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Department of Architectural Engineering

تكامل أنظمة التظليل مع الواجهات المزدوجة المهواة طبيعياً لتحسين الأداء الحراري في المباني الفندقية بالقاهرة الكبرى

Integrating Shading Systems with Naturally Ventilated Double Skin Facades for Enhancing Thermal Performance in Hotel Buildings of Greater Cairo.

A Thesis Presented in Partial Fulfillment of the Requirements for Master of Science Degree in Architecture
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Statement

This thesis is submitted to Ain Shams University for the M.Sc. degree in Architecture.

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Abstract

The research aimed at evaluating the efficiency of integrating shading devices with naturally ventilated walls on thermal performance and indoor ventilation rates of a generic five stars hotel double room in Greater Cairo. This research is composed of 4 chapters. Chapter 1 and 2 studied theoretically and analytically naturally ventilated walls and shading devices' working principle, types and how they work in hot arid climates. Also, the parameters of shading devices and naturally ventilated walls were discussed and some parameters were determined to be used in the comparative analysis which took place in chapters 3 and 4. In chapter 3, Cairo's weather was analyzed and moreover a reference case was modeled and tested using Computational Fluid Dynamics simulations. In chapter 4 the results of three more cases were introduced and compared analytically. Those cases are: naturally ventilated wall case, and two cases of integration of shading devices with naturally ventilated wall one with shading devices near the outer skin and one near the inner skin.

The research focused on the extreme conditions of Cairo's climate and the study was made in the day with the highest temperature in summer in South orientation and the hours of the study were the hours which had the highest operative temperature at day and night. Three floors were chosen for the study which were decided to be at the beginning of the building (5th floor), at the middle of the building (20th floor) and the last floor (35th floor). The study was done on South, West, East and North orientations and the research revealed that naturally ventilated walls which depend on stack effect, as a working principle, could achieve reasonable ventilation rates and could lower down operative temperature of the room both at day at night.

The research revealed also that integrating shading devices with naturally ventilated walls could affect cavity's overheating problem positively especially when placing shading devices near the outer skin. The techniques were compared to a single skin façade reference case using the outputs of EnegryPlus as a Computation Fluid Dynamics (CFD) simulation engine to study the efficiency of all techniques on thermal comfort and flow rate using only convective cooling strategy. CFD simulations showed that integrating shading devices with naturally ventilated walls while placing shading devices near the outer skin could enhance thermal comfort and ventilation rates in South, West and East orientations. This technique could lower down the room's operative temperature (OT) by 1.85 Celsius degrees in West façade when compared to ambient temperature. Also, air velocity (AV) values could reach an average of 0.041 m/s in all orientations which is close to comfort zone. The results also showed that placing shading devices near the inner skin could lead to higher operative temperatures at West orientation only at day and night while the difference in other orientations was not significant but gave advantage to the case where shading devices are placed near outer skin over this case because at higher floors the operative

temperature were higher with a difference that could reach 1.57 Celsius degrees. Regarding ventilation rates, the case where shading devices were placed near the outer skin always showed better performance than when shading devices were near the inner skin. Average age of air[1] was significantly lower also in this case.

On the other hand, using naturally ventilated walls alone could enhance thermal performance and ventilation rates in North where an operative temperature difference between the room and ambient air could reach 1.79 Celsius degrees and a maximum value of air velocity could reach 0.041 m/s.

The results give promising indication that although the room couldn't reach comfort zone, it still could have a lower operative temperature than single skin façade case by 2.85 Celsius degrees at South which is considered a significant result gathered with the significant result regarding age of air which was enhanced. More studies on the parameters of shading devices coupled with the introduction of a forced air flow in the cavity need to be investigated.

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[1] Definition in table 3-4 – Page 87.

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List of Abbreviations

ACH	Air Changes per Hour
AOA	Age of Air
AV	Air Velocity
AVG	Average
CFD	Computational Fluid Dynamics
DSF	Double Skin Façade
EMA	Egyptian Meteorological Authority
ETMY	Egyptian Typical Meteorological Year
IAQ	Indoor Air Quality
OT	Operative Temperature
SHGC	Solar Heat Gain Coefficient

Keywords

Natural Ventilation Techniques; Passive Techniques; Naturally Ventilated Wall; Shading Devices; Ventilation Rate; Thermal Performance; Hotel Building; Indoor Air Quality; CFD Simulations.

Glossary

Cooling Load

The amount of heat energy that needs to be removed from the space to maintain at comfort zone.

Emissivity

It is a surface characteristic of a material. It is the relative ability of a surface to absorb and emit energy in the form of radiation.

Energy Efficiency

The concept of utilizing less energy to perform the same functions in a building.

Energy Modeling (Simulation)

The process of designing a model of a real system/building and conducting experiments with this model for the purpose of understanding its behavior and/or evaluating various strategies for the operation of the system/building. A simulation model is a representation of a real system.

Façade

The principal front of a building, that faces on to a street or open space.

Indoor Air Quality

Air; toward which; a substantial majority of occupants express no dissatisfaction with respect to odor and sensory irritation , and in which there are not likely to be contaminants at concentrations that are known to pose a health risk.

The changes in lifestyle were the main reason in the existing of what is called “sick building syndrome”. Low indoor air quality is one of the most factors that can define the sick building, as pollutants within our homes have been recognized as threats to our health. Therefore, the removal of contaminants generated within inner volume is a vital process and can be achieved by keeping the air quality within an acceptable level with comfortable levels of temperature and humidity. One of the main purposes of ventilation is to provide acceptable indoor air quality.

Natural Ventilation

Ventilation is, essentially, the flow of air between the inner space and the outer environment through the ventilation vents within a well-known time, for the following purposes:

- Air Quality Control: By replacing internal air with cleaner outdoor air.

- Direct Cooling: By replacing inner warm indoor air with cooler outdoor air with sufficient velocity to enhance convective transport of heat and moisture.

- Indirect Cooling: By pre-cooling thermally massive components of the building fabric, or a thermal storage system by thermal conduction.

Operative Temperature

The uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment.

Thermal Convection

This form of heat transfer involves energy transfer by fluid movement and molecular conduction. When fluid currents are produced by external sources, the heat transfer is termed forced convection. If it is generated internally caused by temperature variation, the heat transfer is termed free or natural convection.

Thermal Resistance (R)

The measure of a material’s ability to resist heat flow. The formula for Thermal Resistance is R = L / k where (L) is the material’s thickness and (k) is the material’s Thermal Conductivity. The higher a material’s R-value, the better it insulates. The units of R value are m2·K/W.

Total Annual Cooling Load

This refers to the total amount of energy used for cooling by the building over a period of one year.

U-Value (Coefficient of Heat Transmittance)

It is a measure of the rate of heat flow through any given combination of materials, air layers, and air spaces. It is equal to the reciprocal of the sum of all resistances (R). The lower the U-value, the lower the heat loss or the higher the insulating value. The units are $W/m^2.K$.

▪ Introduction

- Overview
- Problem Statement
- Research Objectives
- Research Methodology
- Research Scope and Limitations
- Research Structure

Overview

Double skin façades are becoming a trend in architecture nowadays in terms of energy conservation and natural ventilation. Their different applications and types introduce a wide range of choices regarding energy conservation mainly. They can be used in different types of buildings to cool them naturally or with the less possible use of mechanical ventilation.

Double skin facades, in their form may be used as an interior space if used as a corridor. This could add a value to the design as well.

Nowadays, Egypt suffers from energy problems. Buildings are the major electricity consumers especially those which rely on HVAC systems for cooling in Egypt's hot climate.[1] HVAC systems may cause serious problems to the environment because of the radiations and the use of clouro fluorocarbon that harm the ozone layer[2]. Due to these problems, architects need to consider designing buildings that are naturally ventilated where different passive cooling techniques are applied. These designs should suite Egypt's climate and conditions and should be environment friendly.

Double skin facades are a proper solution that may work in Egypt that needs to be tested and considered in the design phase. This research aims at evaluating how the naturally ventilated walls may affect thermal comfort in hotel buildings in Greater Cairo, as the hotel buildings are considered a type of buildings that consumes a large amount of electricity.

A double skin façade is defined normally as a pair of glass walls which are separated by an air gap. This gap works as insulation against noise, wind with high velocity (especially in high rise buildings), and mainly temperature. It also forces an airflow next to the exterior glazing that can be used as natural ventilation for the interior spaces.

A double skin facade can also be supported by shading device to control the heat gain due to direct sun rays. This adds a value to the environmental aspect where the double skin façade minimizes the heat gain of the interior spaces and help achieving natural ventilation.

However, depending on the location, the double skin façade will cost more financially, because of the glazing, the structure and the mechanical systems' cost.

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[1] Last modified 2015, https://energypedia.info/wiki/Egypt_Energy_Situation, Last visit, April 2016.

[2] Haresh Khemani, 1/15/2010, *Chlorofluorocarbons (CFCs): Refrigerants that Cause Ozone Layer Depletion*, http://www.brighthubengineering.com/hvac/965-chlorofluorocarbons-cfcs-refrigerants-that-cause-ozone-layer-depletion/, Last visit: April 2016

Yet, researchers mentioned that the saving in the energy in the operation phase, due to reducing cooling and heating loads, can justify the cost on the long term.

Problem Statement

Problem:

Most of the hotel buildings in Cairo have a highly ranked consumption of electricity because of using HVAC systems, in order to achieve thermal comfort in Cairo's hot weather that reaches its peak in August[1]. On the other side, using HVAC systems has a lot of environmental effects because of the leaked gas that affects the Ozone layer, which causes problems such as the global warming, and others. In Cairo, the shortage of knowledge about thermal performance of buildings should be solved by studying and doing more research about lowering mechanical ventilation systems usage and relying more on passive techniques.

Hypothesis:

Integrating shading devices with naturally ventilated double skin facades could enhance thermal performance and ventilation rates in hotel buildings in Greater Cairo.

Aim

This research aimed at evaluating the integration of shading devices with naturally ventilated double skin facades to enhance thermal performance and ventilation rates in hotel buildings in Greater Cairo.

Objectives:

The aim could be achieved through the following secondary objectives:

- Identifying naturally ventilated walls, their types, and applications.
- Understanding shading devices integration with naturally ventilated facades.
- Analyzing different parameters of naturally ventilated walls and shading devices to choose the parameters that suits Cairo's hot arid climate.
- Evaluating the performance of a generic reference case.
- Evaluating the enhancement resulting from applying naturally ventilated walls and shading devices integration to the reference case.

Methodologies

The research went through three successive methodologies to achieve its objectives. These methodologies are:

- Theoretical/analytical methodology:

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[1] Average weather in Cairo, Egypt, www.weather-and-climate.com last visit, April, 2016

A theoretical study about naturally ventilated walls, their types, different parameters, working principle and how they perform in hot arid climates was done. Also, the integration of shading devices with naturally ventilated walls was studied by introducing the effect of adding shading devices inside naturally ventilated walls' cavities and the different parameters of shading devices that may affect the performance of the technique. This theoretical study was supported with previous researches and comparative studies that show the best parameters that suits Cairo's weather.

- Analytical methodology:
  An analytical study for Cairo's weather was done and was followed by analyzing the results of computational fluid dynamic (CFD) simulations for a single skin façade of a reference case which is a generic plan for a double room in a five stars hotel.
- Comparative analysis methodology:
  Naturally ventilated wall was applied to the reference case and then two other cases were studied. In those two cases shading devices were integrated within the cavity 25 cm away from the outer skin in a case and 25 cm away from the inner skin in the other.
  The results were compared to the base case's results and after that they were compared to each other to highlight the case with the best results.

Scope and Limitations

The aim of the research was focused on thermal performance and ventilation rates in cooling season so, the compared outputs of the study were operative temperature (OT), air velocity (AV) and age of air (AOA). Other factors were excluded from the study like the effect on energy consumption and daylighting.

The study was done in two hours: 2 PM and 6 PM to assure results' accuracy. Also, when using shading systems, the sun angle used was 31 degrees based on the angle of the sun at 4 PM on the 23rd of August. Also, the openings used in the study were placed in the inner and outer skins and open 24 hours and used as air inlets and outlets at the same time. The building's exposure to wind option is normal on DesignBuilder. The building is not supposed to be surrounded by any high-rise buildings.

Chapters' Overview

- <u>Chapter 1: Integrating Shading Devices with Naturally Ventilated Walls.</u>
  In this chapter, naturally ventilated walls were defined and studied. The working principle of naturally ventilated walls was introduced with their types, performance in hot arid climates, advantages and disadvantages.
  Also, integration of shading devices with naturally ventilated walls was discussed as a solution for naturally ventilated walls problems in hot arid climates. The working principle of shading devices within the cavity was studied as well.

- Chapter 2: Design Parameters of Naturally Ventilated Walls and Shading Devices
  Chapter 2 discussed the main parameters of naturally ventilated walls including cavity height, cavity width, glazing type, glazing color, inner skin's openings and outer skin's openings. Also, the main parameters of integrated shading devices were studied including shading devices' angle, material, color and placement. The main requirements to achieve thermal comfort in space was also discussed showing the range of required criteria of temperature, humidity, air velocity, etc.
- Chapter 3: CFD Simulation Analysis
  In chapter 3, Cairo's weather was analyzed and modeling the reference case was discussed. Preparation for CFD simulations was done including choosing certain hours for simulation at certain day and month. The criteria of comparison were discussed and were followed by simulations results of the reference case which were analyzed at the end of the chapter.
- Chapter 4: CFD Simulations Results
  Modeling naturally ventilated wall model and integration of shading devices with naturally ventilated walls two model were discussed in this chapter and the results of simulations were analyzed and compared to the reference case and to each other in order to highlight the case with the best thermal performance.
- Conclusion and Recommendations
  The research ended with a conclusion that is based on the simulations results which recommended integrating shading devices with naturally ventilated walls in South, East and West façade where shading devices are placed near the outer skin. Also, it was concluded that naturally ventilated wall performs better in terms of thermal comfort when it is applied in North façade. Some recommendations were mentioned after conclusion for future research work.

The next table shows how the structure of the research and the methodology works to achieve the aim, and the objectives of the research.

Research Aim	Objectives	Methodology	Structure
Evaluating the integration of shading devices with naturally ventilated walls in hotel buildings in Greater Cairo.	Defining Naturally Ventilated Walls, Their Types and Different Applications	Theoretical / Analytical Study	Chapter 1: Integrating Shading Devices with Naturally Ventilated Walls
	Identifying Shading Devices Configuration When Integrated with Naturally Ventilated Walls		
	Analyzing Applied Studies of Parameters of Naturally Ventilated Walls and Shading Devices	Analytical Study	Chapter 2: Design Parameters of Naturally Ventilated Walls and Integrated Shading Devices
	Evaluating A Base Local Case’s Performance	Comparative Applied Study (CFD Simulations)	Chapter 3: CFD Simulations Analysis
	Evaluating the Case’s Performance After Applying Naturally Ventilated Walls And Shading Devices	Evaluation	Chapter 4: CFD Simulations Results
			Conclusion & Recommendations

Chapter 1 -

Integrating shading devices with naturally ventilated Double skin facades

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- Introduction
- Double Skin Facades
- Naturally Ventilated Walls
- Shading Devices
- Conclusion

Chapter 1: Integrating Shading Devices with Naturally Ventilated Double Skin Facades

1.1 Introduction

The increasing use of HVAC and active cooling systems has a tremendous effect on the indoor air quality in addition to high energy consumption rates and environmental worldwide issues including global warming and ozone layer depletion. This led architects and researchers to look for new techniques for improving thermal comfort without consuming much energy. One of these techniques that has been introduced in the last century is double skin facades. The idea behind double skin facades is creating a cavity between two layers of glass to force air movement inside to cool down the attached spaces.

This chapter discusses integrating shading devices with naturally ventilated walls as a passive cooling technique that could enhance thermal comfort of buildings in hot arid climates.

The study explains passive cooling strategies that work with naturally ventilated walls mainly and thermal comfort conditions. The chapter continues with explaining double skin facades concept, history, design parameters, types, advantages, disadvantages, and how they work in different climatic conditions focusing on naturally ventilated walls. After that, the effect of integrating shading devices inside double skin façade’s cavity is studied showing shading devices design parameters and their working principles.

The information mentioned in this chapter can help in designing a double skin façade and choosing the type which fits hot arid climate of Cairo. This will be used to assess the thermal performance of the case study in chapter three.

1.2 Double Skin Facades (DSF)

As sheltering people from the outside climate is considered the basic reason why buildings were mainly thought of, it is important to think carefully, about the elements of the buildings in the design phase. Those elements include the roof, the ground, and the walls, which are the most important element because they are the largest elements that face and connect people to the outside. As a result, facades technologies have been improved through the years in construction type, materials, and sustainable design.[1]

Double skin façade is a remarkable environmental solution, a sustainable system and a European architectural trend where two layers of glass are separated by an air gap in which air flows to create natural ventilation for the building. It was evolved due to the aesthetic desires the architects have; to build a transparent all-glass façade which is considered as a dominant feature of modern architecture where occupants inside a building are connected to the outside.[2] On the other hand, it was evolved because architects became very cognizant about the environment's needs, and the energy resources consumption which increased in the last few decades.

The urge to design buildings with pleasant indoor climates led to thinking about different passive cooling techniques, where the double skin façade was a tremendously attractive approach.[3]

In a double skin façade heat gain is reduced when shading devices are integrated within the air gap. And the ventilation can happen with mechanical, natural or hybrid mechanisms. The mechanism choice depends on HVAC strategy, occupational hours, site location, building use, and the climatic conditions.[4] In this technique, natural ventilation occurs due to the pressure difference created by the wind and the 'stack effect'. The fact that the temperature inside the gap is higher than the temperature outside leads to air moving to the top of the gap to escape from it.[5] In addition to natural ventilation, DSFs have a lot of pros. These include daylighting opportunity through the large glass areas, and sound insulation.

According to different literatures, DSF is mostly studied to be used in cold and moderate climates, while limited researches tested the solution's efficiency in hot and

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[1] Amaireh, I., 2017, Numerical Investigation into A Double Skin Façade System Integrated with Shading Devices, With Reference to The City of Amman, Jordan.

[2] Azarbayjani, M., 2013, Climatic Based Consideration of Double Skin Façade System: Natural Ventilation Performance of a Case Study with Double Skin Façade in Mediterranean Climate.

[3] Mousavi, S., & Alibaba, H., 2015, A State of Art for Using Double Skin Façade in Hot Climate.

[4] Heimrath, R., Hansberger, H., Mach, T., Streicher, W., et al., 2005, Best façade: Best Practice for Double Skin Façades.

[5] Richter, J., Fei Lu, Zeiler, W., Boxem, G., and Labeodan, T., 2014, Double Façades: Comfort and Ventilation Aspects at an Extremely Complex Case Study.

arid climates where excessive heat gain can be a dominant obstacle. So that, more studies to test the efficiency and techniques to avoid the heat gain in a DSF in hot arid climates should be done.[1] The elements that affect DSF performance are temperature, solar radiation, and wind velocity. Gratia and de Herde (2007 a, 2007 b, 2007 c) studied the effect of a DSF in a northern hemisphere temperate climate, and found that ventilation rates can be sufficient at day and night by window openings, even in case the wind characteristics are not favorable.[2]

Figure 1-1 classifies passive cooling strategies and highlights double skin facades as technique that uses buoyancy driven method of natural ventilation under convective cooling. Convective cooling falls under the passive cooling strategy: heat dissipation.

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[1] Mousavi, S. *Op. Cit*.

[2] Azarbayjani, M., 2013, Climatic Based Consideration of Double Skin Façade System: Natural Ventilation Performance of a Case Study with Double Skin Façade in Mediterranean Climate.

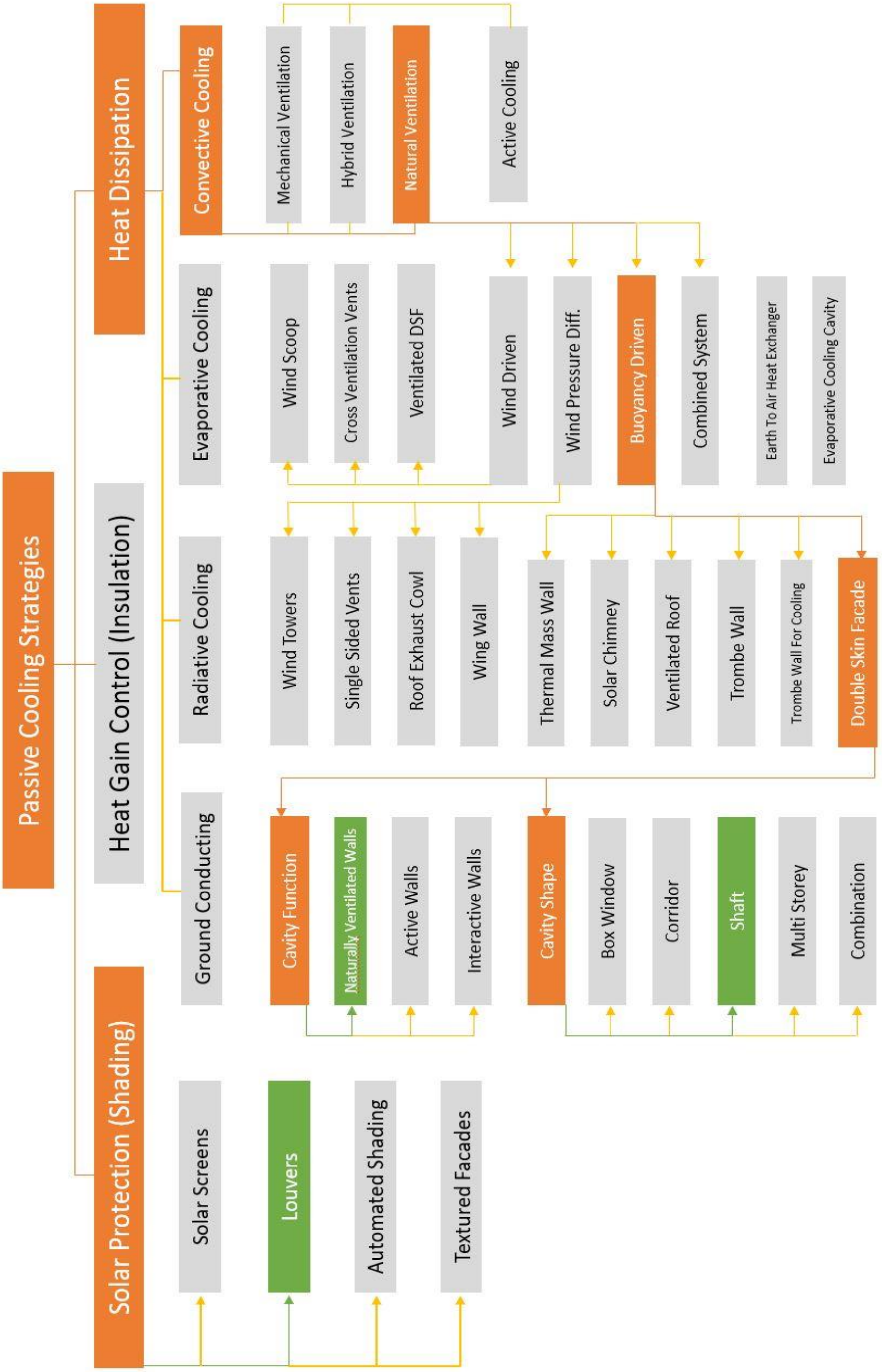

Figure 1-1- Double Skin Facades – Passive Cooling Strategy

1.2.1 Definition

Double skin façades were defined by many architects and researchers in the past few decades.

A double skin façade contains a cavity where air flows inside. This cavity separates an inner skin of glazing and an outer skin. The outer skin is usually a hardened single layer, while the interior is double layered to work as an insulator. Inside the cavity, shading devices are added to decrease the direct solar gain to reduce cooling demands.[1]

Arons (2000) also defined the double skin façade as *"a façade that consists of two distinct planar elements that allows interior or exterior air to move through the system. This is sometimes referred to as a twin skin."*

Uuttu (2001) described a double-skin facade as, *"a pair of glass skins separated by an air corridor (also called cavity or intermediate space) ranging in width from 20 cm to several metres. The glass skins may stretch over an entire structure or a portion of it."*

Oesterle, et al, (2001) gave a very comprehensive definition of a double skin façade claiming that it consists of *"a multi layered façade envelope, which has an external and internal layer that contains a buffer space used for controlled ventilation and solar protection"*

The characteristics of the double skin facades components help achieve three main functions with respect to energy efficiency, which are natural ventilation, daylighting and solar heat gain control.[2]

Another author, Saelens (2002) defined the double skin facade as *"an envelope construction, which consists of two transparent surfaces separated by a cavity, which is used as an air channel. This definition includes three main elements: (1) the envelope construction, (2) the transparency of the bounding surfaces and (3) the cavity airflow".*

According to Loncour, et. al., (2004) a double skin façade is *"a facade covering one or several storeys constructed with multiple glazed skins. The skins can be air tighten or not. In this kind of facade, the air cavity situated between the skins is naturally or mechanically ventilated."*

To conclude, a double skin façade – also called a multiple skin façade, is a façade consisting of two glazing skins separated by an air cavity where air flows inside.

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[1] Mousavi, S., & Alibaba, H., 2015, A State of Art for Using Double Skin Façade in Hot Climate.

[2] Yellamraju, V., 2004, Evaluation and Design of Double-Skin Facades for Office Buildings in Hot Climates.

Inside this cavity a possibility of adding shading devices will give an advantage solving the direct solar gain problem. This cavity also works as a sound insulator and a protection from the outside conditions.

1.2.2 Functions of DSF

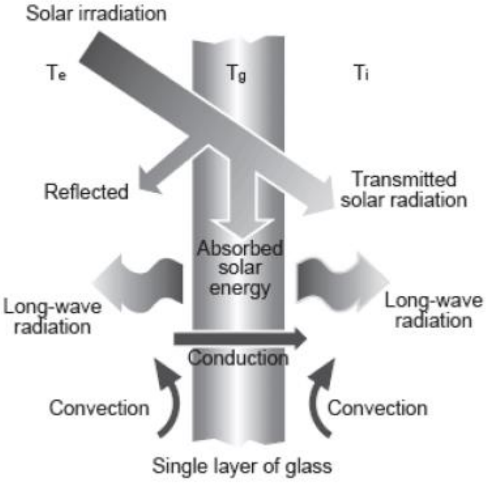

Figure 1-2 Heat Transfer through a Single Pane of Glass

Double skin facades have three main functions with respect to energy efficiency. These three functions are natural ventilation, heat gain control and daylighting. DSFs also have some other functions, like sound and smells insulation using different techniques.[1]

1.2.2.1 Natural Ventilation

Natural ventilation occurs in a double skin façade because of the exterior glazing which creates a buffer zone near the exterior skin. This buffer zone is not affected by high velocity wind and is accessible by the building's users. The exterior glazing can be operable also, although it is not the right option in high temperature climates where hot air can flow in the buffer zone. Yet, the operability of the exterior glazing can be a good solution at night providing natural ventilation.[2]

Using the natural airflow to ventilate the building will save energy consumption through HVAC systems, and furthermore will reduce CO2 output of the building. One of the strategies used in double skin facades is the separation between building levels using grilles or vents. This strategy slows down the wind speed, especially in high floors. The separation also helps eliminating noise, smoke and heat transfer from a level to another, or from a space to the other.[3]

1.2.2.2 Heat Gain Control

To understand how a double skin façade can control the direct heat gain, we firstly need to understand how glass responds to it. Visible light and infrared are the main components of the light spectrum that are responsible for bearing the direct heat

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[1] Ibid
[2] Ibid
[3] Boake, T., Harrison, K., & Collins, D., Chatham, A., Lee, R.., 2003, Understanding the General Principles of the Double Skin Façade System.

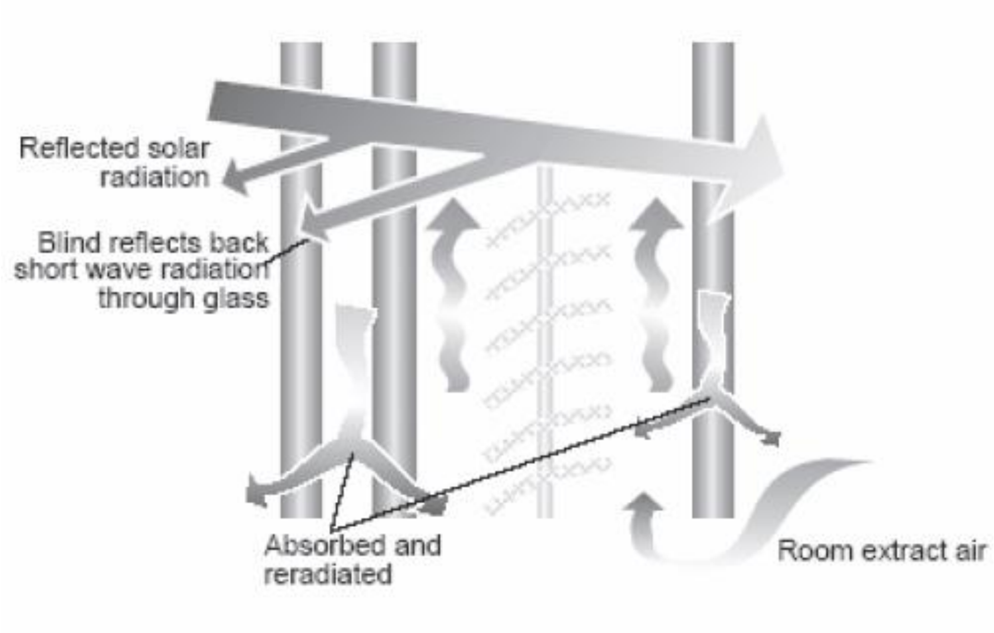

Figure 1-3 Heat Transfer through a Double Skin Facade

coming from outside. Scientists refer to them as shortwave and longwave solar radiation, respectively. And a general rule concerning the relation between light and energy, is that the longer the wavelength of a light component, the lower energy it carries. While clear glass is almost transparent to short wave radiations, it works as a barrier to long wave radiations. And when the solar heat enters the space through the glass, the internal surfaces' temperature rises by absorption. As a result for this temperature rise, they begin to radiate heat. The re-emitted heat, is long wave radiations that cause the temperature of the interior space to rise.[1] (Figure 1-2).

Another way for heat transfer through single pane glass is heat conduction. As air is a poor heat conductor, the air gap in the double skin façade will prevent heat entering the interior spaces through conduction.

In order to keep the interior spaces in a good thermal condition, it is better to block the heat source from entering the space.[2] To control direct solar heat gain when using double skin facades, installing shading devices inside the cavity can help reflecting some shortwave radiation, and absorbing some of it. The re-emitted longwave radiations in this case will not affect the interior spaces because of the clear glass

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[1] Yellamraju, V., 2004, Evaluation and Design of Double-Skin Facades For Office Buildings In Hot Climates

[2] Op Cit., Boake, T., et al.

ability to work as a barrier against longwave radiations (Figure 1-3).[1] The shading devices are normally horizontal devices, and they are either fixed or movable by the users or by sensors maintaining some of the exterior view. The air gap gives the shading devices protection, and it costs less than installing them outside the façade because of the installation cost and safety issues.[2] The air gap also extracts the heat gained continuously. The choice of glazing type is a very critical factor when designing double skin facades. The solar heat transmittance values for glazing which reflects the absorption and reflection of heat, can minimize solar heat gain. Nowadays, various advanced glazing types exist and each of them responds differently to different solar radiations which is known as “spectral selectivity”.[3] Glass that highly transmits visible light, and reduces solar heat gain is considered selective glass. Spectrally selective glass is coated or tinted and is usually neutral in color or blue or green/blue. [4] The air buffer gap in a double skin façade can control the heat gain and be an alternative for mechanical cooling/heating systems.

1.2.2.3 Daylighting

Double skin façades which consist of very large glazing areas allow daylight to enter the spaces easily. Although, fundamentally, due to the double glazing light transmittance shall decrease, the areas where daylight penetrates in the building will increase and this will overcome the decrease in light transmittance. Furthermore, the elements of the double skin façade such as the interior shading devices will increase the lit depth of the spaces because of light reflections caused by them.[5] Daylight is considered better than artificial light due to electricity saving and the quality of daylight which is of a great importance to physical and mental health. Yet, glare remains a result that needs to be addressed while designing double skin facades and the integrated shading devices.[6] Adding shading devices will affect the lit depth of the interiors, so it is recommended to use small tilt angles when possible which will let daylight enter the spaces, and reduce glare. Yet, using shading devices inside the cavity may affect air flow motion, so deep studies about the effect of using shading devices inside the double skin façade’s cavity are highly recommended.[7]

Double skin façade functions address two major energy consumers which are cooling/heating devices, and artificial lights. So that, deep studies considering the

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[1] Op Cit., Yellamraju, V.
[2] Op Cit., Boake, T., et al.
[3] Op Cit., Yellamraju, V.
[4] Op Cit., Boake, T., et al.
[5] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan.
[6] Ibid
[7] Ibid

double skin façade components should be done before execution to make sure that the three main functions it addresses will not contradict each other.

1.2.3 DSF Components

Double skin facades are mainly composed of inner and outer skins, façade cavity, air-intakes and extracts, and optional shading devices. The design of each element highly affects the effectiveness of the façade considering ventilation, daylighting, and insulation. This section will discuss the elements of the double skin façade.[1]

1.2.3.1 Inner and Outer Façade

The two noticeable components of the double skin façade are its inner skin and outer skin. Though, glass is the most used material for them, the two skins can be of different materials. The outer skin is usually a single pane glass skin, and it is the component that works as a barrier that faces the ambient climate. It also works as a protection from high velocity wind which may affect the ventilation system, and also protects from the noise. The inner skin in contrary with the outer skin, can be made from varied glass-opaque materials. Yet it is usually made from double panes glass. The inner skin has windows that are operable and facing the cavity to control the ventilation of the interior spaces. Also, the outer skin can have operable windows that can be either controlled by the users or automated. These windows can be opened in case of need for cross ventilation.[2] Figure 1-4 shows double skin facades' main components.

Figure 1-4- Double Skin Façade Components (https://bergami.it/facciata-ventilata-hi-tec-cose-le-principali-tipologie-esistenti/vetro/ Last visit: 22-7-2018)

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[1] Danik, S., 2014, Natural Ventilation Through Double-Skin Facades in Tall Buildings

[2] Ibid

1.2.3.2 Façade Cavity

The cavity, also called “buffer zone” or “intermediate space”, is considered the most important component in the double skin façade. This is because it is the main reason why a double skin façade can work as a passive technique for ventilation, as the cavity temperature and airflow rate inside it are considered very effective factors that affect the system performance. The façade cavity is defined as the space that results from building the two separated skins. Important factors that affect the system’s performance are the cavity’s width, height and length. Yet, cavity’s width and height are the most affecting factors (Height-to-width ratio). Several factors including microclimate, building type, and intended ventilation mode should be considered before designing the double skin façade’s cavity.

The buffer zone can be continuous along the whole façade or separated horizontally to insulate one floor from the other or even vertically to optimize the stack effect. This variety in the cavity design later led to classifying double skin facades according to cavity shape. It can also be equipped with service platforms to enable cleaning and maintenance. The cavity also works as a protection for the shading devices –if added- from the ambient weather factors. [1]

1.2.3.3 Openings

The outer and inner skins of the double skin façade could have openings integrated into them. The openings of the inner skin are mainly used for naturally ventilating the spaces, while the openings of the outer skin could be added in hot arid climate to reduce air temperature inside the cavity due to heat gain. There are three main factors that are highly effective and important to consider while designing the double skin façade, which are their type, size, and position. These factors highly influence the air velocity, flow pattern, cavity’s temperature and interior spaces’ temperature.[2]

1.2.3.4 Shading Devices

When double skin facades were firstly thought of, the architects designed it in cold climates. And they were mainly used for heating. But after that, it became an international construction system even for hot humid climates. The main problem that faced this system in hot arid climates was the excessive heat gain and the rise in the temperature of cavity’s air due to solar irradiance. To overcome this problem, shading devices were introduced as an integrated solution within the cavity that reflect and obstruct direct heat gain during hot times.

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[1] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan.

[2] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan.

Figure 1-5- Shading Devices Integrated with Double Skin Facades (http://udis-tmc.blogspot.com/2011/09/skin-of-architecture-double-skin-3.html Last Visit: 22-7-2018)

Technically, shading devices could be installed inside or outside the cavity, though the cavity will work as a protection for them from rain, and dust. They also can have different forms, from roller blinds (screens) to venetian blinds and movable or fixed slats.

Shading devices can be either automatic responding elements depending on the sun direction and the needed obstruction level, or controllable by the users, or even fixed. Many parameters affect the performance of the DSF considering its shading devices; such as their position, size, material, color, emissivity, and tilt angle.[1]

1.2.4 DSFs Classification

Double skin facades can be classified according to their working principle (the nature of airflow reaching the cavity and the driving force of the airflow), and their compartmentalization (cavity's form). And this gives every double skin façade type a different definition.

1.2.4.1 Based on Air Flow Origin:

According to air flow origin double skin facades can be classified to 3 types which are (see fig. 1-6):

a- Air supply: In this type fresh air coming from outside the building flows into the cavity and ventilates the interior spaces.

