THE IMPACT OF WIND CATCHER TYPOLOGY ON VENTILATION RATE OF BUILDINGS IN HOT, DRY CLIMATES: AN EXAMPLE ON A MOSQUE IN NIZWA, OMAN

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I certify that in my opinion the thesis submitted by Ahmad RATEB ALHRAKI titled "THE IMPACT OF WIND CATCHERS TYPOLOGY ON VENTILLATION RATE OF BUILDINGS IN HOT AND DRY CLIMATES: AN EXAMPLE ON A MOSQUE IN NIZWA-OMAN " is fully adequate in scope and in quality as a thesis for the degree of Master of Science.

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Ahmad RATEB ALHRAKI

ABSTRACT

Master Thesis

THE IMPACT OF WIND CATCHER’S TYPOLOGY ON VENTILATION RATE OF BUILDINGS IN HOT DRY CLIMATES: AN EXAMPLE ON A MOSQUE IN NIZWA- OMAN.

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In traditional architecture, wind Catchers had been used widely as a passive cooling strategy in hot climates in certain countries of the Middle East. This building element proved its effectiveness in improving the indoor thermal conditions in these regions. However, it is still not obvious of ignoring using wind catchers in other regions with the same climate characteristics. This study aims to investigate the impact of using wind catchers on the ventilation rate of buildings in these areas. For the purpose, a case study was selected in the city of Nizwa in Oman. A mosque building was chosen to perform the scope of the study. Within this context, the existing case of the case study was analyzed and simulated to examine the existing conditions of indoor ventilation rate. Then some successive Scenario including wind catchers plan shape (Square and Rectangular) and internal partitions type such as X blades, + blades, and H blades were generated. The scenarios of wind catcher’s typology were conducted to the existing case and CFD analysis was performed for each as well. The obtained data from the

CFD simulation was extracted, presented, and analyzed to be compared. As a result, it was found that square shape wind catcher with X+ composed (Star) type internal partitions increased the indoor ventilation rate in term of air velocity from 0.333508 m/s in the existing case to 0.693379 m/s in this Scenario. With this increment, the indoor ventilation rate was improved by 51.9% compared to the base case. At the end, conclusions and recommendations were drawn to guide architects and designers in the study area to examine the using of wind catcher principles in modern architecture and future investigations.

Keyword : Wind catchers, Hot- arid climates, CFD analysis, BIM, Ventilation Rate, Air Velocity, Wind catcher shape, Internal blades.
Science Code : 80408

ÖZET

Yüksek Lisans Tezi

RÜZGAR BACASI TİPOLOJİSİNİN SICAK KURU İKLİMLERDE BİNALARIN HAVALANDIRILMASINA ETKİSİ: NİZVA-UMMAN'DAKİ BİR CAMİ ÖRNEĞİ.

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Orta Doğu'nun belirli ülkelerinde sıcak iklimlerde pasif bir soğutma stratejisi olarak rüzgâr bacaları yaygın olarak kullanılmıştır. Bu yapı elemanları, bu bölgelerdeki iç mekânın termal koşullarının iyileştirilmesindeki etkinliğini kanıtlamıştır. Bununla birlikte, aynı iklim özelliklerine sahip diğer bölgelerde rüzgâr tutucu kullanımının göz ardı edilmesi hala açık değildir. Bu çalışma, rüzgâr tutucu kullanımının bu alanlardaki binaların havalandırma hızına etkisini araştırmayı amaçlamaktadır. Bu amaçla Umman'daki Nizwa şehrinde bir vaka çalışması seçilmiştir. Uygulama için bir cami binası seçilmiştir. Bu bağlamda, mevcut vaka çalışması örneği analiz edilmiş ve mevcut iç mekân havalandırma hızı koşullarını incelemek için simülasyon edilmiştir. Daha sonra rüzgâr bacalarının plan şekli (kare ve dikdörtgen) ve iç bölme tipi (X bıçaklar, + bıçaklar ve H bıçaklar) dahil olmak üzere senaryolar geliştirilmiştir. Mevcut koşullar, rüzgâr tutucu tipolojisinin senaryolarını oluşturmak için kullanılmış ve her biri için CFD analizi yapılmıştır. CFD simülasyonundan elde edilen veriler karşılaştırılmak üzere çıkarılmış, sunulmuş ve analiz edilmiştir. Sonuç olarak, X+ (yıldız) tipi iç bölme ile kare şekilli rüzgâr tutucunun, mevcut durumda iç mekân havalandırma hızını 0,333508 m/s'den bu öneride 0,693379 m/s'ye yükselttiği bulunmuştur. Bu artış ile iç mekân havalandırma oranı temel modele göre %51,9 artırılmıştır. Sonuç olarak çalışma alanındaki mimar ve tasarımcılara, modern mimaride rüzgâr baca ilkelerinin kullanımını ve gelecekteki araştırmaları incelemeleri için rehberlik edecek sonuçlar ve öneriler çıkarılmıştır. Gelecekteki çalışmalarda, bu faktörleri göz önünde bulundurarak çokgen plan şemalı rüzgâr bacalarının formu ve yükseklikleri, nem oranı dikkate alınarak farklı sıcak iklimlerde incelenebilir.

Anahtar Kelimeler : Rüzgâr bacalar, Sıcak-Kuru iklimler, CFD analizi, YBM, Havalandırma Oranı, Hava Hızı, Rüzgâr bacası şekli, İç bıçaklar.

Bilim Kodu : 80408

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SYMBOLS

m/s : meter per second
% : Percentage
Pa : Pascal (N/m^2)
C° : Celsius Degree
m^2 : Meter square

ABBREVITIONS

CFD : Computational Fluid Dynamics
BIM : Building Information Modeling
BA : Bibliometric Analysis
WWR : Window to Wall Ratio
3D : Third Dimension
SSV : Single- Sided Ventilation
CV : Cross Ventilation
SV : Stack Ventilation
WC : Wind Catcher
SAT : Standard ACIS Text
Vx : Air Velocity in the X direction
Vy : Air Velocity in the Y direction
Vz : Air Velocity in the Z direction
TED : Turbulent Energy Dissipation
TKE : Turbulent Kinetic Energy

PART 1

INTRODUCTION

1.1. BACKGROUND

Today, most countries solely rely on fossil fuels for buildings, heating, and cooling loads. One significant issue that everyone should be aware of is the impact of increased energy use on the atmosphere, which would increase air pollution and ozone-depleting gas emissions (greenhouse effect). Moreover, buildings consume more than 40% of the total global energy consumption and due to future energy resource limitations, this will result in a variety of issues with buildings, especially in hot climates.

People who reside in hot climates struggle to adapt to their surroundings. There are various reasons for this issue, some of which may be related to the harsh weather and others to the nation's poor economic situation [1]. For these reasons, the current study in the built environment promotes using passive design strategies in which buildings adapt with their ambient surroundings as well as reduce building energy cooling loads.

In literature, it was found that natural ventilation techniques were used in traditional architecture in hot climates such as the mashrabiya, the courtyard, and the wind catcher. The main purpose behind these building elements is to afford comfortable indoor conditions for building users without any active intervention. Although the mashrabiya and the courtyard were useful tools for controlling the air circulation and increasing the air current's moisture. Wind catcher proved its effectiveness as a passive cooling strategy in hot climates.

Wind catchers are fixed chimney shaped devices that are constructed as building element and works as air inlet and outlet. Its main function is to act as passive cooling technique by providing natural ventilation especially in hot dry and humid climate zones.

Through literature survey, it was found that there is various distribution of wind catchers' structures and types about the border of the hot zone of the Middle East countries. Some regions in countries such as Iran, Iraq, and Egypt have their own construction properties of wind catchers. However, although there are other areas within the same borders with comparable climatic characteristics, wind catchers do not exist there. For instance, from architectural style view, Yazd in Iran and Nizwa in Oman can be considered as twin cities. However, the city of Yazd is famous for its dense existence of wind catchers while the buildings in Nizwa city do not contain these elements. Within this context, examining the effectiveness of wind catcher as a passive cooling technique in these kinds of areas is useful to adopt passive design techniques to go ahead toward sustainable architectural design. In addition, architects and designers should get benefits of the natural ventilation methods in their modern architecture in hot and dry climates.

Depending on these hypotheses, this study aims also to provide enough data and a clear workflow that could help architects in the early design stages in investigating the impact of several types of wind catchers on the indoor ventilation rate. This study is limited to investigating the effect of wind catcher plan shape (Square, Rectangular) and the type of wind catcher internal partitions (X, +, and H types). Other design parameters and Scenarios could be examined in future studies.

1.2. PROBLEM STATEMENT

Wind catchers are one of the passive cooling strategies that have been used in vernacular architecture through centuries. However, they were mostly used in some arid-hot zones such as Iran and Iraq while not used in other regions with the same climate types. Therefore, examining the efficiency of using wind catcher as a passive cooling strategy in Nizwa- Oman (a twin city for the famous wind catcher's city Yazd in Iran) with an appropriate workflow can be considered the main problem of this study.

Additionally, wind catcher’s typology plays a significant role in determining the indoor ventilation rates in buildings. For that reason, investigating the best scenario of wind catcher’s typology including its geometry and design parameters can also be considered as a research problem.

1.3. RESEARCH OBJECTIVES

Wind catchers have shown to be useful study materials and may yet have roots in the early communities of nations like Iran, Iraq, and Egypt. This type of passive cooling techniques may be utilized in current architecture in other hot regions with similar climate conditions such as Oman. This hypothesis could provide a more comfortable indoor environment and ventilation rate. For that purpose, a more comprehensive study is needed.

Consequently, the main goal of this research is to provide a systematic workflow that could be utilized in the early design stages for testing various Scenario of wind catcher typology. Within this context, the study aims to examine the impact of several types of wind catcher geometry and internal partitions on the natural ventilation rate in hot arid regions buildings. For the purpose, a case study was selected in hot dry region represented by a mosque building to perform the scope of the study.

1.4. RESEARCH QUESTIONS

The research aims to investigate the impact of wind catcher’s typology on the indoor ventilation rate in buildings. Within this context, the main research question could be formulated as the following:

What is the best typology of wind catcher that will achieve the highest indoor ventilation rate in the study area?

