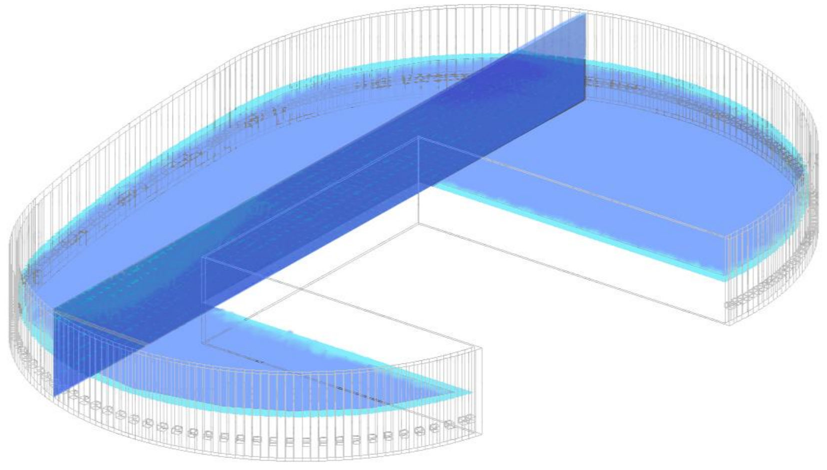


Fig.5.137: Existing ventilation conditions in the office after introduction of permamnet vents. Average air speed is 0.18m/s with an average of 1.8 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti

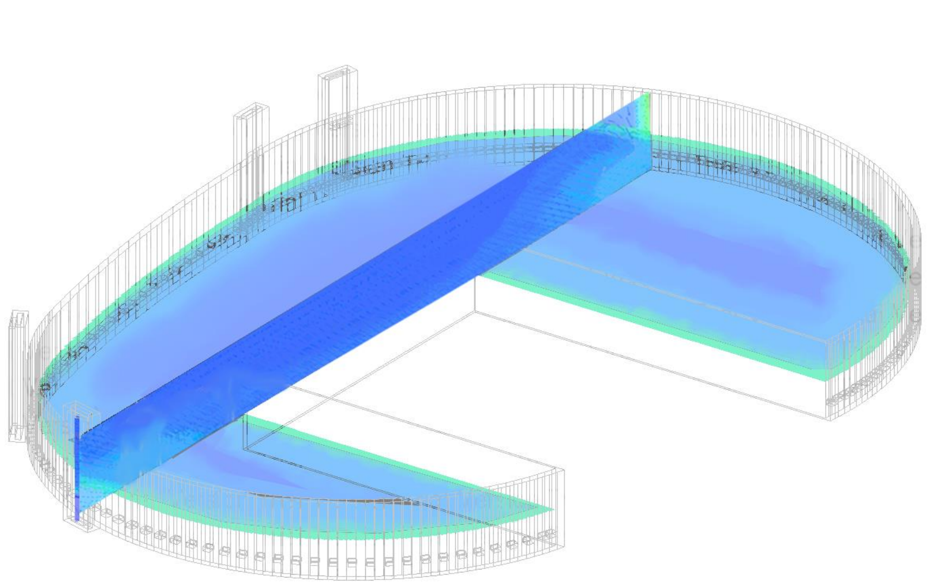


Fig.5.138: Ventilation conditions in the office with the first trial of the thermal chimney. Average air speed is 0.22m/s with an average of 2.3 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

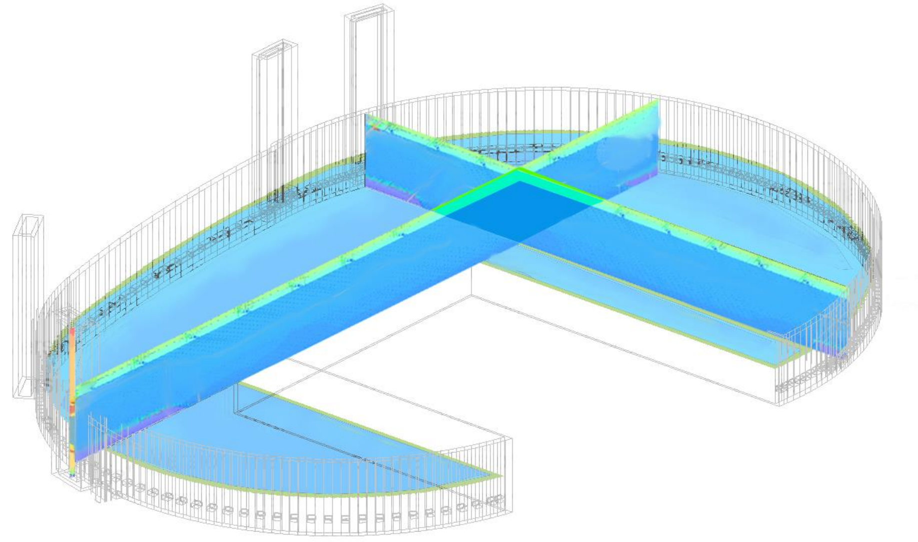


Fig.5.139: Ventilation conditions in the office with the second trial of the thermal chimney. Average air speed is 0.6m/s with an average of 6.1 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

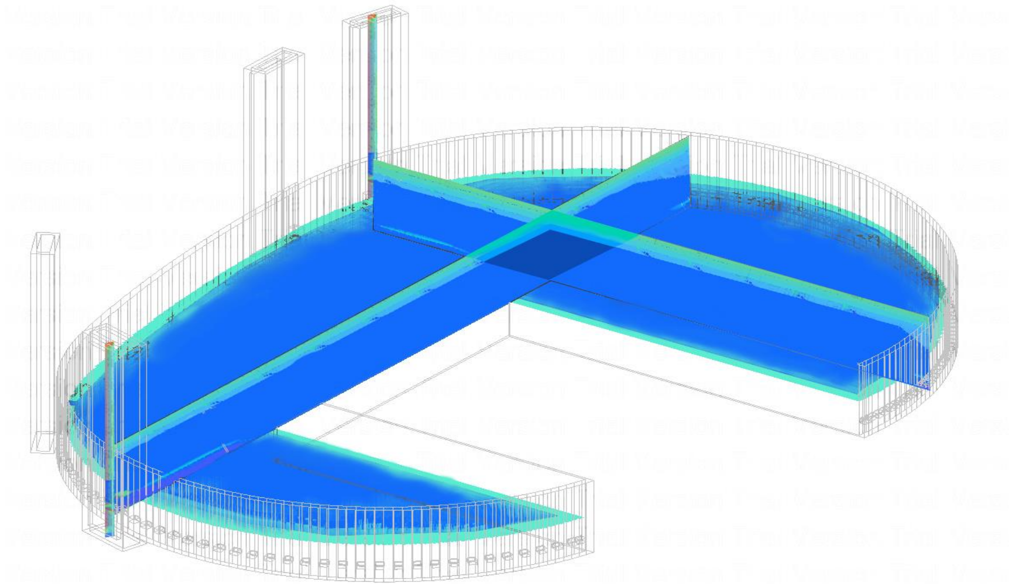


Fig.5.140: Ventilation conditions in the office with the third trial of the thermal chimney. Average air speed is 0.37m/s with an average of 3.8 air changes per hour
Source: Author- simulated using Designbuilder software and weather statistics from Dagoretti Meteorological Station

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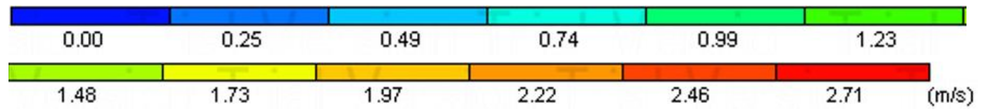


Analysis: After introduction of the permanent vents on the top and bottom frames of the windows, the office experiences majorly has a single-flow directional ventilation system due to its orientation with regards to the prevailing wind direction. The existing conditions indicate that the office has an average of 1.8 air changes per hour, which is below the recommended minimum of 4 air changes per hour.