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[1] Op. Cit., Amaireh I.

b- Air Exhaust: Exhausted air coming from the interior spaces is extracted outside the façade.

c- Air Curtain: Here, air flows from outside to outside without entering the interior spaces (exterior air curtain), or flows from the inside of the building to upper spaces without exiting the cavity (interior air curtain).[1]

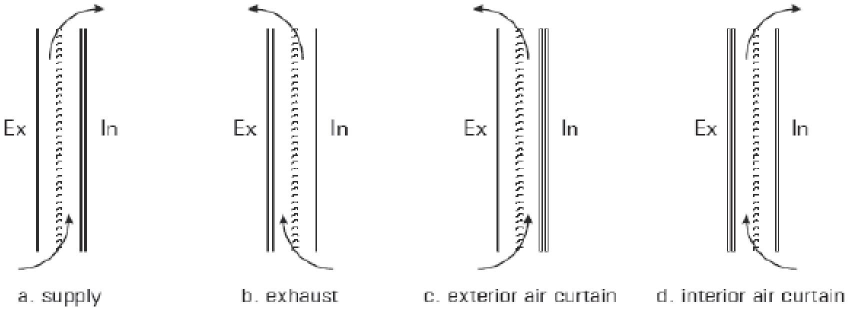

Figure 1-6 Double Skin Façade Types Based on Air Flow Origin (Yellamraju, V., 2004, Evaluation And Design Of Double-Skin Facades For Office Buildings In Hot Climates)

1.2.4.2 Based on the driving force of air flow (Ventilation Type):

Loncour, X., Flamant, G., (2004) explains that according to the intention or possible control of ventilation in DSFs, it is decided whether the double skin façade should be non-ventilated or ventilated regardless of the elements added inside the cavity including shading devices. According to their air flow driving force, double skin facades are classified to 3 main types:

a- Naturally Ventilated Double Skin Facades:

In the naturally ventilated double skin facades, the forces that cause fresh air to flow inside the cavity and then to the interior spaces are thermal buoyancy and pressure difference. These forces help achieving the stack effect. In this case the air flow rate cannot be measured as a quantity because it depends on the ambient climatic conditions. This type is not very sufficient in very hot climatic conditions and where the temperature difference between outside the cavity and inside it is not big enough to allow achieving stack effect. The façade in this type works as an insulator in winter and a chimney in summer. This type will be explained in details in the following sections.

b- Mechanically Ventilated Double Skin Facades:

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[1] Yellamraju, V., 2004, Evaluation And Design Of Double-Skin Facades For Office Buildings In Hot Climates

Mechanically ventilated double skin facades can either be integrated with certain HVAC system to force airflow inside the cavity or it can use small fans to create the air flow.[1]

c- Hybrid Double Skin Facades:

Authors describe hybrid double skin facades as a system where integrated ventilation units and automated glasses are combined. Motorized windows are introduced in this ventilation type. They help windows to be opened continuously. Also mechanical ventilation systems are used which are composed of controlled system of natural and mechanical ventilation. Those mechanical systems are capable of supplying fresh air and extracting it from the interior spaces.[2] In this type, the materials used in the system can be other materials than glass.[3]

1.2.4.3 Based on the Function of the Cavity:[4]

a- Naturally Ventilated Walls

In this type, the façade is naturally ventilated due to buoyancy and pressure difference as mentioned before. And another skin is added to the outside of the building envelope. In cases of no solar radiation it provides additional thermal insulation while in cases of high solar radiations, the skin is naturally ventilated from-to the outside by stack effect. The temperature difference between the outside air and the air inside the cavity should be noticeable for the system to work. So, shading devices might be added to protect from solar heat gain in hot climates to make the temperature difference that is needed by the system to work properly.

b- Active Walls

Active wall type facades work with HVAC systems which preheat air and recover heat in winter and use the stack effect to extract the air through the cavity in summer. This type is recommended in cold climates. In this type an extra skin is added to the inside of the building envelope. This inner façade is kept at a close temperature to the interior temperature both during high solar gains and when there are no solar gains. This leads to occupants' thermal comfort on the perimeter near the façade. It is preferred to use this type in cold climates because of the ability to ventilate the building in times of solar heat gains and to recover heat in cold times.

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[1] Ibid

[2] Daneshkadeh, S., 2013, The Impact of Double Skin Facades on Thermal Performance of Buildings.

[3] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan.

[4] Poirazis, H., 2006, Double Skin Facades, a Literature Review.

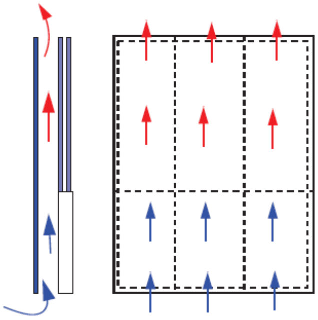
c- Interactive Walls

In this type the façade works similarly to the naturally ventilated façade. However, the façade doesn’t depend solely on the stack effect for ventilation but rather depends on mechanical systems to force air movement. This system is recommended for hot climates.[1] In cold times, the ventilation can be minimized and the cavity is used as thermal insulator. This type allows using operable windows to ventilate the interior spaces naturally even in high-rise buildings.[2]

1.2.4.4 Based on Compartmentalization:

Compartmentalization means the form of the cavity and its shape whether complete or divided, and based on that, double skin facades can be classified to the following types in table 1-1.[3]

Table 1-1- Double Skin Facades’ Types Based on Compartmentalization

Type	Figure	System	Working Principle
Façade Type (Multistorey Cavity)	 *Figure 1-7 Façade Type - DSF Schematic Drawing*	The cavity in this type is along the whole façade horizontally and vertically and is not divided. In this system, large openings near the ground floor and the roof help ventilating the cavity.	In winter, the openings can be closed and the greenhouse effect is achieved within the cavity. In summer, the openings are opened and the air moves in the cavity through the created buoyancy.

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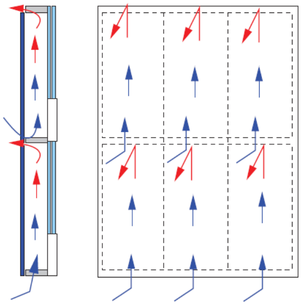
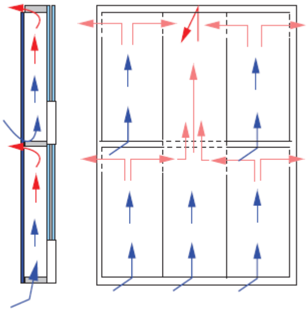
[1] Tascon, M., 2008, Experimental And Computational Evaluation of Thermal Performance And Overheating in Double Skin Facades.

[2] Op. Cit., Poirazis, H.

[3] Op. Cit., Yellamraju, V.

Corridor Type	 *Figure 1-8 Corridor Type - DSF Schematic Drawing*	The cavity in this type is divided horizontally in every storey or every number of storeys. In this type there are openings in the corridors to facilitate the movement of air inside the cavity. The openings are placed near ground level and ceiling level and are usually placed in a staggered form on every floor to prevent mixing the exhausted air of a floor with the fresh air entering the upper floor.	The heat moves by convection, and the corridors exist for firefighting, acoustic, and insulation reasons. [1] Corridor facades can decrease the overheating rate in the upper levels as well as providing natural ventilation of the cavity without allowing hot air to move upward because there are air intakes and outlets at each floor.[2]
Shaft Type	 *Figure 1-9 Shaft Type - DSF Schematic Drawing*	The cavity is divided vertically along the height of the façade using compartments. And it is considered as a combination of a façade type DSF and a box window DSF	The box window areas at both sides of the central shaft discharge air into the central zone. The air in the central zone is warmed up and rises due to stack effect to be extracted at the top of the shaft. In winter, the central shaft can be closed and the box windows can be used to bring warm air inside the rooms. While, in summer, the stack effect of the central shaft can form good ventilation for the spaces. Fans can be added to force air

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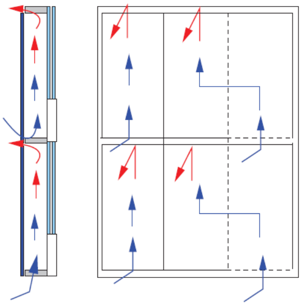
[1] Op. Cit., Yellamraju, V.

[2] Daneshkadeh, S., 2013, The Impact of Double Skin Facades on Thermal Performance of Buildings.

			convection in the central cavity.[1]
Box-Window Type	 *Figure 1-10 Box-Window Type DSF Schematic Drawing*	In the box type, the façade is divided horizontally and vertically with full transparent envelopes. On the other hand, the façade is divided horizontally and vertically to windows and the windows in this case are double glazed in window type.[2] The air inlets and outlets (also called fish mouth) are placed at each level.	Here, Some researches described a variant of this type where air inlets and outlets are located in cross form to produce diagonal air streaming. This arrangement helps avoiding the movement if air from a zone to the other and it also prevents fire spreading.

Alahmed, Z., (2013), tested three types of DSF cavities in Riyadh, KSA and compared them to a base case and a base case with shading devices using IES software.

1. Baseline Case
2. Baseline Case with shading
3. Different scenarios for DSF

Figure 1-11- Different Models (Alahmed, Z., 2013, Double-Skin Façade in Hot-Arid Climates Computer Simulations to Find Optimized Energy and Thermal Performance of Double Skin Facades)

Different parameters were studied like DSF orientation, cavity width and cavity shape in his study. The researcher concluded in his research that the wider the cavity, the

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[1] Faggembauu, D., 2006, Heat Transfer and Fluid-Dynamics in Double and Single Skin Facades.

[2] Yellamraju, V., 2004, Evaluation And Design Of Double-Skin Facades For Office Buildings In Hot Climates

lower energy the building will consume. Also, he concluded that at the western façade which had the best results, multistory type succeeded to reduce the energy by 5.02% compared to the base model and 4.05% when compared to the base model with shading devices. The corridor type façade results were 7.71% and 4.43% energy reduction when compared to the base model and the base model with shading devices respectively. While, the box window type showed 8.05% and 4.78% energy savings when compared to the base model without and with shading, respectively.

Rezazadeh, N., et al, 2017 investigated the total comfort hours of the different types of naturally ventilated walls in an office building located in Rasht, Iran where the weather is hot and dry in summer.

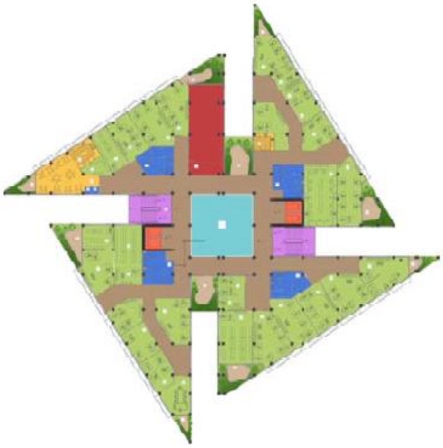

Figure 1-12- Building Plan Designed for Simulation by Rezazadeh, N., et al (Thermal Behavior of Double Skin Facade in Terms of Energy Consumption in the Climate of North of Iran-Rasht)

The different models were modelled and tested on ECOTECT and the results were shown as the total comfort hours in each case

The results showed that the shaft type had the highest total hours of comfort with a 75 cm wide cavity which were 677 Hrs. Box window type had slightly higher total hours of comfort than the corridor type but both with a 100 cm cavity width showed a high value of 643 total hours of comfort. Multistorey façade results were 640 total hours of comfort placing fourth.

To conclude, double skin facades variety in types indicates its numerous features and shows the possibilities to design a lot of unique environmental solutions through DSFs relying on their specific purpose and microclimate. Tables (1-2 and 1-3) conclude different types of double skin facades.

Table 1-2 Classification of DSF Systems by (Gelesz & Reith 2011)

Ventilation mode		Mechanically ventilated	Non-ventilated buffer systems	Partly or fully naturally ventilated
Operation mode/ Construction type		Indoor air curtain air exhaust	Buffer zone	Outdoor air curtain Air supply Air exhaust (buffer zone)
Window type systems		Exhaust-air window	Compound window	Box-type window
Double skin facades	Vertically & horizontally partitioned	Exhaust-air facade	Buffer facade	Box-type window
	Horizontally partitioned	Multi-storey exhaust-air facade		Corridor façade
	Multi-storey			Multi-storey façade
	Mixed partitioning mode		-	Shaft-box type facade

Table 1-3 Summary of Main Structure of DSFs by (Haase, 2007)

Main Type	Box window facade	Corridor facade	Shaft-box window facade		Multi-storey facade
Cavity ventilation	Natural ventilation		Mechanical ventilation		Hybrid ventilation
Airflow concept	Supply air	Exhaust air	Static air buffer	External air curtain	Internal air curtain

1.3 Naturally Ventilated Walls

An advantage of the double skin façade is that it allows natural ventilation if it was well designed because of the outer skin that protects from wind in case of high wind and allows operable windows in the inner skin to naturally ventilate the interior spaces. This can lead to reducing energy consumption. This also leads to reduction in CO2 emission in the operation phase.

Different types of double skin facades should be applied according to the climate, orientation, location of the building, and its type so that it can help providing fresh air.[1] There are some factors that controls achieving natural ventilation through double skin facades including difference in temperature that causes air changes, pressure differences which causes air flow, and stack effect. In hot weathers, these forces are not always enough for achieving natural ventilation.[2]

1.3.1 Natural ventilation performance of double skin facades

In this part, items that affect natural ventilation performance of double skin facades including wind, opening sizes and width of cavity will be discussed.

a) Wind
Wind is considered the most dominant component of the force that drives natural ventilation, especially in hot seasons. In areas of high and low pressure, wind can be generated by thermal buoyancy so it can balance the difference in pressure.

b) Opening sizes of air intakes and extracts
The removal of heat from interior spaces and from the cavity is considered a major criteria while designing the air intakes and extracts especially on hot days. If possible, it is recommended to keep the interior spaces temperature lower than the exterior temperature. The cavity temperature is not recommended to be above this level. Studies show that air intakes and extracts' area should not be less than 1 m2.

c) Width of façade cavity
Choice of cavity width affects natural ventilation as will be discussed in chapter two.

1.3.2 Naturally Ventilated Walls Working Principle

Natural ventilation performance of double-skin facades is the main attraction of this

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[1] Danik, S., 2014, Natural Ventilation through DSF in Tall Buildings.
[2] Daneshkadeh, S., 2013, The Impact of Double Skin Facades on Thermal Performance of Buildings

literature survey; hence, the basics of this subject, particularly aerophysics, and items contributing to it are provided in this chapter.

1.3.2.1 Aerophysics

The term aerophysics involves all questions that relate to the flow of air toward, around and within the buildings. This term covers different aspects including thermodynamics and aerodynamics. To understand this term, its principles and requirements will be explained in this part.[1]

Aerophysics Principles:

The main points of interest in this section are ventilation of the cavity and airstreams. Airstream as mentioned by Oesterle, et al. (2001) is the movement of air currents caused by pressure differences. That's where air flows from spaces with high pressure to spaces with low pressure when the two spaces are linked.

Airstreams in buildings context are caused by three main sources which are pressure differences caused by mechanical operations, thermal buoyancy or action of wind. Among the three main sources, pressure difference due to thermal buoyancy is considered a base for the working principle of naturally ventilated walls. When cooler and heavier exterior air forces pressure at the bottom, it takes its way into the cavity where the air is lighter and warmer because of insolation. This warmer air rises and causes excess pressure at the top where the air is extracted. The pressure difference between bottom and top of the cavity creates the phenomenon called thermal buoyancy. Also, the difference between indoor spaces and external temperatures is the main force for ventilation. Yet, excessive heat gains should be avoided. When determining maximum excess temperature, the temperatures measured at head level and at about half the height of windows within an accessible cavity or above the height of the air intakes in the inner skin are more important compared to exhaust air temperature.[2]

Aerophysics Basic Requirements

In the case of double skin facades, aerophysical requirements mainly depend on the strength of the air flow. Oesterle et al., (2001), mention that strength of the air flow is mainly described in terms of speed of the airstream and the volume of air that is needed for ventilation. They explain that there are certain boundary values and parameters that could provide adequate natural ventilation of indoor spaces and they mentioned that one of these parameters is the requirement of a high air-change rate when the inner façade is open. This should be possible where natural ventilation is wanted to function as the main ventilation for a large period of time in the year. (Air

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[1] Ibid
[2] Ibid

change rate is the ratio between the volume of air supplied per hour and the volume of the relevant space).[1]

Wind Characteristics

Wind has a major effect on air currents around and in buildings. That is because buildings form an obstacle to the airstream. Airstreams reaching buildings' façade are dammed up in front of the building and so it creates a state of excess pressure. Also, due to the airstreams moving around the building, significant pressure differences are expected at the corners.

Wind loads on buildings play a very important role and there are mainly two types of wind loads which are stationary loads that act on the entire buildings and instationary loads that result from gusts. Gusts are increment of wind speed that is limited in time and place. They also occur with slight changes of wind direction.[2]

Building Envelope

EREC and NREL, (2000) claim that energy efficient buildings' elements are composed of walls, windows, insulation, roofs, caulking and air/vapor retarders. They also imply that thermal envelopes of buildings are thought to protect indoor spaces from the outside.

In energy efficient buildings, the R-value of their elements are supposed to be too high. (R-value is described as materials' ability to resist heat transformation). For example, low R-value leads to more heat transfer. Figure (1-13) shows the recommended R-values and U-values for buildings' envelopes for climate zones 2 and 3.[3]

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[1] Ibid

[2] Ibid

[3] Danseskhadeh, S., 2013, the Impact of Double Skin Facades on Thermal Performance of Buildings.

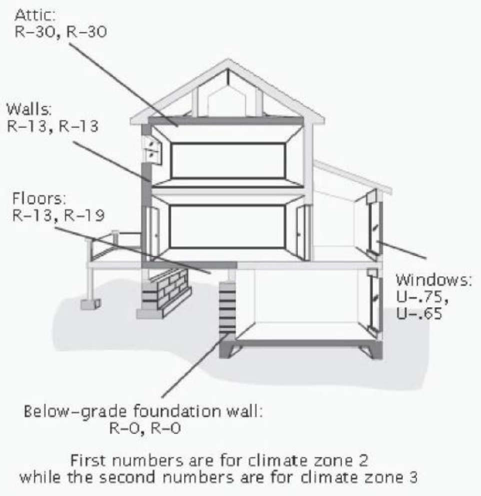

Figure 1-13 Recommended R-values for building envelope's elements (Heinberg, 2007)

<u>Solar Heat Gain and Loss</u>

Performance of naturally ventilated walls in hot and cold times will be described in this section.

In winter, using qualified insulation can increase exterior heat transfer resistance. This qualified insulation is provided by using the external supplemental skin. Moreover, in spite of the low U-value of constantly ventilated DSF in thermal transmission equivalent compared to single skin façade, its performance can be improved when there is no opening in the cavity during heating process, partly or totally. In addition to that, heat loss rate is reduced as a result of heat transfer reduction through raised temperature and lower airflow speed in the cavity.[1]

In summer, building envelope receives the emitted energy which reaches the building. The re-scattered waves of infrared energy cannot exit the cavity through glass. This causes air to be trapped in the cavity and its temperature will increase through convection. Also the transfer of heated air inside the cavity occurs by conduction through glazing.
Applying naturally ventilated walls into the buildings results in decreasing heat transfer amount from the exterior to the interior and thus the amount of energy that is needed for cooling purposes.

1.3.2.2 Forms of Heat Transfer through a Double Skin Facade

There are two forms of heat transfer through double skin facades which are direct radiation through glass and conductive and convective transfer due to temperature

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[1] Ibid

differences.

Direct radiation through glass is described by the solar heat gain coefficient (SHGC). The SHGC is the fraction of solar radiation admitted through a window both absorbed and directly transmitted. The solar radiation are subsequently released inward. SHGC helps determining the solar radiant heat gain of glazing. When describing windows' energy performance, SHGC value should be included along with U-value and other properties.[1] The other form of heat transfer happens due to difference in temperature from inside to outside.[2] Figure 1-14 show heat transfer and air movement in double skin facades.

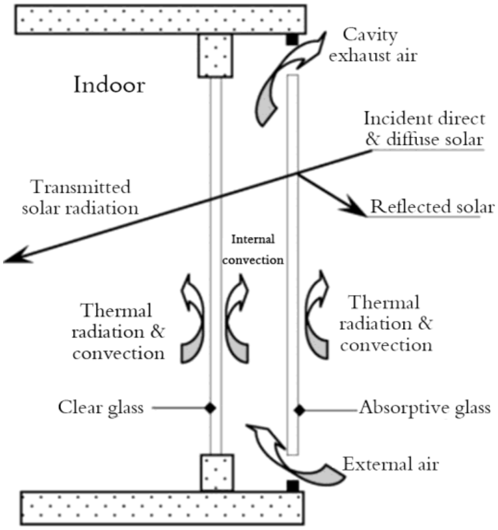

Figure 1-14- Heat Transfer and Air Movement in Double Skin Facades (Mostafa M., et al., 2016)

1.3.2.3 Quality of Indoor Space

In order to reach good interaction between living spaces and the exterior environments, buildings should be able to perform well in fluctuating temperatures, humidity levels and air pressures. The quality of the living environment can be achieved by keeping certain factors in pleasant levels. These factors include moisture levels, air quality, temperature, structural integrity and air movement.[3]

In conclusion, there are two main factors that affect double skin facades performance which are thermodynamics and aerodynamics. Mainly, temperature difference between the outside and the inside is considered the driving force of the working

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[1] Yellamraju, V., 2004, Evaluation And Design Of Double-Skin Facades For Office Buildings In Hot Climates

[2] Ibid

[3] Danseskhadeh, S., 2013, The Impact of Double Skin Facades on Thermal Performance of Buildings.

mechanism of naturally ventilated double skin façade in hot climate. When cavity's air temperature rises due to solar radiations, the hot air rises because of the stack effect while air streams move through the façade either naturally or mechanically. This keeps the cavity's air temperature lower and thus the indoor spaces temperature reaches the comfort level. However, low airflow can cause excessive increase in temperature inside the cavity and therefore the cavity is overheated and the hot air starts moving by convection to the indoor spaces causing the rise of temperature inside them and thus discomfort. To overcome this problem, shading devices are integrated inside the cavity to absorb and reflect some direct radiations. And thus, the choice of the type of double skin façade, and its elements and their characteristics carefully in the early design stage is considered a key factor for the system's performance success.

1.3.3 Naturally Ventilated Walls in Hot Arid Climates

In hot regions, the main challenge that faces buildings is ensuring indoor thermal comfort for their occupants. Some regions' weather is constantly hot, and this can be easier in dealing with their buildings' envelopes regarding sustainable design. Other regions have partially hot weather (Moderate/Mediterranean) where the weather in summer is hot while moderate-cool-cold in winter. This variation in weather requires dynamic building envelopes that are capable of achieving thermal comfort regardless of the weather conditions. As large glass facades were introduced to the Middle East in the seventies of the twentieth century, a lot of solutions had to show up to protect the interior spaces from high solar gain. A promising solution that appeared to solve the problem is the double skin façade.[1]

In hot weather, high irradiance levels and high ambient temperatures could seriously affect DSF's thermal efficiency. That's because a large amount of direct solar gains can penetrate through the outer façade and heat up cavity's components and some will reach the interior spaces depending on the incident angle, irradiance levels, and the properties of glass. Many authors mention that DSFs show acceptable thermal performance if designed properly even in extreme hot climates. The proper design includes providing sufficient ventilation for the cavity and adding shading devices to block an amount of the direct solar gain. When using natural ventilation to provide thermal comfort to the interior spaces, architects and designers have to give more attention to air direction and velocity to successfully apply the technique.[2]

In summer, the hot air inside the cavity can be trapped out when the cavity is ventilated. When the absorbed radiations are reemitted into the cavity, a natural stack

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[1] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan.

[2] Ibid

effect occurs forcing the air to rise and take additional heat with it. Several factors should be considered in the design phase to ensure proper ventilation including a careful combination of the types of the skins, and the types of the shading devices to avoid overheating and the geometry of the cavity especially in case of naturally ventilated walls. Another important parameter to consider is the positioning of shading devices. Researches claim that shading devices should be positioned in the outer half of the cavity.

Stec et al (2000) mentioned that half of the inner façade has to be insulated to achieve thermal comfort with natural ventilation, otherwise the application of mechanical cooling will be a must.

During hot summer days, the interior spaces can be easily overheated. And to overcome this problem night time ventilation can be used as a technique where allowing natural airflow to enter the indoor spaces at night. This will lead to pre-cooling the spaces during night and the indoor temperature will be lower in this case during the early morning hours leading to improved air quality and providing thermal comfort for the occupants. The low temperature in this case occurs because the cool night air affects the heat storage if the materials (walls, floors, ceilings, furniture, etc.). On the other hand, if the doors and windows are closed at night and the indoor spaces were ventilated using mechanical ventilation systems, the heat will be trapped inside and will lead to discomfort in the early morning.

An aspect to study before providing night cooling by natural cross ventilation is the openings areas which are required to be large in the outer façade to ensure a good result. Stec et al, claim that the area of the outer façade opening can be 2% of the floor area.[1]

Common Issues Associated with Naturally Ventilated Walls in Hot Arid Climates:

The use of large glazed areas in facades in modern architecture led to certain issues regarding cooling demands for buildings especially in hot climates. DSFs as a suggested solution are expected to face major problems in hot climates which are excessive direct solar gains, and indoor overheating. So, DSFs' performance is threatened when executed in such climates.

a) Excessive Direct Solar Gains:

Using large glass areas in facades that are built in hot climates would increase total transmitted solar gains (g-value). Both glass properties (transmittance, conductance and reflectance) and ambient conditions including solar irradiance and incident angles

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[1] Ibid

highly affect the transmitted rates. Optical properties of glass depend mainly on the angle of incidence. The increase in the angle of incidence, decreases solar transmissivity. Solar irradiance, on the other hand, which consists of the beam and diffuse components depends on the site's coordinates, season, and time. Direct beam solar gains which are shortwave irradiance are thought to be the main contributor to g-value in highly glazed buildings. This component can dramatically increase the temperature of the indoor spaces in hot weather conditions. So, direct beam solar gains show a main obstacle when designing double skin facades in extreme hot conditions. And the decrease in cavity's width will increase the opportunity of this component to reach the indoor spaces.[1]

b) Indoor Overheating:

Internal heat gains which include human body, electric lights, and equipment radiations show a very important threat to the application of double skin facades in hot climates. Internal heat gains will cause overheating problem in the indoor spaces. Overheating as a term, expresses uncomfortable thermal conditions inside spaces. It noticeably reflects on the occupants of the building causing discomfort to them. Practically, when the building's temperature exceeds the benchmark temperature it is said that the building becomes "overheated", and if this occurs for more than a certain designated time it is said that the building suffers from "overheating". In residential spaces, the peak points of temperature were determined to be 26°C and 28°C while the designated period of time was determined to be 1% of the annual occupied time. (CIBSE, 2006). These set points are likely to be different based on the space use. While thermal comfort is defined as "the condition of mind which expresses satisfaction with the thermal environment" (BSI, 2005), no comprehensive definition was put to define overheating phenomenon. Yet, it could be characterized comparing to the maximum determined temperature for the indoor spaces which assure the occupants' satisfaction. Overheating is mainly caused by high levels of heat gains in addition to insufficient ventilation and high ambient temperature. When solar gains penetrate through glazing, the interior elements (i.e. floor, ceiling, furniture, etc.) partially absorb them and then reradiate them as heat to the surroundings. And in case of DSFs where the air inside the cavity works as insulator, the heat is trapped in the cavity causing overheating inside the cavity which is conducted to the indoor spaces through the inner layer, infiltration means and ventilation openings. So, good ventilation inside the cavity is required to help removing the heated air and refreshing the heated cavity. For this reason, and especially in hot regions, microclimate conditions over the year and DSF components should be investigated in the early stage of design to avoid overheating threats. In addition, many passive and active

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[1] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan.

techniques can be integrated to the DSF to overcome this issue. The passive cooling techniques that can be integrated include ventilating the cavity and indoor spaces, applying shading devices and manipulating glass characteristics which will be mentioned in the coming sections.[1]

To conclude, naturally ventilated walls can work efficiently at any time of the year if it was well designed. In summer, natural ventilation occurs due to the stack effect where air is extracted outside the cavity taking heat with it. Yet, overheating solutions should be addressed in the design phase. In winter, DSF would be used in heating efficiently if the façade was designed to have a thin cavity and if the cavity was partially or fully closed.

1.4 Integrating Shading Devices with Naturally Ventilated Walls

A lot of studies of shading devices inside DSFs cavities showed that shading devices affect thermal comfort for the occupants by reducing the amount of direct solar gain reaching the indoor spaces. Thus, shading devices highly affect energy performance of buildings where double skin facades are applied, especially in hot climates, where overheating can occur inside the cavity because of the high solar radiations transmission through the DSF glazing which leads to high air temperature inside the cavity.[2]

Shading devices positions, size and angle are the main parameters that affect cooling energy saving. Although shading devices are installed to control direct solar gains and thus reduce energy consumption, placing them inside the cavity may affect the air flow speed and pattern which needs to be studied in the early design stage for the shading devices placement and angles.

Oesterle, et al, 2001 investigated the integration of shading devices inside the air cavity and stated that the exterior skin can reduce a minimum of 10% of solar irradiance while the integrated shading devices could reduce around 50% to 60% of solar irradiance when compared to interior blinds. Therefore, the optimal integration of shading devices with DSFs can show up as a solution that overcomes disadvantages of DSF concepts in hot climates.[3]

While shading elements act as heat collector, the part of heat they absorb stays inside the cavity and therefore it enhances the cavity’s buoyant flow. And with sufficient natural ventilation, the performance of DSF systems in hot climates will be enhanced.

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[1] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan.

[2] Lee, J., et al, 2015, A Study of Shading Device Configuration on the Natural Ventilation Efficiency and Energy

[3] Ibid.

In this case, the quality of natural ventilation is a key factor that decides whether the system will succeed or not.[1]

The following sections will study the characteristics of the integrated shading devices and how they influence DSF performance.

1.4.1 Integrated Shading Devices Working Principle:

Integrating shading devices with double skin facades would divide their cavities into two asymmetrical thermos-flow sections. That is because of significant variations in solar radiation absorption by DSF's different components like shading devices' surfaces, outer skin and inner skin. This can lead to variations in the influence of shading devices regarding indoor thermal comfort through secondary heat transmissions.[2]

1.4.1.1 Influence of Cavity-Integrated Shading Devices on Thermal Performance of DSF and Indoor Spaces

Generally, there are some factors affecting heat transfer by convection which include temperature difference between the surface and air, velocity of air (in case of mechanical ventilation) and the height of the surface. As shading elements existence inside the cavity could influence its air flow rates, convection heat transfer associated with these elements would be affected. This affects convection by both the shading elements and glass layers. Yet, a lot of parameters affects this influence like shading devices' size, characteristics and position.

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[1] Ibid.
[2] Ibid.

Heat transfer by radiation depends mainly on the temperature difference between surfaces. Radiative heat exchange also depends on the size, shape and tilt angles of surfaces. This applies to shading elements where surface characteristics would have a significant role.

In extremely hot climates, temperature of the inner skin could be increased and secondary heat transmissions become highly critical to cooling loads despite integrated shading devices ability to block direct solar gain. Yet, with a ventilated cavity in hot arid climates, simple shading technique by dividing plates and placing them at floor levels inside the cavity (figure 1-15) could reduce cavity temperature by 7-12°C below ambient temperatures and thus indoor cooling loads will be significantly reduced.[1]

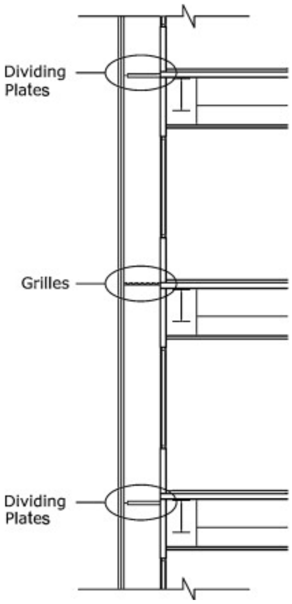

Figure 1-15 DSF with Dividing Plates and Grilles. (Hashemi, et al., 2010)

Experimental and theoretical works show that temperatures of both cavity and indoor spaces depend on shading devices' tilt angle and cavity's airflow rates. Those two factors could prevent summer overheating and enhance occupants' thermal comfort.
Studies also show that integrating solar shading devices with double skin facades could reduce energy consumption by 15% and 30% in summer and in winter, respectively.[2]

Researchers have developed a new multifunctional external shading device where solar collectors are integrated into it. In this system the heat absorbed by the surface of solar shading is transferred to the integrated solar collector where more thermal energy is captured.

This concept can be used with cavity-integrated shading devices where more thermal energy will be collected and then extracted from the cavity. This combination would help minimizing possibilities of overheating phenomenon in hot climates and thus reducing thermal loads. Moreover, the collected thermal energy could be stored to be used after that for different purposes like solar water heating.[3]

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[1] Ibid

[2] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan.

[3] Ibid.

1.4.1.2 *Influence of Cavity-Integrated Shading Devices on Airflow of Ventilated DSFs*

In hot climates, DSFs' cavities overheating is considered the most important problem. The cavities' temperature could be considerably increased if they were provided by insufficient airflow to extract the trapped heat. In this case, mechanical ventilation could overcome this issue but the total energy consumption would be increased. That's why natural ventilation is always preferred.

In naturally ventilated DSFs, air flow inside cavities is determined by buoyancy, wind or by both. Buoyant airflow is driven when there's difference between air density inside and outside the cavity. This difference happens due to temperature difference. Complexity in airflow in naturally ventilated DSFs is usually experienced near the cavity's inlet, outlet and horizontal dividers. Moreover, changes in flow fields occur between shading devices and the adjacent layers (skins). The level of change relies on the cavity width and the complexity of elements. However, factors like size, position, installation and design of shading devices could successfully enhance the façade's natural ventilation and avoid overheating.

Safer, N., et al, investigated integrating venetian blinds inside the cavity. The results showed that the cavity was divided into two vertical sub-cavities and that the distance between the shading elements and the skins had an impact on air velocity. Moreover, tilt angle of the venetian blinds affected the airflow field. This effect was significant when the blinds were positioned in the center and became less significant when placed in away from the external skin. This leads to a conclusion that enlarging external lateral distance could enhance airflow and lead to extracting more trapped heat. However, placing the blinds near the inner skin could increase radiative heat exchange with the indoor spaces. That's why attention should be paid to ensure a good result between the two effects of heat transfer and airflow.

Baldinelli, (2008), mentioned that placing moveable shading elements near the outer skin of cavity showed better results regarding overheating and avoiding airflow complexity.[1]

Comprehensive modelling of the system is necessary to understand the effect of cavity-integrated shading elements on airflow and thermal performance.

1.5 **Summary and Conclusion**

This chapter discussed three main sections. The first section discussed double skin facades definition, components and different types and configurations. The choice of naturally ventilated walls in this study is based on the literature review and different

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[1] Ibid

applications which concluded that the mechanism of double skin facades does not only rely on wind.

Moreover, the studies in the second section on how naturally ventilated walls work and their performance in hot arid climates showed that even if the wind is not sufficient, naturally ventilated walls could work efficiently by thermal buoyancy. From the different configurations of cavity shape, shaft type has shown highest hours of comfort when applied in hot arid climates. Table 1-1 show summary of literature review about the performance of different types of naturally ventilated walls in hot arid climates.

Table 1-4 Summary of Literature Review about Naturally Ventilated Walls Types in Hot Arid Climates

Study Topic	Author	Results
Comparison between base case (curtain wall), base case with shading devices and naturally ventilated DSF in hot arid climate of Riyadh.	Alahmed, Z., (2013)	The corridor type façade results were 7.71% and 4.43% energy reduction when compared to the base model and the base model with shading devices respectively. While, the ***box window type*** showed 8.05% and 4.78% energy savings when compared to the base model without and with shading, respectively.
Comparison between base case (curtain wall), shaft type, box window type DSF, corridor type and multistorey types in Iran.	Rezazadeh, N., et al, 2017	The results showed that the ***shaft type*** had the highest total hours of comfort with a 75 cm wide cavity which were 677 Hrs. Box window type had slightly higher total hours of comfort than the corridor type but both with a 100 cm cavity width showed a high value of 643 total hours of comfort. Multistorey façade results were 640 total hours of comfort placing fourth.

Third section of this chapter explained shading devices as a DSF component to reduce direct solar gain in hot arid climates. The working principle of shading devices' integration with naturally ventilated walls and their effects on DSFs working mechanism were discussed to understand the integration and the role of shading devices in the cavity of naturally ventilated walls.

▪ Chapter 2

Design Parameters of Naturally Ventilated Walls and Integrated Shading Devices

- Introduction
- Design Parameters of Naturally Ventilated Walls
- Design Parameters of Shading Devices
- Conclusion

Chapter 2 - Design Parameters of Naturally Ventilated Walls and Integrated Shading Devices

2.1 Introduction

This chapter discusses factors affecting natural ventilation of DSFs, and different design parameters of naturally ventilated walls and shading devices which affect thermal performance of the façade. Knowledge of the parameters and their effects to help in design choices and saves simulations time. Choosing the parameters values for the study that will be conducted in the next chapters.

2.2 Design Parameters of Naturally Ventilated Walls

In order to design an effective DSF which has positive impact on heating and cooling loads, the adjustment of the cavity ventilation should be considered. This will allow increased airflow in cooling seasons and less airflow in heating seasons.[1]

2.2.1 Factors Affecting Natural Ventilation of Naturally Ventilated Walls

There are some factors that affect natural ventilation performance of naturally ventilated walls and should be considered while designing DSFs. These factors include temperature, air flow, humidity and activity level. These factors affect each other and interrelate in the case of ventilation.[2]

Temperature:

Temperature is considered the most important factor that affects occupants' comfort. Those values can be taken as guidelines, though other environmental and personal factors should be considered because they highly affect thermal conditions.[3]

Bradshaw, 2006, determined a guideline for room air temperatures where hotel rooms' air temperature should range between 23-26 Celsius degrees at summer and 20-22 at winter.