The research also aims to answer the following sub-questions:

- What are the differences between the several types of wind catchers?

- What are the functions and purposes of the used wind catchers?
- Is the type and design of wind catcher related to the optimum ventilation?
- To what extent can the best solution of wind catcher typology and parameters improve the building indoor ventilation rate in the study area?

1.5. RESEARCH PROCEDURE

The research focused on assessing the impact of applying a passive cooling strategy (wind catcher) in hot- arid zone (Nizwa-Oman) to improve the indoor building conditions. For the research purpose, the methodology of the research was divided into some stages. In the first stage, a survey was carried out to collect data about the selected case study. In the second stage, the model was prepared by Revit with the required information. In the third stage, some successive Scenarios of wind catchers' typologies (Square and rectangular shape plan with +, X, H types of internal partitions) were generated. The fourth stage is represented by exporting the 3D BIM models for the base case and the suggested scenarios to the CFD analysis software to be simulated. Finally, the results from the previous stages were collected, extracted, and presented in tables and graphs to be discussed.

1.6. RESEARCH STRUCTURE

This thesis consists of five parts. **In the first part**, a general background about the research topic as well as the purposes, the objectives, and the procedure to reach the research results will be presented. **In the second Part**, a considerable amount of literature that is related to the study topic will be presented including natural ventilation systems and using wind catchers as a passive cooling strategy. **Part three** describes the detailed methodology of the research in terms of materials and methods as well as the tools that will be used to achieve the scope of the study. It also describes the selected study area and the selected case study, its location, its climate, function, and structure etc. In addition, this part also includes detailed information about generation of the suggested scenarios that will be applied to the selected building. **Part Four** includes the results and output from the CFD simulation in terms of air velocity for the base case and suggested scenarios. This part also includes analysis and discussion section for the extracted data for clear comparative approach. The final Part represents **Part Five** of the thesis including the conclusions and recommendations that may help architects and designers for adopting and designing the proper wind catchers in the study area in the early design stages in their contemporary design projects.

PART 2

LITERATURE REVIEW

This part investigates a considerable amount of literature that is related to the study topic. The literature was reviewed through scientific articles, Master and PhD theses and internet websites to form a comprehensive overview about the status of using wind catchers all over the world in traditional and contemporary architecture. For this purpose, a bibliometric analysis was performed to determine the most frequent keywords as well as the evolution and the trend topics of wind catcher studies in recent research. After that, the main topics were determined and an overview that serves the current topic was reviewed. Consequently, the chapter was divided into four main sections. The first section will include bibliometric analysis for the field study. The second section will include natural ventilation principles, mechanism and building systems. The third part will include traditional architecture and passive cooling techniques such as the mashrabiya and the courtyard while the fourth section will introduce wind catchers as a passive cooling technique.

2.1. BIBLIOMETRIC ANALYSIS

A bibliometric analysis of the wind catcher and its applications studies was conducted to determine the scope of the study. For the purpose, the bibliometric analysis was performed using Scopus and Web of Science platforms. The analysis process started by determining keywords that include the following form: (“Wind catchers” OR “Wind towers”) AND (“Evaluation”) AND (“Review”)). The search also limited to the most recent studies in the field from 2015 to 2022. The document type was limited to “Article” and “Review” types while “Conference article” and “Conference review” were excluded from the search process. In addition, the source type was limited to “Journal,” or “Conference Proceeding” and the documents language was limited to “English”. In that way, the data mining of bibliometric analysis was conducted in the Scopus and web of science platforms to filter the most related studies to our current study. As a result, a total of 48 documents including journal and conference proceedings articles were determined and exported as BibTex file format to R studio software to conduct the bibliometric analysis.

The results of bibliometric analysis showed that the most used keywords with the most frequently occurrence in recent research are Wind Catchers, Natural Ventilation, Ventilation, Airflow, and Computational Fluid Dynamics CFD. Figure 2.1 illustrates the thematic map produced from the bibliometric analysis using R studio software.

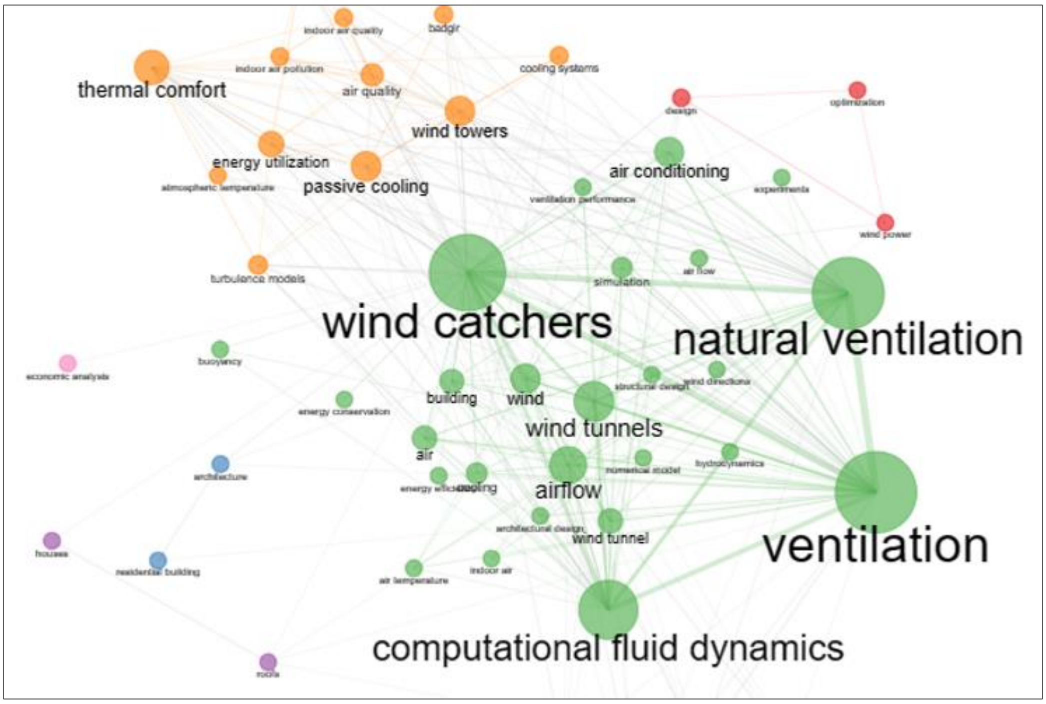


Figure 2.1. Thematic map of the bibliometric analysis using R studio.

The results of the bibliometric analysis also showed the evolution of interesting topics from past studies to the current studies. Within this context, the analysis showed that a great interest has raised in ventilation, passive cooling, and architectural design topics in 2017-2022 studies from building, energy utilization, and wind catchers' topics from 1986-2016. Figure 2.2 shows the thematic evolution produced from bibliometric analysis of the study field.

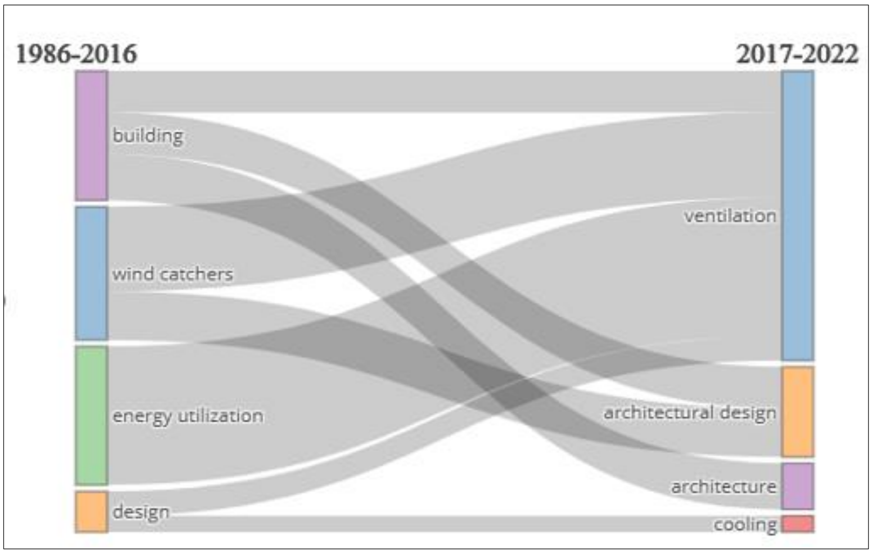


Figure 2.2. Thematic evolution of the bibliometric analysis using R studio.

Another benefit from bibliometric analysis was formed in determining the trend topics in the field. For example, it can be noticed from Figure 2.3 that indoor air, flow visualization, airflow, numerical model, and wind velocity are from the most recent used topics in most recent studies (blue color). This means that these topics need more investigations in future studies. Figure 2.3 illustrates the factorial analysis showing the trends in topics in the field of study.

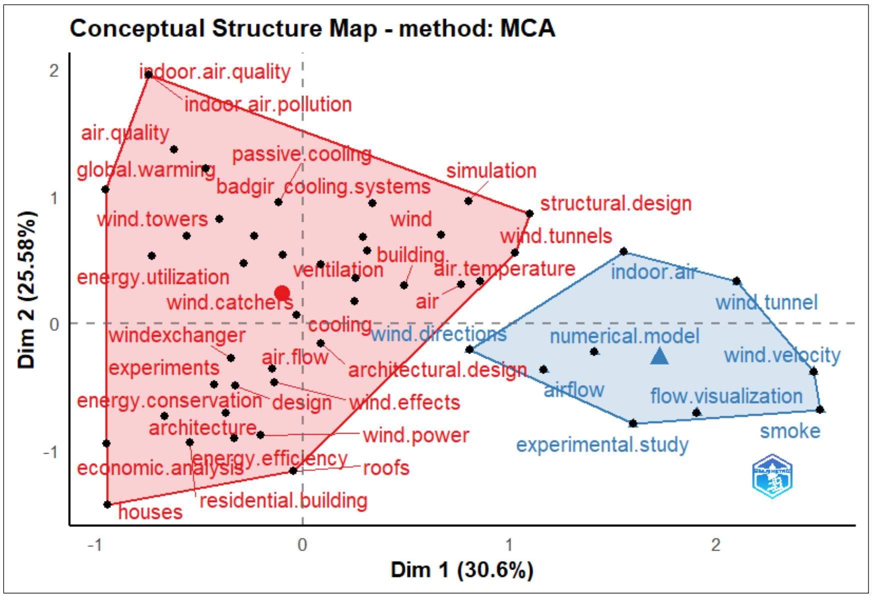


Figure 2.3. Factorial analysis of the field of study using R studio.