The thermal chimneys in the first trial give the lowest number of air changes per hour (2.3) as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.2m wide, the cavity heights are 5.6m and the cavity lengths are 1m. The narrow cavity widths result in friction losses which leads to a decrease in air speed.

The thermal chimneys in the second trial give the highest number of air changes per hour (6.1) as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.4m wide, the cavity heights are 7.6m and the cavity lengths are 1.9m. This combination gives the optimum number of air changes per hour for the office space.

The thermal chimneys in the third trial give 3.8 air changes per hour as indicated in the simulation image. The cavity gaps of these thermal chimneys are 0.6m wide, the cavity heights are 9.6m and the cavity lengths are 2.4m. The wide cavity widths and high cavity heights result in lower heat transfers within the chimney, which creates reverse flows in the stack resulting in decreased air speeds.

5.5.6 THERMAL CHIMNEY DESIGN RECOMMENDATIONS

The following are the design recommendations for two thermal chimneys for an office space with a floor area of 640m^2 and a floor to ceiling height of 3.45m:

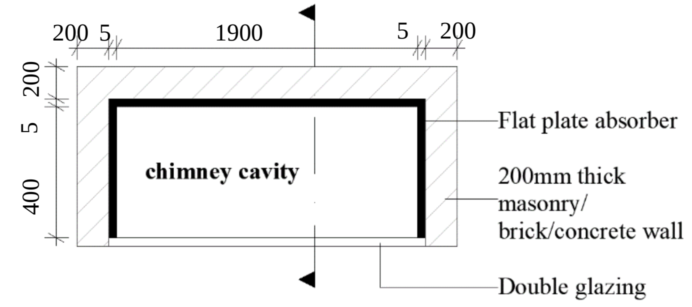


Fig.5.141: Layout plan of recommended thermal chimney
Source: Author

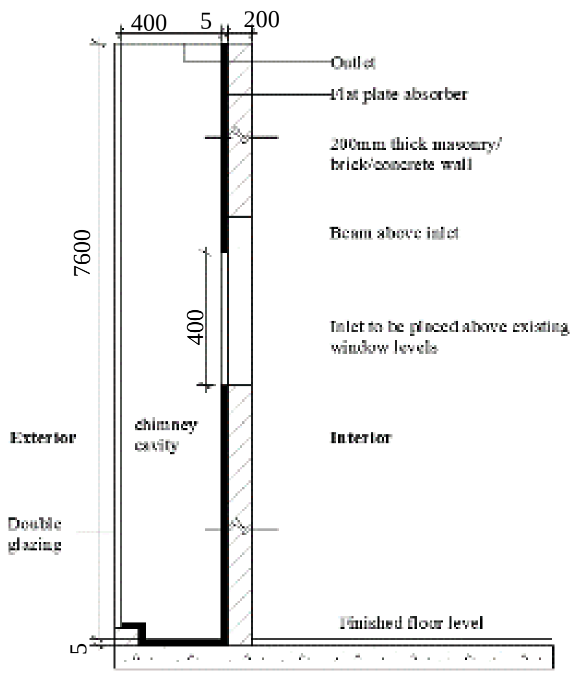


Fig.5.142: Cross section through recommended thermal chimney
Source: Author

Parameters	Variables	Description
Materials	Type of glazing	Double glazing
	Thermal absorber type	Flat copper plate absorber
Configuration	Cavity height	7.6m
	Cavity gap width	0.4m
	Cavity gap length	1.9m
	Inlet area	0.76m^2
	Outlet area	0.76m^2
	Cavity height to gap width ratio	19
Installation	Inclination angle	90^0
No. of chimneys	Quantity	4