Temperature here means dry bulb temperature. Yet, there are some other determinants of the occupants' thermal comfort including operative temperature, humidity, and air flow.[4]

Humidity:

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[1] Kimble, E., 2014, A study of Double Skin Facades
[2] Danik, S., 2014, Natural Ventilation Through Double-Skin Facades in Tall Buildings
[3] Ibid
[4] Ibid

Humidity in a given space is the moisture content of the air in this space. To evaluate humidity level a value called relative humidity (RH) is used. Relative humidity is the ratio of the partial pressure of water vapor in the air to the saturation pressure of the water vapor at the same dry-bulb temperature and the same total pressure. Occupants can bear a wider range of humidity than temperature. So, occupants' thermal comfort is slightly affected by humidity. Bradshaw (2006) proposes that RH should range between 20% and 60% in summer and between 20% and 50% in winter. Although human tolerance to humidity is high, humidity level should still be kept under control because high humidity delays body heat loss by evaporation and low humidity could cause health problems.[1]

Air Flow:

Air flow is a fundamental factor that affects body heat loss by evaporation and convection, and removal of air contaminants. No minimum air flow rate is needed if the temperature of the environment is within the acceptable limits. If the temperature exceeds the limits, removal of excess heat is a must. Removal of excess heat could be done when airflow with velocity as high as 0.8 m/s exists. Although there's no lower limit for air flow rate, velocities lower than 0.05 m/s may cause air stratification and stagnation. It should be kept in mind that air speed that satisfies occupant comfort depends also on other factors including humidity, MRT, and temperature.[2]

Activity Level:

Metabolic rate, according to ASHRAE (Standard 55, 2004), is defined as "the rate of transformation of chemical energy into heat and mechanical work by metabolic activities within an orgasm, usually expressed in terms of unit area of the total body surface". The unit of metabolic rate is "met" and met is "the amount of heat produced per unit surface area of an average sedentary person and any metabolic rate can be derived from this basic unit." (ASHRAE, 2004). Metabolic rate differs according to age, body weight, gender, environmental conditions, and activity level. Activity levels should be determined during certain physical activities in order to designate comfort conditions. That's because the amount of heat produced by human body depends on the level of exercise.[3]

Bradshaw, 2006, mentioned the metabolic rate at sleeping as 0.7 met and at resting/reading as 0.9 met.

ASHRAE Standards:

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[1] Ibid
[2] Ibid
[3] Ibid

Although, the requirements mentioned in the previous parts were based on ASHRAE and are often referenced in building codes, it is essential to cover ASHRAE's Standard 55 (Thermal Environmental Conditions for Human Occupancy) and Standard 62.1 (Ventilation for Acceptable Indoor Air Quality) under a separate heading. The comfort conditions proposed by the standards are acceptable to at least 80% of the occupants within an experimental space.

Temperature limits in ASHRAE standards:

When the combinations of air temperatures and MRTs provide thermally acceptable environmental conditions together with factors like air flow, clothing insulation, humidity and activity level, a comfort zone is determined. ASHRAE standard demonstrates two methods to designate a range of temperatures for the comfort zone. The first is a simplified graphical method and the second is based on a heat balance model in a form of computer program that is used for a wider range of applications than the first method. The graphical method is appropriate when determining temperature limits for spaces with activity levels between 1.0 and 1.3 met, air velocity is below 0.20 m/s and clothing insulation is between 0.5 and 1.0 clo. Figure (2-1) illustrates the comfort zone that satisfies the mentioned criteria. From figure 2-1, two zones are established for clothing insulation of 0.5 and 1.0 clo for warm and cool environments, respectively. For other clothing insulation values, a range of temperatures can be calculated by linear interpolation.

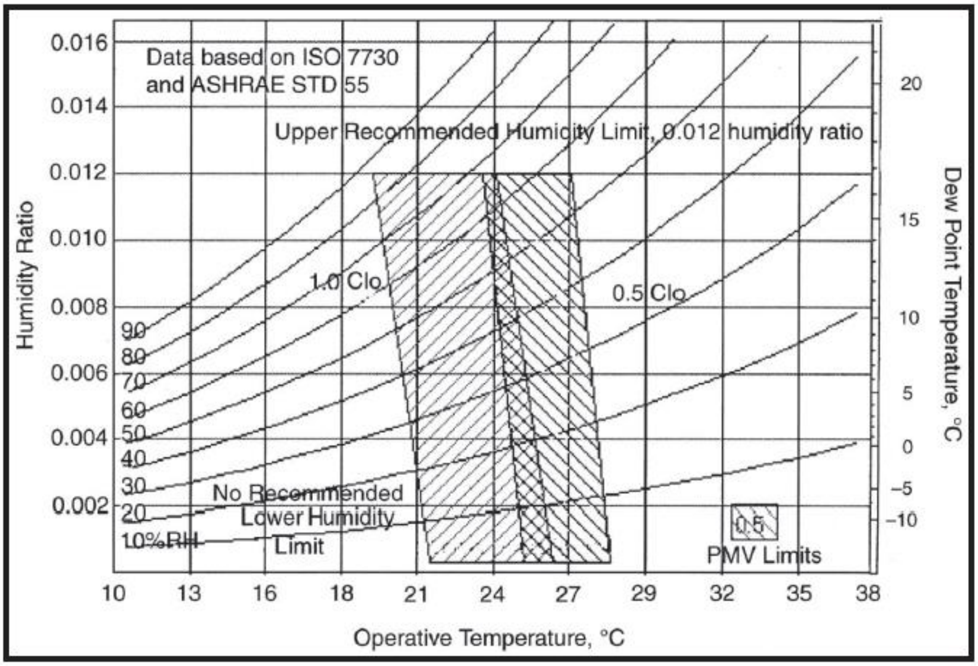

Figure 2-1 Acceptable Range of Operative Temperature and Humidity for Spaces Satisfying above Criteria (ASHRAE, Standard 55, 2004)

If we use the clo value ranges mentioned by Bradshaw (2006), we can conclude that operative temperatures will range between 22.5 and 26°C in summer and between 20 and 23.5°C in winter. These values are based on RH 60% and activity level of 1.2 met. And the temperature will lower down by 0.6°C with each 0.1 clo increment of clothing insulation.[1]

Humidity:

ASHRAE (Standard 55, 2004) suggests that in order to achieve thermal comfort RH should not exceed 70%. On the other hand, no minimum RH limit is proposed because of the fact that there is no specified lower limit for humidity to achieve thermal comfort. Yet, factors that are not related to thermal comfort like eyes and throat dryness and nasal passages can put an unwritten limit for low humidity values in environments.[2]

Air Flow:

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[1] Danik, S., 2014, Natural Ventilation Through Double-Skin Facades in Tall Buildings

[2] Ibid

ASHRAE mentions 0.20 m/s as an upper air flow rate limit to achieve thermal comfort while the standard didn't mention lower limits for air flow speed. When temperature is above the upper limit, air velocity can be elevated to achieve thermal comfort. In this case air flow can be controlled by the occupants and this process is called "elevated air speed". This process can be used to increase the air temperature and MRT limits by up to 3°C in an environment with activity level between 1.0 and 1.3 met and clothing insulation between 0.5 and 0.7 clo. It should be noted that air speed should not exceed 0.8 m/s and that the increment steps should not exceed 0.15 m/s.

Another important factor related to air flow is the indoor air quality (IAQ). According to ASHRAE Standard 62.1, IAQ can be achieved when there are no known air contaminants at concentrations that can be harmful to the occupants and when the majority of the occupants that are exposed to the indoor air (80% or more) don't feel dissatisfied with its quality.

An important indoor air contaminant that should be kept under control is the carbon dioxide (CO2) concentration. ASHRAE Standard 62.1 mentions that the outdoor air's CO2 concentration ranges between 300 and 500 ppm, and the concentration of CO2 in an indoor space where sedentary activities take place reaches 600 and 700 ppm above the outdoor level.

2.2.2 Design Parameters of Naturally Ventilated Walls

The naturally ventilated walls as mentioned before has components including the outer and inner skin, air cavity, and shading systems. Each component has its own characteristics that affects the working principle and thermal comfort of the façade if its design parameters changes. Figure 2-2 shows double skin facades' parameters.

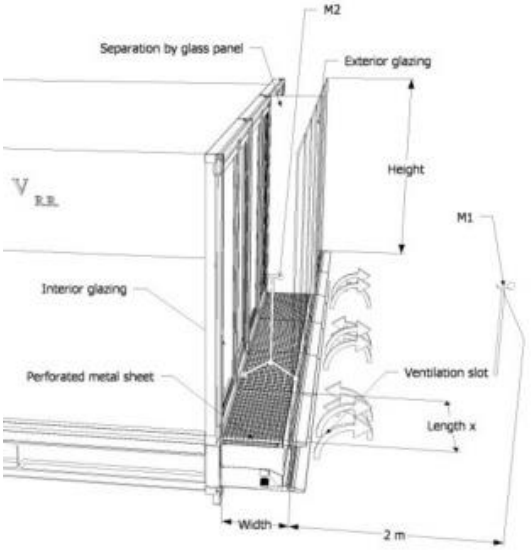

Figure 2-2- Naturally Ventilated Walls Parameters (Urban D., et al, Assessment of Sound Insulation of Naturally Ventilated Double Skin Facades (2016)

2.2.2.1 Cavity:

Air exchange between the outside and the cavity depends on the stack effect, wind pressure conditions on the building's skin and the discharge coefficient of the openings. These openings can either be left open all the time (passive techniques) or opened by hand or by machine (active techniques). Although active systems seems to be handy, they are more complicated and expensive in terms of construction and maintenance. Faist (1998), compared between air tight facades and ventilated facades and concluded that:

In air tight facades:

- Width of the cavity doesn’t critically affect the temperature of air inside it.
- Windows are usually closed. Opening them does not guarantee good ventilation for the indoor spaces.
- The cavity is open at the bottom and can be closed at the top by a valve.
- The cavity height is limited to 4 levels because of the temperature rise of the air inside the cavity.

In a ventilated façade:

- Width of the cavity should be precisely determined because it affects the performance of the system.
- To ventilate the rooms, appropriate valves are opened in every floor.
- The canal is closed at the bottom and extends above the last floor level.
- Depending on the cavity size, a maximum height is allowed. An upper limit is given by the allowed air temperature rise in the cavity which is 10 to 15 storeys.

The function and the airflow inside the cavity relate with constructional parameters. When the cavity is relatively shallow (40 cm) significant pressure losses occur. On the other hand, when the cavity is relatively deep, the intermediate space offers no major resistance to the air flow.[1]

Height of the Cavity:

Studies show that the increase of the height of the cavity enhances the performance of the double skin façade. That’s because the increase of the height will enhance thermal buoyancy and then increase the velocity of the air. This leads to reduction of the heat gain of the cavity, and then reduces heat conduction through the internal glass. The height of the double skin facade could be extended after the top floor and work as a chimney to facilitate a stronger stack effect. Though it is mostly dependent on the number of storeys of the building. Studies show that adding the chimney will enhance natural ventilation even if there were no sufficient wind. The reason is that the higher the cavity the more pressure difference it will make between the top of the

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[1] Ibid

cavity and the bottom of it and this difference will enhance the stack effect of the chimney and thus its ventilation.

Khazkar, G., studied the effect of applying double skin facades to the Health Center Building, EMU, in Gazimagusa, Cyprus and compared it to the results of the original building in his thesis.

<u>Study Method:</u>

To compare between the building performance before and after applying double skin façade, TAS software is used. The software is used for thermal analysis using humidity, wind direction, temperature, radiation and wind speed values. At first the building was modeled as it exists and simulations were done. The second simulations included a 50 cm gap double skin façade and in the third simulation a 100 cm chimney was added to the double skin façade.[1]

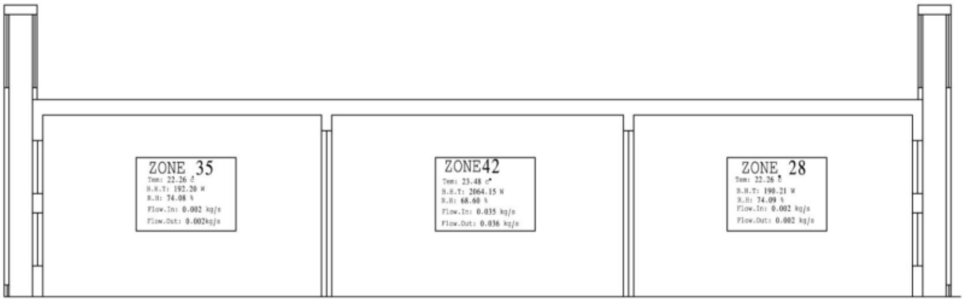

Figure 2-3- Section Showing Chimney Added to DSF (Khakazar, G., 2014, Evaluation of Facade Performance, in Terms of Thermal Comfort for Health Center Building, EMU)

<u>Study Results:</u>

The temperature results in models 1, 2 and 3 were 35, 38 and 30 Celsius degrees respectively. The reason behind this result was the increase in temperature inside the cavity in the second model, while the third simulation showed 5 degrees drop in temperature after adding the open chimney which forced an airflow that cooled down the gap and thus the interior space. Relative Humidity results were 49%, 46% and 57% for model 1, 2 and 3 respectively.[2]

To conclude, previous research and studies show that double skin facades should perform better if it was two storeys high at least, and the addition of a 100 – 150 cm

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[1] Khakazar, G., 2014, Evaluation of Facade Performance, in Terms of Thermal Comfort for Health Center Building, EMU

[2] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan.

chimney at the top would increase the buoyancy and trap out the overheated air from the cavity while being acceptable cost-wise.[1]

Width of the Cavity:

The cavity's width is a very important parameter in a double skin façade. It varies based on the configuration and the climate in which the double skin façade is used. That's because it strongly affects air velocity and airflow patterns inside the cavity (Poirazis, 2004). According to BBRI (Belgian Building Research Institute, 2002), a cavity with narrow width ranges from 10 cm to 20 cm, while a wide cavity range from 50 cm to 100 cm or above.

Studies show that increasing the width of the cavity would enhance the airflow due to the increase of overheated air inside the wide cavities, and because the vents and boundary walls will be less resistant to airflow. On the other hand cavities with smaller widths has a slight temperature rise more than those with wider cavities. They also allow more heat gain to the interior spaces.

Many studies are done to test the performance of double skin façades with different widths, and they all recommend that the width in hot arid climates is better to range from 70 to 150 cm while affirming that the wider the cavity, the better it will perform. Studies also show that after a certain width, the façade's performance will remain constant even if its width increases more.

Apart from thermal performance, wider cavities are shown to perform better in fire resistance.
Yet, changing the façade's type and other parameters may cause higher thermal performance and lower energy consumption in case of narrower cavities.

Rhadi, H., et al, (2013), studied thermal performance of double skin façade on the department of architecture building in Al Ain University, UAE. One of the studied parameters was the cavity's width. The results of the numerical and CFD experiment showed that although narrower cavities lead to less heat exchange, the beam radiation increases causing increasing in surface temperature and heat gains. On the other hand, wider cavities showed higher air flow rates and gave balance between solar gain and heat transmission. He concluded that an air cavity that ranges from 70 to 120 cm wide can achieve this balance.

2.2.2.2 Openings Principles:

Air speed and type of air flow inside the cavity depend on the following:

- Width of the cavity (both for natural and mechanical ventilation)

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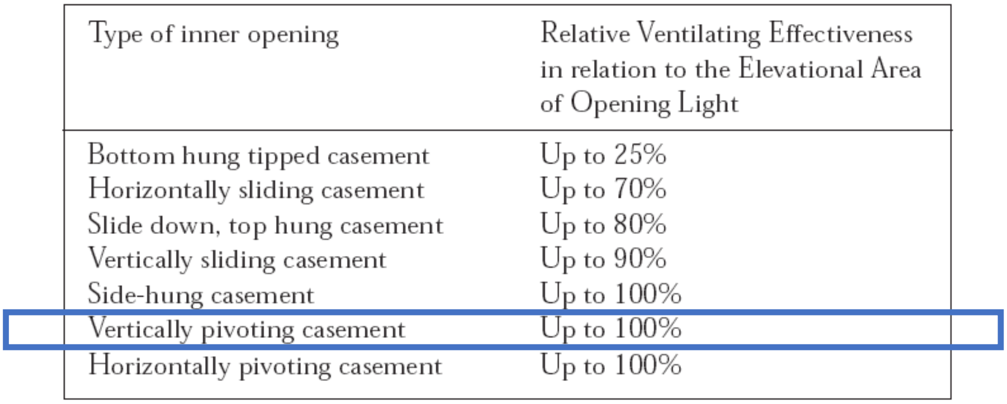
[1] Ibid

- Interior openings type (both for natural and mechanical ventilation)
- Exterior openings type (for natural ventilation)[1]

Inner Skin's Openings:

The inner skin's ventilation function is affected by its openings movement. Oesterle, et al., (2001) compared between different openings types in the inner skin and showed their relative ventilating effectiveness in relation to the elevational area of opening light. The comparison is shown in table (2-2).

Table 2-1 Relative Ventilating Effectiveness in Relation to the Elevational Area of Opening Light for Various Types of Inner Openings. (Oesterle, et al., 2001)



Type of inner opening	Relative Ventilating Effectiveness in relation to the Elevational Area of Opening Light
Bottom hung tipped casement	Up to 25%
Horizontally sliding casement	Up to 70%
Slide down, top hung casement	Up to 80%
Vertically sliding casement	Up to 90%
Side-hung casement	Up to 100%
Vertically pivoting casement	Up to 100%
Horizontally pivoting casement	Up to 100%

From the table, it could be concluded that side hung casement, vertically pivoting casement and horizontally pivoting casement has the best relative ventilating effectiveness compared to other types of openings.

Inner Skin Openings' Positions:

While positioning the openings of the inner skin, it is preferable that the inlet and outlet openings be staggered, so that the exhausted air that reaches the cavity doesn't return back to the interior spaces. Also, cross ventilation can be considered when using the openings though it mainly relies on the type of the building, and its surroundings.

Outer Skin's Openings:

Studies show that optimizing the openings configuration is very critical especially in hot arid climates because it can help cooling down the cavity's temperature, and it affects the ventilation of the building. In general, the openings are better to be large

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[1] Poirazis, H., 2006, Double Skin Facades, a Literature Review.

in hot arid climates to reduce cavity's overheating, and to ventilate the interior spaces. Regarding the outer skin's openings, it is recommended to use automatic operation so that the windows open and close as a response to the outside climate. Furthermore, the outer façade's openings are suggested to be less in height than the width of the cavity to cause an initial velocity peak with pressure loss. If they are not designed as operable windows, and were designed to be void openings, they may cause insects and birds to enter the cavity, so researchers suggest to apply wires or meshes over them.[1]

Torres, M., et al, 2007, tested the effect of changing the size of the outer skin's openings in the hot arid climate of Spain in South orientation. The simulations were done by TAS software to test the parameter on the corridor and multistorey facade.

The results showed that in case of corridor type façade and the multistorey type façade, the wider the external openings areas, the lower the annual cooling loads. The effect in case of corridor façade type led to a decrease around 1.25 KWh/m2 in the annual cooling loads (figure 2-3 and 2-4).

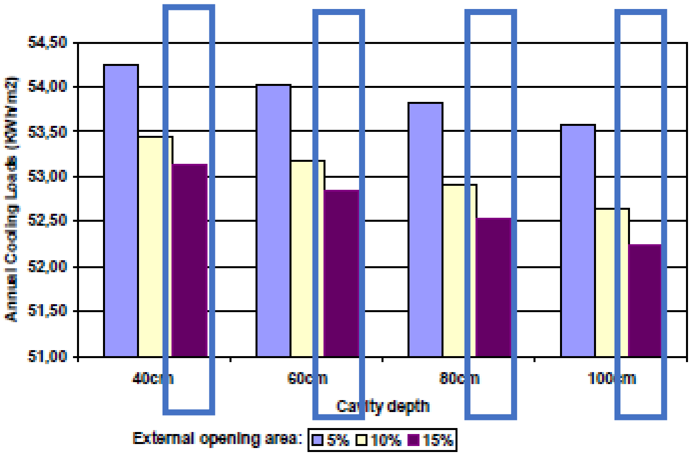

Figure 2-4-Annual Cooling Loads for 1 floor Corridor Façade (Torres, M., Et Al, 2007, Double Skin Façades – Cavity and Exterior Openings Dimensions for Saving Energy on Mediterranean Climate)

The multistorey type showed a maximum annual cooling loads decrease of 2.75 KWh/m2.

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[1] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan

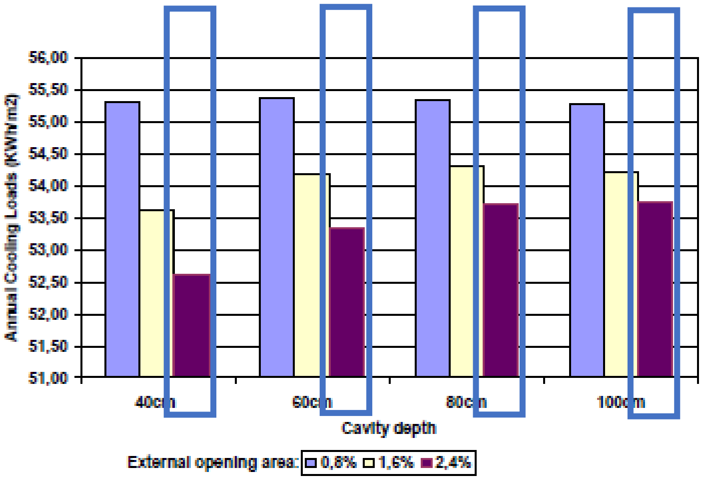

Figure 2-5- Annual Cooling Loads for Multistorey Façade (Torres, M., Et Al, 2007, Double Skin Façades – Cavity and Exterior Openings Dimensions for Saving Energy on Mediterranean Climate)

To conclude, increasing the area of the external openings in hot arid climates could lead to lower annual cooling loads which reflects better thermal performance of the system.

2.2.2.3 Air Intakes and Extracts

Another openings type in the double skin façade is the air extracts, which direct the airflow that ventilates the cavity and the exhausted air from interior spaces outside the cavity. The same principles that apply to air intakes, applies also to air extracts, with the addition of an important factor to be considered which is the deflection of the air steam.

In conclusion, openings size, type, and position are three main factors that need to be addressed while designing double skin facades, especially in hot climates because of the very need to cool down the excessive heat gain of the cavity, and to control the ventilation performance for the façade system and for the interior spaces.[1]

In a double skin façade, the principles that apply to inbuilt elements in air-intakes apply also to air extract openings as Oesterle et al., (2001) claims. According to the authors, while airstream moves vortices can occur along its path, with eddies spinning off at tight curves and along the edges. Once these turbulences have formed, the effective area of the opening is reduced. In this case, the cross-section available for the air flow will be the residual area that is free of any turbulence which dimensions are the ones that should be used in calculations.[2]

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[1] Danik, S., 2014, Natural Ventilation Through Double-Skin Facades in Tall Buildings

[2] Poirazis, H., 2006, Double Skin Facades, a Literature Review.

2.2.2.4 Material Choice

Mainly, when choosing Double skin façade's construction materials, caution should be paid to both shading devices and pane type. Designers should take care when choosing materials used with glass. That's not only because of the difference in natural properties of the base material and glass such as coefficient of thermal expansion. But also, because the coatings used with materials could be incompatible and then need maintenance that would be difficult to carry out without harming the coatings and glass in some way.[1]

Selection of Glass:

It is important to study the characteristics of glass used in double skin facades to choose wisely the glass type according to the needed performance and the climate where the double skin façade is applied.

Glass has three main factors which determine its performance to different radiations. These factors are reflectance, Absorptance and light transmittance. The three factors are affected by the tint of glass, its thickness and coatings.

Reflectance (p) is the incident beam of light which is reflected by the material. Glass reflection can be diffuse, specular or spread depending on the glass surface. Absorptance (a) is defined as the fraction of incident radiation which is absorbed by the body of glass.

The spectral transmittance for clear glass differs from tinted glass and also depends on glass thickness. (Figure 2-4 & figure 2-5)

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[1] Ibid

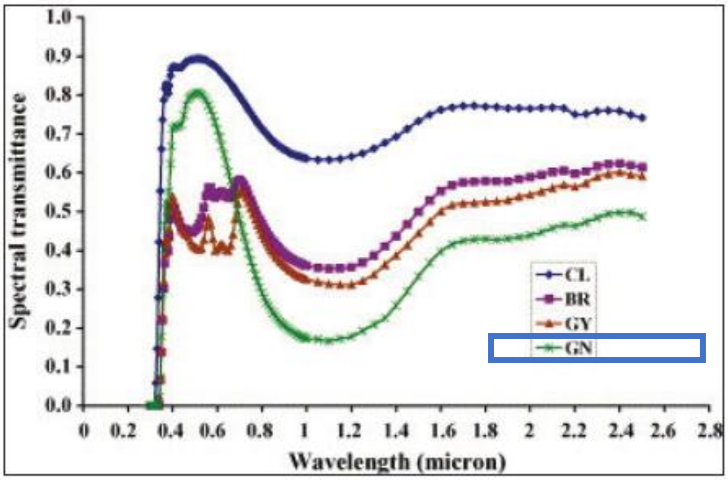

Figure 2-6 Spectral Transmittance of Clear and Tinted Glass (Chaiyapinunt, S., et al, 2005)

The comparison in Figure 2-5 is made between clear glass and tinted glass of 0.6 cm thickness. Mostly, glass has very low transmittance for UV radiation while clear glass has an overall high transmittance on visible and near infrared radiations. Glass capacity to transmit infrared radiation depends on its chemical composition and color. For example, green glass (GR) transmits visible light highly, but has very poor performance on the infrared. Bronze (BR) and grey (GR) glass have low transmittance for visible light and moderate transmittance for infrared.[1]

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[1] Mousavi, S., & Ali Baba, H., 2015, A State of Art for Using Double Skin Façade in Hot Climate.

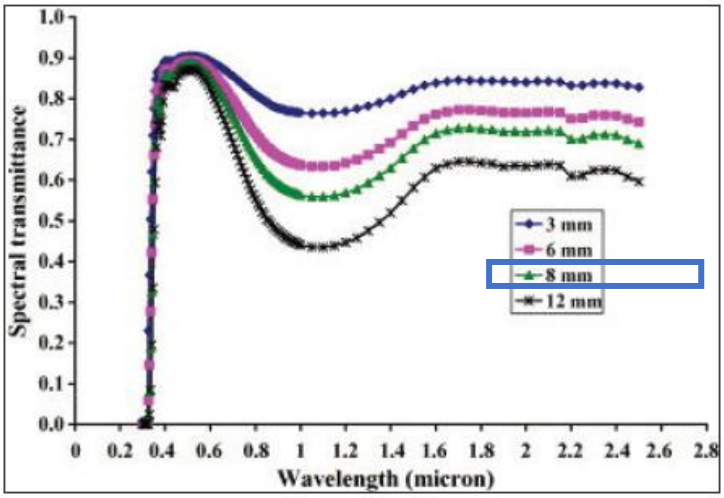

Figure 2-7 Spectral Transmittance of Clear Glass for Different Pane Thicknesses. (Chaiyapinunt, S., et al, 2005)

Glass thickness also highly affects the way the light and radiations are transmitted. When glass thickness increases, visible light transmittance slightly reduces while short-wave and long-wave infrared transmittance is considerably reduced as shown in figure 2-6.[1]

Most of literature mentioned some types of glass panes as the most commonly used in double skin facades. For the internal skin, the most used type consists of thermal insulating double pane or triple pane. Those panes are usually unhardened float or toughened glass with air, argon or krypton filling the gaps between the panes. On the interior glass, low-emittance coatings can help reducing radiative heat gains to the interior and windows could be hopper or casement windows.[2] For the external skin, single pane toughened (tempered) glass is used and sometimes safety laminated glass is used instead. Oesterle et al., (2001) suggests using flint glass in the exterior layer for higher degree of transparency.

Hamza, (2004), investigated three types of glass with different properties in Cairo’s hot arid climate which were, clear glass, body tinted, and reflective glass. The results showed that the U value was similar for the three types while solar shading coefficient (SC) was 0.89, 0.59 and 0.27 for clear glass, body tinted and reflective glass respectively. Comparing the results tells that body tinted glass could reduce cooling demand for summer and winter seasons and then annual consumption rates.

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[1] Ibid

[2] Poirazis, H., 2006, Double Skin Facades, a Literature Review.

Moreover, using reflective glass showed more reductions in cooling demands which were reduced by 35% annually.

The good result of reflective glass was again confirmed by Hamza, 2008. A comparison between a base model, single skin façade, clear DSF, tinted DSF and reflective DSF was done for different façade orientations.

The results showed that reflective DSF could lower down the annual cooling loads from 1450 W.h/m2 in the case of base model to 900 W.h/m2 in the hottest three orientations (figure 2-7).

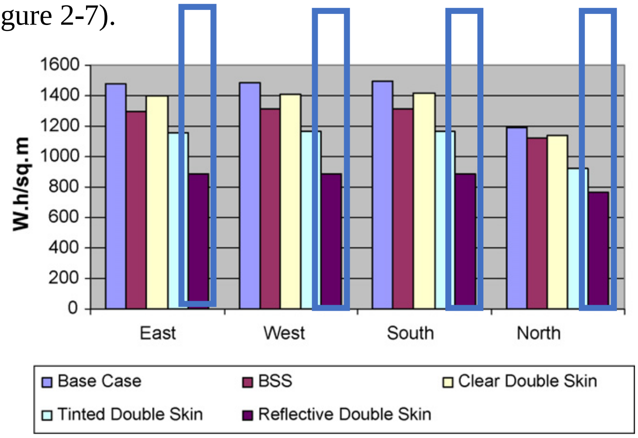

Figure 2-8- Annual Cooling Loads for Different Glazing Types (Hamza, N., 2008, Double Versus Single Skin Facades in Hot Arid Areas)

Radhi, et al, 2013, investigated the impact of glass properties on double skin facades in UAE by studying three properties of glass which are U-value, solar heat gains coefficient (SHGC) and emissivity. The results showed that SHGC has the largest impact on thermal performance of the system and that decreasing SHGC reduces heat transfer rates. However, low values of SHGC coupled with low values of U-value could lead to overheating.[1]

Another aspect to take care of while designing DSFs is Window-wall ratio for the inner skin which is thought to be vital for DSF performance. WWR investigated in Cairo was 40% while a ratio of 60% was tested in Hong Kong. Yet, some buildings could require a ratio of 100% forming a fully glazed envelope. Of course this case could increase overheating possibilities and thus cooling demands.[2]

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[1] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan.

[2] Amaireh, I., 2017, Numerical Investigation Into A Double Skin Façade System Integrated With Shading Devices, With Reference To The City Of Amman, Jordan.

To conclude, it’s thought that using a single pane for the outer skin is a good solution because using double pane glazing could cause overheating and thus increase cooling demands. Yet, choosing different properties of glass while using double pane glazing could lead to thermal enhancements. Also studies show that using double pane glazing for the interior skin means less heat transfer from the cavity to the indoor spaces which enhances thermal comfort. Also, it is very important to study the optical properties of the glass to avoid glare and other natural lighting problems when choosing glazing type.[1]

Conclusion

In conclusion, the early design stage of double skin facades should be studied wisely in order to achieve the intended performance and thus energy consumption. The design stage should include, choosing the type of double skin façade according to the intended working principle and according to the climate where it is constructed. A lot of parameters and factors should be put in consideration while designing the DSF including the airflow mechanism, glazing type, shading devices placement and inner and outer skin openings. Moreover, the standards of thermal comfort should be studied and achieved to make sure that the double skin façade performs well under certain climatic conditions.

2.3 Design Parameters of Shading Devices.

The main purpose of integrating shading devices with DSFs is to maintain the balance between building energy performance and natural ventilation efficiency. And to integrate shading devices inside the cavity, some parameters should be studied to ensure the best performance. In this section the design parameters of shading devices will be mentioned.[2] Figure 2-8 shows the vocabulary and parameters used in shading devices.

Oesterle, et al., 2001, suggests that determining the characteristics of shading devices in the early planning stage can pose a special problem because the properties of the shading devices can vary considerably depending on the ventilation of the cavity and the type of glazing.

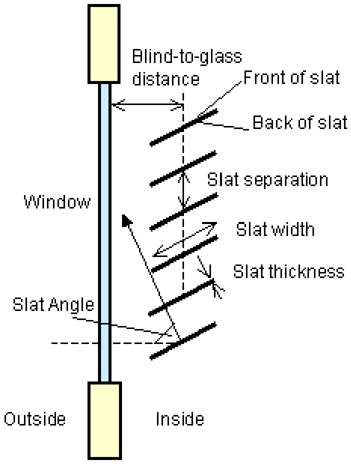

Figure 2-9- Shading Devices Vocabulary (DesignBuilder)

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[1] Ibid.
[2] Ibid.

Sun shading devices could be either complete screening of the indoor area or louvers.

Oesterle, et al. concluded that for large scale projects the combination of glass and sun shading characteristics should be precisely investigated as well as the proposed cavity ventilation in relation to the louvers' angle.[1]

Design parameters of shading devices include their size, shape, inclination angle, surface characteristics (color and emissivity), material, and position. These parameters significantly affect the performance on the cavity and they have been studied in researches to investigate their effect on the temperature and airflow inside the cavity.

2.3.1 Shading Devices Position

Lee, J., et al., (2015), suggested that a minimum distance of 15 centimeters should exist between shading devices and the outer skin for proper ventilation efficiency which would help avoiding overheating and thermal discomfort. Also another study showed that dividing the cavity by horizontal blinds could affect the air velocity so the researchers suggest that horizontal blinds should be placed near the inner skin to minimize overheating through higher velocity airstream. However, this could lead to high reflection of direct heat gain to the interior space, so optimization should be done to balance the effects of shading devices both on heat gain and airflow.[2]

2.3.2 Inclination Angle of Shading Devices

Studies of the inclination angle of cavity-integrated venetian blinds using 2D CFD model showed that natural ventilation could be improved by up to 35% and thus, solar heat loads could be reduced by up to 75%. Safer, et al., 2004 & 2005, studied the position and inclination angle of cavity-integrated shading slats. The results showed a relation between the impact of inclination angle on flow fields inside the cavity and temperature and the level of direct solar radiations as well as the position of the slats. Also, airflow rates significantly affect convective heat transfer although convective heat transfer is smaller than radiative heat transfer which is significantly influenced by slats angles.

According to CFD analyses and studies, the annual energy saving of horizontal shading devices is more prominent than vertical shading device.

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[1] Oesterle, Lieb, Lutz, Heusler. Double-Skin Facades- Integrated Planning: Building Physics, Construction, Aerophysics, Air-Conditioning, And Economic Viability.

[2] Ibid

To assess the effect of shading devices on thermal performance of double skin façade in Kansas, USA, Lee, J., et al, did preliminary simulations of different shading devices cases on the Architecture School Extension at the University of Kansas.

FloVENT was the simulation software used to calculate air flow patterns and air temperature, while Sefaira, was the software to simulate heating and cooling energy consumption. Numerical data was obtained by the software to indicate the performance of horizontal and vertical shading devices which were placed at different angles to determine the best situation.[1]

The simulations showed an increase in the exterior side of the cavity's air temperature in case of 90 degree angle horizontal shading devices while in case of 0 degree angle, air temperature was distributed in both sides of air cavity.[2]

Also, the simulations showed that horizontal shading devices had a higher maximum air temperature than vertical shading devices because of stagnation of heated air due to solar irradiance within the narrow spaces between horizontal shading devices where 90 degree angle had the highest maximum air temperature compared to the other cases.[3] See figure 2-9.

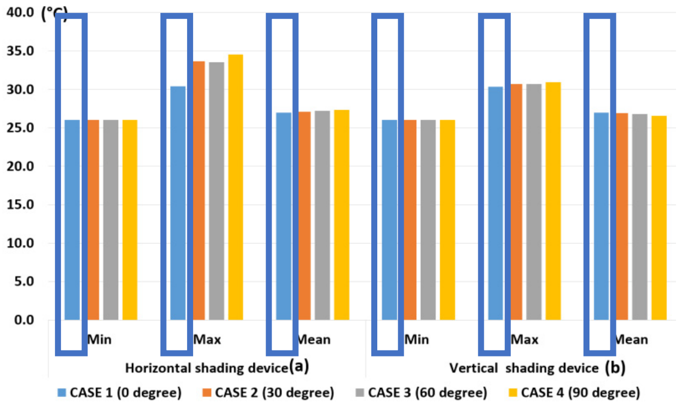

Figure 2-10- Air Temperature of Horizontal Shading Devices (a) and Vertical Shading Devices (b) (Reference: Lee, J., et al, A Study of Shading Device Configuration on the Natural Ventilation Efficiency and Energy Performance of a Double Skin Façade)

Moreover, it was noticed that the air temperature in an exterior facing side's air cavity was higher than the air cavity of an interior facing side in case of shading elements.[4]

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[1] Lee, J., et al, 2015, A Study of Shading Device Configuration on the Natural Ventilation Efficiency and Energy Performance of a Double Skin Façade

[2] Ibid

[3] Ibid

[4] Ibid

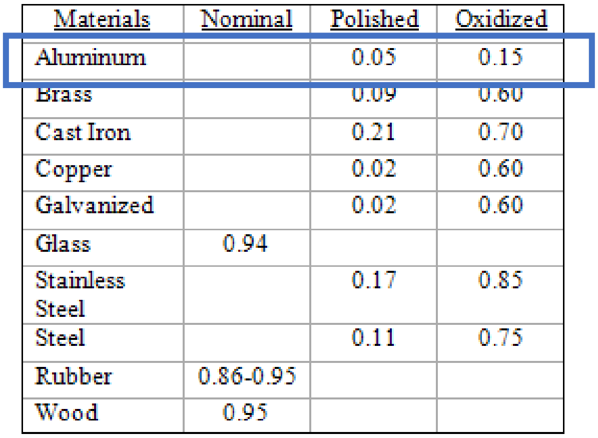
To conclude, the previous numerical analysis showed better annual energy saving results by horizontal shading devices compared to the vertical ones. The 30, 60 and 90 degrees of horizontal shading devices contributed to the annual energy saving by 0.4%, 2.6% and 6.4% respectively. So, using horizontal shading devices at 90 degrees showed a noticeable annual building energy saving when compared to other horizontal shading devices degrees and to vertical shading devices. And overall, integrating shading devices to ventilated double skin facades could enhance thermal comfort and thus contribute to annual building energy saving noticeably. From the previous comparison, lower inclination angles of shading devices could give a better result in case of cooling, in addition to increasing the opportunity of daylighting the indoor spaces.[1]

2.3.3 Shading Devices Material

As mentioned earlier, shading devices absorb some of the heat gain radiations and reflects some of them. That makes the color and material of shading elements a critical factor that affects thermal comfort. The main properties of materials that should be considered while choosing the shading devices are emissivity and solar reflectance of materials.