It can be concluded from the previous analysis that the architectural design issues of wind catchers such as typology, geometry, design parameters, etc.... and their effect on natural ventilation rate and air flow are from the trend topics in the literature. For that reason, this research is concentrated on the effect of wind catcher’s typology on the ventilation rate in buildings. Therefore, natural ventilation methods will be explored in the following section.

2.2. NATURAL VENTILATION SYSTEMS

The natural ventilation concept is the main factor in achieving the passive cooling design principle. This principle is playing a significant role in sustainable and bioclimatic architecture which is defined as "the passive low-energy design approach that makes use of the ambient energies of the climate of the locality to create conditions of comfort for the users of the building" [2]. Sustainable building design promotes applying strategies that adapted with climate and ambient environment to enhance human thermal comfort [3]. Most of the studies concluded that the basic solution of sustainable building design is found in vernacular architecture where many worthy traditional examples are still existing [4]. Within this context, passive heating and cooling subject is playing a significant role that depends on natural ventilation concept [5].

According to Sorensen (2009) three main methods of natural ventilation are commonly used to achieve the passive cooling concept which are: (a) cross ventilation based on the pressure difference across the building, (b) chimney ventilation based on the stack effect, (c) wind towers and wind catches based on overpressure and under pressure [6].

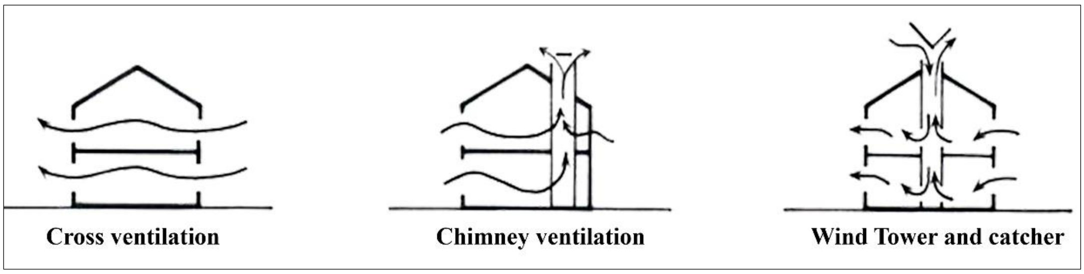


Figure 2.4. Natural ventilation basic models [6].

In general, natural ventilation rate depends on wind pressure and temperature differences [7]. For that reason, passive cooling design strategies are preferred to be used in hot climates. This presents the most obvious factor of the building's adaptation to the local conditions, which is usually based on natural ventilation and the use of water. Figure 2.5 shows some of natural cooling ventilation techniques.

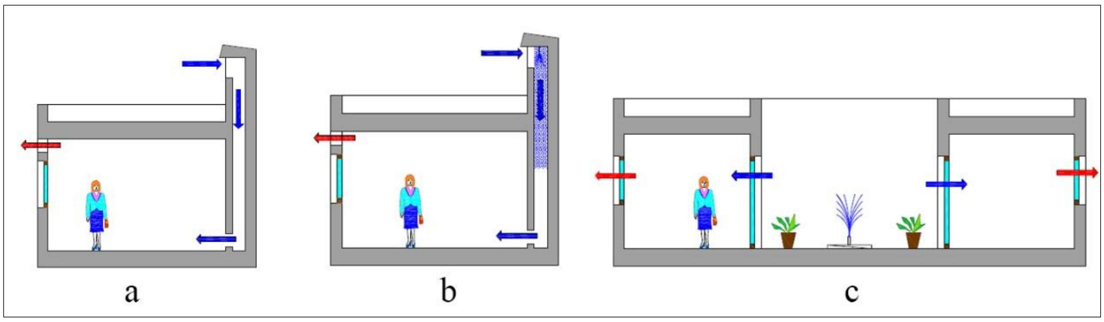


Figure 2.5. Natural & cooling ventilation techniques (a) Wind tower (b) evaporative wind tower (c) Patio as a natural ventilation-mediated cooling solution [8].

2.2.1. Single-sided Ventilation (SSV)

The single-sided ventilation can be distinguished as a ventilation method where air normally enters a space from single side of the house or building- Figure 2.6. This method is commonly used in practice due to its simplicity. However, it has a lot of disadvantages such as: the low air level, the difficulty of air to regulate, and it is only effective in places close to the window [1]. Within this context, studies indicated that the depth of a room must be 2 to 2.5 times the height from the building floor to the top roof for comfortable internal ventilation by single-sided ventilation method [9,10]. In addition, single-sided ventilation can provide healthy indoor ventilation instead of improving thermal comfort conditions in hot and dry regions due to the poor airflow rate [11].

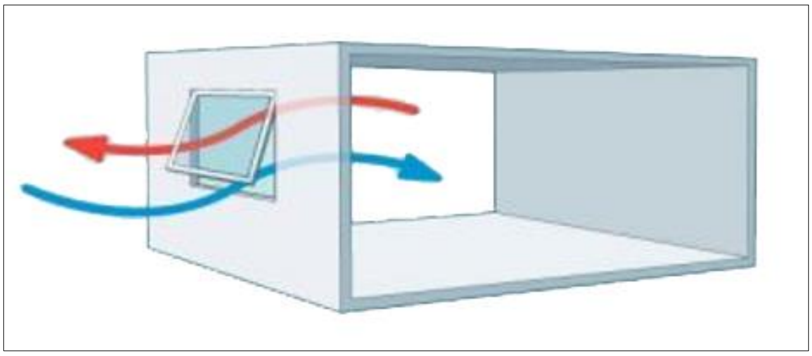


Figure 2.6. Single-sided ventillation concept [9].

2.2.2. Cross Ventilation (CV)

Cross ventilation is also called two-sided airflow method. This ventilation method can be explained as a “ventilation concept in which air enters an indoor room via a window on one of the structure’s side, travels through the area within the structure, and then escapes through another window on certain side of the building which could be on the opposite wall” [1] as shown in Figure 2.7.

According to Carrilho da Graça & Linden (2016) cross ventilation could be effective in rooms with a maximum depth of 12 m and depth of 2.5 to 5 times the height of the ceiling. In addition, it is an effective technique to improve thermal comfort conditions in hot climates by increasing the physiological evaporative cooling building occupants [12]. In this context, the size, the height, and the location of windows or openings plays a significant role in enhancing natural ventilation through cross ventilation concept [13].

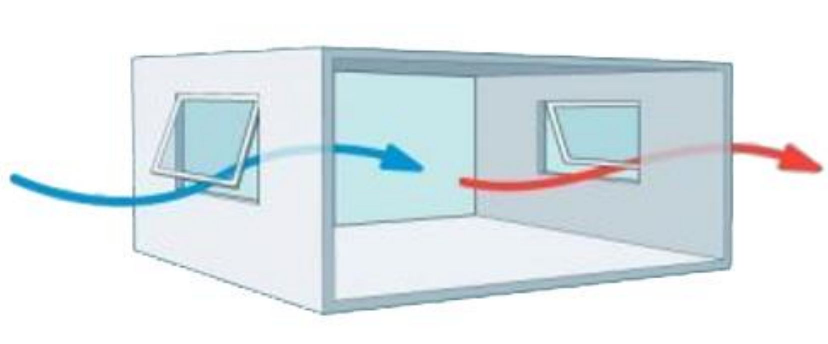


Figure 2.7. Cross ventillation concept [9].

2.2.3. Stack Ventilation (SV)

Stack ventilation can be defined as a ventilation concept where air travels vertically through the structure affected by the stack force. In this ventilation method, large windows or at least two openings are used at various distances from the ground to increase the airflow. Consequently, stack ventilation is effective in high structures with more height room [1].

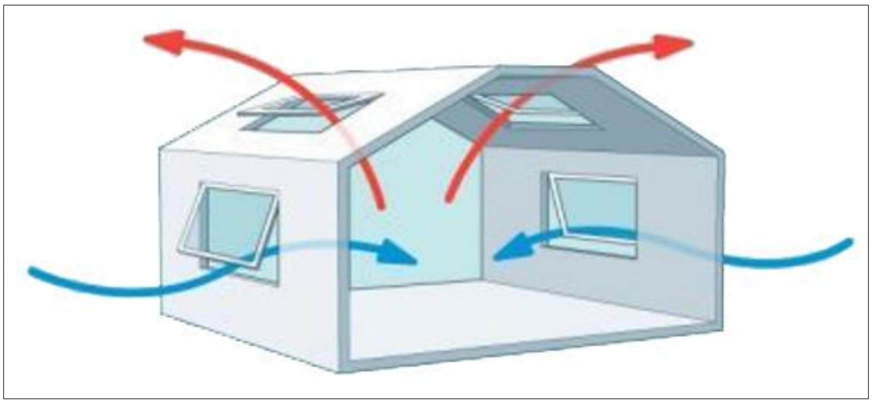


Figure 2.8. Stack ventillation concept [9].

Stack ventilation is benefitable in high-rise buildings with deep structures where vertical shafts and openings could be offered as shown in Figure 2.9. It is important to offer a pressure differential between the structure’s windows (Inlet) and the outlet at the top of the stack. As a result, a large negative pressure gap between the inlet and the outlet exists allowing the air to flow and be regulated within the building’s spaces [14]. However, on the other hand, the stack ventilation concept cannot improve thermal comfort conditions in hot and humid climates [1].