Table 5.10: Thermal chimney design recommendations
Source: Author

5.6 COMPARATIVE ANALYSIS OF CASE STUDIES

5.6.1 COMPARATIVE ANALYSIS OF VENTILATION PERFORMANCE OF CASE STUDIES

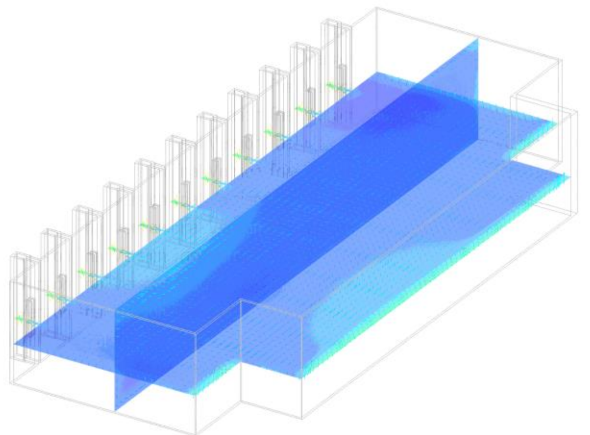
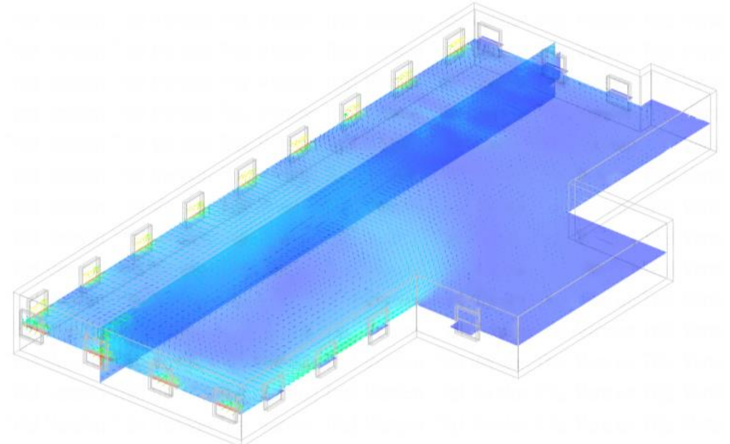
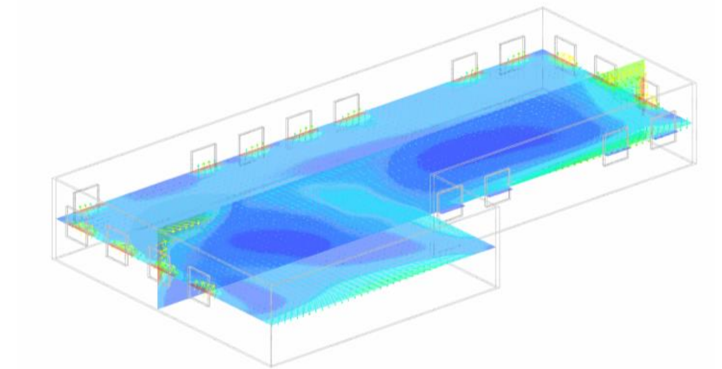
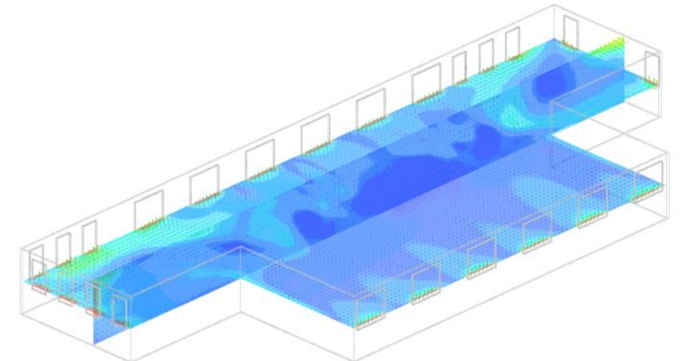
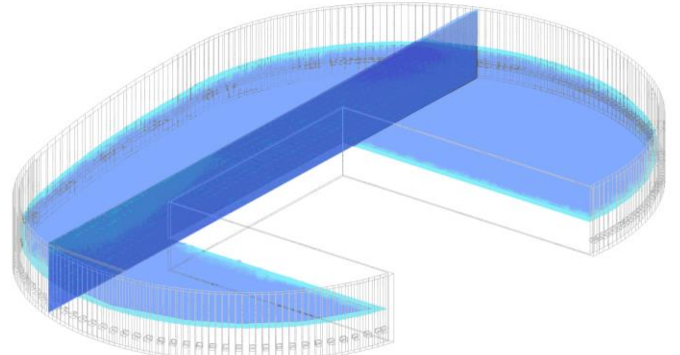
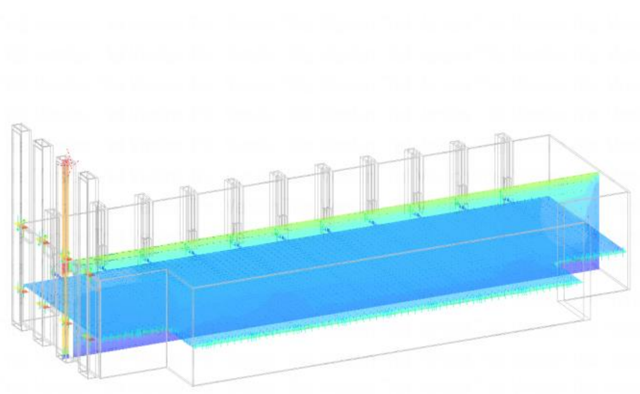
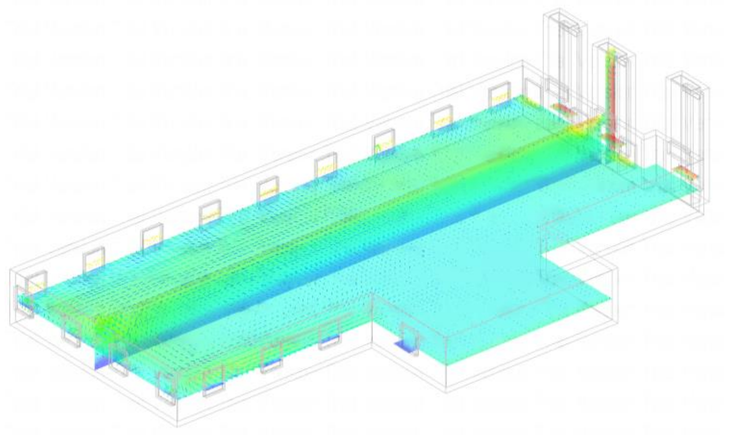
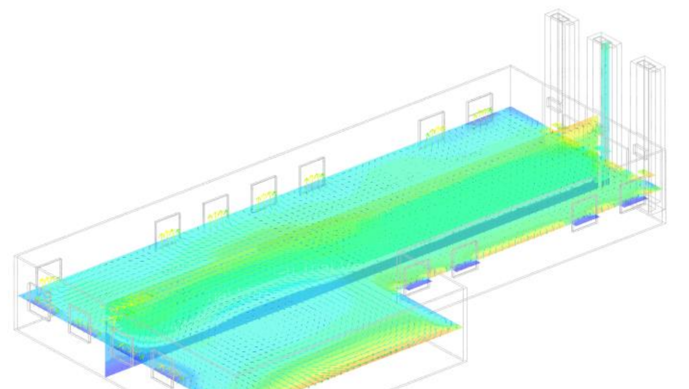
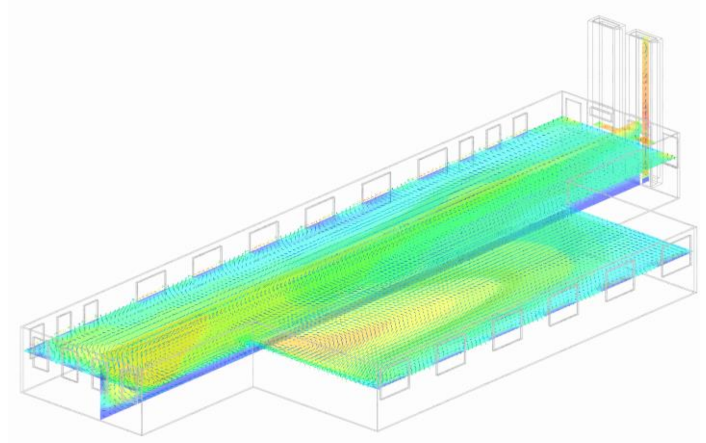
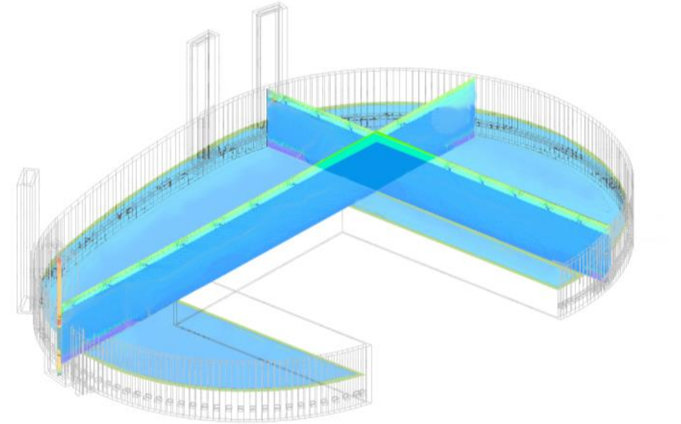
	GLOBAL TRADE CENTRE OFFICE TOWER	THE RIVERFRONT	ICEA LION GROUP HEAD OFFICE	DELTA CORNER TOWERS	ONE AFRICA PLACE
PRE- INSTALLATION	 Existing office conditions with an average air speed of 0.08m/s with an average of 1.2 air changes per hour	 Existing office conditions with an average air speed of 0.18m/s with an average of 2.5 air changes per hour	 Existing office conditions with an average air speed of 0.12m/s with an average of 2.8 air changes per hour	 Existing office conditions with an average air speed of 0.18m/s with an average of 2.2 air changes per hour	 After introduction of permanent vents, the average air speed is 0.18m/s with an average of 1.8 air changes per hour
POST- INSTALLATION	 After introduction of thermal chimneys, the average air speed is 0.35m/s with an average of 5.3 air changes per hour	 After introduction of thermal chimneys, the average air speed is 0.4m/s with an average of 5.5 air changes per hour	 After introduction of thermal chimneys, the average air speed is 0.21m/s with an average of 4.9 air changes per hour	 After introduction of thermal chimneys, the average air speed is 0.5m/s with an average of 6.2 air changes per hour	 After introduction of thermal chimneys, the average air speed is 0.6m/s with an average of 6.1 air changes per hour

Table 5.11: Comparative analysis of thermal chimney design recommendations
Source: Author

KEY:

5.6.2 COMPARATIVE ANALYSIS OF THERMAL CHIMNEY DESIGN RECOMMENDATIONS

PARAMETER	VARIABLES	GLOBAL TRADE CENTRE OFFICE TOWER	THE RIVERFRONT	ICEA LION GROUP HEAD OFFICE	DELTA CORNER TOWERS	ONE AFRICA PLACE
SPACE DESCRIPTION	–	Office area- 278m^2 Floor to ceiling height- 4m	Office area- 471m^2 Floor to ceiling height- 3.2m	Office area- 273m^2 Floor to ceiling height- 3.2m	Office area- 527m^2 Floor to ceiling height- 3.3m	Office area- 624m^2 Floor to ceiling height- 3.5m
MATERIALS	Type of glazing	Double glazing	Double glazing	Double glazing	Double glazing	Double glazing
	Materials of thermal absorber	Copper	Copper	Copper	Copper	Copper
CONFIGURATION	Cavity height	8.15m	7.35m	7.35m	7.45m	7.6m
	Cavity gap width	0.4m	0.4m	0.4m	0.4m	0.4m
	Cavity gap length	1m	1.5m	1.1m	1.8m	1.9m
	Inlet area	0.4m^2	0.6m^2	0.44m^2	0.72m^2	0.76m^2
	Outlet area	0.4m^2	0.6m^2	0.44m^2	0.72m^2	0.76m^2
	Cavity height to gap width ratio	20.4	18	18	18.6	19
INSTALLATION	Inclination angle	90^0	90^0	90^0	90^0	90^0
	Thermal collector plate pattern	Flat plate	Flat plate	Flat plate	Flat plate	Flat plate
NO. OF CHIMNEYS	Quantity	4	3	3	3	4
ACHIEVED AIR CHANGES PER HOUR	Quantity	5.3	5.5	4.9	6.2	6.1