Table 2-3 and table 2-4 show the approximate emissivity and solar reflectance of commonly used materials respectively.[2]

Table 2-2- Approximate Emissivity of Common Materials (https://www.pro-therm.com/infrared_basics.php, Last Visit: 20-March-2018)



Materials	Nominal	Polished	Oxidized
Aluminum		0.05	0.15
Brass		0.09	0.60
Cast Iron		0.21	0.70
Copper		0.02	0.60
Galvanized		0.02	0.60
Glass	0.94		
Stainless Steel		0.17	0.85
Steel		0.11	0.75
Rubber	0.86-0.95		
Wood	0.95		

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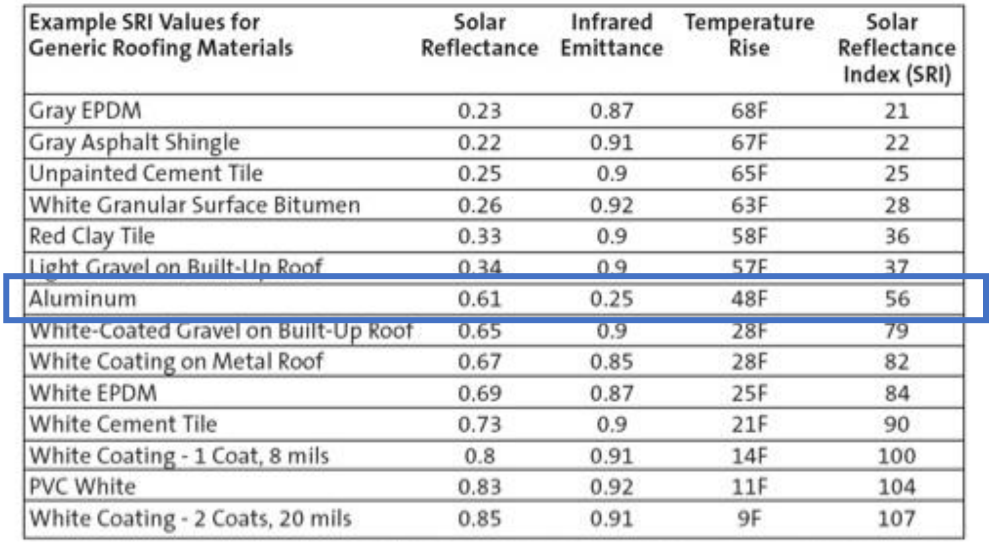
[1] Lee, J., et al., 2015, A Study of Shading Device Configuration on the Natural Ventilation Efficiency and Energy Performance of a Double Skin Façade

[2] The Researcher

Table 2-3- Solar Reflectance for Commonly Used Building Materials (LBNL Cool Roofing Materials Database)



Example SRI Values for Generic Roofing Materials	Solar Reflectance	Infrared Emittance	Temperature Rise	Solar Reflectance Index (SRI)
Gray EPDM	0.23	0.87	68F	21
Gray Asphalt Shingle	0.22	0.91	67F	22
Unpainted Cement Tile	0.25	0.9	65F	25
White Granular Surface Bitumen	0.26	0.92	63F	28
Red Clay Tile	0.33	0.9	58F	36
Light Gravel on Built-Up Roof	0.34	0.9	57F	37
Aluminum	0.61	0.25	48F	56
White-Coated Gravel on Built-Up Roof	0.65	0.9	28F	79
White Coating on Metal Roof	0.67	0.85	28F	82
White EPDM	0.69	0.87	25F	84
White Cement Tile	0.73	0.9	21F	90
White Coating - 1 Coat, 8 mils	0.8	0.91	14F	100
PVC White	0.83	0.92	11F	104
White Coating - 2 Coats, 20 mils	0.85	0.91	9F	107

From the two tables, solar reflectance index (SRI) of Aluminum is 0.61 which is considered as good reflectance value which can help in case of DSF to reflect more direct solar radiations (depending on the inclination angle). However, PVC material has higher solar reflectance with a value of .83 compared to Aluminum.

Also, in case of polished aluminum the emissivity is 0.05 which is low compared to wood's 0.95 value. This could make Aluminum a good material to be used in shading devices. In the same way, a comparison between materials has to be done to choose the suitable material depending on the other parameters and the climate where the double skin façade is implemented.[1]

In 2015, Barbosa, S., studied the effect of naturally ventilated walls on thermal performance of office buildings in Rio de Janeiro. Barbosa also investigated the significance of shading devices decisions in the design of double skin facades.

A simulation was done to assess the effect of naturally ventilated walls on the base model. A lot of parameters were studied including shading devices design. The software used for simulation was IESVE and a comparison was done between the base model and different proposals with different parameters.

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[1] The Researcher

To study shading devices effect, simulations were carried out for the base model, and other two models with concrete and metal shading devices added.[1]

Results of simulations showed that adding shading devices improved thermal comfort of the office spaces. When shading devices made of concrete were applied, cavity temperatures were higher due to higher absorptance of concrete. While the results showed lower cavity temperatures when aluminum was used. However, metal shading devices reduced overall airflow in the offices but improved thermal comfort in the building by 9% compared to the base model result. This can be explained by conduction and direct solar gains reduction from the cavity.

Although the application of metal shading device within the cavity reduced the overall airflow in the offices, the reduction in solar gains was much higher. On the other hand, using concrete instead of aluminum increased heat gain in the cavity and thus in the internal spaces and its thermal performance was higher than the base model by 4.3%. [2]

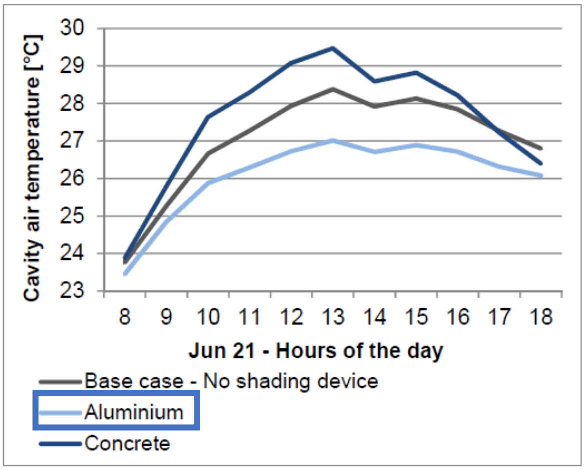

Figure 2-11- Cavity Alternatives Shading Devices. (Reference: Barbosa, S., Thermal Comfort in Naturally Ventilated Buildings with Double Skin Façade under Tropical Climate Conditions: The Influence of Key Design Parameters)

Results show that shading devices integration is the most effective parameter on thermal performance of the building. Cavity width and tapered cavity follow shading devices in the effectiveness on thermal comfort while other parameters improved specific floors' thermal comfort. The results tell that DSF can achieve 70% of

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[1] Barbosa, S., 2015, Thermal Comfort in Naturally Ventilated Buildings with Double Skin Façade under Tropical Climate Conditions: The Influence of Key Design Parameters

[2] Ibid

occupied hours within acceptable comfort levels. This will significantly lower energy consumption of the building (figure 2-10).[1]

In conclusion, the use of cavity integrated shading devices could help blocking part of direct solar radiations. In addition, the adjustment of shading slats could reduce the solar gains and save more energy because of the reduction that happens in cooling loads. Some factors affect the performance of the shading devices which should be considered while designing them which include, tilt angles, position, materials, surface characteristics and size. Horizontal shading devices are believed to perform better than the vertical ones in terms of energy saving. In addition, tilt angles of the horizontal shading devices are recommended to be at 90° or 35° to achieve better performance regarding the movement of air inside the cavity, daylighting and avoiding overheating. The position of the shading devices is also a critical factor, and their effect of reradiating the absorbed heat to the adjacent indoor spaces should be taken into consideration. Last but not least, the natural daylighting efficiency should be highly considered while designing the shading devices because it is considered a main advantage of the double skin facades.[2]

2.4 Summary and Conclusion

Chapter two discussed factors affecting thermal performance of naturally ventilated walls.
Those factors include activity level, temperature, airflow rate and relative humidity.

Chapter two determined values of these factors to be compared to the study results in chapter four. The mentioned metabolic rate of hotel rooms' activities could range between 0.7 and 0.9 met. While the air temperature should range between 23 and 26 in summer and between 20 and 22 in winter. Relative humidity should range between 20 and 60% in summer and between 20 and 50% in winter according to Bradshaw (2006) while ASHRAE mention that RH should not exceed 70%. Also, ASHRAE Standard 55 mention 0.20 m/s as a fair air flow rate that could achieve thermal comfort and that air speed should not exceed 0.8 m/s with increment steps not exceeding 0.15 m/s. However, air speed that reaches 0.8 m/s considered satisfying range. In case of higher temperature, the temperature could be offset up to 3°C down the current temperature by the process which is called elevated air speed.

Moreover, the chapter studied different parameters of naturally ventilated walls design in its second section including cavities which is stated to have good performance if their width ranged between 70 and 120 cm in hot arid climates. Table

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[1] Ibid
[2] Ibid

2-5 show a brief for the studied literature review regarding naturally ventilated walls' parameters.[1]

Table 2-4 Literature Review Brief on Naturally Ventilated Walls Parameters

Study Topic	Author	Results
The effect of applying naturally ventilated walls with a 100 cm chimney.	Khazkar, G., 2014	The results showed that, ***Adding a 1m chimney*** to the naturally ventilated wall could force an airflow that cooled down the space by 5 Celsius degrees when compared to single skin façade and by 8 degrees when compared to naturally ventilated wall model.
The effect of cavity's width on thermal performance.	Rhadi, H., et al, 2013	The results showed that wider cavities could give a balance between solar gain and heat transmission through air flow rates. The researcher suggested that ***an air cavity that ranges from 70 to 120 cm could reach the balance in hot arid climates.***
The effect of different openings' type in the naturally ventilated wall on ventilation.	Oesterle, et al., 2001	The study suggested that using side-hung casement type, ***vertically pivoting casement*** type or horizontally pivoting casement type could lead to up to 100% relative ventilating effectiveness.
The effect of outer skin openings' sizes on cooling loads.	Torres, M., et al, 2007	The results showed that the larger the outer skin openings' size the lower the annual cooling loads will be in South facade.

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[1] Illustrations and drawings are in pages 49, 51, 53, 55, 56.

The effect of glazing type on spectral transmittance	Chaiyapinunt, S., et al, 2005	The results showed that, ***green colored reflective glazing*** could lower down spectral transmittance (40%) while clear glass could lead to the highest possible spectral transmittance (90%).
The effect of glazing thickness on spectral transmittance	Chaiyapinunt, S., et al, 2005	The results showed that the thicker the glazing the lower the spectral transmittance. ***0.8 cm glass*** could lead to 60% spectral transmittance while 3 mm glass could lead to 90% spectral transmittance.

The third section of this chapter discussed design parameters of shading devices which include their position, geometry, color, material, and inclination angle. Table 2-6 show a brief for the studied literature review regarding the parameters of shading devices.[1]

Table 2-5 Literature Review Brief on Shading Devices Parameters

Study Topic	Author	Results
Comparison between different shading devices angles when using shading devices with naturally ventilated walls.	Lee, J., et al, 2015	The numerical analysis showed better annual energy saving results when using ***horizontal shading devices*** compared to the vertical ones. The 30, 60 and 90 degrees of horizontal shading devices contributed to the annual energy saving by 0.4%, 2.6% and 6.4% respectively.

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[1] Illustrations and drawings are in pages 60-63.

Comparison between using aluminum, concrete shading devices and not using shading devices at all.	Barbosa. S., 2015	The results showed that ***Metal shading devices*** could reduce overall airflow in the offices but improved thermal comfort in the building by 9% compared to the base model result.

From this chapter, some parameters are determined for the studied cases in chapters 3 and 4 as shown in table 2-7.

Table 2-6- Determined Double Skin Facade's Parameters from Literature Review

Naturally Ventilated Wall Parameters	
Cavity Width	100 cm
Chimney Height	100 cm
Glazing Type	Highly reflective glass
Glazing Color	Green
Openings’ Size	Three openings each is 120x120 cm
Openings Ratio	30%
Openings’ Placement	Inner and outer skin
Shading Devices Parameters	
Shading Devices’ Material	Aluminum
Shading Devices’ Angle	90 degrees – Horizontal shading devices

Chapter 3 – CFD Simulations Analysis

- Introduction
- Climatic Description of Egypt
- Simulation Software Review
- Reference Case Specifications
- Reference Case CFD Simulations
- Summary and Conclusion

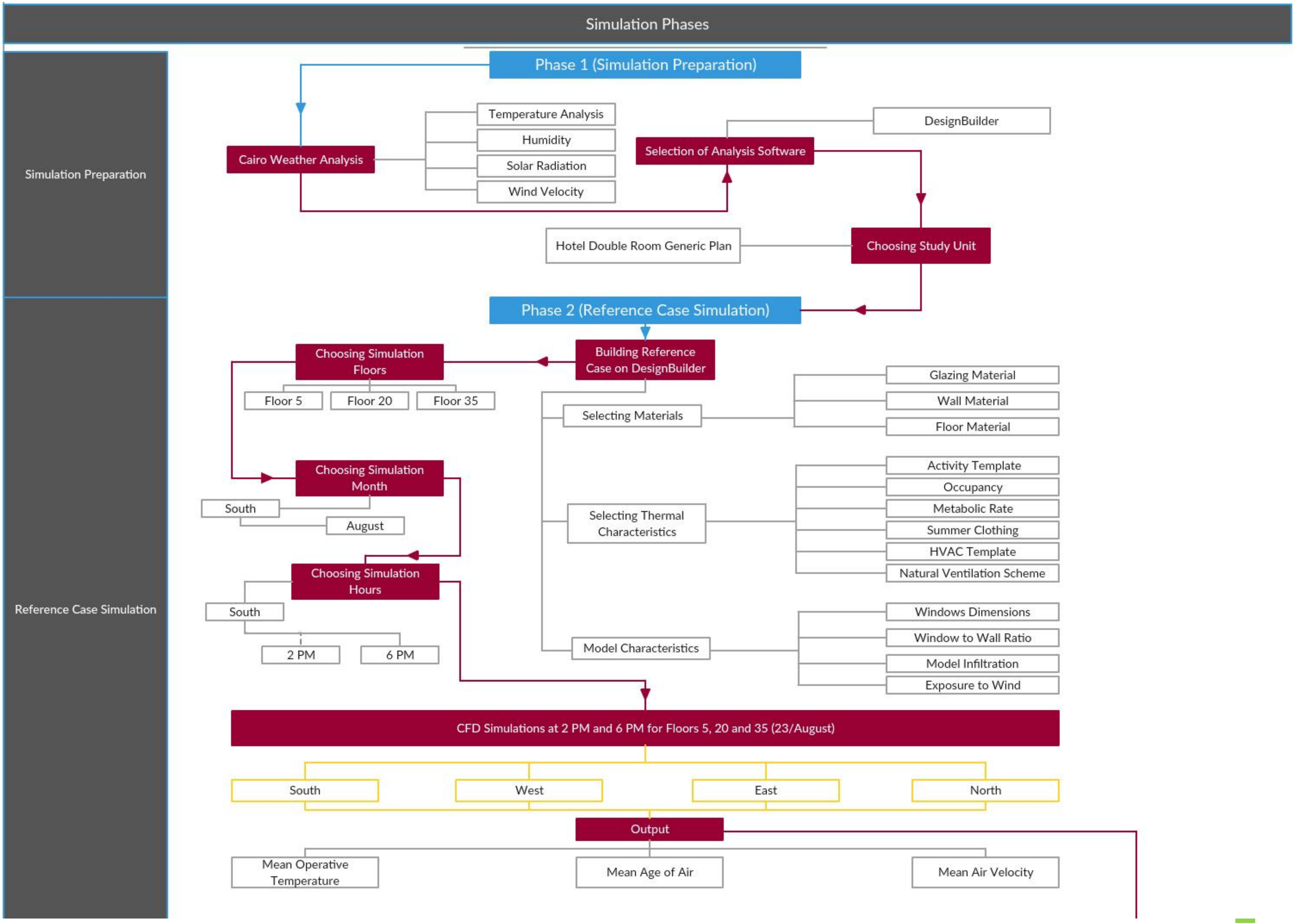
Chapter 3 – CFD Simulation Analysis

3.1 Introduction

Chapter three discusses CFD modeling and simulation of a 5 stars hotel double room generic plan (reference case). The chapter has three sections. The first section discusses the climatic classification of Egypt and its weather data files. The second section reviews simulation softwares used to measure the thermal performance of buildings and leads to choosing a software that will be used later in the simulations. At the last section, a reference case is modeled and tested in Cairo weather with single skin facade and the CFD simulations results are discussed. Figure 3-1 shows simulation phases that will be conducted in this chapter.

The study focuses on cooling season in Cairo, Egypt.

The outputs of the study are operative temperature (OT), air velocity (AV) and age of air (AOA). Other factors were excluded from the study like the effect on energy consumption and daylighting. The study will be done in two hours: 2 PM and 6 PM to assure results' accuracy. Also, when using shading systems, the sun angle used was 31 degrees based on the angle of the sun at 4 PM on the 23rd of August.


Simulation Phases
Simulation Preparation
Reference Case Simulation
Phase 1 (Simulation Preparation)
Cairo Weather Analysis
Temperature Analysis
Humidity
Solar Radiation
Wind Velocity
Selection of Analysis Software
DesignBuilder
Choosing Study Unit
Hotel Double Room Generic Plan
Phase 2 (Reference Case Simulation)
Building Reference Case on DesignBuilder
Selecting Materials
Glazing Material
Wall Material
Floor Material
Selecting Thermal Characteristics
Activity Template
Occupancy
Metabolic Rate
Summer Clothing
HVAC Template
Natural Ventilation Scheme
Model Characteristics
Windows Dimensions
Window to Wall Ratio
Model Infiltration
Exposure to Wind
Choosing Simulation Floors
Floor 5
Floor 20
Floor 35
Choosing Simulation Month
South
August
Choosing Simulation Hours
South
2 PM
6 PM
CFD Simulations at 2 PM and 6 PM for Floors 5, 20 and 35 (23/August)
South
West
East
North
Output
Mean Operative Temperature
Mean Age of Air
Mean Air Velocity

3.2 Climate Description of Egypt

Based on National Geographic classification, Egypt falls under the dry climate – arid category. Also, according to Köppen Geiger, 2017, the climate in Egypt is classified as a BWh climate (Figure 3-2). Where 'B' refers to an arid main climate, 'W' refers to a desert precipitation and 'h' refers to a hot arid temperature.

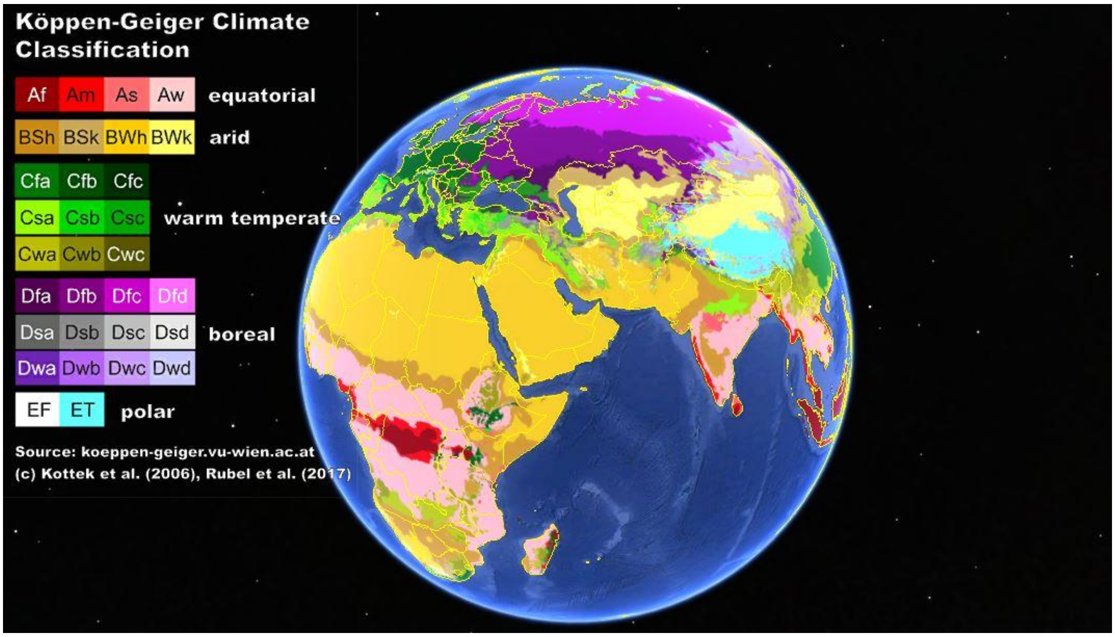


Figure 3-2- Köppen Geiger's Climate Classification, 2017, Google Earth Pro.

According to Egyptian Meteorological Authority (EMA) records, Cairo was classified to have a semi-desert climate.

3.2.1 Weather Data File

In order to have a detailed description of Egypt's weather all over the year, a weather data file is used. This file consists of parameters that describe the weather in the location of question. A typical meteorological year is used in this file which gives consistent annual averages based on information collected years earlier.

The weather data file of Cairo used in this research is based on Egyptian Typical Meteorological Year (ETMY) which was developed by Joe Huang from data provided by U.S. National Climatic Data Center for 12 to 21 years ending in 2003 for standards development and energy simulation. And this weather data was arranged by World Meteorological Organization.

Table 3-1 shows details for the weather data file of Cairo used in this research.

3-1- Details of the Energy Plus Weather Data File of Cairo, Egypt.

Weather File	Type	Coordinates	Elevation	Data Record End
EGY_Cairo.Intl.Airport.623660_ETMY.epw	Hourly weather data file	30.13° north ,31.4° east	74 m above sea level	2003

The .epw are energy plus weather data files.

3.2.2 Cairo's Weather Analysis

In order to have a picture of the climatic characteristics of Cairo, the weather data file mentioned above was used in Climate Consultant 6.0 software to get information about the radiation, temperature and wind speed in Cairo, Egypt.

3.2.2.1 Temperature

Figure 3-2 shows that Cairo reaches an average maximum temperature of 44 Celsius degree in July while the lowest average temperature recorded is 3 Celsius degree in January with an average of nearly 22 Celsius degrees all over the year.

Figure 3-3 also shows that in June, July, August and September the mean temperature is higher than the comfort zone's temperature. Also, in November, December, January, February and March, the mean temperature is lower than the comfort zone's temperature.

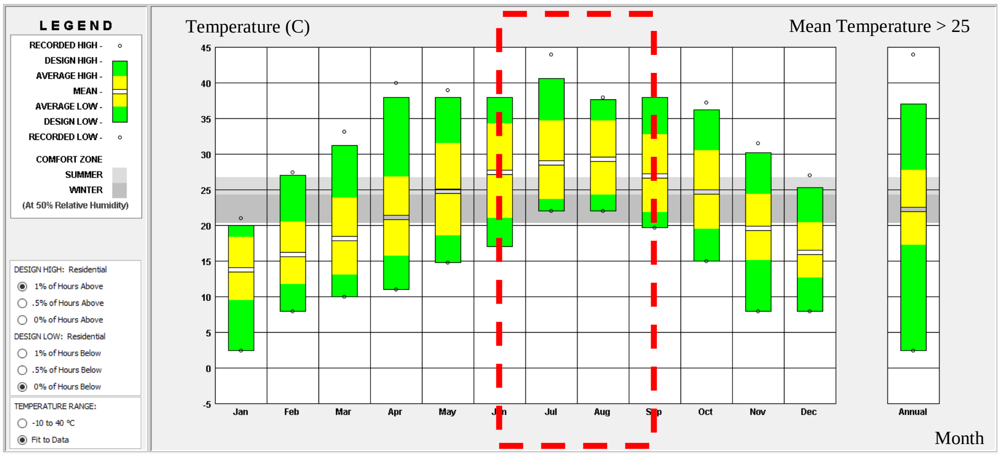
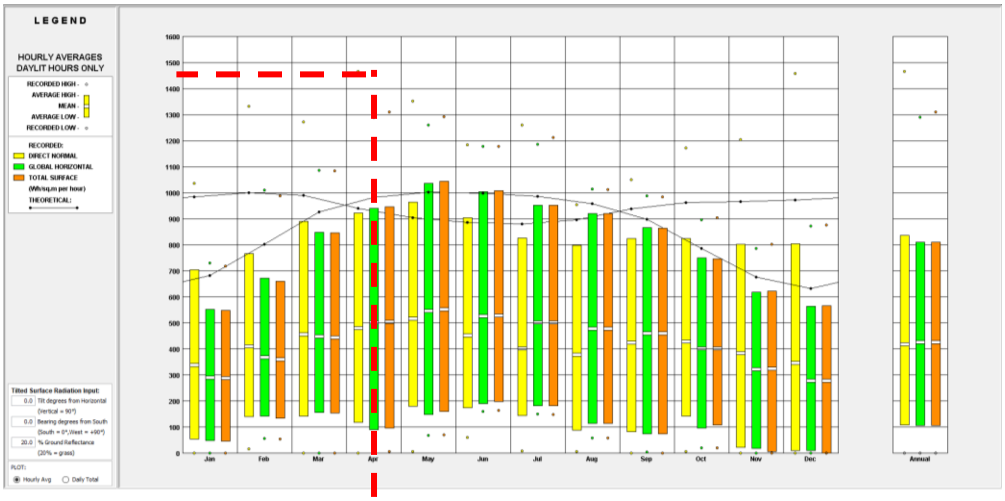


Figure 3-3- Temperature Range Chart for Cairo (Climate Consultant 6.0)

3.2.2.2 Solar Radiation

Figure 3-4 shows the direct solar gain all the year. The maximum recorded direct solar gain was in April of nearly 1475 W/sq.m per hour. In Cairo, the annual mean direct radiation range is 410 W/sq.m per hour.

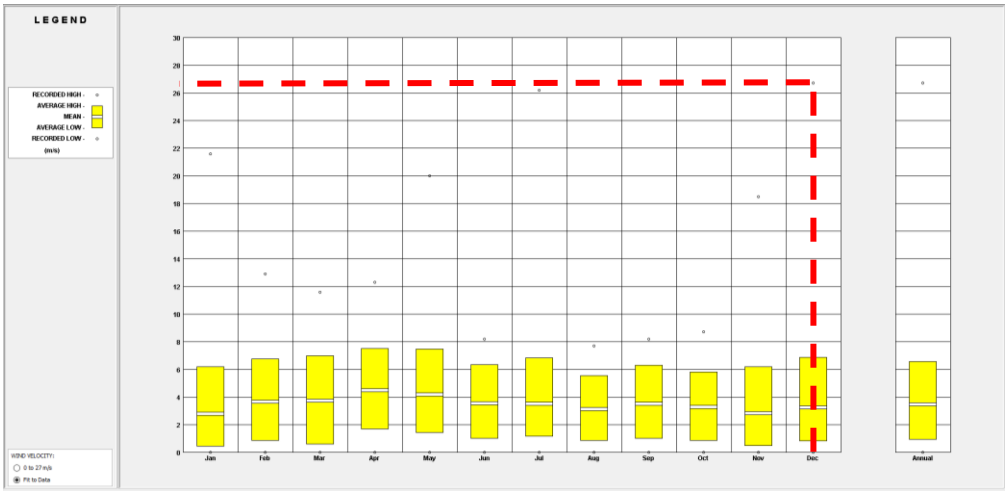


Tilted Surface Radiation Input:
0.0 Tilt degrees from Horizontal (Vertical = 90°)
0.0 Bearing degrees from South (South = 0°, West = +90°)
20.0 % Ground Reflectance (20% = grass)
PLOT: ● Hourly Avg ○ Daily Total

Figure 3-4- Radiation Range Chart for Cairo (Climate Consultant 6.0)

3.2.2.3 Wind Velocity

Maximum wind velocity recorded in Cairo as per figure 3-5 was in December with a value of 26.5 m/s. The annual mean velocity is nearly 3.75 m/s.



WIND VELOCITY:
○ 0 to 27 m/s
● Fit to Data

Figure 3-5- Wind Velocity Range in Cairo (Climate Consultant 6.0)

3.2.2.4 Relative Humidity

Figure 3-6 shows relative humidity in Cairo. From the figure, August, November and December have a slightly higher RH than the comfort zone's RH with a record of

61%. However, all over the year RH falls in the comfort zone with a minimum of 46% recorded in May.[1]

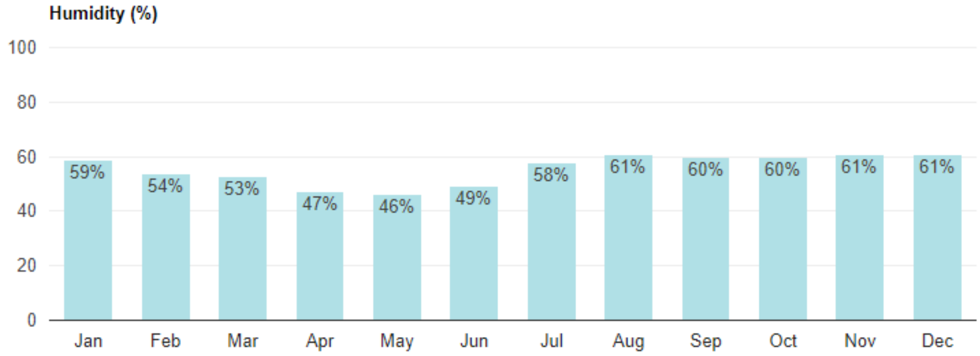


Figure 3-6- Relative Humidity in Cairo, Egypt (https://www.weather-atlas.com/en/egypt/cairo-climate?c,mm,mb,km, last visit: 16-8-2018)

3.3 Selected Energy Modeling Software

Designbuilder V. 4.6.015 was the chosen software for CFD simulations and thermal performance predictions of naturally ventilated walls in this research.

Integrated Environmental Solutions (IES <VE>), eQuest and Designbuilder are ranked the best three BPSs among the different simulation softwares. And the three softwares fulfill the requirements of natural ventilation and multi-zone air flow.[2]

However, IES is a more complex software which takes longer time to learn due to its more processes and capabilities which include hybrid and mechanical ventilation, while eQuest and design builder could still do the same job IES does regarding energy performance simulation for natural ventilation.[3]

Design builder's simulation engine is validated under the following building codes and standards (Until August – 2018):

- ASHRAE Research Projects 865 and 1052
- ANSI/ASHRAE Standard 140-2011
- International Energy Agency Solar Heating and Cooling Program (IEA SHC)
- BESTest (Building Energy Simulation Test).
- EnergyPlus HVAC Component Comparative tests
- EnergyPlus Global Heat Balance tests[4]

Design builder's simulation engine is Energy Plus which has been validated by Energy Efficiency and Renewable Energy (EERE) program, U.S. Department of

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[1] Egyptian General Authority of Meteorology, April-2018.

[2] Attia, S., et al, 2009, "*Architect Friendly*": A Comparison of Ten Different Building Performance Simulation Tools.

[3] Kensek, K., et al, 2012, Comparison of Two Different Simulation Programs While Calibrating the Same Building.

[4] Energy Plus, Testing and Validation, https://energyplus.net/testing, last visit: 24/8/2018

Energy (DOE). Energy plus provides access to mostly all the required simulation capabilities of thermal performance including natural ventilation, shading systems, glazing, thermal mass, building fabrics and HVAC systems.[1]

3.4 Reference Case Specifications

The reference case in this study will be a standard hotel room which will form a thermal study unit. The hotel room is supposed to be a part of a 35 floors five stars hotel building, to be located in Cairo, Egypt. Most of the high-rise hotel buildings in Cairo range between 25 floors (The Fairmont Cairo) and 43 floors (El Gezira Tower, Movenpick Hotel) and that's why an average number floors (35 floors) was selected.

3.4.1 Reference Case Geometry

The internal bathrooms generic plan arrangement is the chosen arrangement for a double room in a hotel.

In design standards, the more expensive the hotel, the larger the room should be with a minimum net area of 36 m^2 for five stars hotels' rooms.[2] Also, the ministry of tourism in Egypt has set a minimum of 28 m^2 for bedrooms in 4 and 5 stars hotels. So, the designed room is chosen to be 4.5 m x 8 m (36 m^2) and is supposed to be a module that should later be repeated along the facades. The study unit will have a 2.70 m clear height and 50 cm false ceiling giving a total of 3.20 m height.

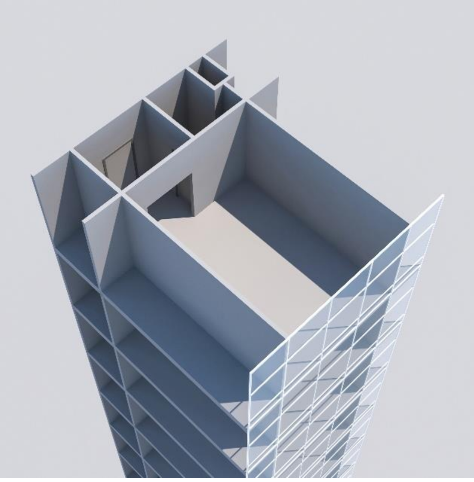

Figure 3-7- Perspective of the Reference Case - Thermal Study Unit – Typical Floor No. 35

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[1] Design Builder, Simulation Engine, https://www.designbuilder.co.uk/simulation?highlight=WyJzaW11bGF0aW9uIiwiZW5naW5lIiwic2ltdWxhdGlvbiBlbmdpbmUiXQ== , Last Visit: 24/8/2018

[2] David Adler, 1999, The Metric Handbook Planning and Design Data, 2nd edition.

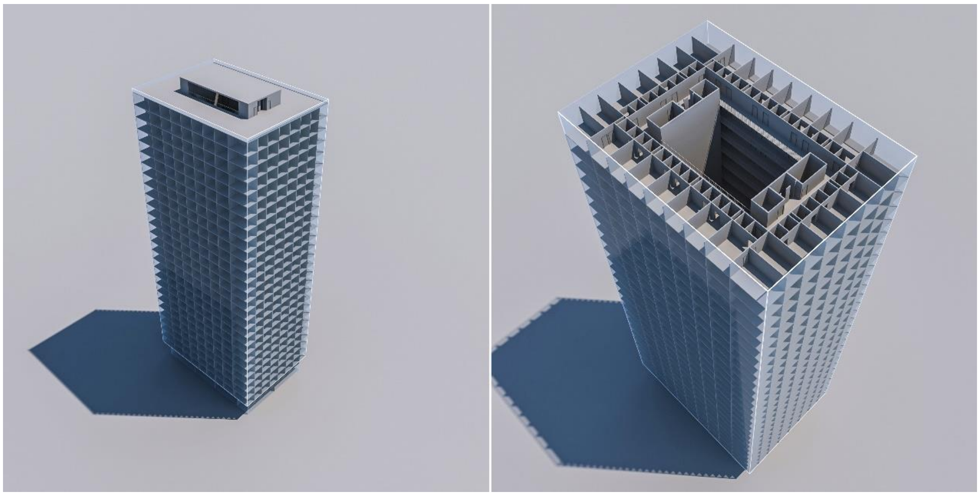


Figure 3-8- Perspective of the Repeated Rooms in Reference Case's Curtain Wall Facade (Left) and Repeated Thermal Study Unit – Typical Floor No. 35 (Right)

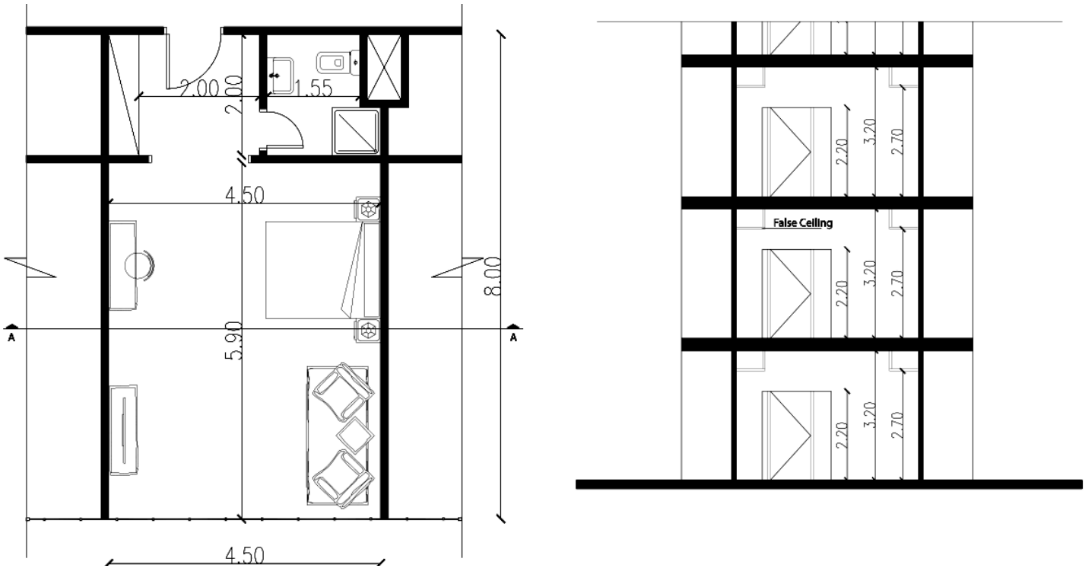


Figure 3-9 Plan of Reference Case (Left) and Section (A-A) Passing through Plan (Right)

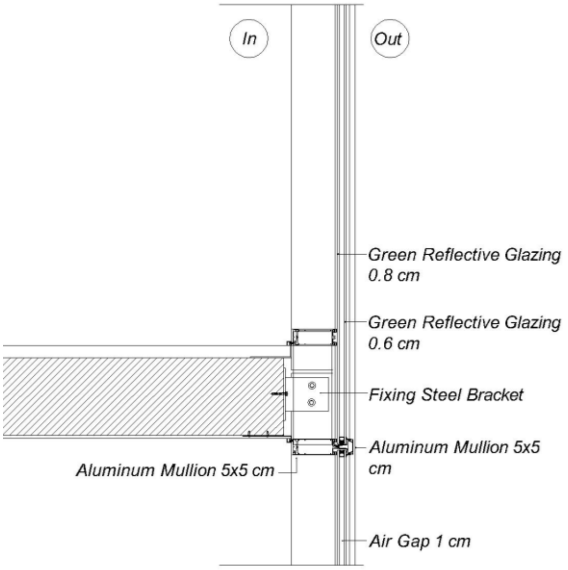
3.4.2 Parameters of the Hotel Room (Reference Case):

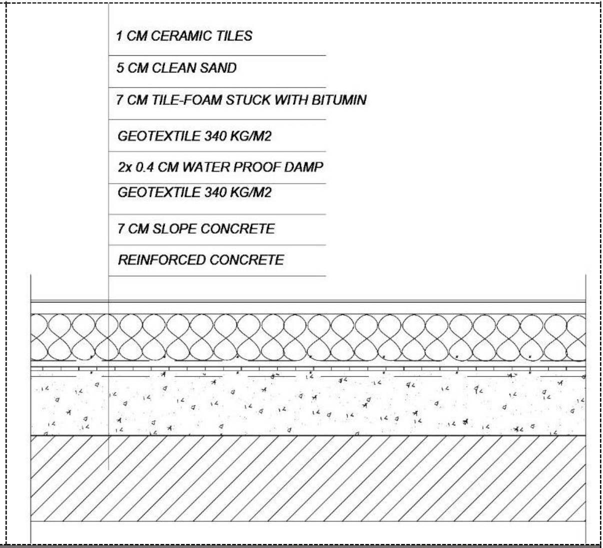
Figure 3-10- Single Skin Facade (Reference Case)

Table 3-2 shows the parameters used for the reference case's hotel room in DesignBuilder.