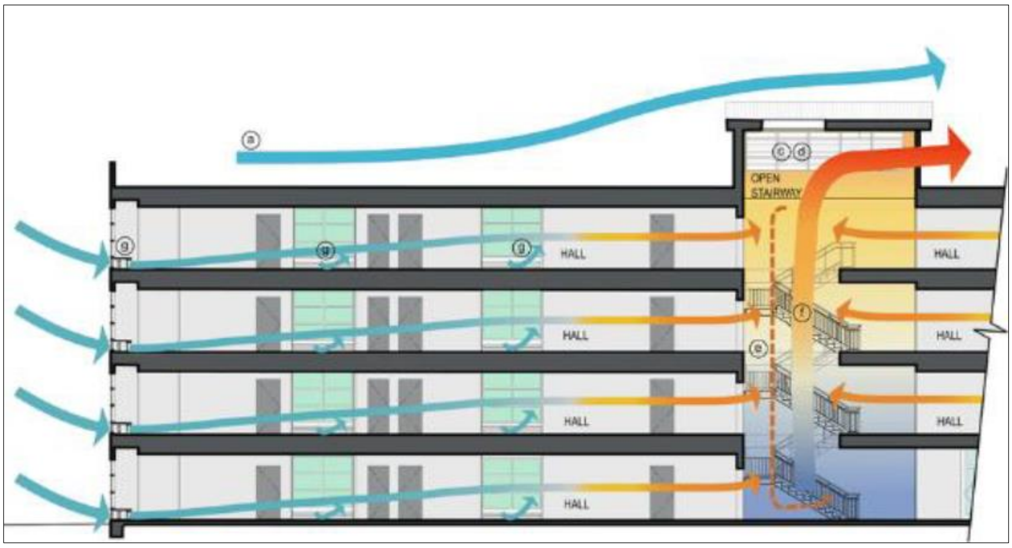


Figure 2.9. Stack ventilation in high-rise building [15].

2.3. TRADITIONAL ARCHITECTURE AND VENTILLATION METHODS

Ventilation methods in traditional architecture have been used for centuries and continue to be used in many buildings today. The benefits of using ventilation techniques in traditional architecture were always that they can enhance a building's ability to react effectively to climatic conditions as well as other urban requirements [16]. In the following are some ventilation techniques used in the traditional architecture including the Mashrabiya, the courtyard, and the wind catchers or towers those are used as passive cooling design strategies in the traditional buildings.

2.3.1. The Mashrabiya

The Mashrabiya is a mesh-opening cantilevered space [1]. It has different names: ‘Moshabak’ which is common in Iran [17] and ‘Rawshan’ or ‘Shanasheel’ which are common in the Arab region [18]. In this element water pots are traditionally placed next to the mesh to be cooled by evaporation when outdoor air went through the mesh gaps. Mashrabiya is a common Arabic architectural component that consists of a window surrounded by wooden latticework on the upper level [18]. Figure 2.10 illustrates schematic drawings of a Mashrabiya showing its properties and its functions.

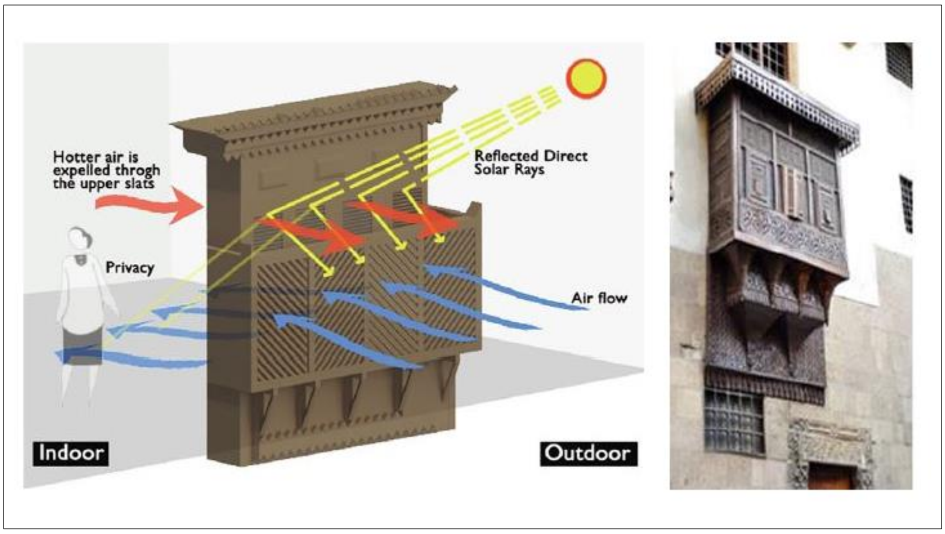


Figure 2.10. Schematic of a Mashrabiya [19].

The mashrabiya serves several functions like controlling the air circulation, controlling the light that can pass, increasing the air current's moisture, ensuring privacy, and lowering the air current's temperature [18]. Various patterns of the mashrabiya have been used in various hot climate regions including Northern Africa and the Middle East, the Western and Southern of Asia especially India, south of Turkey and Spain [1]. Figure 2.11 illustrates examples of the mashrabiya patterns used in different countries.

Figure 2.11. Examples of the mashrabiya in different countries [18].

2.3.2. The Courtyard

The courtyard is a passive cooling technique in hotter climates that has been used for centuries to help decrease the heat index. In the summer months, courtyard installations can help to lower temperatures in large public spaces. As a result, common summertime discomforts such as heatstroke and sunburn can be reduced and, in some cases, avoided. A courtyard can act as a buffer against extreme heat [20].

Figure 2.12. (a) Al Suhaymi house ground floor plan, (b) courtyard garden, (c) rear garden [20].

In contrast to the open-air areas on the perimeter, the enclosed space in the center has lower air movement. As a result, the air inside the courtyard is cooler than the air outside. This is a beneficial effect because when it is windy, the outside air moves in, bringing heat with it, increasing the temperature of the courtyard. During sunny days, however, the wind is not as strong. Hence, the warmer air inside the courtyard tends to stay there [20].

Figure 2.13. (a) Air movement during noon (b) air movement after noon [20].

2.3.3. The Wind Catchers

A wind catcher is a fixed chimney shaped device. Its function is to act as an air inlet and outlet simultaneously [21]. Wind catchers are mostly constructed in hot and dry or humid areas to provide natural ventilation and act as passive cooling design strategy [22]. In the following section, wind catchers will be described in detail.

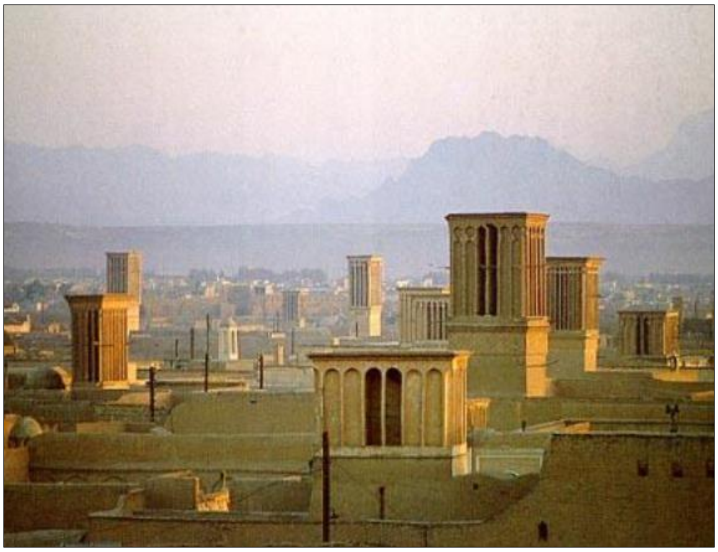


Figure 2.14. Wind catchers in Yazd City- Iran [23].

2.4. WIND CATCHERS AS A PASSIVE COOLING STRATEGY

This section reviews the wind catchers as a passive cooling strategy used in buildings. Firstly, the section will provide information about the purpose and function of wind catchers. Secondly, a historical background about the evolution of using wind catchers will be explored. Then, the main components and the several types of wind catchers will be reviewed.

2.4.1. Purpose and Function of Wind catcher

2.4.1.1. Purposes of Wind Catchers

The main purpose of wind catchers or towers is to achieve thermal comfort conditions and provide a fresh air to the indoors [24]. According to Roaf (2005) wind towers could be used for:

1. Provide evaporative cooling in hot dry climates where the indoor temperature exceeds 35 C°.
2. Enhancing natural ventilation rate and airflow where the indoor temperature lies between 25-35 C°.
3. Having night ventilation [25].

2.4.1.2. Function of Wind Catchers

Wind towers are ventilation tools used for obtaining natural cooling [26]. The wind catchers or towers have the same concept as natural ventilation systems that includes the stack ventilation effect and wind effect which depends on the temperature variations. Designing of openings and solids used in wind catchers and the vertical shaft geometry control these features and assist directing the wind down to the interior of the building [27]. Figure 2.15 illustrates the main principles of a wind catcher.

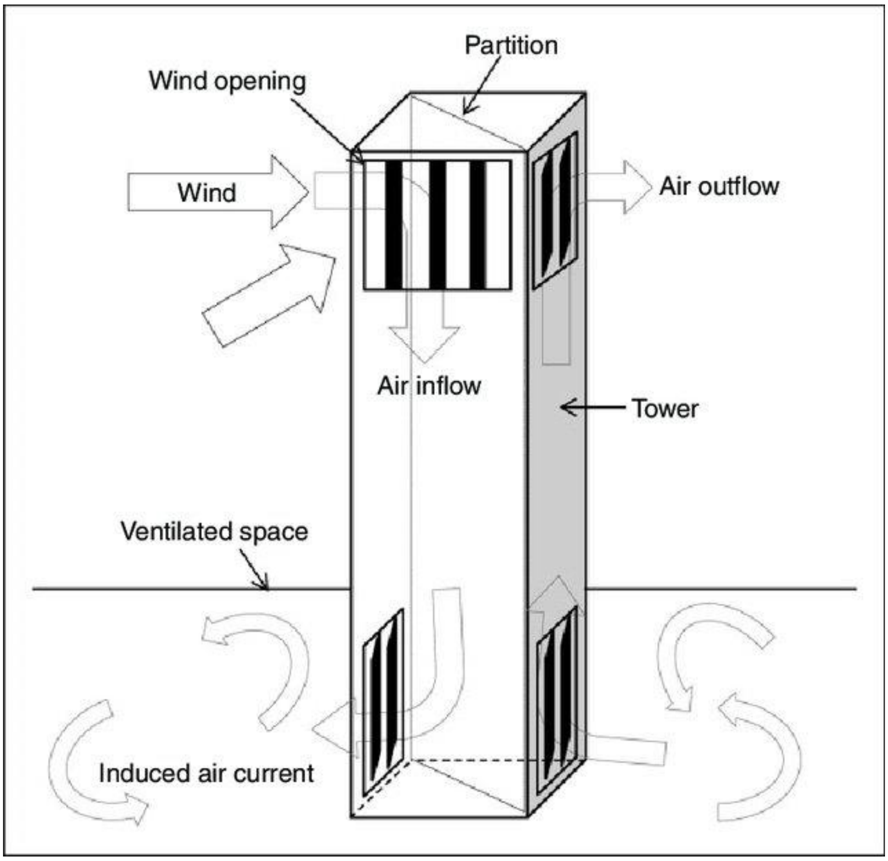


Figure 2.15. Wind catcher basic principles [28].