Table 5.12: Comparative analysis of thermal chimney design recommendations
Source: Author

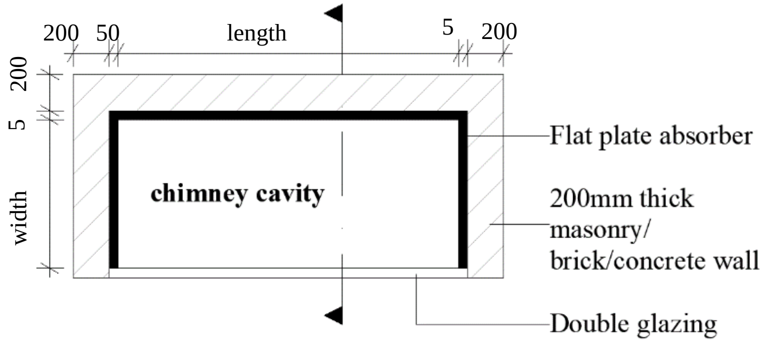


Fig.5.143: Layout plan of typical thermal chimney used for the simulations
Source: Author

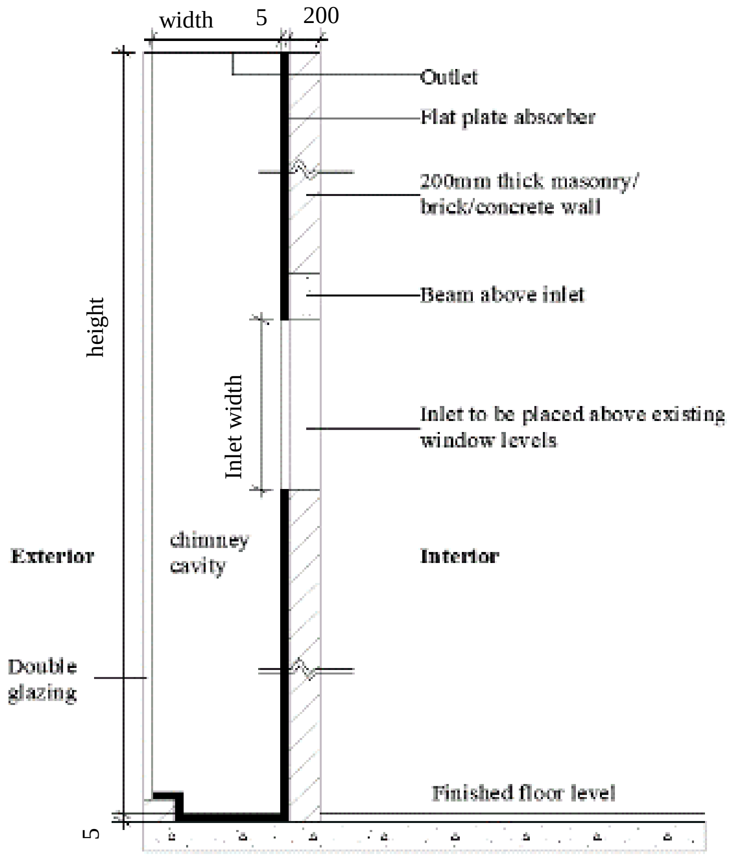


Fig.5.144: Cross section through typical thermal chimney used for the simulations
Source: Author

5.7 SUMMARY

This chapter focuses on the fieldwork findings carried out in Westlands, Kenya. The findings of the study reveal that all of the case studies have air changes per hour that are below the recommended minimum air changes per hour for office spaces. In order to improve this situation, thermal chimneys are designed for each office and their performance and effects on air changes per hour are investigated using computational fluid dynamics simulations.

Based on this analysis the design parameters for optimum performance of thermal chimneys have been generated and documented. These form the basis of the parameters that will be used to design thermal chimneys in the tropical uplands climate.

It is important to note that the thermal chimneys can take any form, as long as the basic variables as higlighted in the table are adhered to. In cases where the chimneys are to be used as architectural features, they can project from the building facade as shown in the simulation models. In cases where purity of form is to be observed, the glazing of the chimney can flush with the external walls so that the chimney cavity is within the interior of the building. In addition to this, since these recommendations are based on specific areas floor to ceiling heights and air volumes, the thermal chimneys will increase proportionally as the floor areas, heights and interior air volumes increase.

CHAPTER SIX: RECOMMENDATIONS

Figure 6.1: Rotating vane anemometer that was used during the field study
Source: Author

6.0 INTRODUCTION

The conclusions and recommendations of this research seek to satisfy the aims and objectives upon which the study was set. The author identifies the passive design strategies used in hospitals in Lamu and Zanzibar. The author also summarizes the design strategies for thermal chimneys in the tropical uplands climate, hence providing direction for future developments of hospitals in Westlands, Nairobi.

6.1 CONCLUSIONS

6.1.1 CHAPTERS SUMMARY

Chapter one: Introduction

This chapter gives a background study on the subject matter, first by highlighting the use of thermal chimneys for natural ventilation, then stating the general climate of Nairobi and requirements of indoor air changes per hour for offices. The geographical extent of the study is also mentioned. Highlighting the problem as the contentious issue of the increase in the number of developments as well as in the complexities and capacities of developments in Nairobi which has led to an increase in the demand for building systems to provide sufficient air change rates for the occupants, the chapter goes on to identify the key objectives of the study. Being a scientific study, the aims are to document the configurations, installation parameters and materials used in the design of thermal chimneys, analyze the air changes per hour in the office buildings in Nairobi and develop design strategies for thermal chimneys in the tropical uplands climate. Because of the limitation of resources the scope of the study is limited to specific buildings in Westlands, Nairobi. The significance of the study is to fill the gap in the existing knowledge on design of thermal chimneys in the tropical uplands climatic region.

Figure 6.2: Tape measure that was used during the field study
Source: Author


Figure 6.3: Entrance area at The Riverfront Offices
Source: Author

Chapter two: Literature review

In this chapter, the characteristics of the tropical uplands climate have been documented as well as the various categories of ventilation and the ventilation rate requirements for buildings. In addition to this, the various types of thermal chimneys have been discussed and their respective mathematical models have been documented. Relevant case studies have been included in this chapter for an in-depth understanding of the working mechanism of thermal chimneys. The factors influencing the performance of thermal chimneys such as configuration factors, installation factors, construction materials and environmental factors have been analysed. Based on this analysis the design parameters for optimum performance of thermal chimneys have been generated and documented. These form the basis of the parameters that will be used during the field work study.

Chapter three: Research Methods

This chapter spells out how this study is undertaken and further describes the research design, research strategy, data collection techniques, data analysis methods and presentation. The primary sources of data have been identified as interviews, observations, physical measurements and scientific measurements. These have been presented in the documentation of the case studies in the next chapter in the form of photographs, analytical notes, tables, charts and architectural sketches.

Chapter four: Urban environmental analysis of Westlands

This chapter analyses the environmental concerns of the built environment in Nairobi. A historical development of buildings in Nairobi is undertaken by analyzing their evolution over the years. A brief introduction of Westlands area, Nairobi, investigating its urban history in terms of its built density, circulation and land use is done, followed by an environmental analysis of the specific area of study within the larger Westlands area by analyzing its urban climatology and building form analysis. In addition, a historical study of the evolution of the area's building typologies and


Figure 6.4: JW Marriott Hotel at the Global Trade Centre Development
Source: Author

forms over the years is undertaken which in turn introduces the five buildings being investigated for thermal chimney design parameters in Chapter 5.