Table 3-2- Parameters of the Hotel Room (Reference Case)

Hotel Room Dimensions	
Dimensions	4.50x8.00x3.20 m
Thermal Parameters	
Activity Template	Hotel Bedroom
Occupancy	2 Persons
Metabolic Rate	0.90 met
Summer Clothing	0.50 clo
HVAC Template	Natural ventilation (No heating/cooling)
Natural Ventilation Scheme	Calculated ventilation (natural ventilation and infiltration air flow rates are calculated based on openings and cracks sizes, buoyancy, and wind pressures)

Model Infiltration	Zero infiltration (naturally ventilated)	
Openings Dimensions		
Opening Dimensions	1.20x1.20 m	
Casement Dimensions	1.30x2.20 m	
Openings' Ratio	30%	
	Note: The openings' ratio is taken as the highest possible ratio according to the study mentioned in the previous chapter. It's based on the standard dimensions of curtain walls panel sizes which is 1.20x1.20m and as the width of the model's main wall is 4.50 it can take a maximum of 3 windows which gives a ratio of 30%. (3x(1.2x1.2))/(4.5x3.2) = 0.30	
Other Parameters		
Exposure to Wind	Normal	
Materials		
Internal Walls	***Type:*** Brickwork ***Thickness:*** 29 cm ***Layers:*** 2 cm lightweight plaster – 25 cm brickwork – 2 cm light weight plaster	 *Figure 3-11 Reference Case Wall's Detail*
Curtain Wall	***Type:*** Reflective double-glazed curtain wall ***Layers:*** 0.6 cm reflective glass, 1 cm air, 0.8 cm reflective glass	
Floor	***Type:*** Reinforced Concrete ***Thickness:*** 37 cm ***Layers:*** 2 cm Lightweight plaster, 25 cm RC slab, 7 cm clear sand, 2 cm cement	

	mortar, 1 cm ceramic tiles	
Roof	***Type:*** Reinforced Concrete ***Thickness:*** 52.8 cm ***Layers:*** 2 cm Lightweight plaster, 25 cm RC slab, 7 cm sloped concrete, 0.8 cm DPC, 7 cm heat insulation, 5 cm clear sand, 2 cm cement mortar, 1 cm ceramic tiles	

Materials Characteristics

Element	Conductivity (W/m-K)	Specific Heat (J/Kg-K)	Density (Kg/m^3)
Brick	0.62	800	1700
Plaster (Lightweight)	0.16	1000	600
RC	2.50	1000	2400
Glazing	1.00	750	2500
Double Glazing	Emissivity	Solar Absorptance	Visible Absorptance
	0.90	0.70	0.70
	SHGC		Visible Transmittance (VT)
	0.42		10%

3.4.3 Reference Case Modeling

Modeling the reference case was divided to three parts:

1- Modeling the repeated units.
2- Modeling the thermal study unit.
3- Assigning activity template and construction template for the units.

3.4.3.1 Modeling the Repeated Units

In design builder, a block was modeled containing an en-suite room and was cloned 35 times vertically shaping the 35 floors model.

3.4.3.2 *Modeling the Unit to Be Thermally Studied*

The reference case thermal study unit was modeled as per previous generic hotel bedroom design containing 3 zones which are the entrance, the bathroom and the bedroom. To lower down simulations' time, walls of bathroom and entrance zones were modeled to be thermally adiabatic and bathrooms zones are not included in thermal simulations. The modeled zones have the exact dimensions of the generic bedroom design. Figure 3-12 shows study model on DesignBuilder.

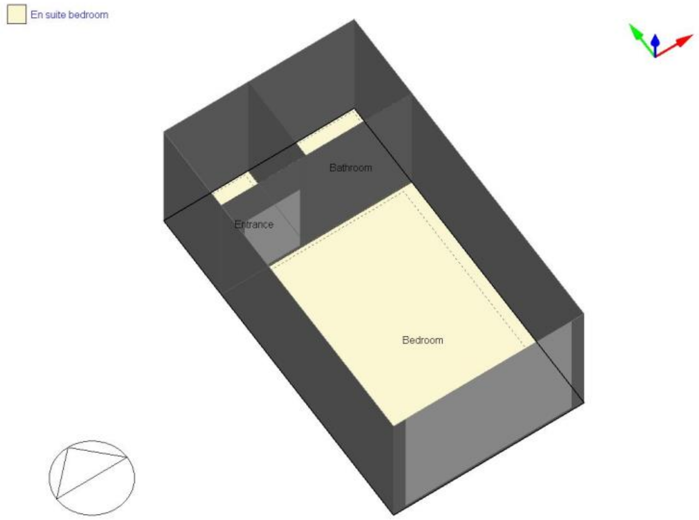


Figure 3-12- Model of Study Unit on DesignBuilder

The unit has three main elements:

Floors and ceilings: horizontal surfaces that separate units from each other.

Envelope: vertical surfaces that separate unit from the outside.

Partitions: Adiabatic vertical surfaces that separate between different zones.

The roof of the building is thermally insulated, and the last floor is simulated.

The building's exposure to wind option used in DesignBuilder simulations is normal (not sheltered nor exposed).

A 1 m chimney was added as shown in figure 3-13.

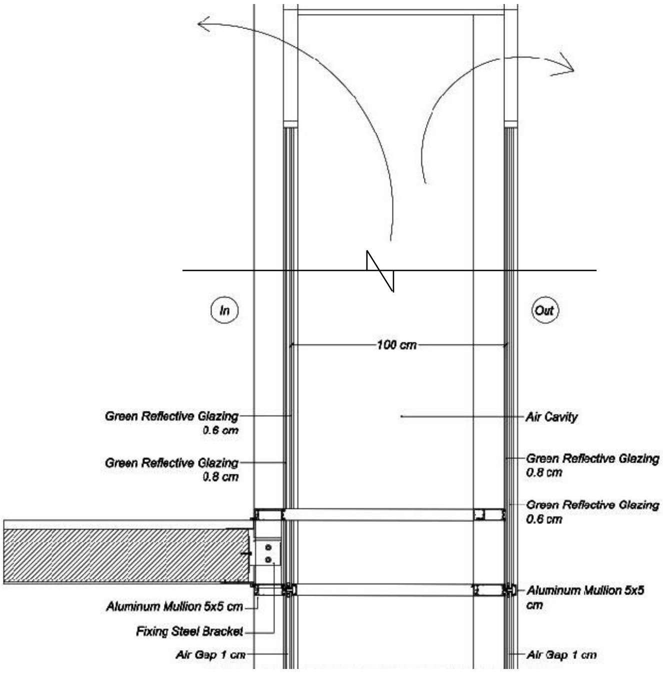


Figure 3-13- Chimney Detail

3.4.3.3 Unit Activity Template

The activity template set for the units is a typical hotel room activity template in DesignBuilder which is Hotel_EnsuiteBed_Occ. The typical density is set to 0.0556 people/m^2 and gain by TV (hotel bedroom equipment) is set to 3.15 W/m^2.

3.5 Choosing CFD Simulations' Floors

Three floors were chosen for simulation which are floor 5, 20 and 35. It was intended to check the performance of the techniques that will be used in chapter 4 on different floors at the beginning, middle and end of the building.

3.6 Thermal Simulation

In order to perform CFD simulations in design builder, a certain hour at a certain day needs to be determined. In order to determine the hours of study, thermal simulations were done on the reference case while openings are set to be open all time of the day to read the operative temperatures in the highest month of the year to choose certain study hours of day and night in the highest day.

Selecting CFD Simulation Hours:

August was found to have the highest temperature average which is the same as Cairo's temperature that is mentioned before (Figure 3-14).

Figure 3-14- Average Site Year Temperature

Thermal simulations were carried on again, but for the month of August to detect the highest day in South orientation which is the extreme condition for operative temperatures. The simulations were carried on the three chosen floors which are floor number 5, 20 and 35. The three floors showed that the temperature at the 23rd of August is the highest with 33.78 °C, 33.37 °C and 33.39 °C, operative temperatures respectively.

Further simulations were carried out on the full model to determine operative temperatures at different times of 23rd of August to determine the highest hours of the day in the four orientations (Figure 3-15).

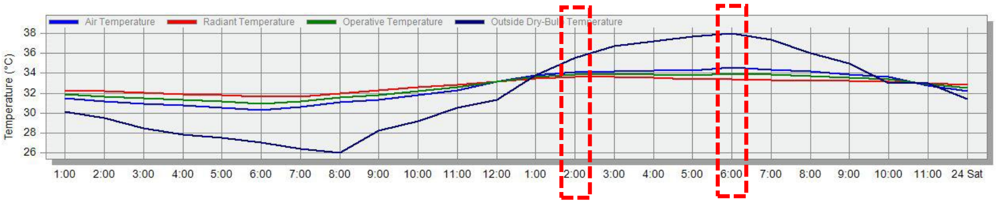


Figure 3-15- Temperature Records on the 23rd of August in South Orientation

In South orientation, the highest recorded operative temperatures at day and night were 33.89°C at 2 PM and 33.96°C at 6 PM (Figure 3-16).

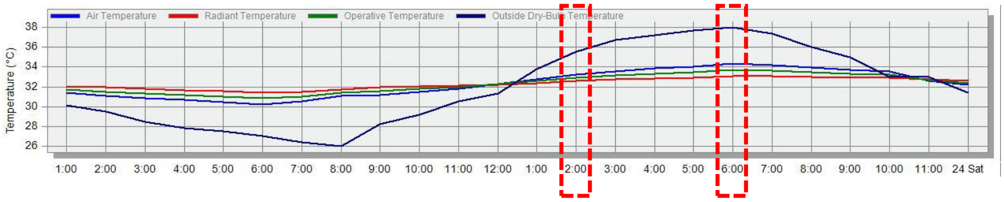


Figure 3-16- Temperature Records on the 23rd of August in North Orientation

In North orientation, the highest recorded operative temperatures at day and night were 33.27°C at 2 PM, 34°C at 5 PM and 33.73°C at 6 PM (Figure 3-17).

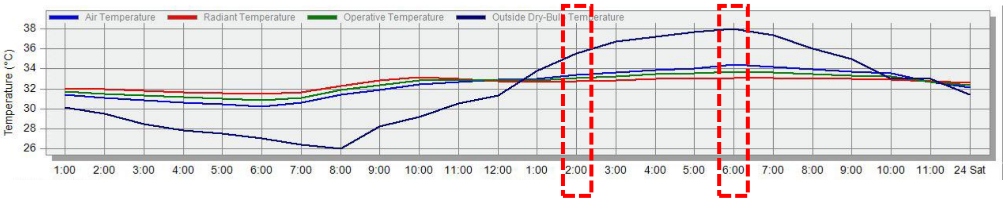


Figure 3-17- Temperature Records on the 23rd of August in East Orientation

In East orientation, the highest recorded operative temperatures at day and night were 33.05°C at 2 PM and 33.74°C at 6 PM (Figure 3-18).

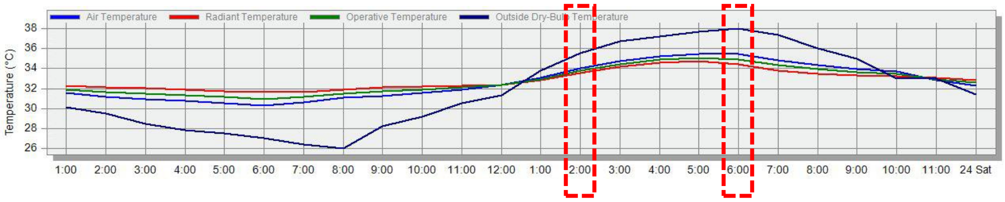


Figure 3-18- Temperature Records on the 23rd of August in West Orientation

In West orientation, the highest recorded operative temperatures at day and night were 33.79°C at 2 PM, 35.07°C at 5 PM and 34.93°C at 6 PM.

The results show that operative temperature in East orientation is lower than in North orientation. This could be resulted from wind coming from North-East that helps in changing air continuously inside the space.

Difference between 5 PM and 6 PM temperatures in North orientation equals 0.007941% and in West orientations the difference is 0.003992%. These differences are not significant and could be neglected. Thus, the main chosen simulation hours are 2 PM and 6 PM.

Two more simulation hours were chosen, at day and night for assurance of simulations' results and for precise results which are 7:00 AM (31.66 °C) and 11:00 PM (33.91 °C).

Table 3-3- Chosen Simulation Hours for the Study

Chosen Simulation Hours in the 23rd of August	
At Day	2:00 PM
At Night	6:00 PM

3.7 CFD Simulation

Simulations in this study will be conducted on:

1- Case 1: Reference case (Single Skin Façade).
2- Case 2: Applying the shaft-box type naturally ventilated wall to the space.
3- Case 3: Integrating shading devices with naturally ventilated wall (shading slats near external skin).
4- Case 4: Integrating shading devices with naturally ventilated wall (shading slats near internal skin).

Vertical slicing planes were used in the study to show the output of the whole room. For standardization, in the whole study, three slice planes will be placed perpendicular to the main study-façade and at the middle of each of evenly divided three sectors.

The simulations were conducted while the main wall faces the four orientations and in two different times (2 PM and 6 PM) according to scope limitations.

In this chapter, simulations will be conducted on reference case only and the results will be kept for evaluating the other two designs later.

Simulations Considerations:

While carrying out simulations, it is important to consider some points:

1- Any un-balanced air flow should be corrected in order to ensure mass balance in the simulation. This means that total flow in and out must balance.
2- CFD grid must be reset in each case.
3- After CFD simulation, comfort calculations and local mean age of air have to be performed and calculated for results completion.
4- Calculations convergence is a must for simulation results approval.

3.8 Evaluation Criteria and Measurement Units

To compare the results of the reference case and the applied techniques in the research, CFD simulations were carried out on the hotel room in the three floors (5, 20 and 35). Simulations were done on South, East, West and North orientations. The results of the simulations were operative temperature (OT) air velocity (AV) and age of air (AOA) which will judge thermal performance, air flow rate and indoor air quality (IAQ) respectively of the three design options.

The case which has the lowest mean OT, highest mean AV and lowest mean AOA will be considered better in terms of thermal comfort and ventilation rates. When the operative temperature is lowered down by 1.5 °C or more it will be considered significantly enhanced and when AV reaches 0.8 m/s or higher it will be considered significantly enhanced. Also, if AOA is lowered down by 50 s or more the result will be considered significantly enhanced.

Table 3-4 shows study outputs definitions, standards and measurement units.

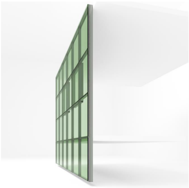
Table 3-4- Study Outputs' Definitions, Standards and Measurement Units

Average OT	Average AV	Average AOA
Definition		
A uniform temperature of an imaginary black enclosure in which an occupant would exchange	Mean speed of the air.	The average time that air spends in a space.

the same amount of heat by radiation plus convection as in the actual non-uniform environment.		
ASHRAE Standard 55		
Temperature in summer should range between 22.5 °C and 26 °C.	0.8 m/s.	-
Measurement Units		
Celsius Degrees (°C)	m/s	Seconds (s)

3.9 **CFD Simulations Results for Reference Case**

CFD simulations were done for the reference case and the inputs for all simulations in this research including surface temperatures, wind direction and wind velocity were imported from energy plus thermal simulation results by importing boundary conditions option in designbuilder.



3.9.1 CFD Simulation Results for Reference Case at 2 PM

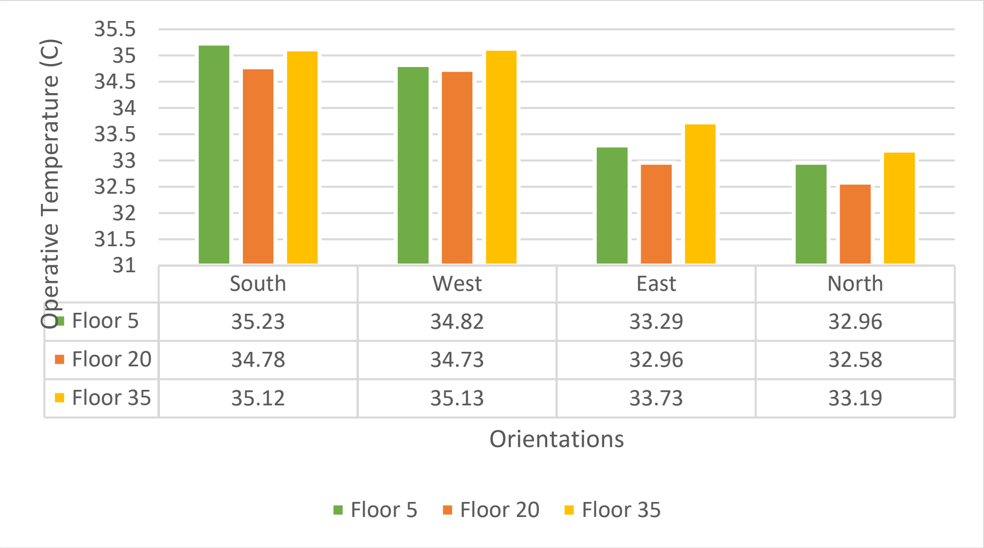


Figure 3-19- Average Operative Temperatures in Reference Case at 2 PM in C°

The results of average OT at 2 PM show that all of the 4 orientations fall far from thermal comfort zone by at least 5.79 C° at North and East and a maximum of 9.23 C° at South.

Overall, North façade had the lowest average OT followed by East, West and South respectively.

Overall, floor 35 had the highest average OT followed by floors 5 and 20 respectively. This could be a result of direct exposure to solar gain in floor 35 and lower insulation compared to floor 20.

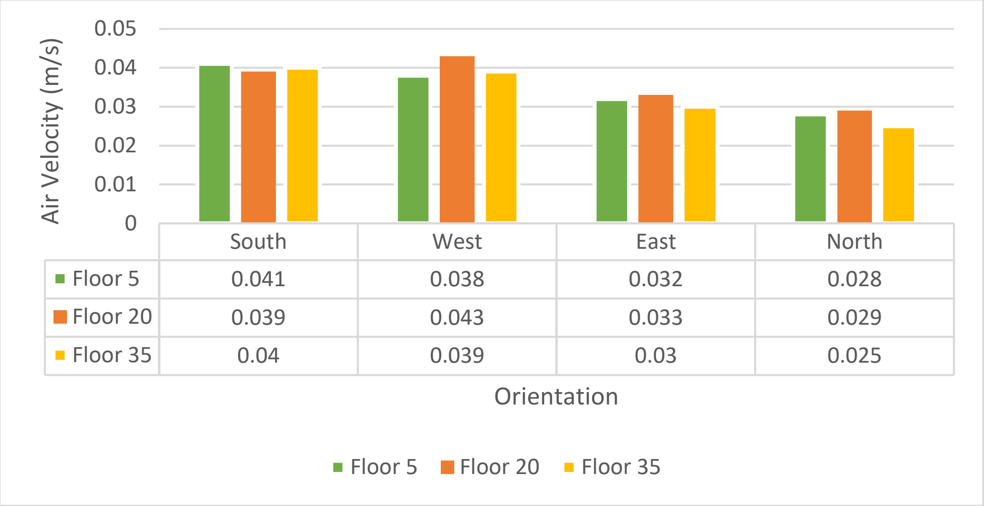
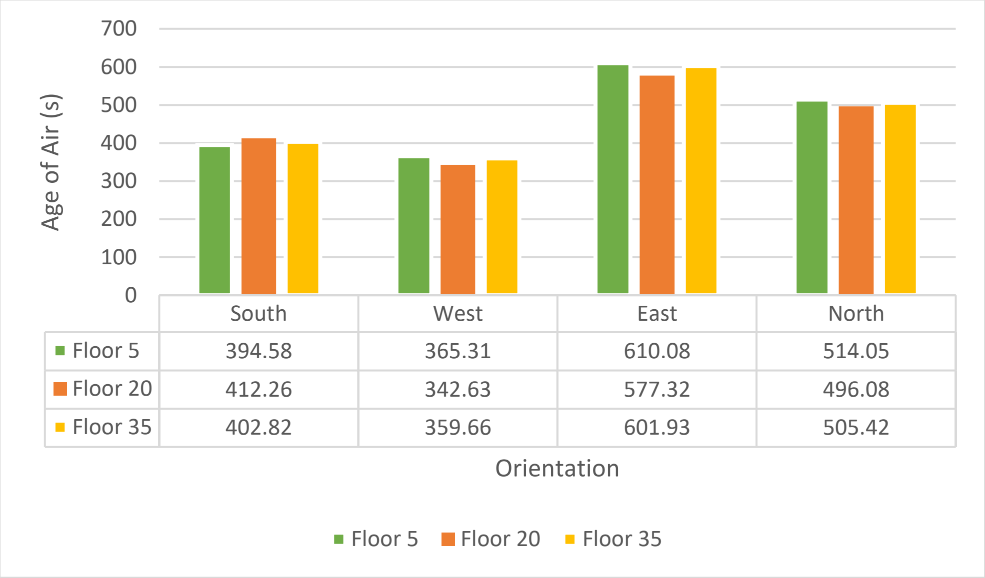


Figure 3-20 Average Air Velocities in Reference Case at 2 PM in m/s

West orientation showed the closest range of average AV to comfort level (0.05 m/s) with a minimum of 0.039 m/s and a highest value of 0.043 m/s. South façade results were higher than East and North which showed the worst average AV among the 4 facades with a highest average AV value of 0.029 m/s.

Overall, floor 5 had the highest average AV followed by floor 20 and 35 respectively except in North and East orientations where floor 20 had the highest average AV followed by floors 5 and 35 respectively.



	South	West	East	North
🟩 Floor 5	394.58	365.31	610.08	514.05
🟧 Floor 20	412.26	342.63	577.32	496.08
🟨 Floor 35	402.82	359.66	601.93	505.42

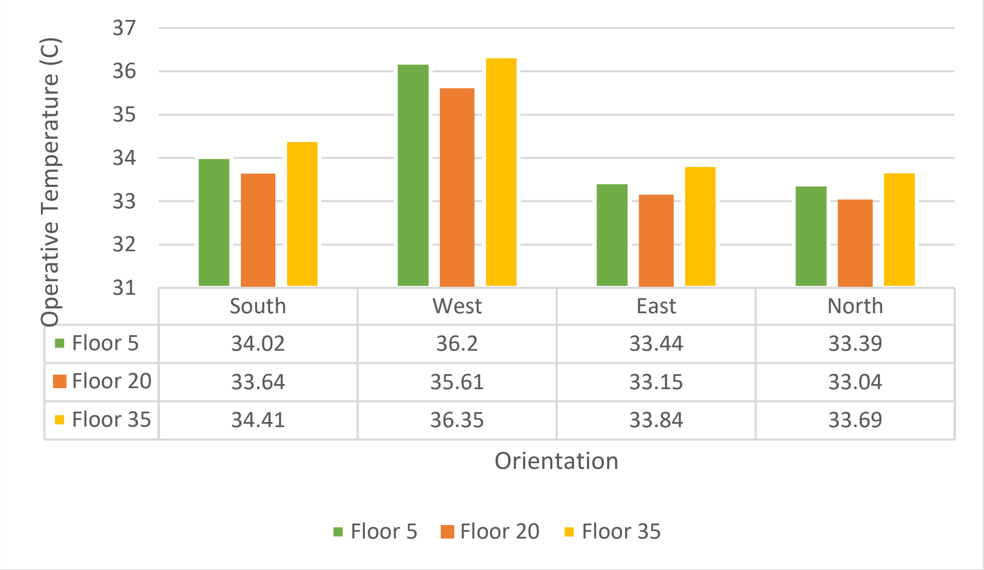
Figure 3-21 Average Age of Air in Reference Case at 2 PM in Seconds

In terms of average AOA, West façade showed better results followed by South, North and East facades respectively. The difference between East and West façade could reach 244.77 seconds.

In South, East and North facades the difference between the 3 floors was not significant while in West façade floor 35 had the highest average AOA. Yet, floors 5 and 20 in West façade did not show a significant difference.

Overall, the reference case is considered to have high average AOA values in the 4 orientations.

3.9.2 CFD Simulation Results for Reference Case at 6 PM



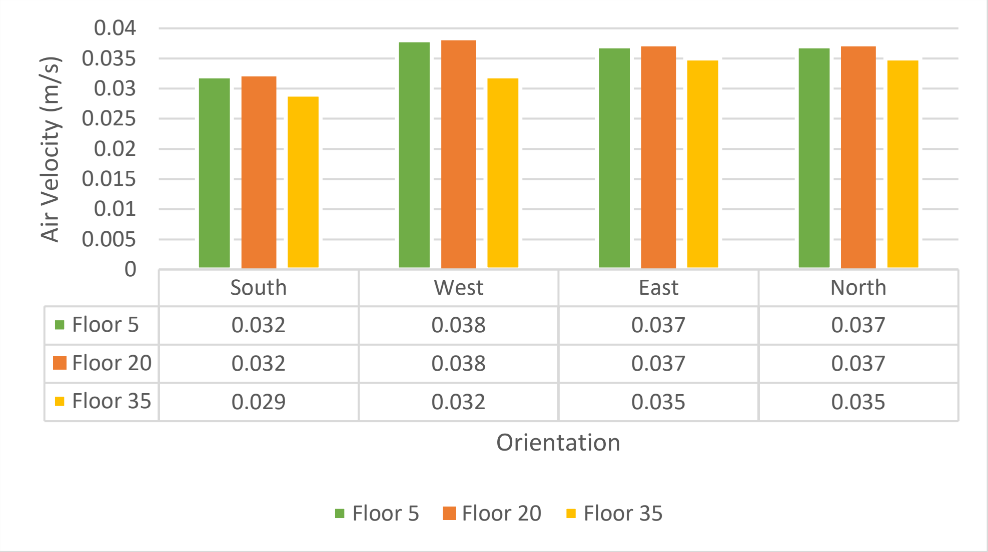
	South	West	East	North
🟩 Floor 5	34.02	36.2	33.44	33.39
🟧 Floor 20	33.64	35.61	33.15	33.04
🟨 Floor 35	34.41	36.35	33.84	33.69

Figure 3-22 Average Operative Temperatures in Reference Case at 6 PM in C°

The results of average OT at 6 PM show that all of the 4 orientations fall far from thermal comfort zone by at least 7.04 C° at West and a maximum of 10.53 C° at South.

Overall, North façade had the lowest average OT followed by East, West and South respectively.

Overall, floor 35 had the highest average OT followed by floors 5 and 20 respectively.



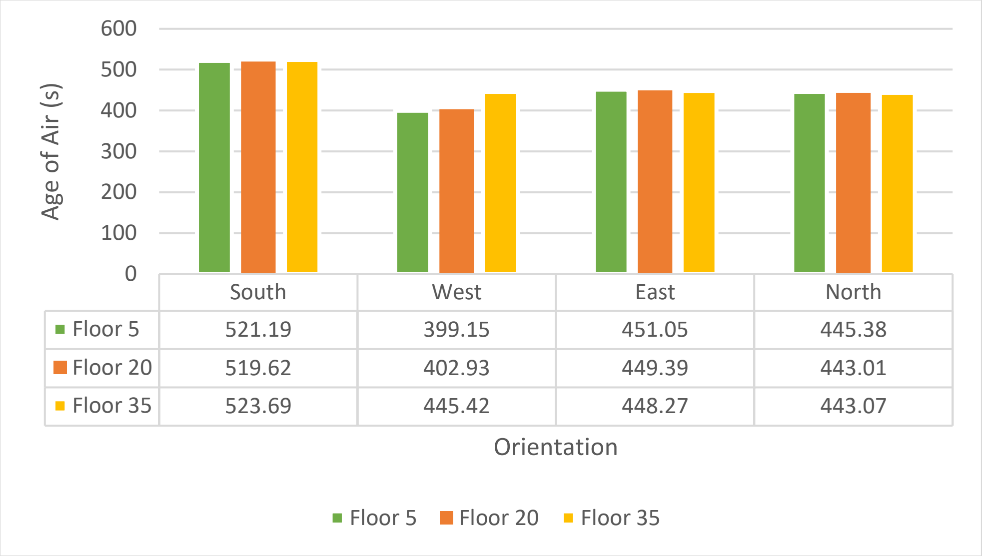
	South	West	East	North
🟩 Floor 5	0.032	0.038	0.037	0.037
🟧 Floor 20	0.032	0.038	0.037	0.037
🟨 Floor 35	0.029	0.032	0.035	0.035

Figure 3-23 Average Air Velocities in Reference Case at 6 PM in m/s

West orientation showed the closest range of average AV to comfort level with a minimum of 0.032 m/s and a highest value of 0.038 m/s. Both North and East facades almost had the same results of average AV with a minimum value of 0.035 m/s and a maximum value of 0.037 m/s.

South façade had the lowest average AV with a lowest value of 0.029 m/s and a highest value of 0.032 m/s. Overall, the four orientations showed a lower value comparing to comfort level.

Floors 5 and 20 almost had the same results (highest) while floor 35 had the lowest value of average AV in all orientations.



	South	West	East	North
🟩 Floor 5	521.19	399.15	451.05	445.38
🟧 Floor 20	519.62	402.93	449.39	443.01
🟨 Floor 35	523.69	445.42	448.27	443.07

Figure 3-24 Average Age of Air in Reference Case at 6 PM in Seconds

In terms of average AOA, West façade showed better results followed by North, East and South facades respectively. The difference between East and North façade was not significant. While the difference between West and South could reach 122.04 s.

In South, East and North facades the difference between the 3 floors was not significant while in West façade floor 35 had the highest average AOA. Yet, floors 5 and 20 in West façade did not show a significant difference.

Overall, the reference case is considered to have high average AOA values in the 4 orientations.

3.10 Summary and Conclusion

The chapter discussed Cairo’s climate which is classified as semi-desert climate.

Selection of CFD simulations software was discussed as well whereas Designbuilder V 4.6.015 was chosen and the validation of the software was discussed.

After that, modeling the reference case on designbuilder was discussed. The reference case an internal bathrooms generic plan arrangement for a hotel room with a single skin glazing facade. The room’s specifications, materials and thermal characteristics were illustrated in this chapter before doing thermal simulations for choosing certain hours for CFD analysis.

Three floors were selected for simulation which are floors 5, 20 and 35. And then, thermal simulations were done for choosing the month with the highest temperature (August). And then further simulations were done to choose certain hours for CFD simulations. The results showed that 2 PM and 6 PM showed the highest OT at day and night respectively.

The chapter ends by showing results of CFD simulations for floors 5, 20 and 35 and comparing the results of operative temperature, age of air and air velocity in South, West, East and North at 2 PM and 6 PM.

The results of CFD simulations showed that thermally, the reference case was falling out of thermal comfort zone where a maximum value of 9.23 C° was the difference between South orientation's average OT and the value needed to reach the comfort zone at 2 PM. The minimum difference could reach 5.79 C° to reach the comfort zone at North at 2 PM.

The results also showed that average AV was low overall in all orientations. Also, age of air results were relatively high in all orientation.

On the other hand, comparing between floors showed that floor 35 always had the highest average OT followed by floor 5 and floor 20. While average AV results showed that floor 20 had the highest average AV followed by floors 5 and 35 respectively. AOA results showed that floor 35 had the highest average AOA in West façade while floors 5 and 20 in West façade did not show a significant difference. Overall, average AOA was not affected by floors.

The results of this chapter will be used later in chapter four to compare between the reference case's results and the results of naturally ventilated wall technique and results of integrating shading devices with naturally ventilated wall.

▪ Chapter 4 – CFD Simulations’ Results

- Introduction
- Naturally Ventilated Wall Specifications
- Naturally Ventilated Wall CFD Simulations’ Results
- Integration of Shading Devices with Naturally Ventilated Wall Specifications
- Integration of Shading Devices with Naturally Ventilated Walls Simulations’ Results
- Summary and Conclusion

Chapter 4 – CFD Simulations' Results

4.1 Introduction

In chapter 4, simulation results of the application of naturally ventilated wall and integration of shading devices with naturally ventilated wall are discussed.

Three cases are introduced which are:

Case 2: Applying naturally ventilated wall.

Case 3: Integration of shading devices with naturally ventilated wall (shading devices near external skin).

Case 4: Integration of shading devices with naturally ventilated wall (shading devices near internal skin).

At first, specifications of naturally ventilated wall will be discussed showing the geometry and materials used. Then, simulations' results will be shown. After that, specifications of shading devices integrated with naturally ventilated walls will be discussed and two proposals will be studied where shading devices are near the inner glazing layer at one proposal and near the outer glazing layer in the other. At last, results of the three alternatives are be discussed. The openings used in the study were open 24 hours and used as air inlets and outlets at the same time. Figure 4-1 shows simulations stages conducted in this chapter.

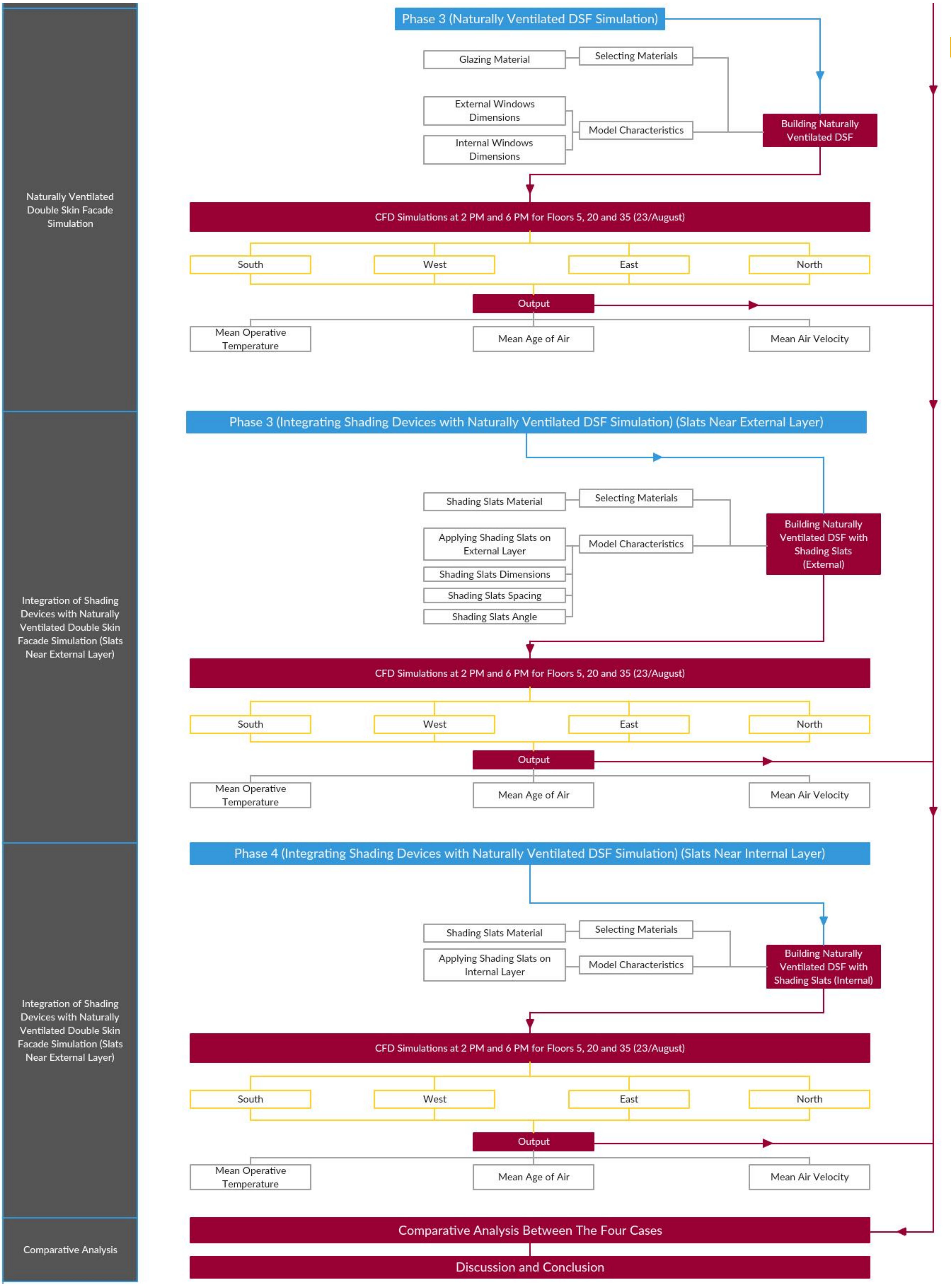


Figure 4-1 Simulation Phases Diagram

4.2 Naturally Ventilated Wall's Specifications

In this part of simulations, a naturally ventilated double skin façade will replace the curtain wall used in the reference case.