2.4.2. History of Wind Catcher

The wind catchers, also referred to as wind towers, are natural air-cooling systems. For decades, particularly in the Middle East, they have been used in numerous nations with hot, dry climates as natural ventilation methods in buildings. A tower with a head that extends above the building's top is a traditional wind catcher. The tower may have one side facing the prevailing wind direction or two or four sides may be opened allowing the wind from all paths [29,30]. In all cases, the tower should be split into two or three sets of internal shafts [1]. In this subdivision, more surface area will be in contact with air because of the tower's airflow being divided into various directions at the same time [31].

Egyptian drawings on papyrus from around 1500 BC described wind catchers. The illustrations that sketched the home of the wealthy in the New Kingdom feature two triangular-shaped wind catchers- Figure 2.16 [29].

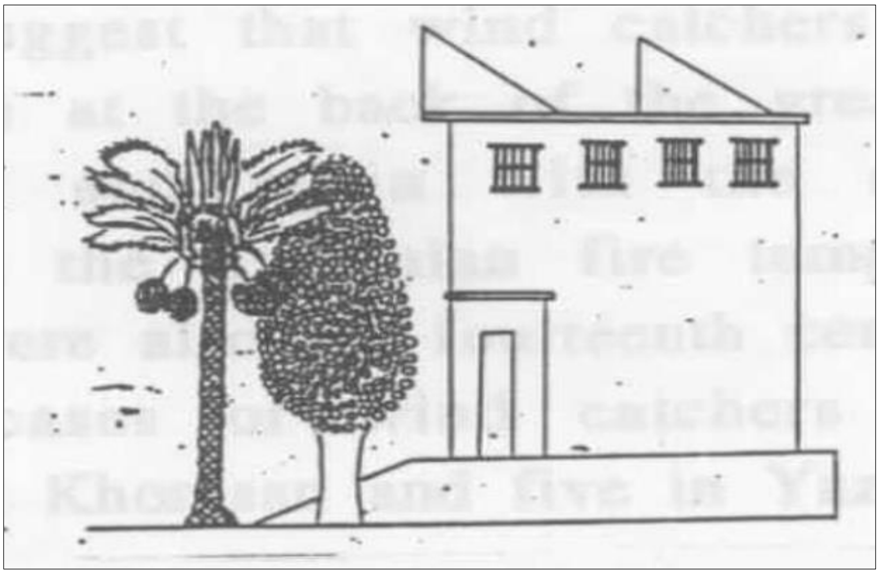


Figure 2.16. Wind catcher of the pharaonic house from a papyrus painting [29]

According to literary sources and facts, a novel type of wind catcher called a "badahanj" (Persian for "wind drawer") was transported from Iran to Egypt. In Cairo, a variety of "badahanj" were placed, and by the fourteenth century, people knew them as "malqaf " [25]. Additionally, they can be seen on buildings all over the globe, in a variety of sizes and shapes, from Pakistan to Egypt, where the environment is hot, dry, and occasionally humid [1].

2.4.2.1. Geographical-based Distribution of Wind Catcher Use

There are many diverse types of wind catchers in the nations that make up the Middle East's hot zone border. They can be categorized into a wide range of major classes depending on their origin and general arrangement. For instance, those connected to Iran's big cities (like Ardakan and Yazd) are referred to as "Ardakani type". Similar wind catchers can also be found in littoral regions along the Persian Gulf, including Rarat in Afghanistan, Sind in Pakistan, Cairo in Egypt, and Baghdad in Iraq. Those may be referred as "Bandar-e-Abbassi type" [32]. Figure 2.17 shows the geographical distribution of wind catchers in the middle east region.

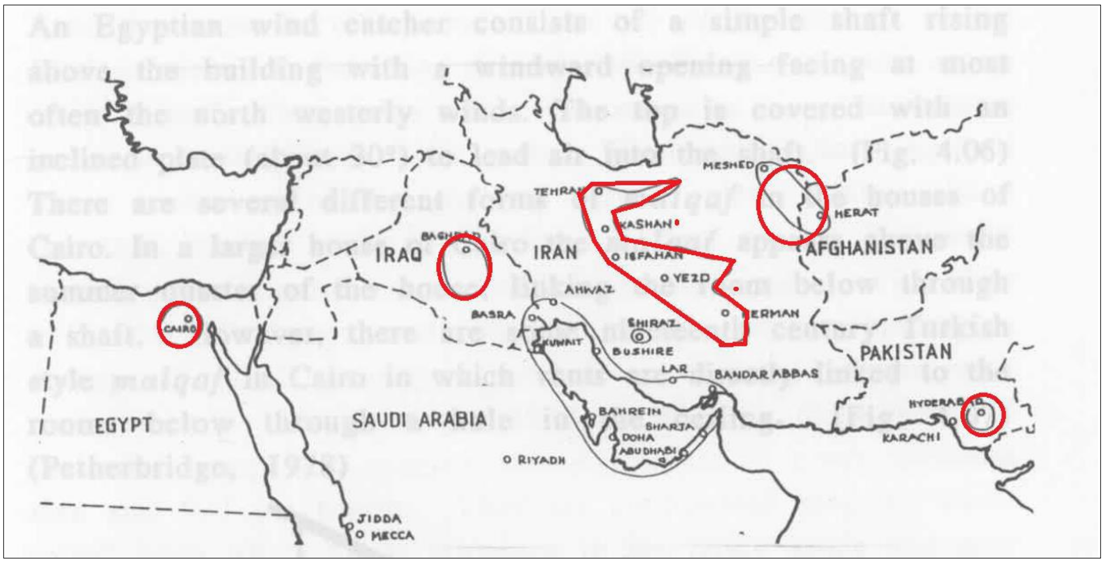


Figure 2.17. Location of wind catchers in countries of the middle east [1].

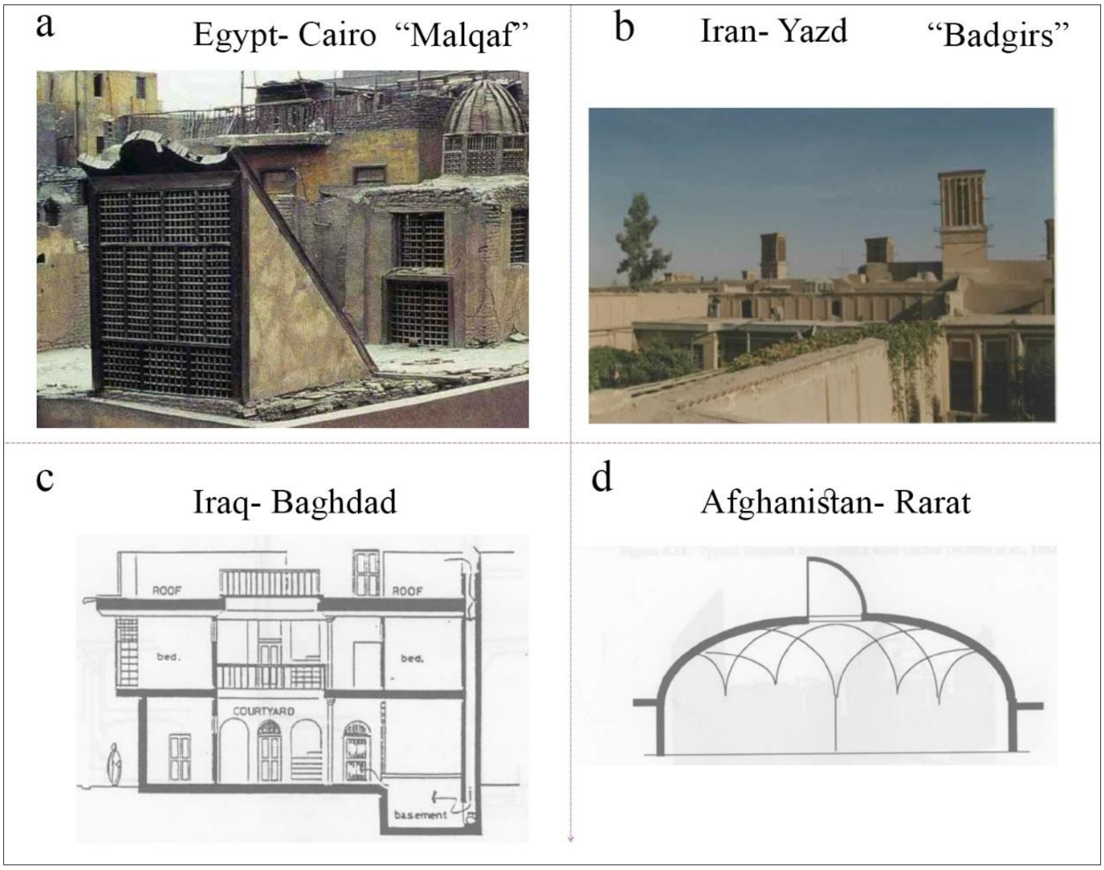


Figure 2.18. (a) Example of one sided Malqaf in Cairo- Egypt (b) Example of four sided Badgir in Yazd- Iran (c) Example of wind tower in Baghdad- Iraq (d) Sketch of Wind catchers in Rarat- Afghanistan [29,32,33].