Chapter five: Field work

This chapter focuses on the fieldwork findings carried out in Westlands, Kenya. The study is based on the identified broad parameters of climatic analysis, morphology, spatial design and ventilation performance analysis of the case studies.

Five buildings of interest have been selected and an in-depth study was carried out from 20th March to 16th April, 2022. The findings of the study reveals that all of the case studies have air changes per hour that are below the recommended minimum air changes per hour for office spaces. In order to improve this situation, thermal chimneys are designed for each office, based on the factors influencing the performance of thermal chimneys such as configuration factors, installation factors and construction materials. Their performance and effects on air changes per hour are investigated using computational fluid dynamics simulations.

Based on this analysis the design parameters for optimum performance of thermal chimneys have been generated and documented. These form the basis of the parameters that will be used to design thermal chimneys in the tropical uplands climate.

6.1.2 RESPONSE TO AIMS AND OBJECTIVES

I. Document the configurations, installation parameters and materials used in the design of thermal chimneys

The design recommendations based on configuration factors are:

i. A large cavity height is beneficial to enhance passive ventilation via a thermal chimney, which is due to the increased pressure difference and heat gain.

Figure 6.5: Operable pane at the Global Trade Centre Office Tower
Source: Author

However, if the cavity height is too large, the thermal chimney will capture wind at higher heights, leading to reverse flows.

ii. An appropriate cavity gap width is significant to the performance of a thermal chimney. This is because the airflow rate does not always increase with a bigger cavity gap due to reverse flow under uneven heating of air inside the cavity. An optimum cavity gap of 0.2 - 0.3 m is appropriate.

iii. An equal area for the inlet and outlet is a good way to improve the performance of a thermal chimney. For unequal openings, it is advisable to have a bigger outlet area and a smaller inlet area.

iv. A cavity height to cavity gap (width) ratio of 10 is appropriate.

The design recommendations based on installation factors are:

i. For a roof mounted thermal chimney, the optimum inclination angle is 45^0 to 60^0, which is dependent on the latitude of the building.

ii. A bigger fenestration area within a room is not always worthwhile when it comes to enhancing the performance of a thermal chimney. The total fenestration area should not exceed $16m^2$.

iii. With regards to a solar collector, a design that favours heat gain can improve the performance, such as increasing the area of the collector plate, using a plate with the chevron pattern, using a collector with a double glazed system and using materials with high absorptivity and low thermal conductivity.

The design recommendations based on construction materials are:

i. Regarding the selection of glazing, properties of transmissivity are more important than those of reflectivity and absorptivity. The higher the transmissivity, the better the performance of the thermal chimney. Double glazing enhances the performance of the thermal chimney.


Figure 6.6: Operable pane at the Global Trade Centre Office Tower
Source: Author

ii. The solar collector material should have high absorptivity and emissivity rates for better thermal chimney performance. A thermal storage layer and absorber plate with black-polished surface should be incorporated.

iii. Thermal insulation of the cavity wall should have a thickness of at least 5 cm.

The design recommendations based on environmental factors are:

i. High solar radiation enhances the performance of a thermal chimney. Measures should be taken to absorb as much solar radiation as possible. For the tropics, the chimneys should be placed on the Northern or Southern ends of the building so that they can receive solar radiation throughout the day.

ii. The design of a thermal chimney can be taken without considering the effects from external wind because of its unpredictable profile.

II. Analyse the air changes per hour in the office buildings in Nairobi

The air changes per hour of the offices was analysed to find out whether they meet the recommended minimum of 4 air changes per hour**.**

For naturally ventilated buildings, the formula for calculating air changes per hour is:

ACH= Q/Vol

Where;

Q= Volumetric flow rate of air in m^3*/hr (Velocity of air through the fenestrations in m/s x area of fenestration in* m^2 *x 3600)*

Vol= Volume of room in m^3

For mechanically ventilated buildings, the air changes per hour are fixed due to the air conditioning system's fixed CFM rate. In such cases, the air changes per hour are obtained as explained below:

ACH= (CFM x 60)/ V

Figure 6.7: Operable pane and fixed louvres at the Global Trade Centre Office Tower
Source: Author

Where;

CFM= cubic feet per minute; (the figure is multiplied by 60 to convert it to cubic feet per hour)

V= Volume of room in ft^3

Based on these formulas, the air changes for the case studies are as follows:

i. **Global Trade Centre Office Tower:** The office is naturally ventilated. The average indoor air velocity is 0.08m/s with an average of 1.2 air changes per hour. This is below the recommended minimum of 4 air changes per hour.

ii. **The Riverfront:** The office is naturally ventilated. The average indoor air velocity is 0.18m/s with an average of 2.5 air changes per hour. This is below the recommended minimum of 4 air changes per hour.

iii. **ICEA LION Group Head Office:** The office is naturally ventilated. The average indoor air velocity is 0.12m/s with an average of 2.8 air changes per hour. This is below the recommended minimum of 4 air changes per hour.

iv. **Delta Corner Towers:** The office is naturally ventilated. The average indoor air velocity is 0.18m/s with an average of 2.2 air changes per hour. This is below the recommended minimum of 4 air changes per hour.

v. **One Africa Place:** The office is artificially ventilated. The air conditioning system has a CFM of 1200, which provides an average of 0.9 air changes per hour. This is below the recommended minimum of 4 air changes per hour.

III. Develop design strategies for thermal chimneys in the tropical uplands climate

According to the findings, all of the office case studies have air changes per hour that are below the recommended minimum for offices.

The design strategies for the thermal chimneys for each office are explained below:

PARAMETER	VARIABLES	GLOBAL TRADE CENTRE OFFICE TOWER	THE RIVERFRONT	ICEA LION GROUP HEAD OFFICE	DELTA CORNER TOWERS	ONE AFRICA PLACE
SPACE DESCRIPTION	_	Office area- 278m^2 Floor to ceiling height- 4m	Office area- 471m^2 Floor to ceiling height- 3.2m	Office area- 273m^2 Floor to ceiling height- 3.2m	Office area- 527m^2 Floor to ceiling height- 3.3m	Office area- 624m^2 Floor to ceiling height- 3.5m
MATERIALS	Type of glazing	Double glazing	Double glazing	Double glazing	Double glazing	Double glazing
	Materials of thermal absorber	Copper	Copper	Copper	Copper	Copper
CONFIGURATION	Cavity height	8.15m	7.35m	7.35m	7.45m	7.6m
	Cavity gap width	0.4m	0.4m	0.4m	0.4m	0.4m
	Cavity gap length	1m	1.5m	1.1m	1.8m	1.9m
	Inlet area	0.4m^2	0.6m^2	0.44m^2	0.72m^2	0.76m^2
	Outlet area	0.4m^2	0.6m^2	0.44m^2	0.72m^2	0.76m^2
	Cavity height to gap width ratio	20.4	18	18	18.6	19
INSTALLATION	Inclination angle	90^0	90^0	90^0	90^0	90^0
	Thermal collector plate pattern	Flat plate	Flat plate	Flat plate	Flat plate	Flat plate
NO. OF CHIMNEYS	Quantity	4	3	3	2	4

Table 6.1: Thermal chimney design recommendations
Source: Author

The comparative analysis of thermal chimney design parameters makes it possible to generate average dimensions and quantities for the chimneys, based on average floor areas and heights. This makes it easier to give standard recommendations on design of thermal chimneys for office buildings in the tropical uplands climate.