4.2.1 Naturally Ventilated Wall Geometry:

As per chapter two's summary chosen double skin façade geometry will be of 1 m depth and a 1 m chimney will be added at the top.

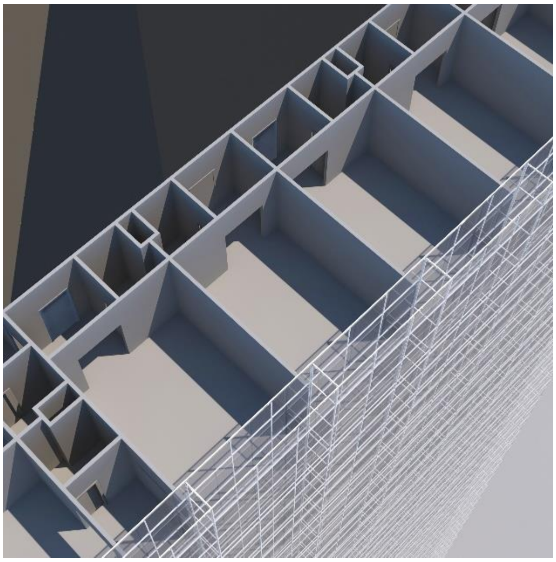


Figure 4-2- Perspective of the Repeated Rooms in a Shaft-Box Type Naturally Ventilated Wall (Left) and Repeated Thermal Study Unit – Typical Floor No. 35 (Right)

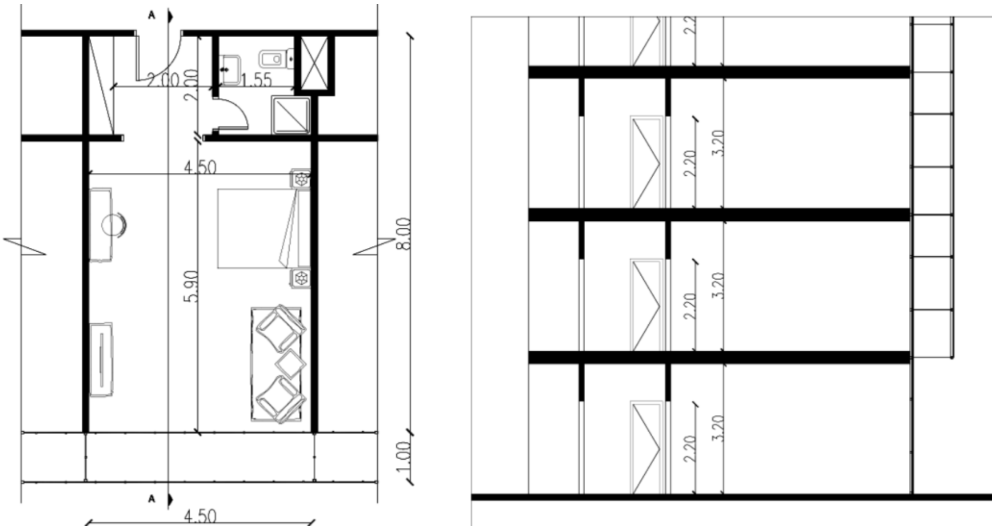


Figure 4-3 Plan of Naturally Ventilated Wall Case (Left) and Section (A-A) Passing through Plan (Right)

4.2.2 Naturally Ventilated Wall Parameters:

Parameters in all simulations in this chapter are exactly the same as the data used in the reference case's simulations.

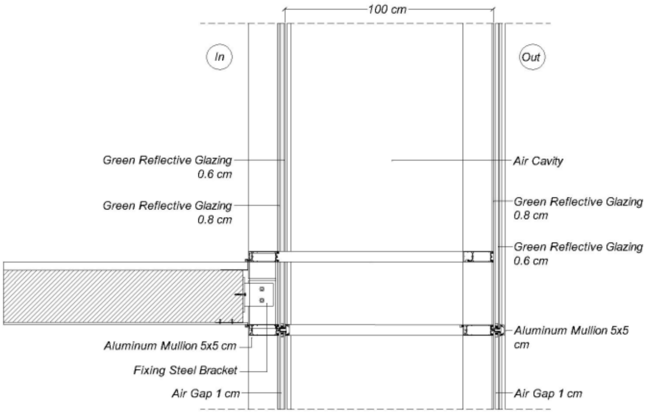
The difference lies in adding the same openings parameters to the inner and outer layer as the ones used in the curtain wall in the previous chapter. The air enters the room and exits it through the same opening. Figure 4-4 shows naturally ventilated wall model used in the study.

Figure 4-4- Model of Naturally Ventilated Wall Used in Research

4.2.3 Unit Materials' Template:

The materials assigned to the naturally ventilated wall model are shown in table 4-1. The glazing found in the table is the commonly used glazing type in hotel buildings in Egypt. Walls, partitions, plaster and floor materials are the same as the ones used in chapter three for the reference case.

Table 4-1- Description of Naturally Ventilated Wall Material

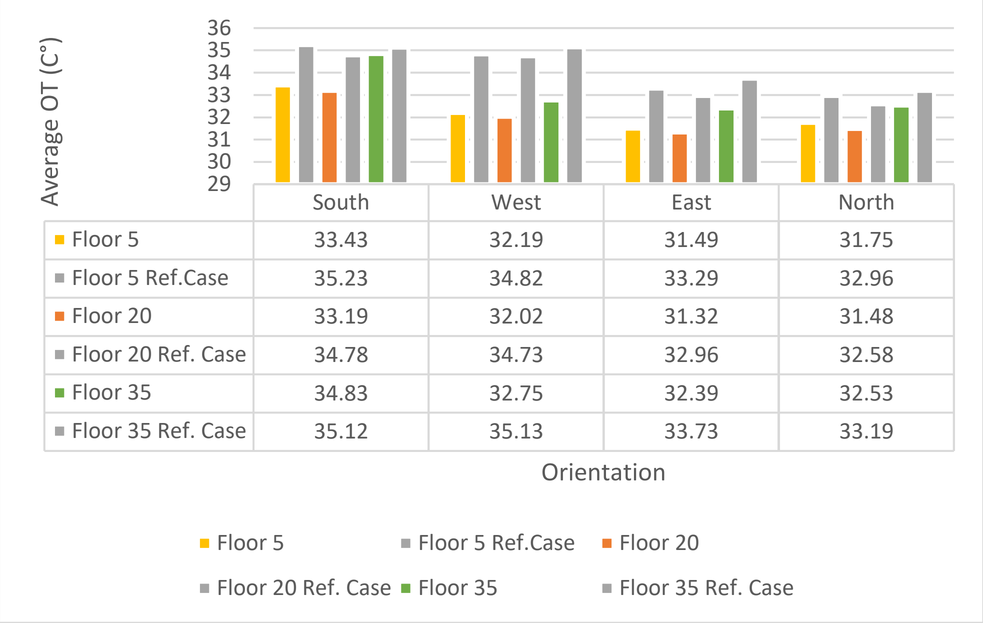
Element	Description	Detail
Naturally Ventilated Wall Glazing Layer	***Type:*** Two layers of reflective double glazed curtain wall separated by 1 m air cavity. ***Layers:*** 0.6 cm reflective glass, 1 cm air, 0.8 cm reflective glass.	 *Figure 4-5- Naturally Ventilated Wall Detail*

Element	Conductivity (W/m-K)	Specific Heat (J/Kg-K)	Density (Kg/m^3)
Glazing	1.00	750	2500
Double Glazing	Emissivity %	Solar Absorptance	Visible Absorptance
	0.90	0.70	0.70

4.3 CFD Simulations Results for Naturally Ventilated Wall (Case 2)

CFD simulations were done for the naturally ventilated wall model and the results of the simulations are shown in the following figures.

4.3.1 CFD Simulations Results for Naturally Ventilated Wall at 2 PM



	South	West	East	North
Floor 5	33.43	32.19	31.49	31.75
Floor 5 Ref.Case	35.23	34.82	33.29	32.96
Floor 20	33.19	32.02	31.32	31.48
Floor 20 Ref. Case	34.78	34.73	32.96	32.58
Floor 35	34.83	32.75	32.39	32.53
Floor 35 Ref. Case	35.12	35.13	33.73	33.19

Figure 4-6 Average Operative Temperatures in Case 2 at 2 PM in °C

The results of average OT at 2 PM show that all of the 4 orientations fall far from thermal comfort zone by a maximum of 8.83 °C at South. Also, the minimum required OT to reach comfort zone is 5.32 °C which is higher than reference case. However, average OT was decreased generally in case 2 when compared to case 1. It could be reduced by 2.74 °C for example in floor 35 in Western facade.

The result could be due to airflow that moves inside the cavity which could lift the hot air up outside the chimney and exchange it with cooler air. This process didn't occur when single skin façade was used.

Overall, East façade had the lowest average OT followed by North, West and South respectively at 2 PM.

Overall, floor 35 had the highest average OT followed by floors 5 and 20 respectively.

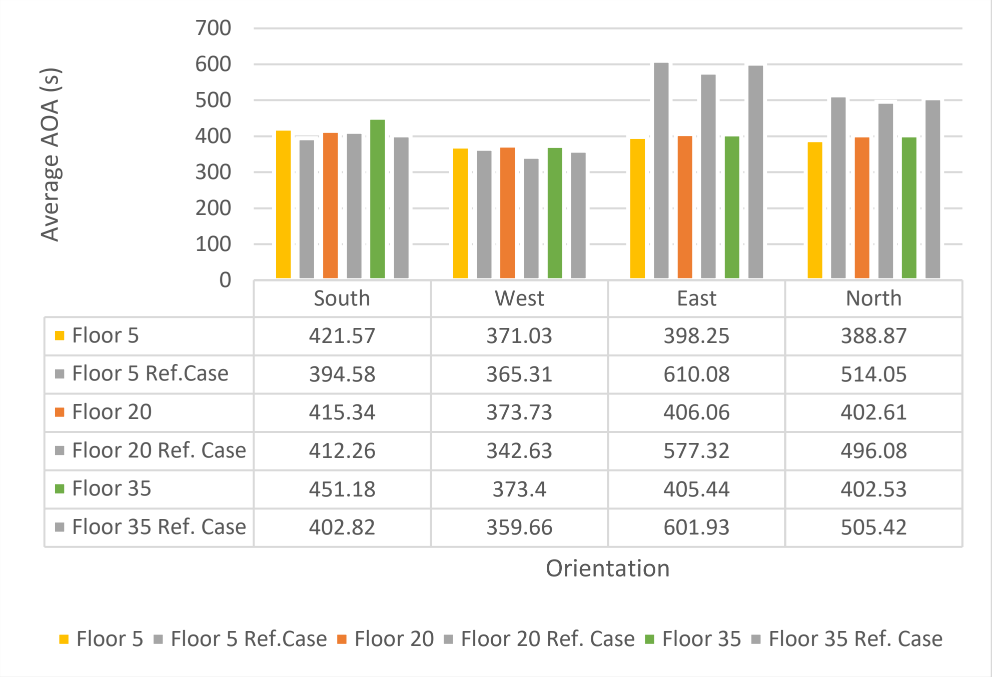
	South	West	East	North
Floor 5	0.03	0.04	0.037	0.038
Floor 5 Ref.Case	0.041	0.038	0.032	0.028
Floor 20	0.031	0.04	0.036	0.037
Floor 20 Ref. Case	0.039	0.043	0.033	0.029
Floor 35	0.024	0.038	0.033	0.034
Floor 35 Ref. Case	0.04	0.039	0.03	0.025

Figure 4-7- Average Air Velocities in Case 2 at 2 PM in m/s

Case 2 could not show enhancement in air flow rates in any orientations at 2 PM. West façade had the highest operative AV followed by North and South respectively for which the difference was not significant. The highest recorded average AV value was 0.038 at North and West while the lowest recorded value was 0.024 at South.

Overall, floor 5 had the highest average AV followed by floor 20 and 35 respectively.

However, air velocities are very low due to low speed of air coming from outside which means that air speed is not enough to make the double skin façade function as it should.



	South	West	East	North
🟨 Floor 5	421.57	371.03	398.25	388.87
◼ Floor 5 Ref.Case	394.58	365.31	610.08	514.05
🟧 Floor 20	415.34	373.73	406.06	402.61
◼ Floor 20 Ref. Case	412.26	342.63	577.32	496.08
🟩 Floor 35	451.18	373.4	405.44	402.53
◼ Floor 35 Ref. Case	402.82	359.66	601.93	505.42

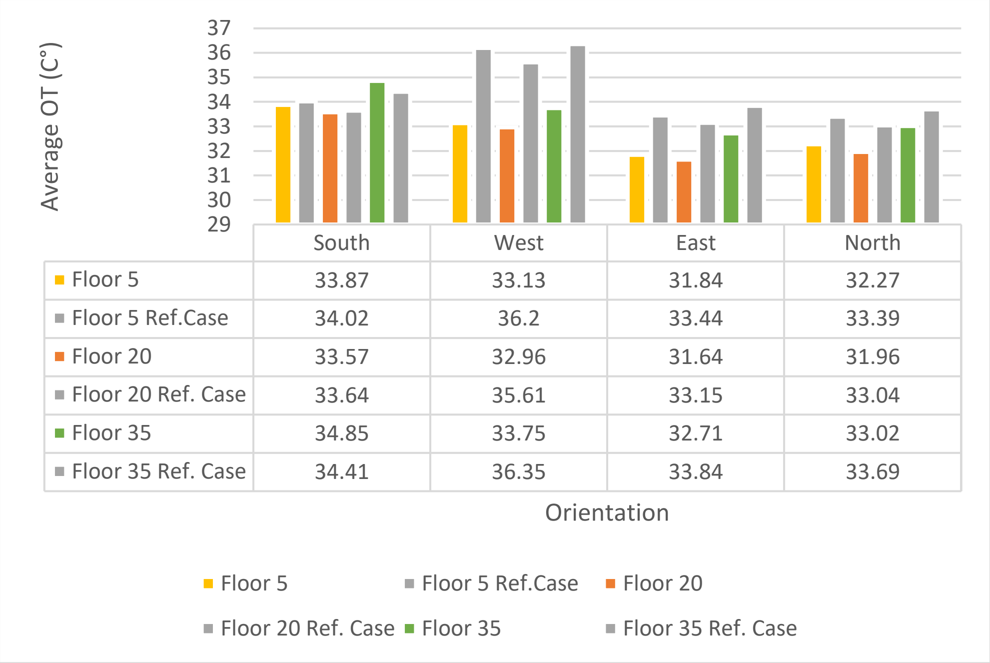
Figure 4-8 Average Age of Air in Case 2 at 2 PM in Seconds

In terms of average AOA, West façade showed better results followed by North, East and South facades respectively. The difference between East and North façade was not significant.

Compared to case 1, case 2 had better results in terms of average AOA at 2 PM in North and East facades where the difference could reach 211.83 seconds in East façade at floor 5.

In the 4 orientations, the difference between the 3 floors was not significant.

4.3.2 CFD Simulations Results for Naturally Ventilated Wall at 6PM



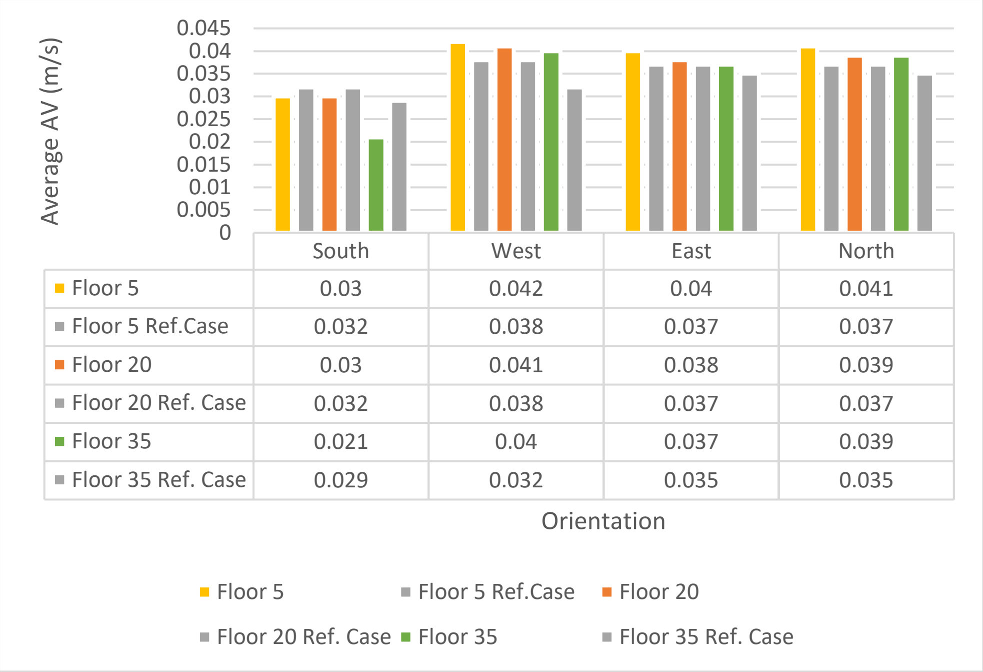
	South	West	East	North
Floor 5	33.87	33.13	31.84	32.27
Floor 5 Ref.Case	34.02	36.2	33.44	33.39
Floor 20	33.57	32.96	31.64	31.96
Floor 20 Ref. Case	33.64	35.61	33.15	33.04
Floor 35	34.85	33.75	32.71	33.02
Floor 35 Ref. Case	34.41	36.35	33.84	33.69

Figure 4-9 Average Operative Temperatures in Case 2 at 6 PM in °C

The results of average OT at 6 PM show that all of the 4 orientations fall far from thermal comfort zone by a maximum of 8.85 °C at South. Also, the minimum required OT to reach comfort zone is 5.64 °C which is lower by 1.40 °C than reference case at East. However, average OT was decreased generally in case 2 when compared to case 1. It could be reduced by 2.62 °C for example in floor 35 in Western facade.

Overall, East façade had the lowest average OT followed by North, West and South respectively.

Overall, floor 35 had the highest average OT followed by floors 5 and 20 respectively.



	South	West	East	North
Floor 5	0.03	0.042	0.04	0.041
Floor 5 Ref.Case	0.032	0.038	0.037	0.037
Floor 20	0.03	0.041	0.038	0.039
Floor 20 Ref. Case	0.032	0.038	0.037	0.037
Floor 35	0.021	0.04	0.037	0.039
Floor 35 Ref. Case	0.029	0.032	0.035	0.035

Figure 4-10 Average Air Velocities in Case 2 at 6 PM in m/s

Case 2 could not show a significant enhancement in air flow rates in all orientations at 6 PM. West façade had the highest operative AV followed by North and South respectively for which the difference was not significant. The highest recorded average AV value was 0.42 at West while the lowest recorded value was 0.021 at South.

Overall, the difference between floors was not significant in all orientations except South where floor 35 has a lower average AV compared to floor 5 and 20 which are almost equal.

	South	West	East	North
Floor 5	416.81	346.47	359.76	360.02
Floor 5 Ref.Case	521.19	399.15	451.05	445.38
Floor 20	427.24	345.86	379.47	372.6
Floor 20 Ref. Case	519.62	402.93	449.39	443.01
Floor 35	523.48	345.96	366.91	357.3
Floor 35 Ref. Case	523.69	445.42	448.27	443.07

Figure 4-11 Average Age of Air in Case 2 at 6 PM in Seconds

The four orientations showed enhancement in IAQ as their results were lower than reference case's results. The difference in average AOA between case 2 and case 1 could reach a maximum value of 104.38 seconds in floor 5 at South façade.

However, South façade had higher average AOA value when compared to the three other orientations which didn't have a significant difference between one and the other.

In the 4 orientations, the difference between the 3 floors was not significant except for South orientation where floor 35 had a higher average AOA value than floors 20 and 35. The difference could reach 106.67 seconds.

<u>Naturally Ventilated Wall (Case 2) Results' Discussion:</u>

The results of applying naturally ventilated wall shows significant enhancement in average operative temperature in all orientations.

West Orientation had the highest average OT difference at 6 PM (3.07°C) and also at 2 PM (2.71°C). South orientation had the lowest average OT difference at 2 PM (0.29 °C) and lowest average OT difference at 6 PM (0.07 °C). The reason for this could be the air current coming mainly from the North, North West and North East sides which leads to air movement in the cavity by the stack effect. Also, the highest reduction in average OT happened in the fifth floor, followed by the 20th floor and then 35th floor. The reason for this could be the exposure of the 20th and 35th floor to the direct solar gain leading to overheating phenomenon where there are no high-rise buildings surrounding the building. Also, floor 5 is the closest to airflow coming from the bottom of the DSF.

Regarding AOA, North and East orientations had positive results where average AOA decreased by an amount as high as 211 second in the East orientation while the average at 2 PM was around 170 seconds and at 6 PM around 70 seconds. The reason for this can be the difference in OT between inside the room and outside it at 2 PM which is higher than the difference at 6 PM. This could lead to air movement which also recorded the highest velocity difference which is 0.009 m/s in East orientation.

On the other hand, West and South orientations read negative results regarding average AOA and average AV records where the highest average AOA difference was recorded at the West orientation where it increased by 177.55 s and also mean AV difference decreased at the West orientation by 0.06 m/s.

Overall, North orientation had the lowest average OT among the four orientations followed by East, West and South respectively. And regarding average AOA, west orientation had the lowest average AOA followed by North, East and South respectively. The same order of average AOA results regarding orientations was recorded for average AV, which was the highest at West followed by North, East and South respectively.

4.4 Shading Devices Specifications

In this part of simulations, aluminum shading devices will be introduced to the cavity of the naturally ventilated wall. Two cases will be simulated. One with shading devices placed 25 cm far from the external glazing and the other with shading devices placed 25 cm far from the internal glazing. Figures 4-12 and 4-13 show the models of naturally ventilated walls with shading slats near outer skin and inner skin respectively.

Figure 4-12- Model of Naturally Ventilated Wall with Shading Slats near Outer Skin

Figure 4-13- Model of Naturally Ventilated Wall with Shading Slats near Inner Skin

4.4.1 Shading Devices Geometry

The slats used in simulations are horizontally oriented. Their dimensions are 40 cm (width) x 5 cm (thickness). Slats separation is 25 cm and slat angle is 90 degrees. The blind to glass distance is 25 cm.

The 24 cm separation distance was chosen based on sun angle in the 23rd of August at 4 PM which is 31 degrees as the sun's radiation strength will start to lower down after that. The sun at 4 PM will be at the South-West direction, and in case of earlier hours, the sun angle will be bigger, and its rays will be prevented from passing by the shading systems.

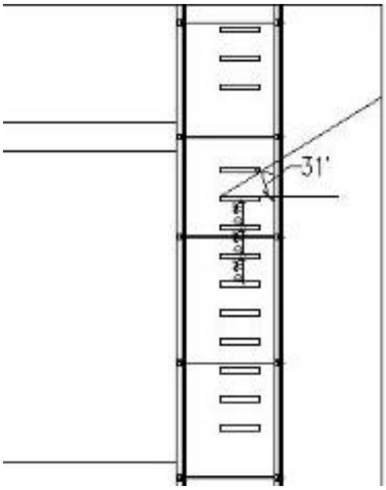


Figure 4-14- Shading Devices Separation Distance Study

4.4.2 Shading Devices Modeling

Shading Devices' Material Template:

The materials assigned to the reference case model are shown in table 4-4. The materials found in the table are the commonly used materials in hotel buildings in Egypt.

Table 4-2- Description of Shading Devices' Material

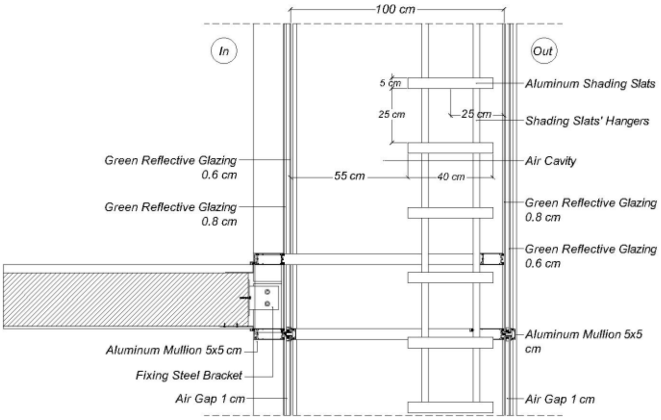
<table>
<tr><th>Element</th><th>Description</th><th>Detail</th></tr>
<tr><td>Shading Devices</td><td>Aluminum Slats (0.4x0.05m)</td><td>


Figure 4-15- Case 3 (Near Outer Glazing)

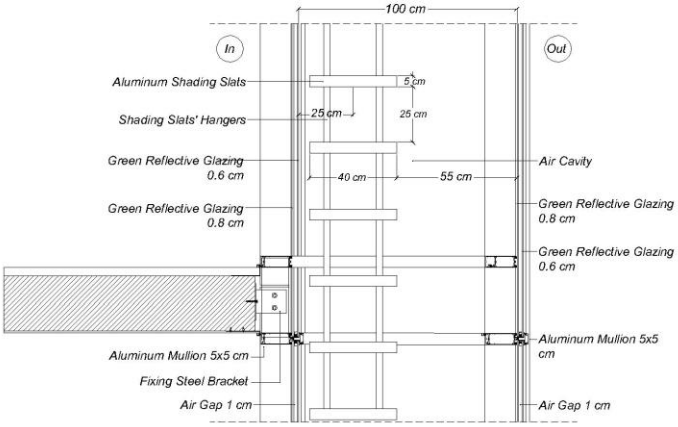


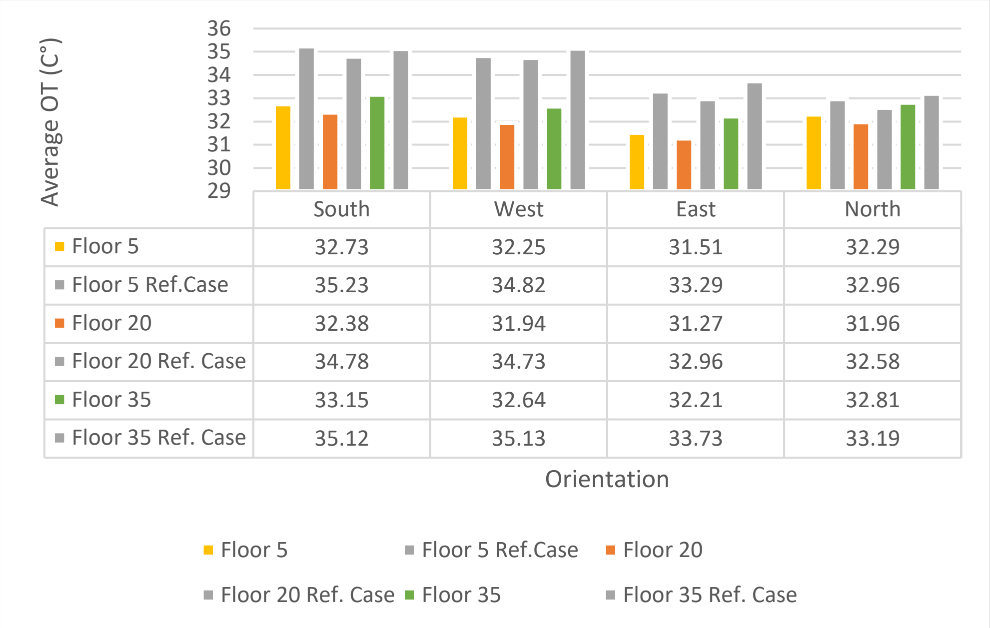
Figure 4-16- Case 4 (Near Inner Glazing)
</td></tr>
</table>

Element	Conductivity (W/m-K)	Solar Radiation Index (SRI)	Material
Shading Slats	0.90	0.80	Aluminum

4.5 CFD Simulations Results for Integration of Shading Devices with Naturally Ventilated Wall (Case 3)

CFD simulations were done for the case of integrating shading devices with naturally ventilated wall where shading slats are 25 cm far from the external glazing layer. The results are shown in this section for different floors and different orientations.

CFD Simulations Results for Integrating Shading Devices with Naturally Ventilated Wall (Case 3) at 2 PM



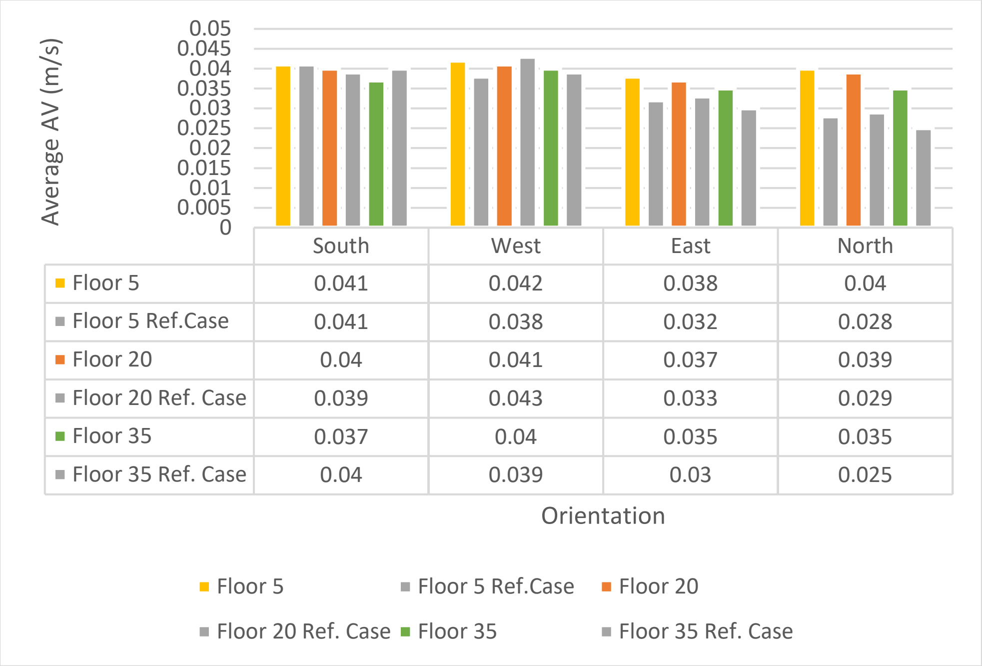
	South	West	East	North
🟨 Floor 5	32.73	32.25	31.51	32.29
⬜ Floor 5 Ref.Case	35.23	34.82	33.29	32.96
🟧 Floor 20	32.38	31.94	31.27	31.96
⬜ Floor 20 Ref. Case	34.78	34.73	32.96	32.58
🟩 Floor 35	33.15	32.64	32.21	32.81
⬜ Floor 35 Ref. Case	35.12	35.13	33.73	33.19

Figure 4-17 Average Operative Temperatures in Case 3 at 2 PM in C°

The results of average OT at 2 PM show that all of the 4 orientations fall far from thermal comfort zone by a maximum of 7.15 °C at South (lower than case 2 (1.68 °C)). Also, the minimum required OT to reach comfort zone is 5.27 °C which is lower than case 2. However, average OT was decreased generally in case 3 when compared to case 2. It could be reduced by 1.68 °C for example in floor 35 in Southern facade.

Overall, East façade had the lowest average OT followed by West, North and South respectively.

Overall, floor 35 had the highest average OT followed by floors 5 and 20 respectively. This result could reflect the high exposure to direct solar gain in case of floor 35 while floor 5's temperature is high due to gaining heat from surroundings.

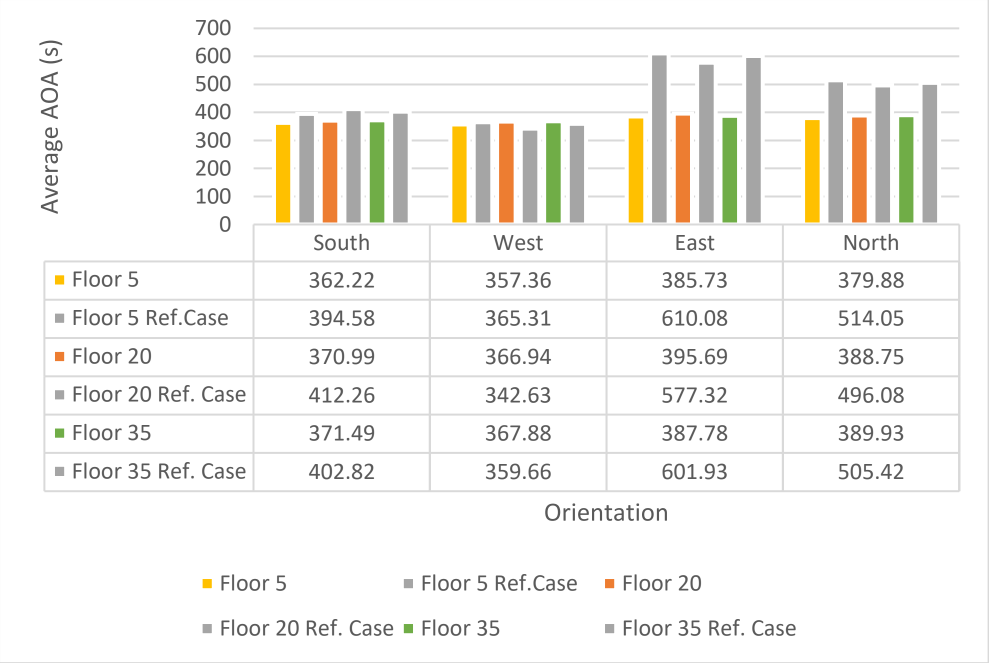


	South	West	East	North
Floor 5	0.041	0.042	0.038	0.04
Floor 5 Ref.Case	0.041	0.038	0.032	0.028
Floor 20	0.04	0.041	0.037	0.039
Floor 20 Ref. Case	0.039	0.043	0.033	0.029
Floor 35	0.037	0.04	0.035	0.035
Floor 35 Ref. Case	0.04	0.039	0.03	0.025

Figure 4-18- Average Air Velocities in Case 3 at 2 PM in m/s

Case 3 could not enhance air velocity. West façade had the highest operative AV followed by North and South respectively for which the difference was not significant. The highest recorded average AV value was 0.042 at West while the lowest recorded value was 0.035 at East.

Overall, floor 5 had the highest average AV followed by floor 20 and 35 respectively.



	South	West	East	North
🟨 Floor 5	362.22	357.36	385.73	379.88
■ Floor 5 Ref.Case	394.58	365.31	610.08	514.05
🟧 Floor 20	370.99	366.94	395.69	388.75
■ Floor 20 Ref. Case	412.26	342.63	577.32	496.08
🟩 Floor 35	371.49	367.88	387.78	389.93
■ Floor 35 Ref. Case	402.82	359.66	601.93	505.42

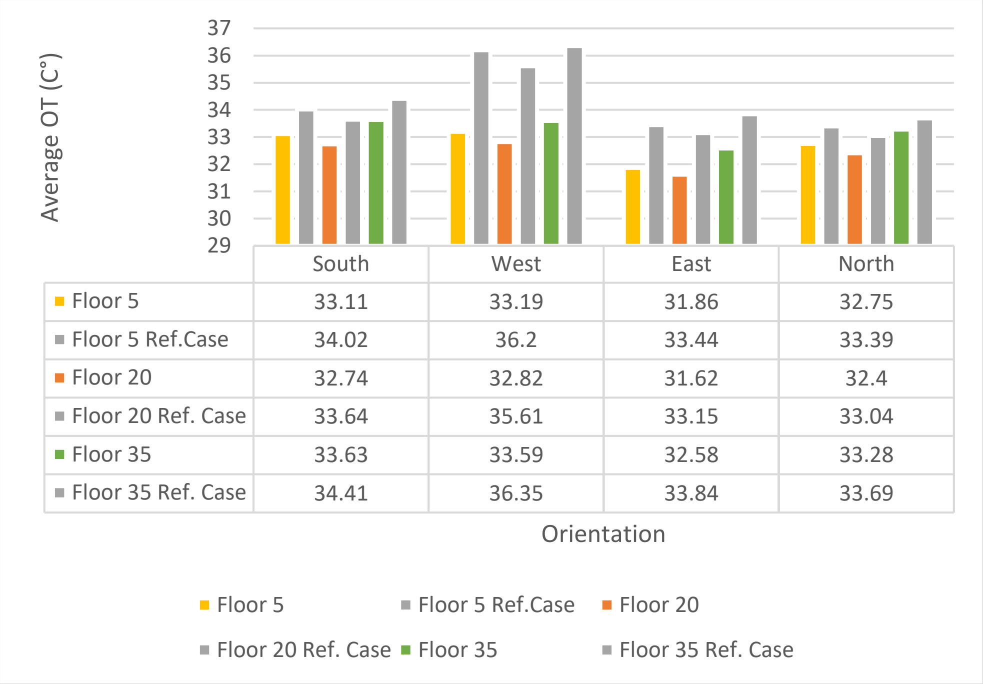
Figure 4-19 Average Age of Air in Case 3 at 2 PM in Seconds

In terms of average AOA, West façade showed better results followed by South, East and North facades respectively. The difference between East and North façade was not significant.

Compared to case 2, case 3 had better results in terms of average AOA at 2 PM in all orientations where the difference could reach 59.35 seconds in South façade at floor 5.

In the 4 orientations, the difference between the 3 floors was not significant.