2.4.2.2. Climate-based Distribution of Wind Catcher Use

The basic purpose of a wind-catcher is to trap wind while simultaneously removing indoor air from a low-pressure area, however the shape is controlled by environmental and climatic considerations. There are two main classifications of traditional wind catchers including (a) Wind catcher in hot and humid regions and (b) Wind catcher in hot and dry regions [1].

Wind Catcher in Hot and Humid Regions

In hot and humid regions, wind catchers have unusually large openings and short shafts because of the low wind power in these regions. To maintain a comfortable indoor air temperature, each room often has its own wind catcher. Especially in hotter cities, wind catchers and most natural cooling systems can provide internal air circulation that can help remove moisture and aid deliver cold air to the users [25].

In these climates, mortar plaster, ashes, and plaster of lime were used, and the color utilized for the wind tower frame and surface was white to limit the absorption of radiation and heat [1]. Moreover, the cross-section plan of such wind tower is typically square, with equal length and width in hot and humid regions [24]. Figure 2.19 illustrates examples of wind catchers in hot and humid areas.

Figure 2.19. Examples of wind catchers in hot and humid climates [25].

Wind Catcher in Hot and Dry Region

In hot and dry climates, the wind catchers' shaft heights are higher than they are in hot, humid areas. The wind catcher's column falls to the ground floor in the hot, dry climate, where the occupants often reside [24]. The air temperature decreases with increasing distance from the earth, and the wind catcher can capture colder, cleaner air with more speed and less dust at the higher area by adjusting the shaft height. Furthermore, the size of this kind is less than that of a wind-catcher in hot and humid regions [1,21]. Figure 2.20 illustrates examples of wind catchers in hot and dry climates.

Figure 2.20. Examples of wind catchers in hot and dry climates- Yazd/ Iran [21].

In these climates, the wind normally flows over a fountain or a stone pool at the bottom of the construction as it enters a structure through a wind catcher, bringing both cold and damp air inside the structure. Since evaporation is enhanced by hot weather, colder temperatures and higher humidity levels occur from this rise in relative humidity and cooling influence [34]. The utilized material of the wind tower is influenced by environmental standards and the available materials in hot and dry regions and is the same as the materials that were used in other conventional buildings [1]. The wind catchers or wind towers are typically constructed of backed brick or mud brick in hot and dry regions. These materials had been lightly painted on the inside and outside to reflect light and give it a rough appearance. Additionally, mud brick has the capacity to both block the sun's rays during the day and absorb them throughout the evening [1,21,25].

2.4.3. Types and Components of Wind Catcher

The traditional wind catchers consist of different components including openings, roof, head, channel, and internal partitions as shown in Figure 2.21.

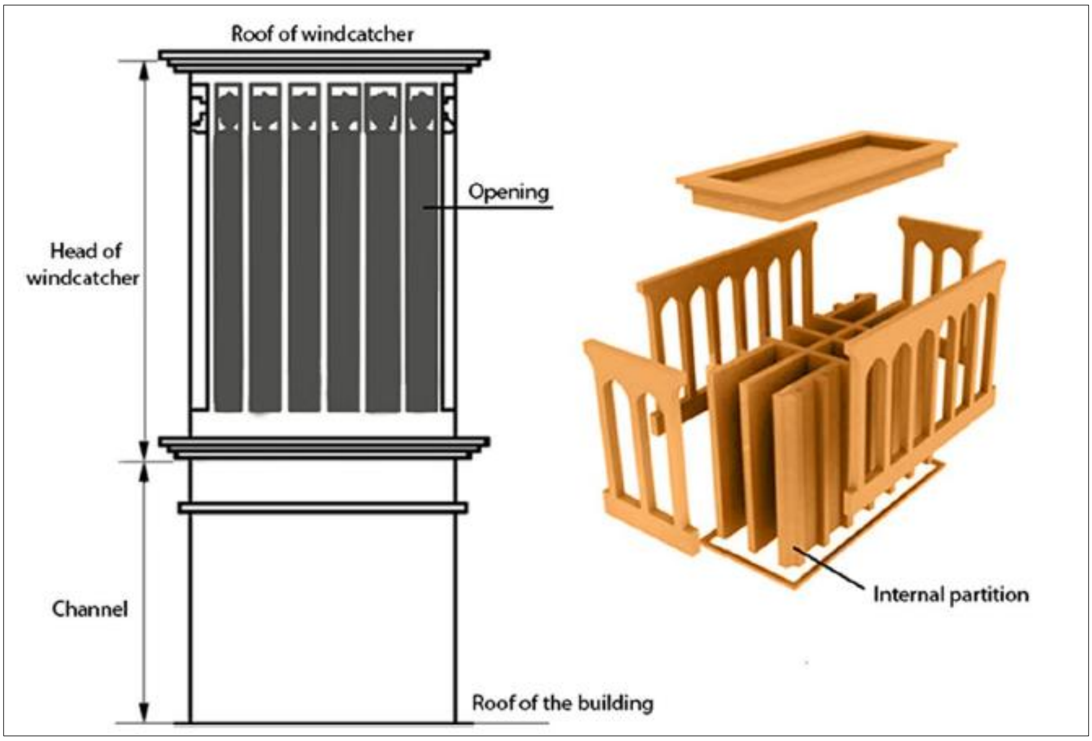
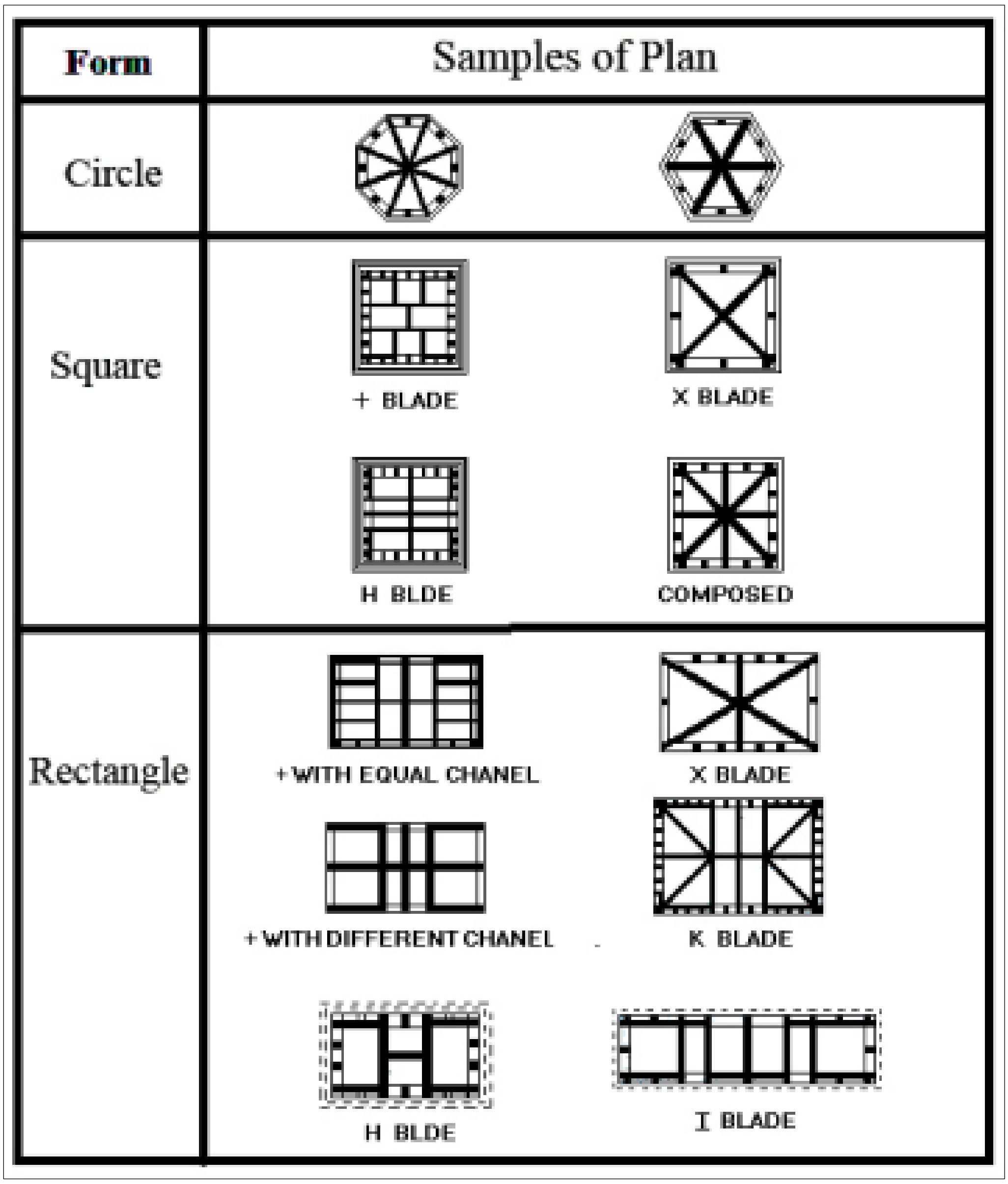


Figure 2.21. Traditional Wind catcher components [22].

Wind catchers are also classified according to their plan shape. Generally, Circular, square, and rectangular plan shapes windcatchers can be found- Figure 2.22 [36]. In this context, some studies classified wind catchers based on their wind exposure sides. Six groups including one, two, four, six, eight sided as well as cylindrical wind catchers were found. In addition, wind catchers can also be classified based on their internal partition type [37,38].



Form	Samples of Plan
Circle	
Square	+ BLADE X BLADE H BLDE COMPOSED
Rectangle	+WITH EQUAL CHANEL X BLADE +WITH DIFFERENT CHANEL K BLADE H BLDE I BLADE

Figure 2.22. Plan shape-based classification of wind catchers [36]

2.4.3.1. One-Sided Wind Catchers

The one-sided wind catcher consists of one opening for inlet and outlet air. In this situation, the wind catcher takes the wind from the top opening of a building to the channel and then the air passes from another opening of the building [39] as shown in Figure 2.23 a. This type of wind catchers was mostly used in areas where air flows in one specific direction [26].