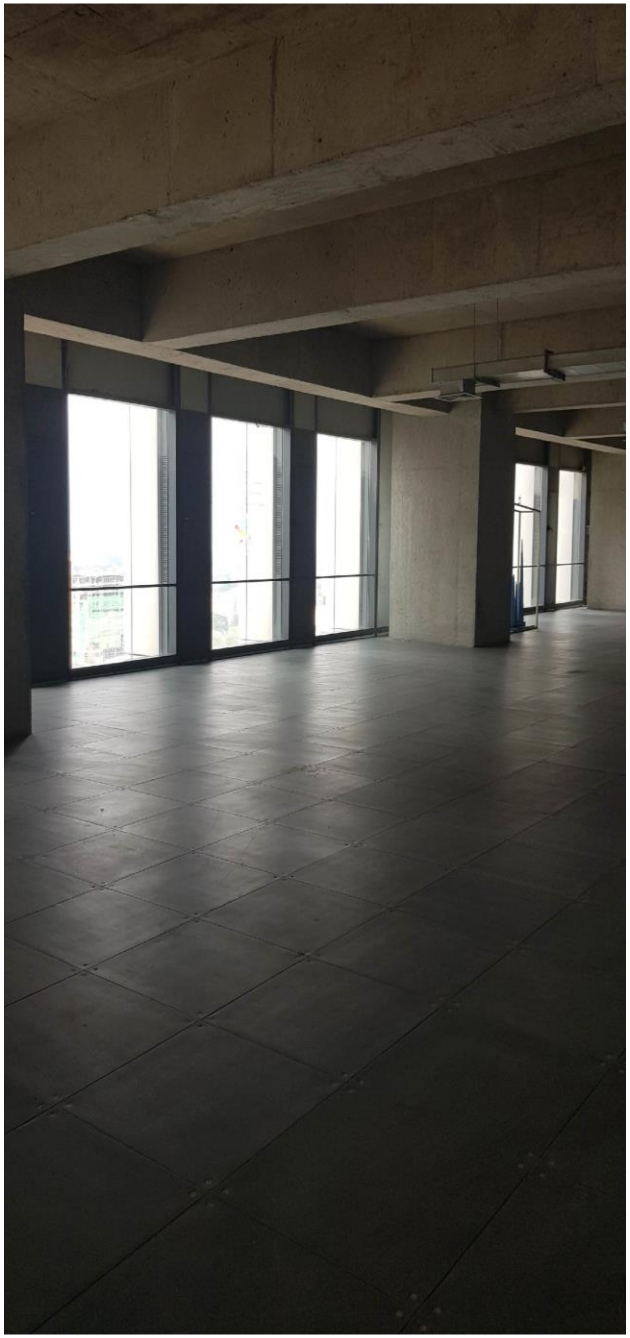


Figure 6.8: Typical lettable office at the Global Trade Centre Office Tower
Source: Author

6.2 RECOMMENDATIONS

As has been noted from the study, thermal chimneys play a significant role in creating spaces with high rates of air changes per hour. This research draws a few recommendations for strategies for design for thermal chimneys within the climate of Nairobi.

6.2.1 PROPOSED DESIGN STRATEGIES FOR THERMAL CHIMNEYS IN THE TROPICAL UPLANDS CLIMATE

The difference in office floor areas and floor to ceiling heights necessitates a change in some parameters of the thermal chimney design as listed below:

I. Materials:

i. Glazing: For the thermal chimney glazing, double glazing is better than single glazing. This is because the gas or air inside the double glazing unit normally acts as an insulator. While this does not prevent heat from completely escaping, it drastically reduces the amount of heat that is lost via the thermal chimney.

ii. Thermal absorber: The thermal absorber should be made of copper due to its high thermal conductivity rates. The absorber should be painted black in order to increase the thermal coefficient of the system. The thermal insulation layer at the back of the absorber plate should be made of 50mm thick rock wool or mineral wool in order to prevent any heat losses within the system.

II. Configuration:

i. Cavity height: A large cavity height is beneficial to enhance passive ventilation via a thermal chimney, which is due to the increased pressure difference and heat gain. However, if the cavity height is too large, the thermal chimney will capture wind at higher heights, leading to reverse flows. The cavity height should be at most 4 metres more than the total height of the area to be ventilated

Figure 6.9: Show office at the Global Trade Centre Office Tower
Source: Author

ii. Cavity gap width: The cavity gap is a significant parameter on thermal chimney performance in terms of air changes per hour. A large cavity gap leads to the occurrence of reverse flow. As the heating of the air in the cavity is dependent on convection processes, the air abutting the hot wall gets additional chances to be heated. The convective heat transfer from the hot wall to the movable air is relatively limited in the middle of the thermal chimney with a bigger cavity gap. The temperature difference and friction between the two air layers are the two main reasons for reverse flow. Narrow cavity widths result in friction losses which leads to a decrease in air speed. For an office space with a floor to ceiling height of at most 4 metres, the cavity gap width should be 0.4m.

iii. Cavity gap length: Since airflow within the thermal chimney is generally a two-dimensional flow based on the cavity width and height, the length of the thermal chimney cavity is commonly overlooked. A cavity length of at least 1 metres and at most 2 metres will provide sufficient air changes for an office space with a floor to ceiling height of at most 4 metres.

iv. Inlet and outlet areas: In this study, the thermal chimneys have outlets at the top of the stack. This means that this area will be determined by the cavity width and length. An equal area for the inlet and outlet improves the performance of the thermal chimney. The levels of the inlets should be above the windows so that warm air can easily exit the space.

v. Cavity height to gap width ratio: A cavity height to gap ratio of 18 to 20 is appropriate for enhanced performance of the thermal chimney.

III. Installation:

i. Inclination angle: The study is limited to wall mounted thermal chimneys. Therefore, for all trials, the inclination angle is set at 90^0.

ii. Thermal collector plate pattern: The thermal collector is a flat pate made of black painted copper for higher absorptivity of solar radiation.


Figure 6.10: Show office at the Global Trade Centre Office Tower
Source: Author

iii. Location: The thermal chimneys should be placed on the opposite side of the main air inlets as illustrated in the simulation models. This location makes it possible for the chimneys to increase air flow rates into the office. They should also be placed on the Northern or Southern facades of the building so that they can receive maximum solar radiation throughout the day.

III. Number of chimneys: For a volume of approximately 1,000m^3 to 2,000m^3, three to four thermal chimneys will adequately provide sufficient air changes per hour.

The thermal chimneys can take any form, as long as the basic variables as explained above are adhered to. In cases where the chimneys are to be used as architectural features, they can project from the building facade as shown in the simulation models. In cases where purity of form is to be observed, the glazing of the chimney can flush with the external walls so that the chimney cavity is within the interior of the building. In addition to this, since these recommendations are based on specific areas and floor to ceiling heights, the thermal chimneys will increase proportionally as the floor areas and heights increase.

6.3 FURTHER RESEARCH

This study focused on the design of wall mounted thermal chimneys in the tropical uplands climate in Nairobi. Other areas of investigation on related research include but are not limited to:

i. Effect of cavity gap on thermal chimney performance.
ii. Effect of cavity height on thermal chimney performance.
iii. Design of roof mounted thermal chimneys in the tropical uplands climate.
iv. Effect of thermal chimneys on the thermal performance of a building.
v. Effect of cavity materials, inclination angle, openings, thermal insulation and external width on optimum cavity height to gap ratio.
vi. Design of thermal chimneys with wind cowls.
vii. Materials for construction of thermal chimneys in the tropical uplands climatic region.

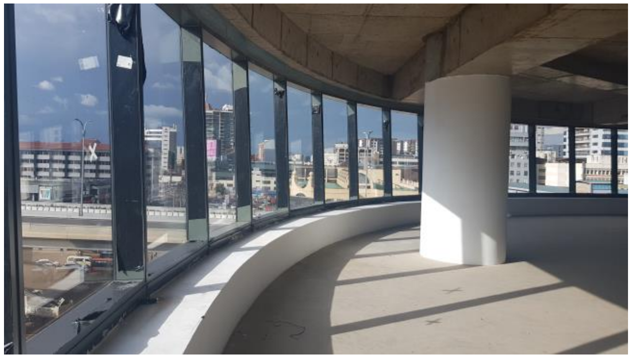


Figure 6.11: Fixed window panes in a lettable office at One Africa Place
Source: Author

viii. Design of thermal chimneys in the hot and dry climate in Kenya.

ix. Design of wind catchers in the hot and dry climate in Kenya.

x. Optimum inclination angle for thermal chimneys in the tropical uplands climate.

xi. Performance of thermal chimneys based on volumes and pressure build up.

xii. This study should be carried out again in 10 years' time in order to determine how the design of thermal chimneys in the study area changes with time, due to the change in the urban environment.