4.5.1 CFD Simulations Results for Integrating Shading Devices with Naturally Ventilated Wall (Case 3) at 6 PM



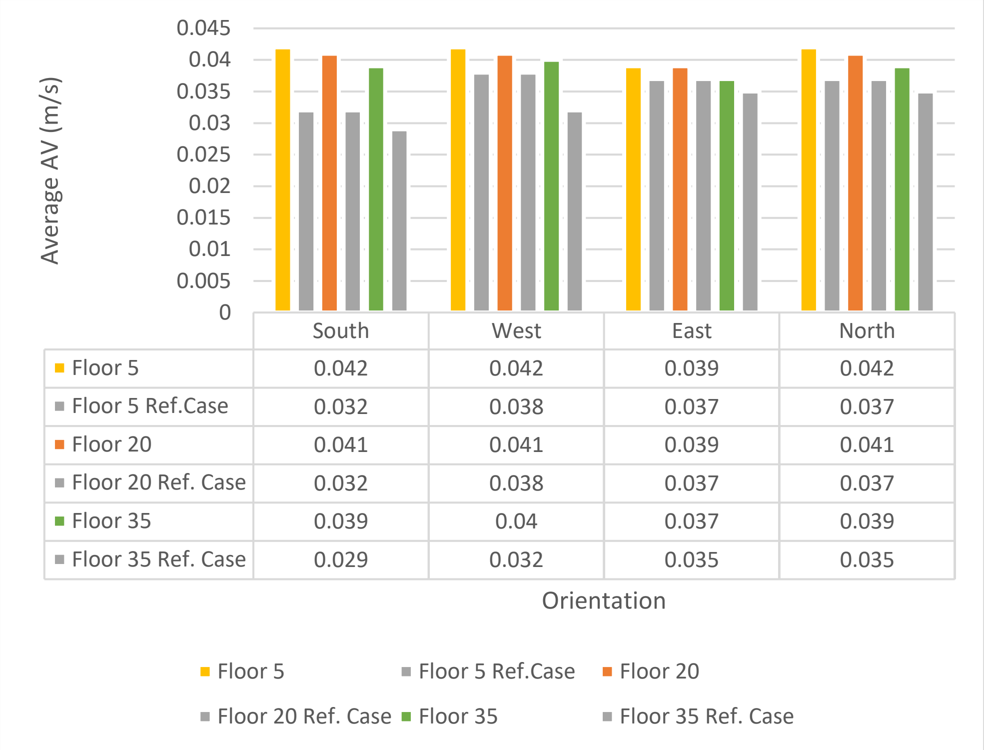
	South	West	East	North
Floor 5	33.11	33.19	31.86	32.75
Floor 5 Ref.Case	34.02	36.2	33.44	33.39
Floor 20	32.74	32.82	31.62	32.4
Floor 20 Ref. Case	33.64	35.61	33.15	33.04
Floor 35	33.63	33.59	32.58	33.28
Floor 35 Ref. Case	34.41	36.35	33.84	33.69

Figure 4-20 Average Operative Temperatures in Case 3 at 6 PM in C°

The results of average OT at 6 PM show that all of the 4 orientations fall far from thermal comfort zone by a maximum of 7.63 C° at South. Also, the minimum required OT to reach comfort zone is 5.62 C° which is lower by 0.02 C° than case 2. However, average OT was not significantly decreased in case 3 when compared to case 2. It could be reduced by 1.22 C° example in floor 35 in Southern façade which had the most effect.

Overall, East façade had the lowest average OT followed by North, South and West respectively.

Overall, floor 35 had the highest average OT followed by floors 5 and 20 respectively.



	South	West	East	North
Floor 5	0.042	0.042	0.039	0.042
Floor 5 Ref.Case	0.032	0.038	0.037	0.037
Floor 20	0.041	0.041	0.039	0.041
Floor 20 Ref. Case	0.032	0.038	0.037	0.037
Floor 35	0.039	0.04	0.037	0.039
Floor 35 Ref. Case	0.029	0.032	0.035	0.035

Figure 4-21 Average Air Velocities in Case 3 at 6 PM in m/s

Case 3 could not show a significant enhancement in air flow rates. South, West and North façade had the highest average AV with no significant difference between them. East façade had the lowest average OT which was 0.037 at floor 35. The highest recorded average AV value was 0.42 at South, West and North facades.

Overall, the difference between floors was not significant in all orientations.

	South	West	East	North
Floor 5	354.46	341.47	369.83	354.91
Floor 5 Ref.Case	521.19	399.15	451.05	445.38
Floor 20	362.04	349.7	375.63	362.59
Floor 20 Ref. Case	519.62	402.93	449.39	443.01
Floor 35	359.55	346.97	372.95	360.51
Floor 35 Ref. Case	523.69	445.42	448.27	443.07

Figure 4-22 Average Age of Air in Case 2 at 6 PM in Seconds

The four orientations showed enhancement in IAQ as their results were lower than case 2 results. The difference in average AOA between case 3 and case 2 could reach a maximum value of 163.93 seconds in floor 35 at South façade.

However, East façade had higher average AOA value followed by South and North (No significant difference) and West respectively.

In the 4 orientations, the difference between the 3 floors was not significant.

<u>Integration of Shading Devices with Naturally Ventilated Walls (Near External Skin) (Case 3) Results Discussion:</u>

The results of applying shading devices with naturally ventilated wall (case 3) show significant enhancement in mean operative temperature in all orientations except North.

South orientation had the highest average OT difference at 2 PM (1.68C°) and also at 6 PM (1.22C°). East orientation had the lowest average OT difference at 2 PM (0.05 C°) and lowest average OT difference at 6 PM (0.02 C°). On the other hand, North orientation had negative results where average OT difference increased by a maximum of 0.54 C° while East orientation didn't have a significant effect. The reason for this could be the exposure of the Southern and Western orientations to direct solar gains which are reflected by the slats outside the cavity while at the other two orientations direct solar gain is much less and in this case the slats could reflect solar gain from surroundings and lead to higher average OT. Also, the highest reduction in average OT happened in the 35th floor, followed by the 20th floor and then 5th floor. The reason for this could be the exposure of the 20th and 35th floor to the direct solar gain which is reflected by highly reflective aluminum shading slats.

For the same reasons, difference in average AOA in South orientation reached its highest with a decrement of 163.93 seconds. East orientation followed South with a highest decrement of 17.66 seconds. West and North reached a highest decrement of 13.67, 13.86 respectively.

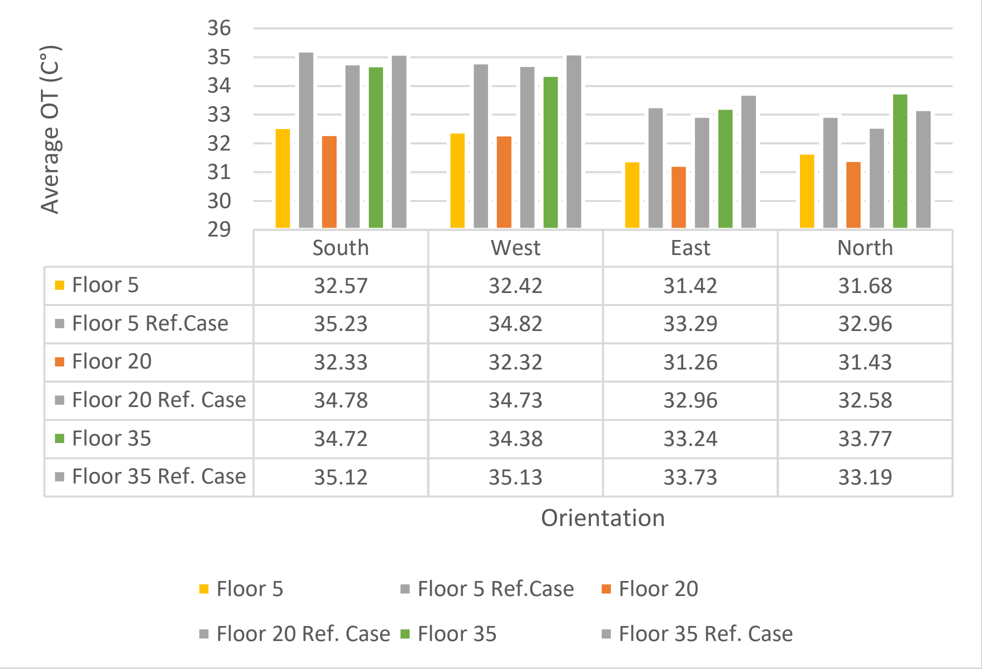
On the other hand, West and South orientations read negative results regarding average AOA and mean AV records where the highest average AOA difference was recorded at the West orientation where it increased by 177.55 s. Also average AV difference decreased at the West orientation by 0.06 m/s. West, East and North orientations didn't have a significant change in AOA at 6 PM.

Overall, East orientation had the lowest average OT among the four orientations followed by North, West and South respectively. And regarding average AV, East orientation had the highest values followed by North, South and West respectively. AOA readings showed that South orientation had the lowest average AOA followed by West, North and East.

4.6 CFD Simulations Results for Integration of Shading Devices with Naturally Ventilated Wall (Case 4)

CFD simulations were done for the case of integrating shading devices with naturally ventilated wall where shading slats are 25 cm far from the internal glazing layer. The results are shown in this section for different floors and different orientations.

4.6.1 CFD Simulations Results for Integrating Shading Devices with Naturally Ventilated Wall (Case 4) at 2 PM



	South	West	East	North
Floor 5	32.57	32.42	31.42	31.68
Floor 5 Ref.Case	35.23	34.82	33.29	32.96
Floor 20	32.33	32.32	31.26	31.43
Floor 20 Ref. Case	34.78	34.73	32.96	32.58
Floor 35	34.72	34.38	33.24	33.77
Floor 35 Ref. Case	35.12	35.13	33.73	33.19

Figure 4-23 Average Operative Temperatures in Case 4 at 2 PM in C°

The results of average OT at 2 PM show that all of the 4 orientations fall far from thermal comfort zone by a maximum of 8.38 C° at South (higher than case 3). Also, the minimum required OT to reach comfort zone is 5.26 C°. However, average OT was not significantly affected generally in case 4 when compared to case 3. It increased by 1.74 C° for example in floor 35 in Western facade.

Overall, East façade had the lowest average OT followed by North, West and South respectively.

Overall, floor 35 had the highest average OT followed by floors 5 and 20 respectively.

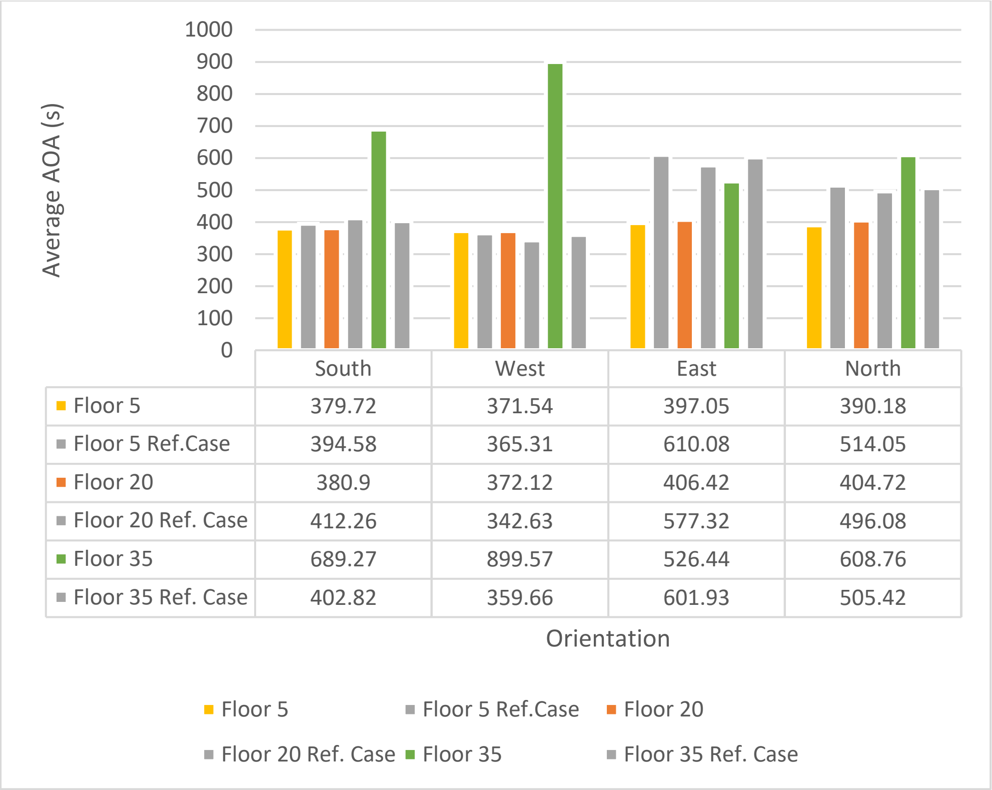
	South	West	East	North
Floor 5	0.039	0.041	0.037	0.038
Floor 5 Ref.Case	0.041	0.038	0.032	0.028
Floor 20	0.039	0.041	0.036	0.037
Floor 20 Ref. Case	0.039	0.043	0.033	0.029
Floor 35	0.015	0.012	0.021	0.017
Floor 35 Ref. Case	0.04	0.039	0.03	0.025

Figure 4-24- Average Air Velocities in Case 4 at 2 PM in m/s

Case 4 did not show significant effect in air flow rates in all orientations in floors 5 and 20 at 2 PM. However, the most effected floor was the 35th where average AV could be reduced by 0.028, 0.022, 0.018 and 0.014 m/s in West, South, North and East facades respectively.

West orientation had the highest operative AV followed by South North and East respectively for which the difference was not significant. The highest recorded average AV value was 0.041 at West and the lowest was 0.012 m/s at West also.

Overall, floor 5 had the highest average AV followed by floor 20 and 35 respectively.



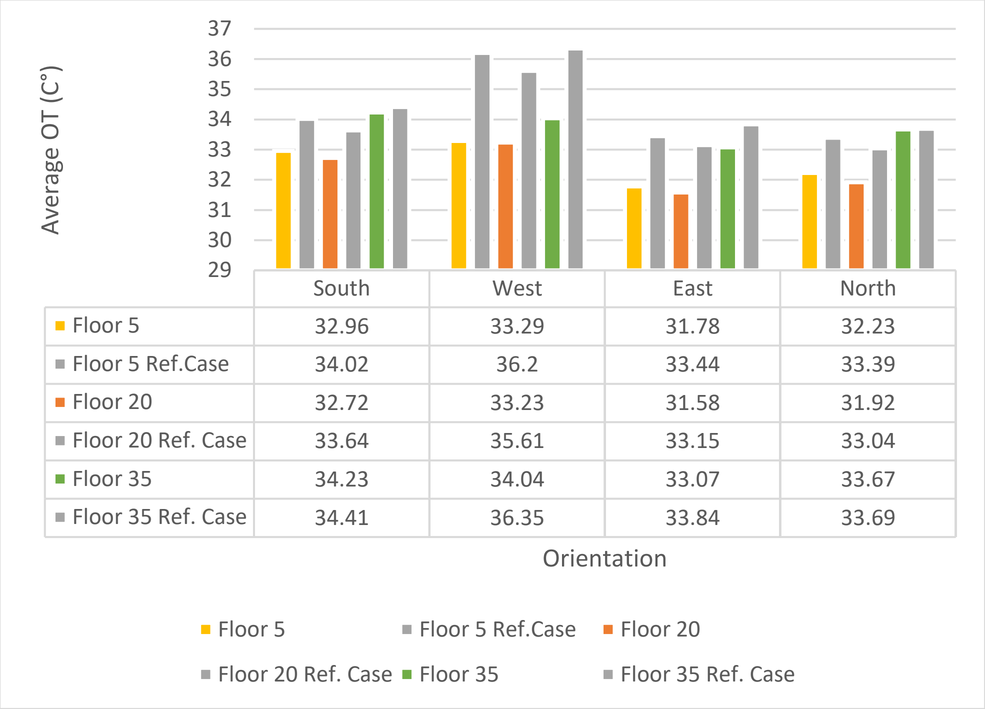
	South	West	East	North
🟨 Floor 5	379.72	371.54	397.05	390.18
■ Floor 5 Ref.Case	394.58	365.31	610.08	514.05
🟧 Floor 20	380.9	372.12	406.42	404.72
■ Floor 20 Ref. Case	412.26	342.63	577.32	496.08
🟩 Floor 35	689.27	899.57	526.44	608.76
■ Floor 35 Ref. Case	402.82	359.66	601.93	505.42

Figure 4-25 Average Age of Air in Case 4 at 2 PM in Seconds

In terms of average AOA, case 4 showed negative results when compared to case 3 generally as average AOA values increased in all orientations and floors. The increment could reach a high value of 531.69 seconds in floor 35 at West orientation.

In the 4 orientations, floors 5 and 20 did not have significant difference in average AOA values while floor 35 always showed higher values.

4.6.2 CFD Simulations Results for Integrating Shading Devices with Naturally Ventilated Wall (Case 4) at 6 PM



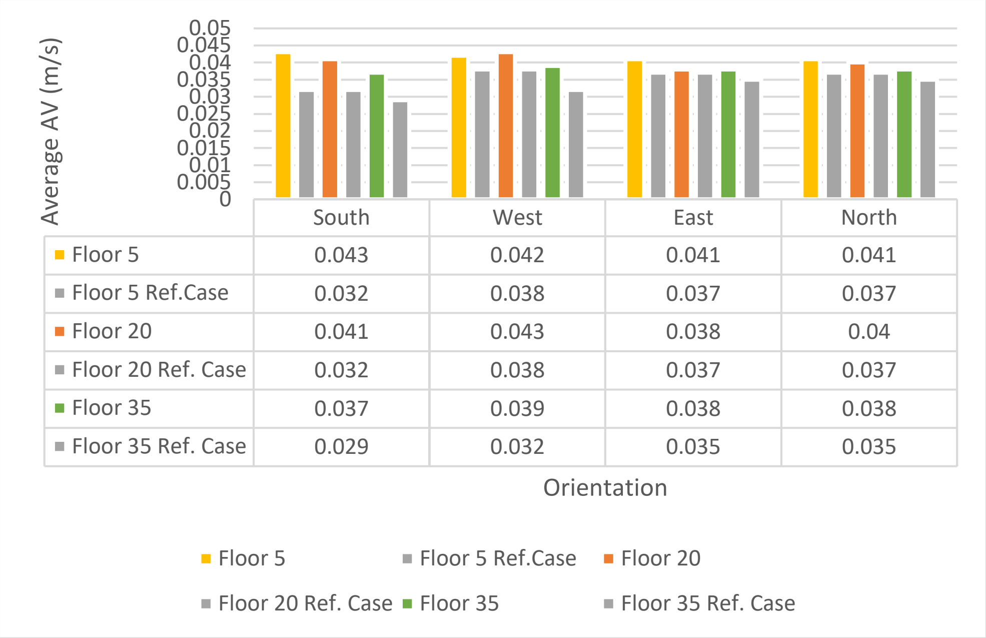
	South	West	East	North
🟨 Floor 5	32.96	33.29	31.78	32.23
■ Floor 5 Ref.Case	34.02	36.2	33.44	33.39
🟧 Floor 20	32.72	33.23	31.58	31.92
■ Floor 20 Ref. Case	33.64	35.61	33.15	33.04
🟩 Floor 35	34.23	34.04	33.07	33.67
■ Floor 35 Ref. Case	34.41	36.35	33.84	33.69

Figure 4-26 Average Operative Temperatures in Case 4 at 6 PM in C°

The results of average OT at 6 PM show that all of the 4 orientations fall far from thermal comfort zone by a maximum of 8.23 C° at South. Also, the minimum required OT to reach comfort zone is 5.58 C°. However, average OT was not significantly decreased in case 4 when compared to case 3. Rather than that, average OT always increased in the 35th floor and in the 5th floor in West orientation.

Overall, East façade had the lowest average OT followed by North, South and West respectively.

Overall, floor 35 had the highest average OT followed by floors 5 and 20 respectively.

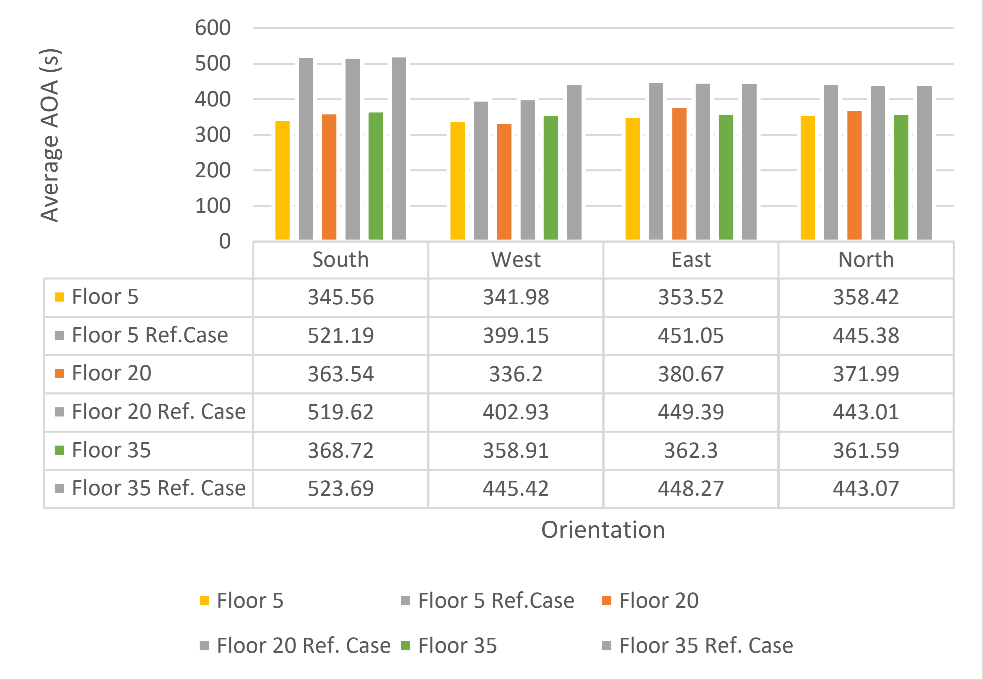


	South	West	East	North
Floor 5	0.043	0.042	0.041	0.041
Floor 5 Ref.Case	0.032	0.038	0.037	0.037
Floor 20	0.041	0.043	0.038	0.04
Floor 20 Ref. Case	0.032	0.038	0.037	0.037
Floor 35	0.037	0.039	0.038	0.038
Floor 35 Ref. Case	0.029	0.032	0.035	0.035

Figure 4-27 Average Air Velocities in Case 4 at 6 PM in m/s

Case 4 did not show a significant enhancement in air flow rates in all orientations when compared to case 3. South, West and North façade had the highest average AV with no significant difference between them. East façade had the lowest average OT which was 0.038 at floor 35. The highest recorded average AV value was 0.43 at South and West facades.

Overall, the difference between floors was not significant in all orientations except South where floor 35 has a lower average AV compared to floor 5 and 20 which are almost equal.



	South	West	East	North
🟨 Floor 5	345.56	341.98	353.52	358.42
▪ Floor 5 Ref.Case	521.19	399.15	451.05	445.38
🟧 Floor 20	363.54	336.2	380.67	371.99
▪ Floor 20 Ref. Case	519.62	402.93	449.39	443.01
🟩 Floor 35	368.72	358.91	362.3	361.59
▪ Floor 35 Ref. Case	523.69	445.42	448.27	443.07

Figure 4-28 Average Age of Air in Case 4 at 6 PM in Seconds

The four orientations showed decrement in IAQ as their results were generally higher than case 3 results. However, the difference was not significant between the two cases. The difference in average AOA between case 4 and case 3 could reach a maximum value of 16.31 seconds in floor 5 at East façade.

East façade had higher average AOA value followed by North, South and West respectively.

Integration of Shading Devices with Naturally Ventilated Walls (Near Internal Skin) (Case 4) Results Discussion:

Placing shading slats near the inner glazing did not always affect average OT, AV nor AOA significantly. However, it could lead to a higher average OT with a value of 1.57 degrees in the South direction the case 1. It also led to a mean increment in AOA that reached 317.78 seconds and a mean decrement in AV that reached 0.023.

In the west orientation, it led to an increment in AOA that reached 531.69 at 2 PM in floor 35. But, the average increment was around 10 seconds. The maximum increment in average OT compared to case 1 was 0.45 at 6 PM. While AV was not highly affected by the change.

East orientation showed the lowest effects where average AOA increased by 138.66 seconds compared to case 1 and age of air and air velocity were not significantly affected.

On the other hand, North orientation showed enhancement in average OT compared to case 1 where average OT could reach 0.61 degrees lower than case 1. However, average AOA and AV where slightly affected.

These results could tell that, using shading slats beside the internal glazing layer leads to more reflection of solar gain towards the internal space which lowers thermal performance of the space. While using shading slats beside the outer layer leads to distracting solar gain outside the internal space which also shows in cavity's operative temperature results.

4.7 Cavity's Operative Temperature Results' Discussion

CFD simulations were carried at 2 PM on the cavity for the four cases. The results are shown in table 4-3.

Table 4-3- Cavity's Average OT Results for the Four Cases

Naturally Ventilated Wall Case (Case 2) – Cavity Temperatures at 2 PM			
Orientation	Floors	Average OT	Average
South	Floor 5	38.42	38.94
	Floor 20	38.09	
	Floor 35	40.32	
West	Floor 5	34.14	34.04
	Floor 20	33.54	
	Floor 35	34.44	
East	Floor 5	31.89	32.01
	Floor 20	31.73	
	Floor 35	32.42	
North	Floor 5	32.42	32.40
	Floor 20	32.12	
	Floor 35	32.67	
Integration of Shading Devices with Naturally Ventilated Wall (Case 3) – Cavity Temperatures at 2 PM			
Orientation	Floors	Average OT	Average
South	Floor 5	32.74	33.1
	Floor 20	32.43	
	Floor 35	34.13	
West	Floor 5	33.25	32.85
	Floor 20	32.52	
	Floor 35	32.78	
East	Floor 5	31.55	31.73
	Floor 20	31.31	
	Floor 35	32.33	
North	Floor 5	32.16	31.86
	Floor 20	31.50	
	Floor 35	31.93	

Integration of Shading Devices with Naturally Ventilated Wall (Case 4) – Cavity Temperatures at 2 PM			
Orientation	Floors	Average OT	Average
South	Floor 5	35.31	35.04
	Floor 20	34.88	
	Floor 35	34.94	
West	Floor 5	36.26	35.96
	Floor 20	35.70	
	Floor 35	35.92	
East	Floor 5	33.33	33.21
	Floor 20	33.02	
	Floor 35	33.29	
North	Floor 5	33.37	33.18
	Floor 20	33.01	
	Floor 35	33.16	

The results of cavity's operative temperature show that using naturally ventilated walls will cause overheating in the cavity especially in the South orientation where the OT reached a maximum of 38.94 Celsius degrees. Using shading devices could reduce cavity's average OT by 5.84 degrees in South orientation.

Overall, East orientation had the lowest average OT in the three cases followed by North, West and South respectively.

Also, case 3 showed better results where it could reduce average OT by a maximum value of 3.11 degrees compared to case 4 where shading slats are near the internal glazing layer. This also explains the better thermal performance of the room in case 3. Because the cavity's OT which is lower than the cavity's OT in case 4 leads to hot air movement from the room to the cavity and thus, lower room OT than the case of using shading devices near the internal glazing layer.

4.8 Results' Conclusion

In chapter four, three cases were studied where the generic design was modified. First case was applying naturally ventilated wall (case 2). Second and third cases were integrating shading devices with the naturally ventilated wall near the external glazing layer (case 3) and the internal glazing layer (case 4) respectively.

Modeling the naturally ventilated wall was discussed at first where all its specifications and materials were built and assigned on designbuilder as preparation for CFD simulations.

The results of applying naturally ventilated wall (case 2) showed that average OT temperature could be reduced to as low as 3.07 degrees compared to reference case (case 1) at 6 PM and could be reduced to as low as 2.71 degrees at 2 PM. However, average AOA increases and average AV decreases in West and South orientations where AOA increases by 177.55 s and AV decreases by 0.06 m/s.

The results showed that at 2 PM North orientation had the lowest average OT followed by East, West and South respectively. Also, West orientation had the lowest average AOA and the highest average AV followed by North, East and South.

After that, modeling shading devices and integrating them with naturally ventilated wall were discussed. All the specifications and materials of the highly reflective aluminum shading slats were added to designbuilder for CFD simulations. The angle of the shading slats was 90 degrees and the spacing between them was studied at 4 PM which is 25 cm.

Two cases for shading devices were studied. One where the shading slats were 25 cm far from the external glazing layer (case 3) and another where the shading slats were 25cm far from the internal glazing layer (case 4).

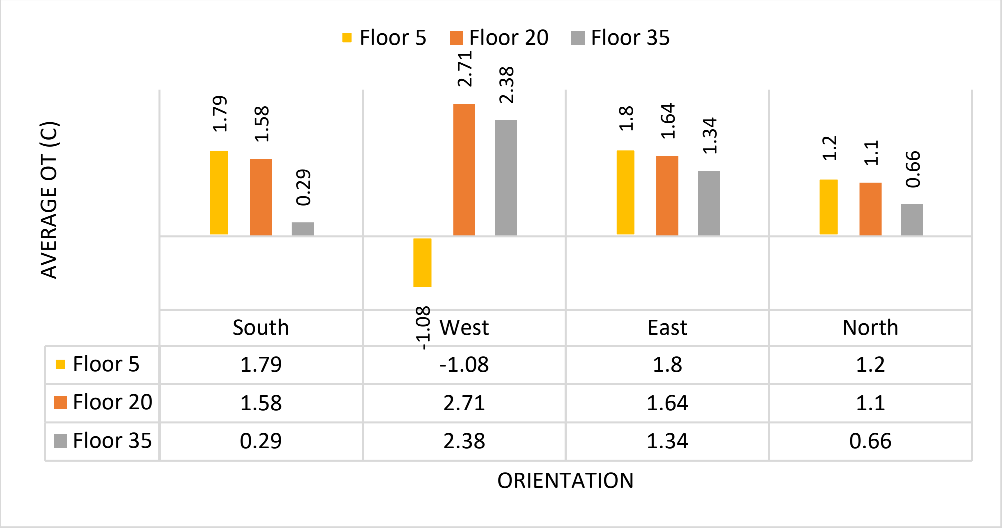
The results of integrating shading devices with the naturally ventilated walls showed enhancement in average OT in all orientations except North. While average AV and average AOA were enhanced in all of the other orientations generally. The difference between average OT in case 3 and case 2 reached the highest value of 1.68 Celsius degrees in South orientation. West and East orientations came second and third in enhancing average OT. While North orientation showed increment in average OT with a maximum value of 0.45 Celsius degrees. The reason behind this could be the reflection of solar gain from surroundings in North direction which is not highly affected by direct solar gain.

Average AOA difference was at its highest in South orientation where a decrement of 163.93 seconds appeared. East, West and North orientations followed that with a maximum decrement of 17.66, 13.67 and 13.86 seconds respectively.

The results of case 4 showed negative results compared with case 3. It reached a highest difference of average OT by an increment of 1.57 Celsius degrees in South direction. An increment in average AOA also happened and reached a maximum value of 531.69 at 2 PM in West orientation. Only North orientation showed enhancement in average OT compared to case 3 and it showed a decrement in average OT of 0.61 degrees.

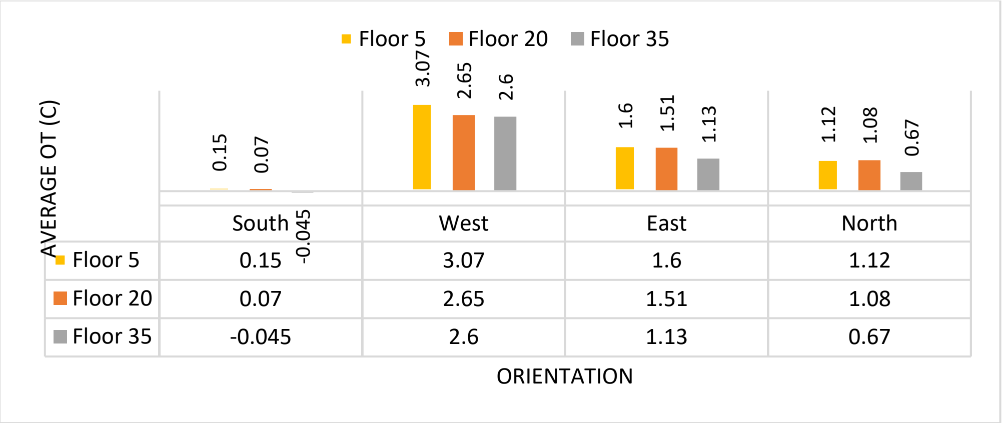
Another study was carried on in this chapter of cavity’s operative temperature in three cases. Integration of shading devices with naturally ventilated wall could lower down the mean OT of the cavity by a maximum of 5.84 Celsius degrees in South orientation. The study showed that case 3 could lower down the average OT of cavity compared to case 4 by a maximum of 3.11 Celsius degrees.

Figures 4-29 to 4-34 show difference in average OT between different cases. Negative results mean that average OT increased.



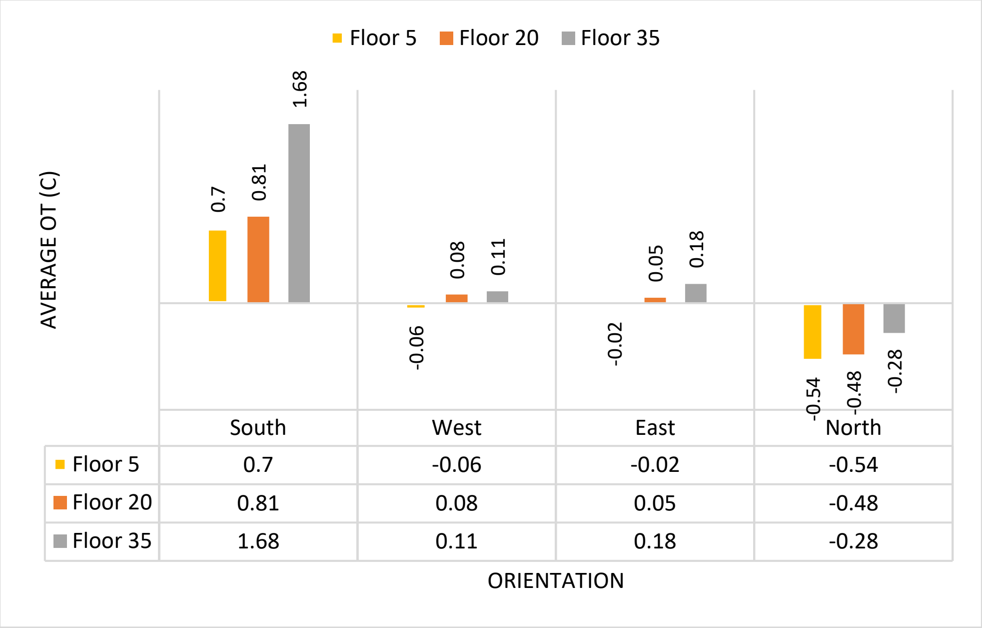
	South	West	East	North
Floor 5	1.79	-1.08	1.8	1.2
Floor 20	1.58	2.71	1.64	1.1
Floor 35	0.29	2.38	1.34	0.66

Figure 4-29 Average OT Difference between Case 2 and Case 1 at 2 PM



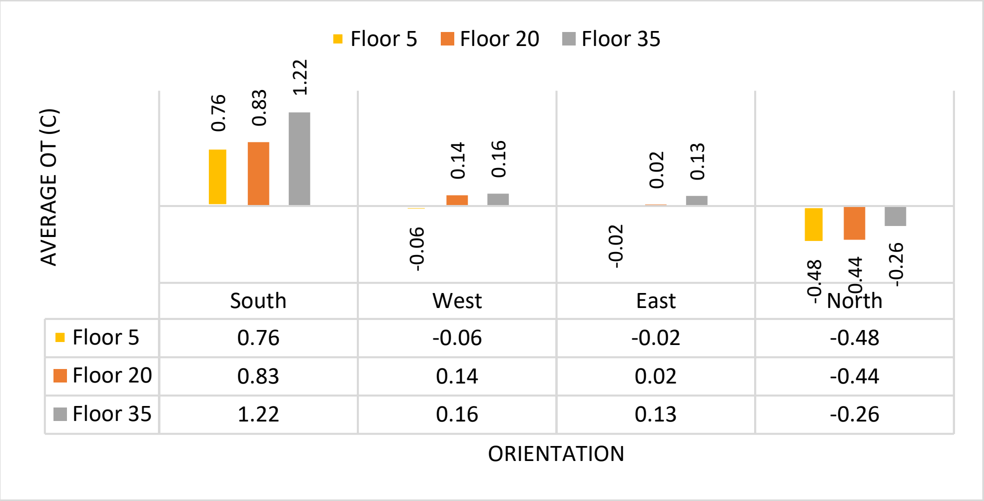
	South	West	East	North
Floor 5	0.15	3.07	1.6	1.12
Floor 20	0.07	2.65	1.51	1.08
Floor 35	-0.045	2.6	1.13	0.67

Figure 4-30 Average OT Difference between Case 2 and Case 1 at 6 PM



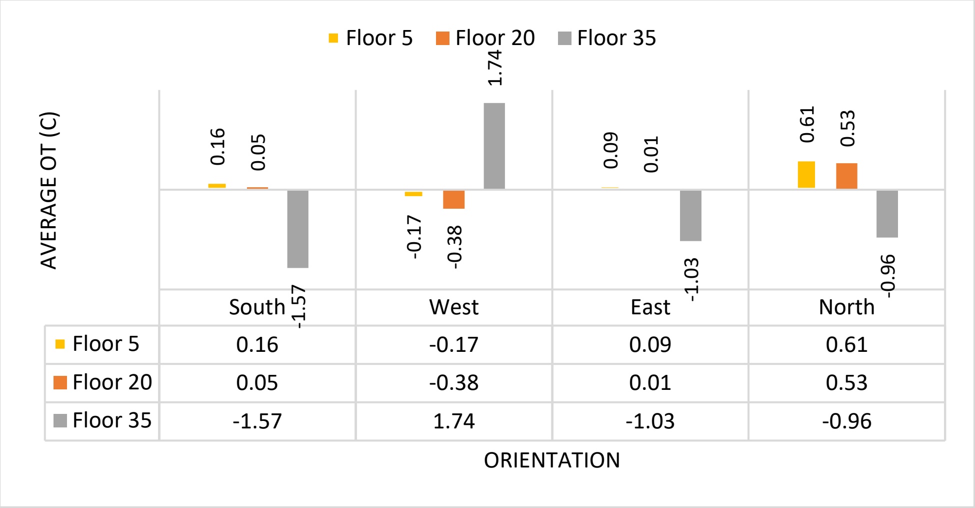
	South	West	East	North
Floor 5	0.7	-0.06	-0.02	-0.54
Floor 20	0.81	0.08	0.05	-0.48
Floor 35	1.68	0.11	0.18	-0.28

Figure 4-31 Average OT Difference between Case 3 and Case 2 at 2 PM



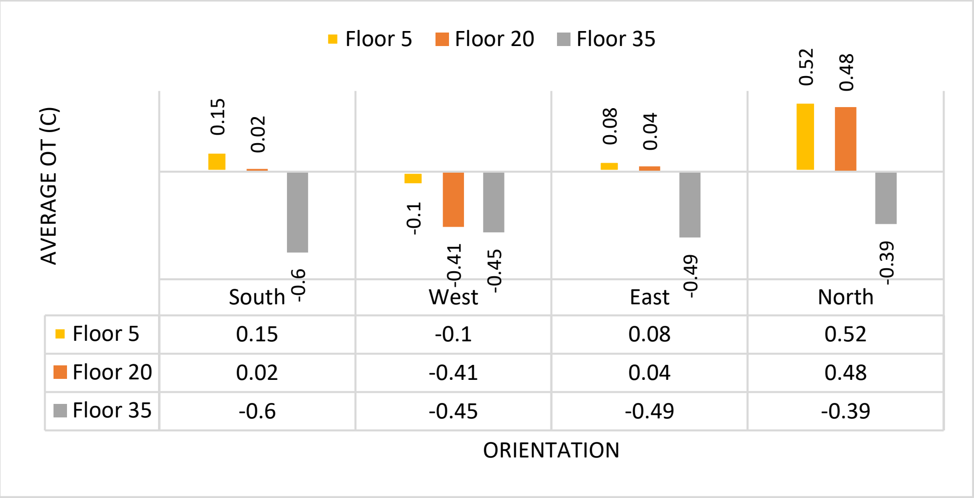
	South	West	East	North
Floor 5	0.76	-0.06	-0.02	-0.48
Floor 20	0.83	0.14	0.02	-0.44
Floor 35	1.22	0.16	0.13	-0.26

Figure 4-32- Average OT Difference between Case 3 and Case 2 at 6 PM



	South	West	East	North
Floor 5	0.16	-0.17	0.09	0.61
Floor 20	0.05	-0.38	0.01	0.53
Floor 35	-1.57	1.74	-1.03	-0.96

Figure 4-33 Average OT Difference between Case 4 and Case 3 at 2 PM



	South	West	East	North
Floor 5	0.15	-0.1	0.08	0.52
Floor 20	0.02	-0.41	0.04	0.48
Floor 35	-0.6	-0.45	-0.49	-0.39

Figure 4-34 Average OT Difference between Case 4 and Case 3 at 6 PM

South façade results:

The results show that single skin façade case showed an average OT higher than ambient OT by at least 0.88 Celsius degrees at 2 PM. Naturally ventilated double skin façade could show a lower average OT than ambient OT. However, it could still reach a high difference of 0.94 Celsius degrees. On the other hand, case 3 could make a difference of at least 0.74 Celsius degrees lower than ambient OT. It could also lower down the average OT of the room by 1.51 degrees at 2 PM.