2.4.3.2. Two-Sided Wind Catchers

The two-sided wind catcher consists of two opposite openings. One of these openings is opposite to the prevailing wind works as entrance for fresh winds while the other extracts the warm air – Figure 2.23 b [35].

Figure 2.23. (a) One sided windcatcher (b) Two sided windcatcher in Yazd-Iran [35].

2.4.3.3. Four-Sided Wind Catchers

The four-sided wind catchers were frequently used in the areas where there is no specific direction of wind. In this situation, the wind catcher function will concentrate on capturing the prevailing wind from all directions [40].

Figure 2.24. Four-Sided wind catchers in Kish island- Iran [40].

2.4.3.4. Six or Eight-Sided Wind Catchers

Six and eight-Sided wind catchers were rarely used in residential buildings. However, they have been seen frequently constructed over the water cistern in Iran [22]. In this situation, a wind catcher with hexagonal or octagonal plan-based shape can be constructed as shown in Figure 2.25. Within this context, the cylindrical wind catcher can be considered as the last generation from the traditional wind catchers that used in few examples in Iran and Dubai [41].

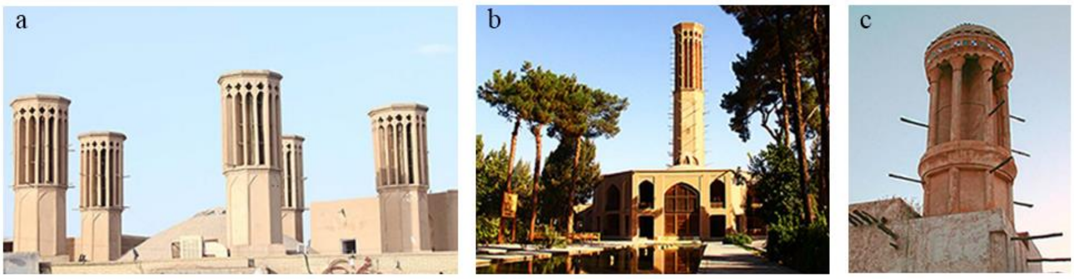


Figure 2.25. (a) Six-sided windcatcher in Yazd-Iran (b) Eight-sided windcatcher in Yazd-Iran (c) Cylindrical windcatcher in Dubai [41].

2.4.4. Review of the Evaluation of Wind Catchers Performance

The utilization of natural ventilation systems, particularly wind catchers, has gained prominence in modern buildings as a strategy to reduce energy consumption and reliance on active environmental control methods. Wind catchers offer an innovative approach to harnessing natural airflow for improved indoor ventilation. For this reason, evaluating the wind catchers performance is one of the vital topics in the current research studies. It is essential to assess the performance criteria of wind catchers in the early design stages.

Many methods were used to assess the performance of wind catchers. In the literature, methods such as Computational Fluid Dynamics (CFD) and numerical Simulation, field surveys and measurements, comfort analysis, as well as comparative studies with and without wind catchers were conducted to evaluate their effectiveness in improving indoor conditions and energy efficiency.

The study of Lia and Mak (2005) described a numerical study that evaluates the performance of wind catchers, and innovative green features used for natural ventilation in modern residential buildings. The aim is to reduce reliance on non-renewable energy and active environmental control methods. The research employed computational fluid dynamics to assess the wind catcher's functionality. The wind catcher system, with a size of 500mm square, is modelled in connection with a room. Various wind speeds ranging from 0.5 to 6 m/s and four wind directions are considered. The numerical results aligned closely with experimental findings from a wind tunnel experiment. The study revealed that wind catcher performance is significantly affected by external wind speed and direction concerning different quadrants of the wind catcher. Across all cases, the air's maximum velocity entering the room is equal to the external wind speed, illustrating the wind catcher's efficacy in bringing fresh air into the room. Moreover, the study finds that the airflow rate of incoming air rises with wind speed but slightly decreases when wind incidence angles are lower than 3 m/s. Additionally, as wind speed and incidence angle increase, the uniformity of air intake decreases [27].

Mahmoudi et al (2009) discussed the role of wind catchers in providing effective cooling and ventilation using renewable wind energy, particularly in the arid climate of Yazd city. The study focused on understanding wind catchers from an architectural perspective through field surveys. The selection of the case study city is based on a random and analytical method. This research pioneers wind catcher typology and explores the architectural principles governing their design. The study analyses fifty-three wind catchers by physically examining their patterns and shared concepts. The research delved into how the architecture of wind catchers affects their performance by analyzing thermal behavior, employing fluid dynamics science, Fluent software, and numerical analysis for accuracy. The results revealed formal specifications for wind catchers that achieve optimal operation in Yazd. They claimed that the knowledge gained from the optimized model could be applied to enhance the design and construction of wind catchers for improved performance [22].

El-Shorbagy (2010) investigates the traditional architecture of Central Asia and the Middle East, shaped by the local land, climate, and cultural influences. Designs of this region prioritize human needs and environmental factors. Among the solutions introduced is the wind catcher, an architectural feature aimed at natural ventilation in buildings as described by him. The paper underscored the significance of wind-catchers and advocated for their use as a natural ventilation alternative to unsuitable modern cooling systems in hot climates. The study examined the theoretical basics of wind catchers, understanding their essence, applications, and functions within the framework of architectural practice and discourse across different time periods [23].

Computational Fluid Dynamics (CFD) Simulation is the most used method in evaluating wind catcher performance. In the study conducted by Ghadiri, et al in (2013) the focus was on wind catchers as natural ventilation systems for buildings. They claimed that designing and evaluating wind catchers' performance requires accurate computational fluid dynamics (CFD) simulations of both indoor airflow and outdoor wind flow. Giving the numerous computational parameters affecting CFD simulations, they conducted comprehensive sensitivity analyses to understand the impact of these parameters on simulation crucial outcomes for guiding CFD studies. The researchers found a need for a broad, generic sensitivity study specifically addressing CFD simulations for natural ventilation in wind catchers, which is addressed in this paper. Within this context, the paper presented a series of 3D steady simulations for a typical two-sided wind catcher attached to a room. These simulations consider wind directions ranging from 0º to 90º in 15º intervals. To validate the CFD simulations, they were compared with detailed wind tunnel experiments. The research delved into the influence of a wide array of computational parameters, encompassing aspects such as computational grid resolution, computational domain size, turbulence models, and the discretization scheme order. This study contributed to better understanding the behavior of wind catchers in natural ventilation through comprehensive CFD simulations and sensitivity analyses [30].

A successive study was conducted in (2014) by Ghadiri et al. The study investigated the performance of a four-sided wind catcher using numerical methods. They introduced the study that wind catchers are common features in regions with hot, hot-dry, and hot-humid climates, particularly in Middle Eastern countries. The research focused on six 3D rectangular wind catchers with varying channel heights, selected based on an examination of wind tower characteristics and their categorization according to physical attributes and parameters. The study employed computational fluid dynamics (CFD) simulations to assess how the height of wind catchers impacts the ventilation rate within the wind catcher room. The findings indicated that the height of the wind catcher plays a significant role in influencing several factors. Wind velocity on the windward side increases with greater wind catcher height. However, the ventilation rate of the room decreases as the wind catcher height increases. The study contributed to understanding the relationship between wind catcher dimensions and their impact on ventilation rates, wind velocities, and volume flow rates through CFD simulations [48].

From previous studies, it is obvious that wind catchers mostly exist in Central Asia and at the hot regions border of the Middle East. Within the same context, this study aims to examine the effectiveness of wind catcher as a passive cooling technique in areas that have the same climate characteristics such as Nizwa city in Oman that is considered as the twin city of Yazd in Iran where a dense distribution of wind catchers was used through the history. As in the mentioned studies there is no specific study about the performance of the shape of wind catchers. Therefore, this research will focus on studying the impact of wind catcher shape on its performance .

PART 3

MATERIAL AND METHOD

This part includes descriptive information about the materials and methods that were used to achieve the research goals. The material section provides knowledge about the selected case study (location, function, weather data) as well as the selected tool to be used. The method section describes the procedure of performing the comparative analysis of the base case and the suggested scenarios of wind catcher's geometry and characteristics.

3.1. MATERIAL

The main goal of this research is to examine the impact of several types of wind catcher geometry and internal partitions on the natural ventilation rate in hot arid regions buildings. For this purpose, a case study located in Nizwa city- Oman (hot arid zone) was selected to conduct the research scope on it. The case study is represented by a mosque building that is located at the center of Nizwa city. The mosque building is in an urban context at the center old town of Nizwa besides the historical Nizwa castle. The following explains the details of the selected case.

3.1.1. Case Study

Nizwa city: Nizwa is the largest city in Ad Dakhiliyah Region in Oman. It is about 140 km from Muscat (capital of Oman). The city can be considered as one of the oldest cities in Oman as it was a center of trade, religion, education, and art. The population of Nizwa city is estimated by 72000 people [42]. From architecture style of view, Nizwa can be considered as the sister of Yazd city in Iran and Homs city in Syria [43]. From historical point of view, Nizwa was the center of Islamic learning in the region during the Islamic era. However, Nizwa has become a more modern city since 1970 under the reign of Sultan Qaboos. Improvements had been achieved in many fields like transportation, health, tourism, education, and rehabilitation of historical buildings [42].