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8.0 APPENDICES

Data logging records for the entire monitoring period:

		GTC OFFICE TOWER	RIVERFRONT OFFICES	ICEA OFFICES	DELTA TOWERS	ONE AFRICA PLACE	
Date	**Time**	**Indoor air apeed (m/s)**	**Indoor air apeed (m/s)**	**Indoor air apeed (m/s)**	**Indoor air apeed (m/s)**	**Indoor air apeed (m/s)**	**Outdoor air speed (m/s)**
Day 1 20/3/2022	00:00 A.M	0.08	0.18	0.12	0.18	0.11	3.08
	06:00 A.M.	0.08	0.15	0.15	0.15	0.13	2.52
	12:00 NOON	0.06	0.16	0.16	0.16	0.11	4.2
	06:00 P.M.	0.05	0.15	0.15	0.15	0.12	4.76
Day 2 21/3/2022	00:00 A.M	0.05	0.12	0.12	0.12	0.1	3.64
	06:00 A.M.	0.1	0.18	0.12	0.2	0.1	2.52
	12:00 NOON	0.12	0.18	0.12	0.2	0.1	3.92
	06:00 P.M.	0.12	0.18	0.12	0.18	0.1	3.92
Day 3 22/3/2022	00:00 A.M	0.12	0.18	0.12	0.18	0.1	2.8
	06:00 A.M.	0.1	0.18	0.12	0.18	0.1	1.4
	12:00 NOON	0.07	0.15	0.15	0.15	0.1	3.36
	06:00 P.M.	0.07	0.15	0.15	0.15	0.1	3.92
Day 4 23/3/2022	00:00 A.M	0.05	0.16	0.16	0.16	0.11	2.52
	06:00 A.M.	0.08	0.17	0.17	0.17	0.12	2.24
	12:00 NOON	0.06	0.18	0.12	0.18	0.1	3.08
	06:00 P.M.	0.05	0.15	0.15	0.15	0.1	2.8
Day 5 24/3/2022	00:00 A.M	0.05	0.15	0.15	0.15	0.1	2.52
	06:00 A.M.	0.1	0.18	0.12	0.18	0.11	1.68
	12:00 NOON	0.12	0.18	0.12	0.18	0.13	2.8

	06:00 P.M.	0.12	0.15	0.15	0.15	0.11	2.24
Day 6	00:00 A.M	0.12	0.15	0.15	0.2	0.12	2.8
25/3/2022	06:00 A.M.	0.1	0.15	0.15	0.2	0.1	2.52
	12:00 NOON	0.07	0.18	0.12	0.18	0.1	3.36
	06:00 P.M.	0.07	0.18	0.12	0.18	0.1	4.2
Day 7	00:00 A.M	0.1	0.15	0.15	0.15	0.1	3.08
26/3/2022	06:00 A.M.	0.12	0.16	0.16	0.16	0.1	2.52
	12:00 NOON	0.12	0.15	0.15	0.15	0.1	3.92
	06:00 P.M.	0.11	0.12	0.12	0.12	0.1	3.92
Day 8	00:00 A.M	0.09	0.18	0.12	0.2	0.1	2.8
27/3/2022	06:00 A.M.	0.1	0.18	0.12	0.2	0.11	2.52
	12:00 NOON	0.09	0.18	0.12	0.18	0.12	4.2
	06:00 P.M.	0.08	0.18	0.12	0.18	0.1	4.76
Day 9	00:00 A.M	0.05	0.18	0.12	0.18	0.1	3.64
28/3/2022	06:00 A.M.	0.04	0.15	0.15	0.15	0.1	2.52
	12:00 NOON	0.06	0.15	0.15	0.15	0.11	3.92
	06:00 P.M.	0.07	0.16	0.16	0.16	0.13	3.92
Day 10	00:00 A.M	0.09	0.17	0.17	0.17	0.11	2.8
29/3/2022	06:00 A.M.	0.1	0.18	0.12	0.18	0.12	1.4
	12:00 NOON	0.05	0.15	0.15	0.15	0.1	3.36
	06:00 P.M.	0.05	0.15	0.15	0.15	0.1	4.76
Day 11	00:00 A.M	0.08	0.18	0.12	0.18	0.1	2.52
30/3/2022	06:00 A.M.	0.06	0.18	0.12	0.2	0.1	2.24
	12:00 NOON	0.05	0.15	0.15	0.2	0.1	3.08
	06:00 P.M.	0.05	0.15	0.15	0.15	0.1	2.8
Day 12	00:00 A.M	0.1	0.15	0.15	0.15	0.1	2.52

31/3/2022	06:00 A.M.	0.12	0.18	0.12	0.18	0.1	1.68
	12:00 NOON	0.12	0.12	0.12	0.12	0.11	2.8
	06:00 P.M.	0.12	0.18	0.12	0.2	0.12	2.24
Day 13	00:00 A.M	0.1	0.18	0.12	0.2	0.1	2.8
1/4/2022	06:00 A.M.	0.07	0.18	0.12	0.18	0.1	2.52
	12:00 NOON	0.07	0.18	0.12	0.18	0.1	3.36
	06:00 P.M.	0.05	0.18	0.12	0.18	0.11	4.2
Day 14	00:00 A.M	0.08	0.15	0.15	0.15	0.13	3.08
2/4/2022	06:00 A.M.	0.06	0.15	0.15	0.15	0.11	2.52
	12:00 NOON	0.05	0.16	0.16	0.16	0.12	3.92
	06:00 P.M.	0.05	0.17	0.17	0.17	0.1	3.92
Day 15	00:00 A.M	0.1	0.18	0.12	0.18	0.1	2.8
3/4/2022	06:00 A.M.	0.12	0.18	0.12	0.18	0.1	4.76
	12:00 NOON	0.12	0.18	0.12	0.18	0.1	3.08
	06:00 P.M.	0.12	0.15	0.15	0.15	0.1	2.52
Day 16	00:00 A.M	0.1	0.16	0.16	0.16	0.1	4.2
4/4/2022	06:00 A.M.	0.07	0.15	0.15	0.15	0.1	4.76
	12:00 NOON	0.07	0.12	0.12	0.12	0.1	3.64
	06:00 P.M.	0.1	0.18	0.12	0.18	0.11	2.52
Day 17	00:00 A.M	0.12	0.18	0.12	0.18	0.12	3.92
5/4/2022	06:00 A.M.	0.12	0.18	0.12	0.18	0.1	3.92
	12:00 NOON	0.11	0.18	0.12	0.18	0.1	2.8
	06:00 P.M.	0.09	0.18	0.12	0.18	0.1	1.4
Day 18	00:00 A.M	0.1	0.15	0.15	0.15	0.11	3.36
6/4/2022	06:00 A.M.	0.09	0.15	0.15	0.15	0.13	3.92
	12:00 NOON	0.08	0.16	0.16	0.16	0.11	4.76