At 2 PM, South façade had the worst results regarding average OT. Case 4 showed the best performance in floors 5 and 20 while case 3 showed the best performance in floor 35. On the other hand, single skin façade case showed the worst results among the 4 cases in all floors.

At 6 PM, case 2 showed the worst results regarding average OT in floors 5 and 35. While it came third in order in all of the other cases. However, case 3 was the best in South orientation at floors 5 and 35 while case 4 was the best in South at floor 20.

As a conclusion, integration of shading devices with naturally ventilated walls (case 3) was the best solution in South façade.

West façade results:

In west façade, difference between room's average OT and ambient OT in reference case could reach a highest value of 1.34 degrees. While using DSF, could reduce the difference by 1.77 degrees. Adding shading devices (case 3) could make the difference even greater than case 2. It could reach 1.85 degrees difference.

At 2 PM, West façade showed the second best results after East when applying case 3. Case 2 came second in the order followed by case 4 and 1 respectively. The results were the same in all floors.

At 6 PM, Case 2 showed the best results in West orientation in all floors. Case 3 and case 4 followed case 2 respectively leaving case 1 with the worst possible results in the study. These results were the same in all floors.

To conclude, integration of shading devices with naturally ventilated walls (case 3) is the best solution to be applied in West façade.

East façade results:

Using single skin façade (case 1) in East façade led to a higher average OT than ambient temperature by at least 0.68 degrees at 2 PM. When using naturally ventilated DSF, the difference could reach a highest value of 1.73 degrees lower than ambient temperature. On the other hand, using shading devices (case 3) could add another 0.05 degrees to the difference in DSF case making it 1.78 degrees lower than ambient temperature.

At 2 PM, East façade showed the best results in the whole study when applying cases 2, 3 and 4. Case 4 was more successful in floors 5 and 20 with no significant difference while case 3 was more successful in floor 35. East façade came second in results in case 1 following North. This could be due to the absence of direct solar radiation in North and East.

At 6 PM, East façade was affected exactly the same as at 2 PM. However, case 4 always showed the best results in all floors followed by case 3, 2 and 1 respectively.

To conclude, case 4 is the best solution to be applied in East façade.

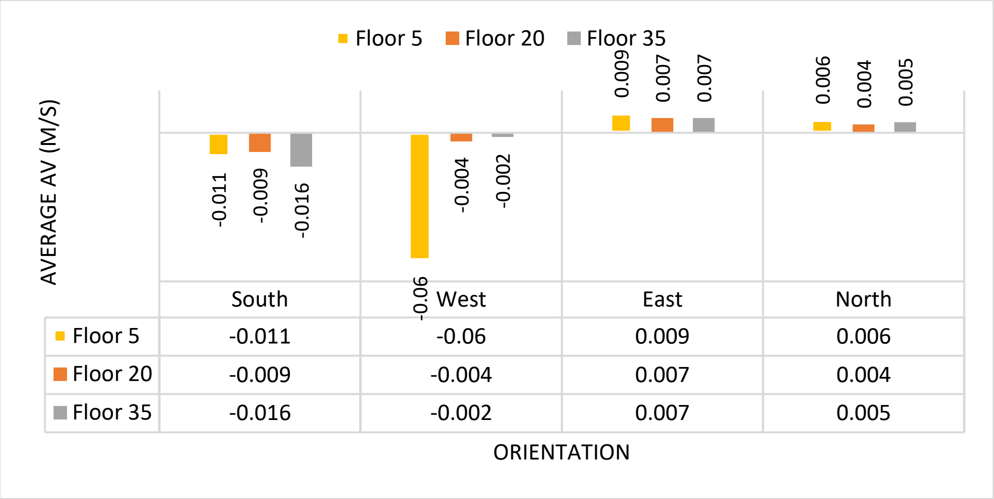
North façade results:

In a North façade, using single skin facade could lower the average OT of the room by 0.69 degrees. Using DSF (case 2) in North façade showed the best results among the 4 cases with an average OT difference between the room and ambient OT by 1.79 degrees. Using shading devices (case 3) came second after DSF with a maximum average OT difference 1.31 degrees.

North façade showed the best results among the four orientations at 2 and 6 PM when applying case 1. While it came second when applying case 2 and case 4 at 2 PM. And came second when applying cases 2 and 3 at 6 PM.

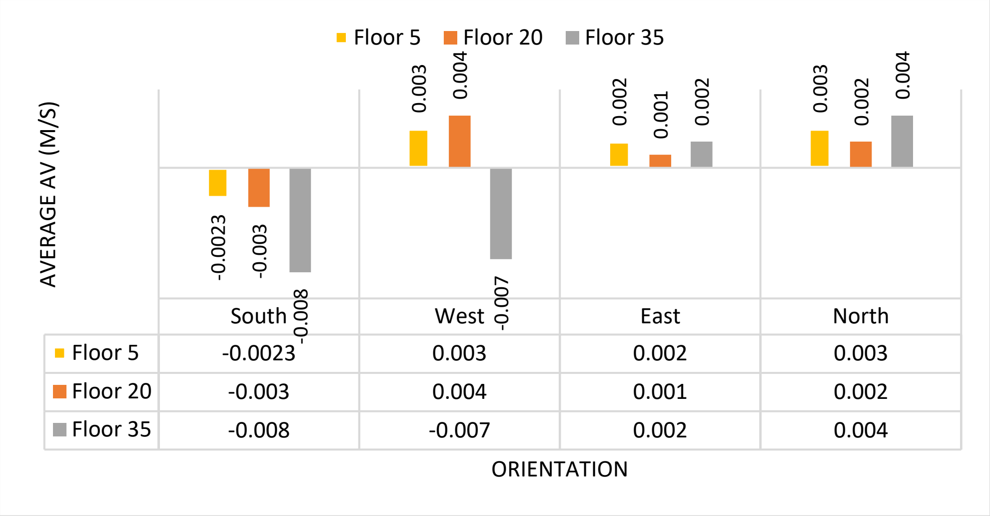
In conclusion, case 1 is the best applied case in Northern façade regarding average OT.

Figures 4-35 to 4-40 show difference in average AV between different cases. Negative results mean that average AV decreased.



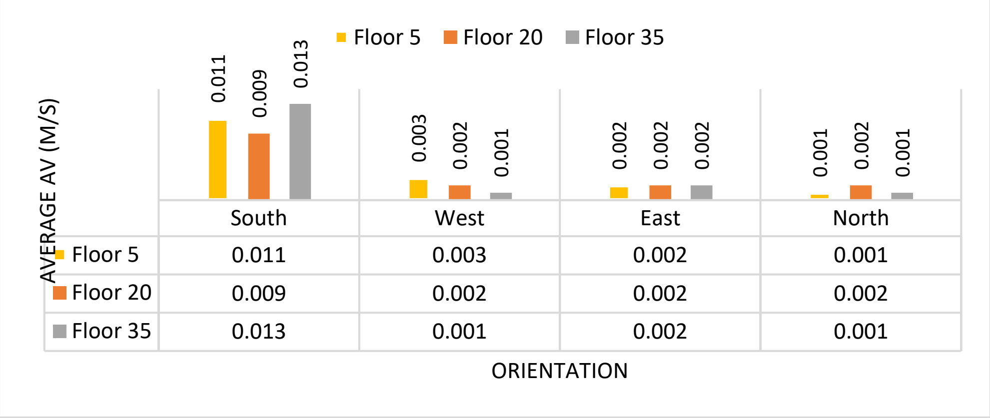
	South	West	East	North
Floor 5	-0.011	-0.06	0.009	0.006
Floor 20	-0.009	-0.004	0.007	0.004
Floor 35	-0.016	-0.002	0.007	0.005

Figure 4-35 Average AV Difference between Case 2 and Case 1 at 2 PM



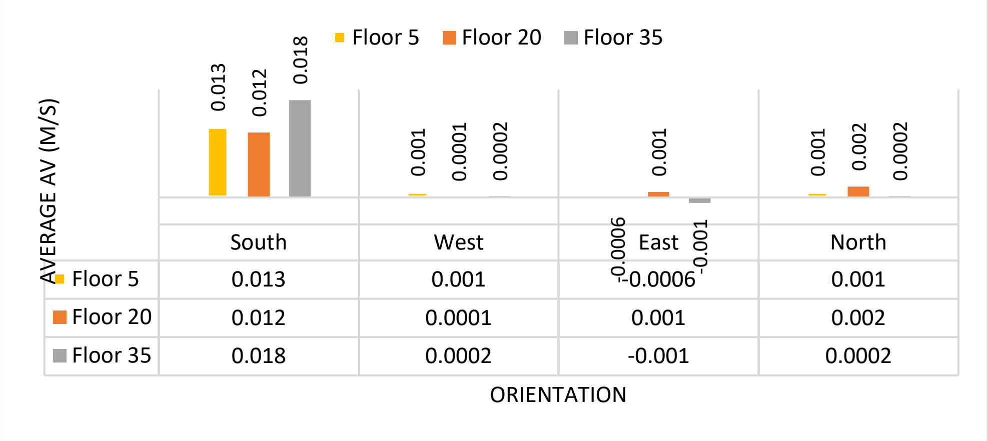
	South	West	East	North
Floor 5	-0.0023	0.003	0.002	0.003
Floor 20	-0.003	0.004	0.001	0.002
Floor 35	-0.008	-0.007	0.002	0.004

Figure 4-36 Average AV Difference between Case 2 and Case 1 at 6 PM



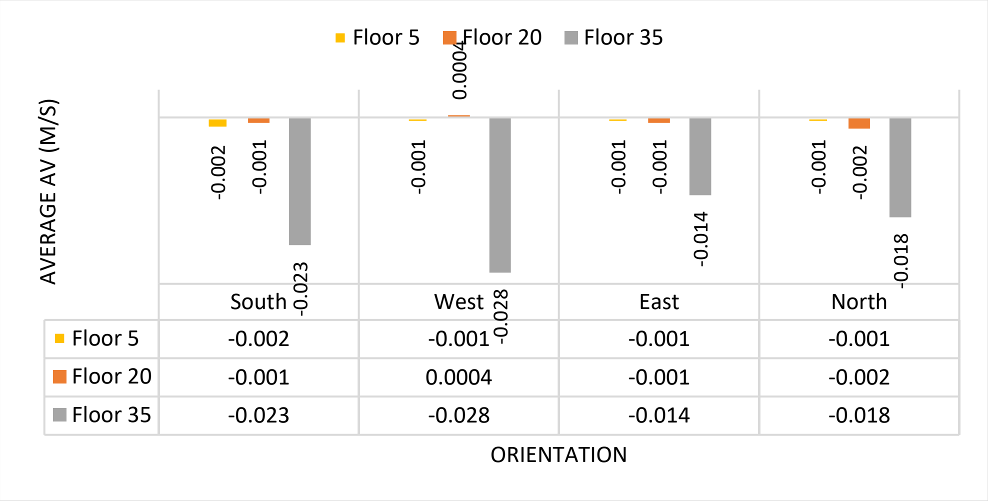
	South	West	East	North
Floor 5	0.011	0.003	0.002	0.001
Floor 20	0.009	0.002	0.002	0.002
Floor 35	0.013	0.001	0.002	0.001

Figure 4-37 Average AV Difference between Case 3 and Case 2 at 2 PM



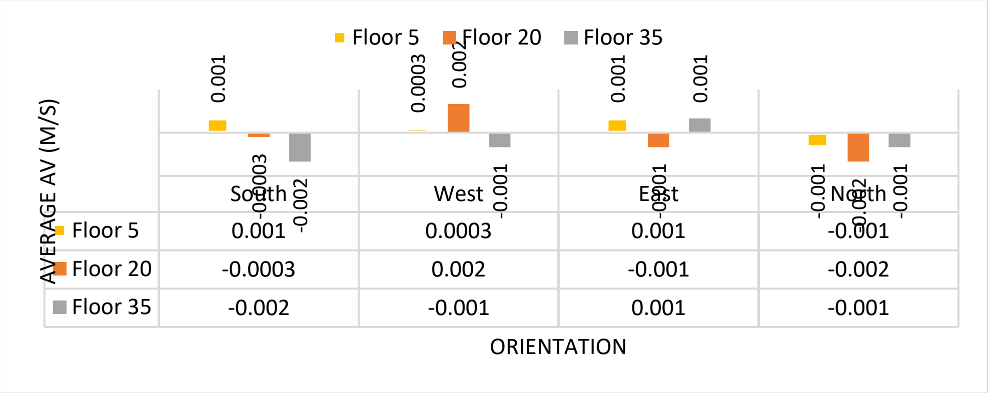
	South	West	East	North
Floor 5	0.013	0.001	-0.0006	0.001
Floor 20	0.012	0.0001	0.001	0.002
Floor 35	0.018	0.0002	-0.001	0.0002

Figure 4-38 Average AV Difference between Case 3 and Case 2 at 6 PM



	South	West	East	North
Floor 5	-0.002	-0.001	-0.001	-0.001
Floor 20	-0.001	0.0004	-0.001	-0.002
Floor 35	-0.023	-0.028	-0.014	-0.018

Figure 4-39 Average AV Difference between Case 4 and Case 3 at 2 PM



	South	West	East	North
Floor 5	0.001	0.0003	0.001	-0.001
Floor 20	-0.0003	0.002	-0.001	-0.002
Floor 35	-0.002	-0.001	0.001	-0.001

Figure 4-40 Average AV Difference between Case 4 and Case 3 at 6 PM

As mentioned before, as per ASHRAE standards, people feel comfort if air velocity falls between 0.05 and 0.25 m/s in the space.

South façade results:

Integrating shading devices with naturally ventilated DSF (case 3) had the best results regarding average AV with a highest value of 0.042 m/s at 2 PM. and a lowest value of 0.037 m/s at 6 PM which is close to the comfort zone. Using shading devices (case 4) had the second best performance regarding air quality in the space followed by the reference case (case 1) and using a naturally ventilated DSF (case 2) only had the worst result with a lowest value of 0.021 and a highest value of 0.031.

At 6 PM, South façade had the worst results of the study regarding average AV in case 1 and case 2 which had the worst results. However, applying case 4 came second in order after West with relatively acceptable AV ranges with case 3 which had a close range of results.

To conclude, case 3 is the best case when comparing the results according to AV ranges.

West façade results:

West façade had the best results in the study regarding average AV in all cases and all floors both at 2 PM and 6 PM. The difference between the four cases in West façade was not significant at the two studied hours. However, case 1 showed better results in all floors than case 3 which came second followed by case 1 and case 4 respectively. The results could reach 0.042 m/s in case 3 with a minimum of 0.040 m/s both at 2 PM and 6 PM.

East façade results:

In east orientation, naturally ventilated wall could enhance the average AV in the space more than the other three cases with a highest average AV (0.040 m/s) and a lowest average AV (0.036 m/s).

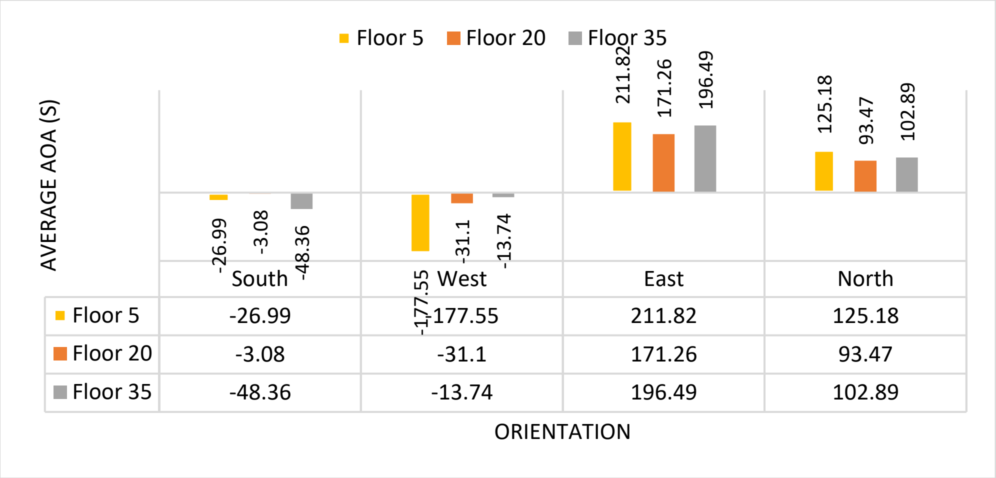
Case 3 results were close to the results of case 2. On the other hand, case 1 had the worst results with a maximum value of 0.037 m/s and a minimum value of 0.029 m/s.

Overall, East façade results were the highest in cases 3 and 4 both at 2 PM and 6 PM with case 3 having better results although they are not significantly far from the results of case 4.

North façade results:

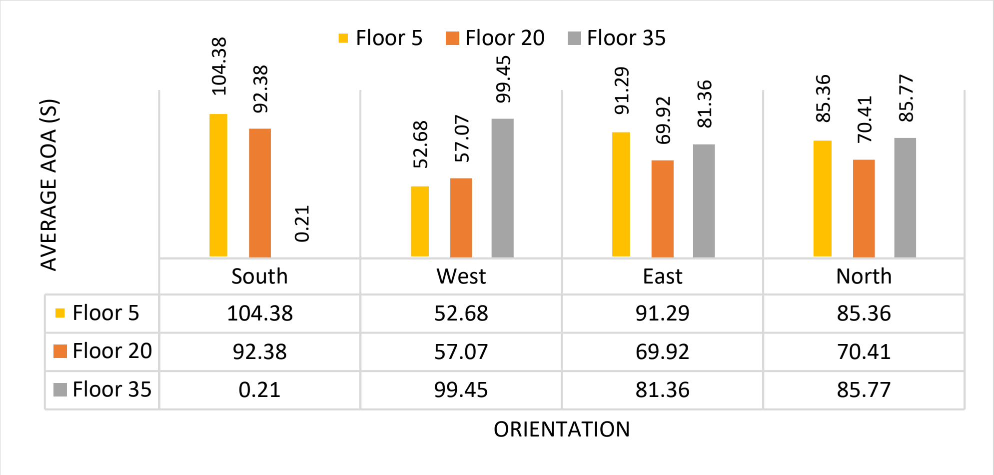
Case 3 showed the best results regarding average AV in the room with a highest value of 0.042 m/s and a lowest value of 0.035 m/s. Case 2 case had the second best results followed case 4 and case 1 respectively. The difference in average AV results between case 3 and case 2 was not significant.

Figures 4-41 to 4-46 show the difference in average AOA between different cases. Negative results mean that average AOA increased.



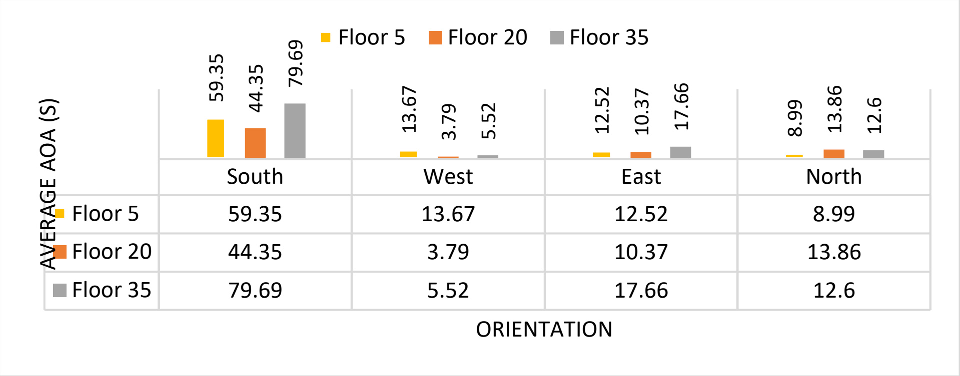
	South	West	East	North
■ Floor 5	-26.99	-177.55	211.82	125.18
■ Floor 20	-3.08	-31.1	171.26	93.47
■ Floor 35	-48.36	-13.74	196.49	102.89

Figure 4-41 Average AOA Difference between Case 2 and Case 1 at 2 PM



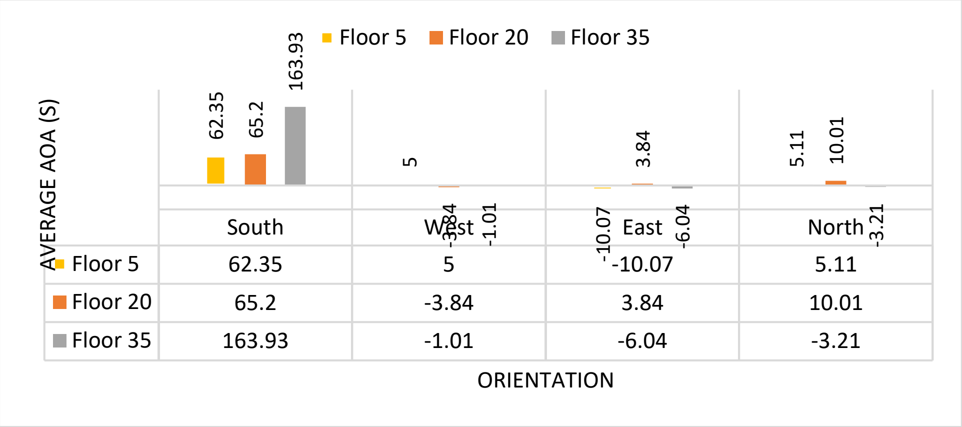
	South	West	East	North
■ Floor 5	104.38	52.68	91.29	85.36
■ Floor 20	92.38	57.07	69.92	70.41
■ Floor 35	0.21	99.45	81.36	85.77

Figure 4-42 Average AOA Difference between Case 2 and Case 1 at 6 PM



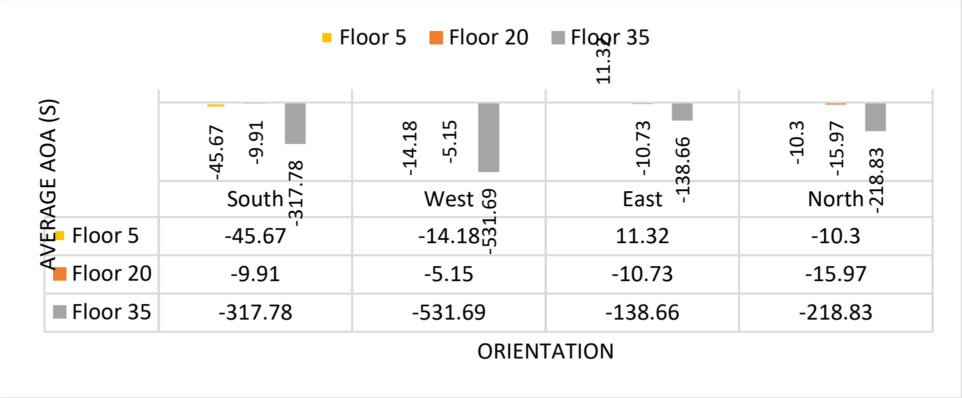
	South	West	East	North
Floor 5	59.35	13.67	12.52	8.99
Floor 20	44.35	3.79	10.37	13.86
Floor 35	79.69	5.52	17.66	12.6

Figure 4-43 Average AOA Difference between Case 3 and Case 2 at 2 PM



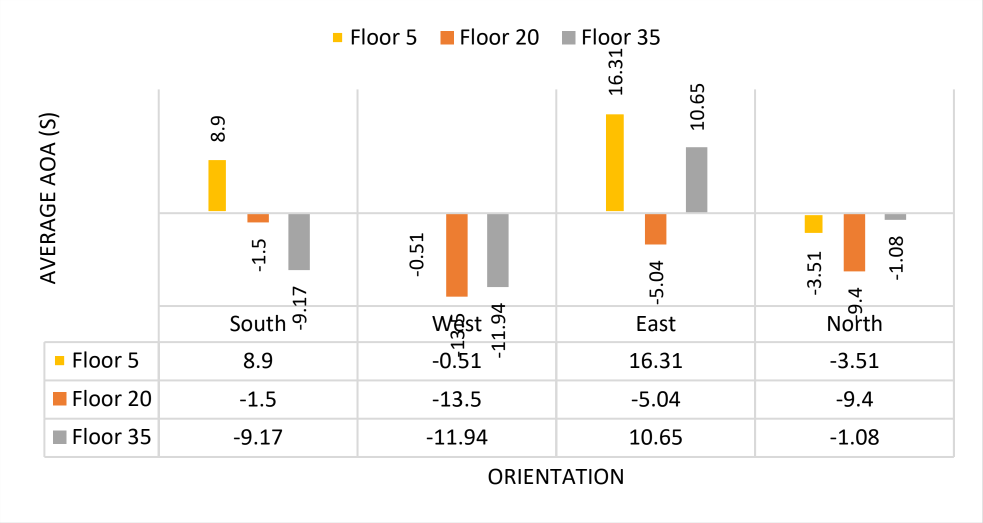
	South	West	East	North
Floor 5	62.35	5	-10.07	5.11
Floor 20	65.2	-3.84	3.84	10.01
Floor 35	163.93	-1.01	-6.04	-3.21

Figure 4-44 Average AOA Difference between Case 3 and Case 2 at 6 PM



	South	West	East	North
Floor 5	-45.67	-14.18	11.32	-10.3
Floor 20	-9.91	-5.15	-10.73	-15.97
Floor 35	-317.78	-531.69	-138.66	-218.83

Figure 4-45 Average AOA Difference between Case 4 and Case 3 at 2 PM



	South	West	East	North
Floor 5	8.9	-0.51	16.31	-3.51
Floor 20	-1.5	-13.5	-5.04	-9.4
Floor 35	-9.17	-11.94	10.65	-1.08

Figure 4-46 Average AOA Difference between Case 4 and Case 3 at 6 PM

South façade results:

At 2 PM, case 3 showed the lowest average AOA in the room in South orientation followed by case 4, case 1 and case 2 respectively in floors 5 and 20 while case 4 had the highest average AOA in the 35th floor.

At 6 PM, case 3 had the best performance regarding average AOA in South orientation followed by cases 4, 2 and 1 respectively.

West façade results:

At 2 PM, case 1 showed the best performance with the lowest average AOA in all floors followed by cases 3, 2 and 4 respectively in all floors.

West façade the best results regarding average AOA at 6 PM when applying cases 4, 2, 3 and 1 respectively. However, the difference between the four cases was not significant at any floor.

East façade results:

Case 3 showed the lowest average AOA in the room in East façade followed by, case 2, case 4, and case 1 at 2 PM.

At 6 PM, case 2 had the best results regarding average AOA followed by cases 3, 4 and 1 respectively.

Overall, floor 5 had the best results followed by floors 35 and 20 respectively.

North façade results:

Both at 2 PM and 6 PM, case 3 had the lowest average AOA in the room in North façade followed by, case 2, case 3 and case 1 respectively.

Floor 5 had the best results when applying shading devices to naturally ventilated wall at 2 PM and 6 PM while floor 35 had the worst results under same conditions. On the other hand, floor 5 had the worst results when applying case 1.

4.9 Summary and Conclusion:

In chapter four the effect of integrating shading devices with naturally ventilated walls was studied.
3 Cases were studied in this chapter using CFD simulations:

a) Case 2: Naturally ventilated wall.
b) Case 3: Integration of shading devices with naturally ventilated wall where shading devices are 25 cm away from the external skin.
c) Case 4: Integration of shading devices with naturally ventilated wall where shading devices are 25 cm away from the internal skin.

Each case had its parameters and materials discussed before showing its results and discussing them. The used naturally ventilated wall was composed of two double glazed skins separated by a 1 m air gap. The glazing is green reflective. The outer skin was 0.6 cm while the inner skin was 0.8 cm. And the two skins were separated by a 1 cm air gap. A 1 m chimney was added at the top of the building. The results of simulations were average operative temperature (OT) indicating thermal performance, average air velocity (AV) indicating flow rate and average age of air (AOA) indicating indoor air quality (IAQ). The openings are 30% of the glazing façade and are placed in the inner and outer skins.

The results of the different cases were compared with the reference case and with each other to show the best case regarding the three outputs.

From the results, it is noticeable that integrating shading devices with naturally ventilated DSF where the shading slats are close to the outer skin could enhance thermal comfort in the hotel room. The enhancement includes lower average OT compared to ambient OT that could reach 1.85 Celsius degrees difference in West facade. It also includes relatively higher average AV in the space than the other 3 alternatives which could reach a highest value of 0.042 m/s which is close to the required AV that achieves indoor air quality (IAQ). At last, this option shows the best results regarding average AOA with a lowest value among the 4 cases which is 349.70 m/s in West façade.

This option achieved acceptable and noticeable results in South, West and East facades. While using naturally ventilated DSF without shading devices showed the best performance in North façade.

Also, the study showed different performance of the three cases regarding the three outputs in different floors. For example, floor 20 showed better results regarding average OT followed by floors 5 and 35 respectively in most of the cases and orientations. The difference in results between the floors indicates that changing the parameters of shading devices between floors could enhance thermal comfort, flow rates and IAQ.

Although the average OT is out of the comfort zone, results of average AV and average AOA could enhance ventilation rates and IAQ. And also, the reduction in average OT could lower down the consumption of energy using HVAC systems.

However, the ambient temperature which is higher than comfort range will always affect the average OT of the indoor space. This is because the temperature of incoming air could affect thermal comfort because the air flow will be hot and will not necessarily enhance IAQ. This problem needs more studies regarding applying another passive cooling techniques and more studies need to be done regarding changing the other parameters of shading devices.

Positively, lowering down the average OT in the room and enhancing air flow rates and IAQ could lower down energy performance as the power needed to close the gap between OT of the room and the standard required temperature.

Conclusion & Recommendations

Conclusion

According to the main goal, this research aimed to evaluate the integration of shading devices with naturally ventilated double skin facades for hotel building in Greater Cairo. To achieve the aim, 4 models were built and simulated on DesignBuilder to evaluate their thermal performance and airflow performance. The 4 models were:

1. Reference case (case 1): single skin façade.
2. Case 2: naturally ventilated double skin façade.
3. Case 3: naturally ventilated double skin façade with shading systems near the outer skin.
4. Case 4: naturally ventilated double skin façade with shading systems near the inner skin.

The research came up with the following conclusions:

1- Naturally ventilated wall (case 2) could enhance thermal comfort because of the air flow that results from buoyancy effect.

2- Cavity's OT is relatively high especially in South façade. This results from overheating phenomena. It could reach 38.94 Celsius degrees in Southern façade. However, the indoor space's OT is still lower than the cavity's OT and ambient OT.

3- Integration of shading devices with naturally ventilated DSF (near outer skin) had the best result regarding average OT, average AOA and average AV among the 4 cases.

4- Integration of shading devices with naturally ventilated DSF (near outer skin) showed enhancements in ventilation rates and thermal comfort in South, West and East facades.

5- Integration of shading devices with naturally ventilated DSF (near outer skin) highly affected the average OT of the cavity in all orientations and could lower down the average OT of the cavity by 5.84 Celsius degrees compared to naturally ventilated DSF in South facade.

6- Average OT near the inner glazing area is the highest dues to exposure to direct solar gain. Also, the zone near the glazing always showed higher AV and lower AOA.

7- Differences between floors outputs results suggests studying different parameters of shading devices in different floors to achieve the best combination and results.

The following are numerical results of the four cases:

South façade:

Integrating shading devices with naturally ventilated DSF (case 3) could lower down average OT by at least 1.97 Celsius degrees compared to reference case at 2 PM. It could also lower down average OT of the room by a maximum of 2.50 degrees at 2 PM. On the other hand, at 6 PM, the results were not significant as the highest difference could be reached was 0.44 Celsius degrees. Average AV could reach 0.042 m/s when using this option at 6 PM and 0.041 at 2 PM. Lowest average AOA recorded in this case was 354.46 s which is lower than any of the other three options.

<u>West façade:</u>

Integrating shading devices with naturally ventilated DSF (case 3) could reduce room’s average OT by a maximum of 2.59 Celsius degrees compared to reference case at 2 PM. At 6 PM, average OT could be reduced by at least 2.45 C degrees when compared with reference case with a maximum reduction that could reach 3.07. In West, Floor 20 had the best results regarding average OT followed by floors 5 and 35 respectively both at 2 PM and 6 PM. The difference in average OT could between floors 20 and 35 reached 0.7 at 2 PM and 0.77 Celsius degrees at 6 PM. Highest average AV was 0.042 m/s at 2 PM and 6 PM. Lowest average AOA in this case was 341.47 s at 6 PM.

<u>East façade:</u>

Integrating shading devices with naturally ventilated DSF (case 3) could reduce room’s average OT by 1.78 Celsius degrees compared to reference case at 2 PM. The minimum difference that could be reached was 1.52 Celsius degrees. At 6 PM the minimum difference that could be reached was 1.26 while the maximum difference was 1.58 Celsius degrees. In East, Floor 20 had the best results regarding average OT followed by floors 5 and 35 respectively both at 2 PM and 6 PM. The difference in average OT could between floors 20 and 35 reached 0.94 at 2 PM and 0.96 Celsius degrees at 6 PM. Average AV could reach 0.40 and the results are not significantly different from using naturally ventilated DSF only. Lowest average AOA in this case was 369.83.

<u>North façade:</u>

Using naturally ventilated DSF in North showed lower average OT than reference case’s OT by a maximum of 1.21 degrees at 2 PM. At 6 PM, the difference could reach 1.12 Celsius degrees. This result was better than integrating shading devices in this orientation. In North, Floor 20 had the best results regarding average OT followed by floors 5 and 35 respectively both at 2 PM and 6 PM. The difference in average OT could between floors 20 and 35 reached 1.05 at 2 PM and 1.06 Celsius degrees at 6 PM. Average AV could reach 0.041 m/s at 6 PM and there were no significant differences between naturally ventilated wall results and integrating shading devices results regarding average AV. Lowest average AOA when using DSF was 357.30 s which was the lowest average value among the other cases.

To conclude the previous results, two cases were the most effective among the four cases in the four orientations as shown in the next table.

In South, West and East facades, integrating shading devices with naturally ventilated DSF where shading devices are 25 cm away from external skin (case 3) showed the best performance regarding operative temperature both at 2 PM and 6 PM.	
In North facade, applying naturally ventilated DSF showed the best performance regarding operative temperature both at 2 PM and 6 PM.	

Future Research Work

For future investigations regarding applying naturally ventilated walls and shading devices in hot arid climate in Cairo. The research recommends some work regarding the following:

- **Building performance:**

1. Investigating the effects of controlling the coming air temperature by integrating different passive techniques.
2. Experimenting within heating seasons to study the efficiency of naturally ventilated walls in Cairo’s winter.

- **Shading devices:**

1. Investigating the efficiency of integrating shading devices and naturally ventilated walls in low rise hotel buildings to check the applicability of the concept on them.
2. Experimenting different parameters of shading devices such as their position, number, and materials.

- **Energy performance:**

1. Investigating the cost of installing a DSF and Shading devices in Cairo with the current results especially if HVAC systems will be used as well to know the efficiency of applying the technique on the long run cost wise.
2. Studying the effect of setting shading devices with different parameters in different floors such as reducing the space between shading devices in higher floors to lower down the operative temperature.

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