	06:00 P.M.	0.05	0.17	0.17	0.17	0.12	2.24
Day 19	00:00 A.M	0.04	0.18	0.12	0.18	0.1	3.08
7/4/2022	06:00 A.M.	0.06	0.18	0.12	0.18	0.1	2.8
	12:00 NOON	0.07	0.15	0.15	0.2	0.1	2.52
	06:00 P.M.	0.05	0.16	0.16	0.2	0.1	1.68
Day 20	00:00 A.M	0.05	0.15	0.15	0.15	0.1	2.8
8/4/2022	06:00 A.M.	0.1	0.12	0.12	0.12	0.1	4.76
	12:00 NOON	0.12	0.18	0.12	0.18	0.1	3.64
	06:00 P.M.	0.12	0.18	0.12	0.18	0.1	2.52
Day 21	00:00 A.M	0.12	0.18	0.12	0.18	0.11	3.92
9/4/2022	06:00 A.M.	0.1	0.18	0.12	0.2	0.12	3.92
	12:00 NOON	0.07	0.18	0.12	0.2	0.1	2.8
	06:00 P.M.	0.07	0.15	0.15	0.15	0.1	1.4
Day 22	00:00 A.M	0.1	0.15	0.15	0.15	0.1	3.36
10/4/2022	06:00 A.M.	0.12	0.16	0.16	0.16	0.11	4.76
	12:00 NOON	0.12	0.17	0.17	0.17	0.13	2.52
	06:00 P.M.	0.12	0.18	0.12	0.18	0.11	2.24
Day 23	00:00 A.M	0.1	0.15	0.15	0.15	0.12	3.08
11/4/2022	06:00 A.M.	0.07	0.15	0.15	0.15	0.1	2.8
	12:00 NOON	0.07	0.18	0.12	0.18	0.1	2.52
	06:00 P.M.	0.05	0.18	0.12	0.18	0.1	1.68
Day 24	00:00 A.M	0.08	0.15	0.15	0.2	0.1	2.8
12/4/2022	06:00 A.M.	0.06	0.15	0.15	0.2	0.1	2.24
	12:00 NOON	0.1	0.15	0.15	0.15	0.1	2.8
	06:00 P.M.	0.12	0.18	0.12	0.18	0.1	2.52
Day 25	00:00 A.M	0.12	0.18	0.12	0.18	0.1	3.36

13/4/2022	06:00 A.M.	0.11	0.15	0.15	0.2	0.11	4.2
	12:00 NOON	0.09	0.16	0.16	0.2	0.12	3.08
	06:00 P.M.	0.1	0.15	0.15	0.15	0.1	2.52
Day 26	00:00 A.M	0.09	0.12	0.12	0.12	0.1	3.92
14/4/2022	06:00 A.M.	0.08	0.18	0.12	0.2	0.1	3.92
	12:00 NOON	0.05	0.18	0.12	0.2	0.11	2.8
	06:00 P.M.	0.04	0.18	0.12	0.18	0.13	5.04
Day 27	00:00 A.M	0.06	0.18	0.12	0.18	0.11	3.36
15/4/2022	06:00 A.M.	0.07	0.15	0.15	0.15	0.12	3.36
	12:00 NOON	0.05	0.15	0.15	0.15	0.1	4.76
	06:00 P.M.	0.05	0.18	0.12	0.2	0.1	4.48
Day 28	00:00 A.M	0.1	0.18	0.12	0.2	0.1	5.04
16/4/2022	06:00 A.M.	0.12	0.15	0.15	0.15	0.1	2.8
	12:00 NOON	0.12	0.18	0.12	0.18	0.1	2.24

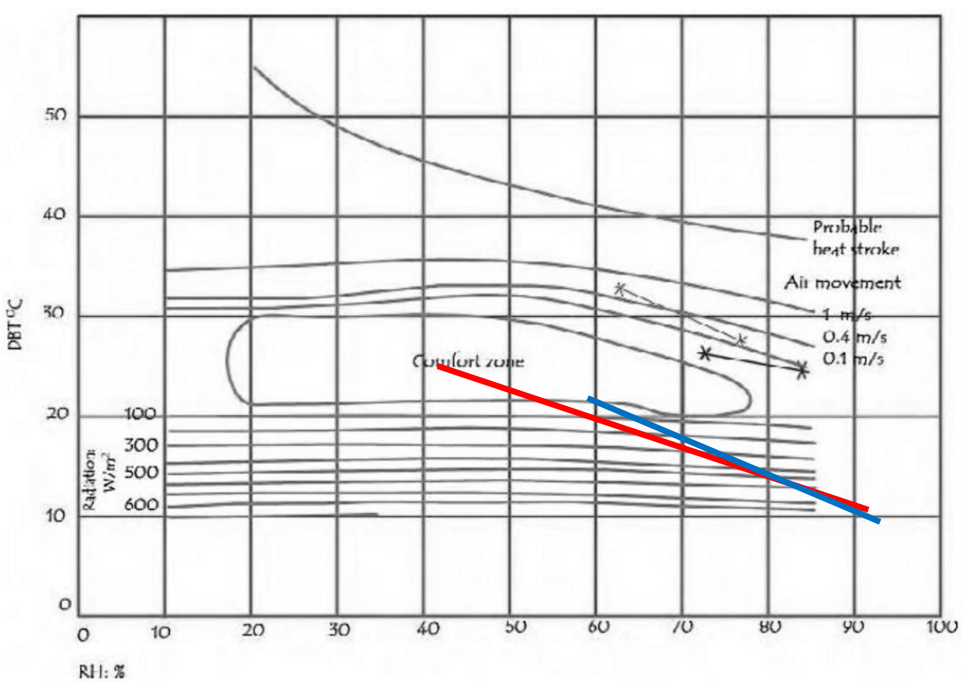
CLIMATIC DATA FOR NAIROBI

		JAN	**FEB**	**MAR**	**APR**	**MAY**	**JUNE**	**JULY**	**AUG**	**SEPT**	**OCT**	**NOV**	**DEC**
WIND	**MAX**	5.7	5.7	5.7	4.6	3.1	3.1	3.1	3.6	4.1	4.6	5.1	5.7
SPEED (m/s)	**MIN**	3.6	3.1	3.1	2.6	2.1	1.5	1.5	1.5	2.6	3.1	3.6	3.6
SOLAR	**MAX**	632	655	612	531	464	427	388	423	529	535	532	588
RADIATION (langleys)	**MIN**	457	497	475	371	354	313	224	267	319	374	379	388

INTERVIEW GUIDE

i. How many people visit the building per day?
ii. Do users exhibit symptoms of sick building syndrome?
iii. What improvements have been made to this building since it was built?
iv. How many hours in a day is the building in use?
v. Do you feel the need to acquire or use a fan?
vi. Which rooms/ spaces are used most during daytime?
vii. Which rooms/ spaces are used most during the night?
viii. Do you ever open the windows, if any? If so, when?

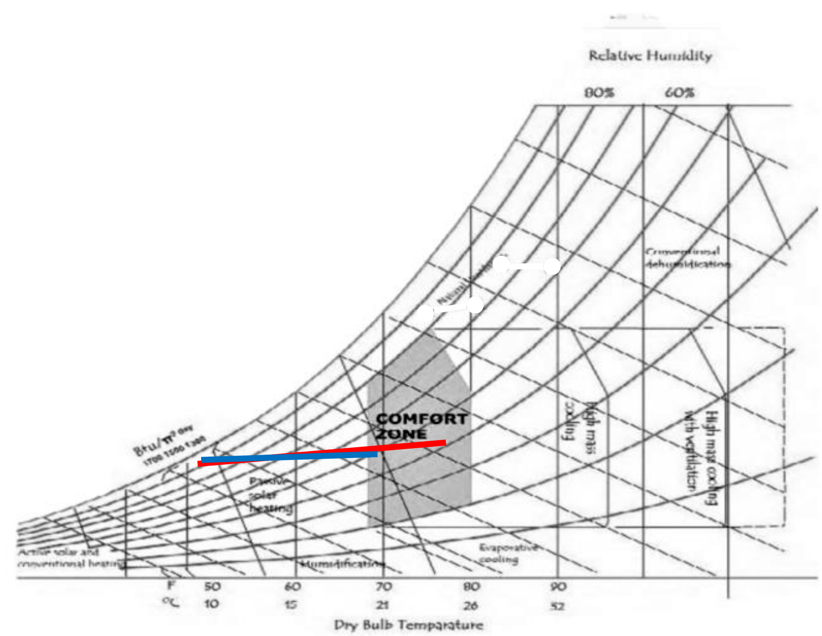
BIOCLIMATIC CHART



COLDEST MONTH (JULY)

HOTTEST MONTH (FEBRUARY)

PSYCHROMETRIC CHART



COLDEST MONTH (JULY)

HOTTEST MONTH (FEBRUARY)

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