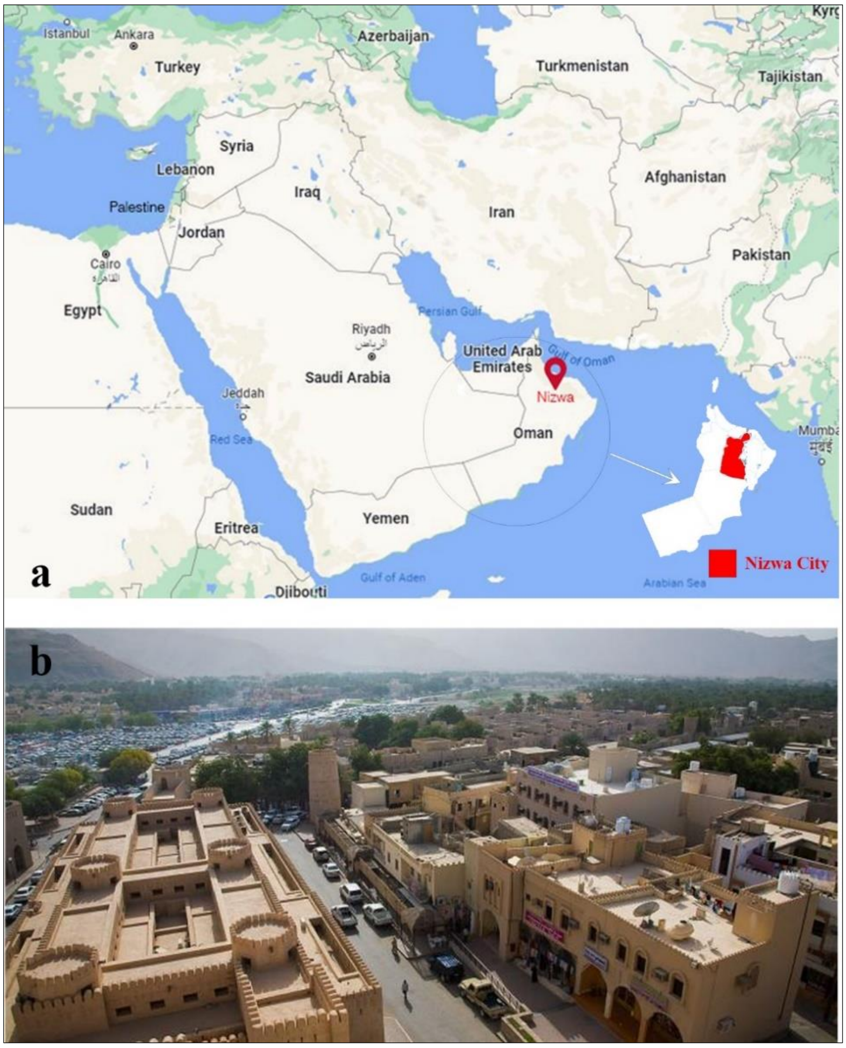
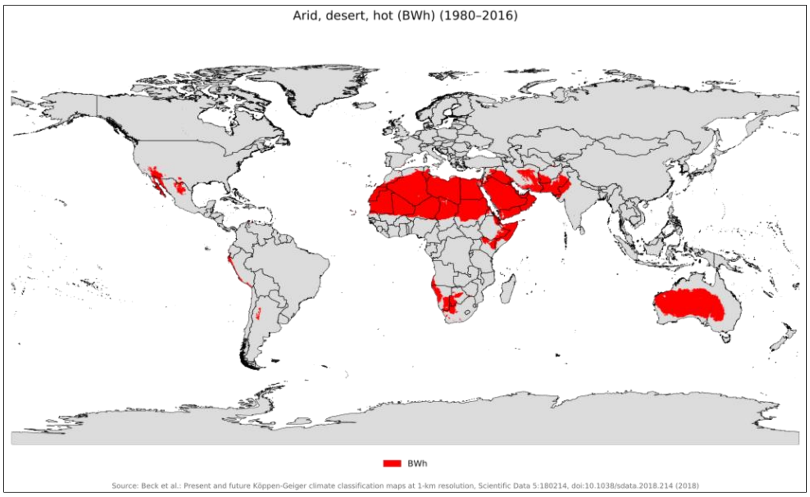


Figure 3.1. (a) Location of Nizwa City (b) Areal view of Nizwa old town [42].

3.1.2. Climate of Nizwa City

Climate Type Classification: Nizwa is located at 22.91-degree latitude and 57.53-degree longitude. It has a hot arid desert climate (BWh) according to Koppen climate classification -Figure 3.5.



Source: Beck et al.: Present and future Köppen-Geiger climate classification maps at 1-km resolution, Scientific Data 5:180214, doi:10.1038/sdata.2018.214 (2018)

Figure 3.5. The hot arid regions according to koppen climate classification.

Air Temperature: The weather data of Nizwa has been gained from ladybug tool between 2007-2021. In that context, the hourly temperature in Nizwa ranges between 7.40 Cº to 46.70 Cº during the year. July is considered as the hottest month with 36 Cº average temperature while January is the coldest month with 19 Cº average temperature.

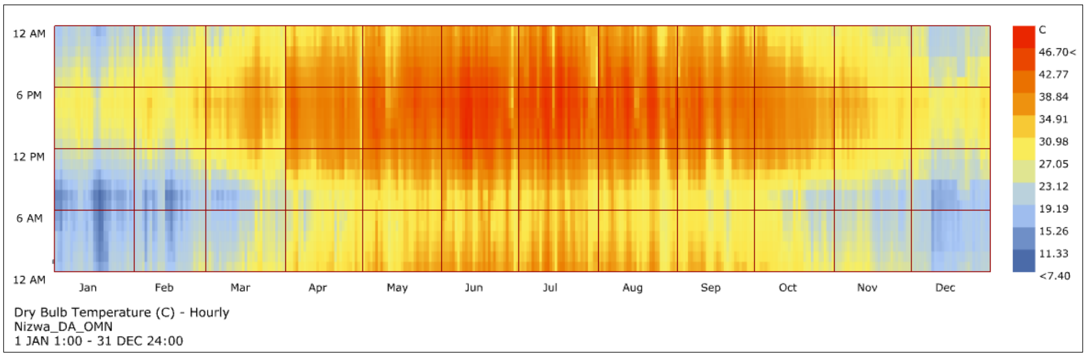


Figure 3.6. The annual dry bulb temperature in Nizwa.

Relative Humidity: The relative humidity in Nizwa ranges between 12.7% to 100%. The highest average of relative humidity was in January which is 41% while the lowest was in May with an average reaching 19%.

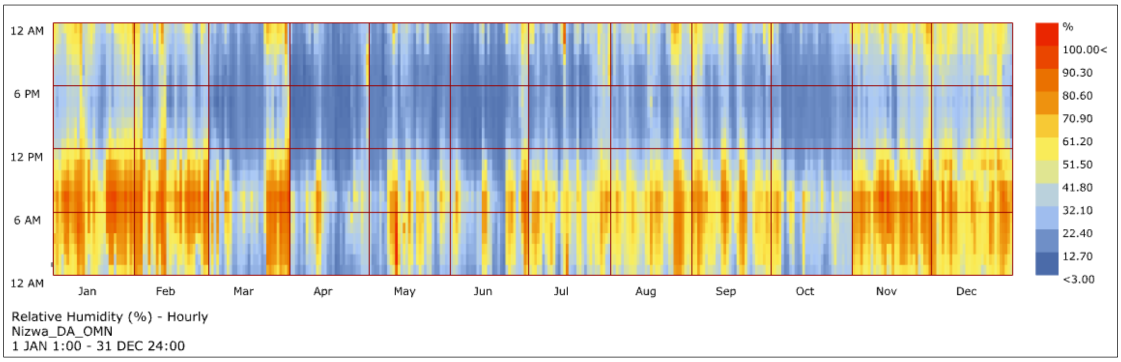
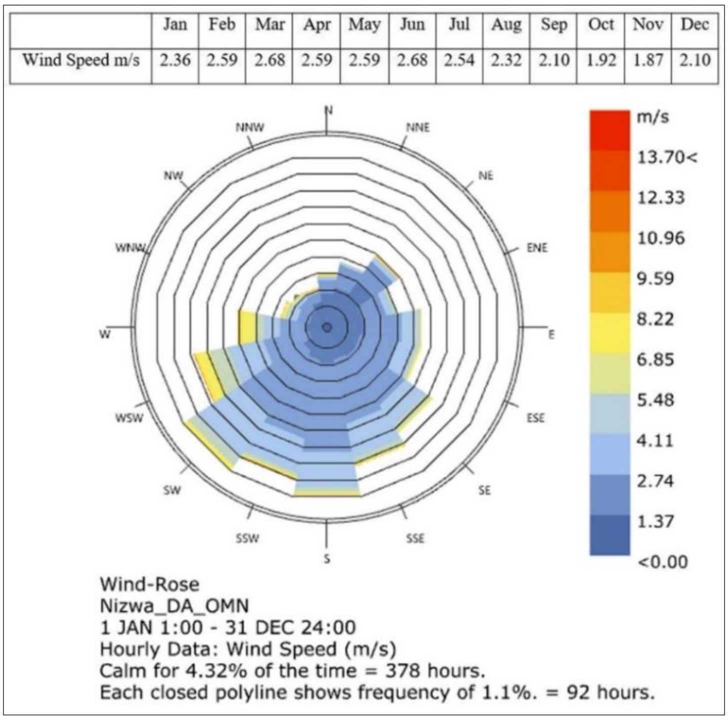


Figure 3.7. The annual relative humidity in Nizwa.

Wind Speed and Direction: The prevailing wind during the year in Nizwa is the **south and southwest wind with 2.36 m/s average wind speed.** Figure 3.8 illustrates the wind rose and the monthly average of wind velocity during the year in Nizwa.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Wind Speed m/s	2.36	2.59	2.68	2.59	2.59	2.68	2.54	2.32	2.10	1.92	1.87	2.10

Figure 3.8. The monthly wind speed and the wind rose in Nizwa.

3.1.3 The Selected Building : "Alqala Mosque"

The case study was selected as a mosque building that is called “Alqala’ mosque” or “mosque of Fort.” The selection of the case depended on some pre-set criteria that included:

1. The case study location must be in an urban context to include the effect of the surrounding on the wind rate flow.
2. The case study should be investigated to have natural ventilation problems due to the opening ratio compared to the opaque parts.
3. The case study should be public building with frequent uses to examine the effect of using wind catcher on the occupant’s comfort.

Depending on these criteria, the selected case was suitable to perform the scope of the study on it.

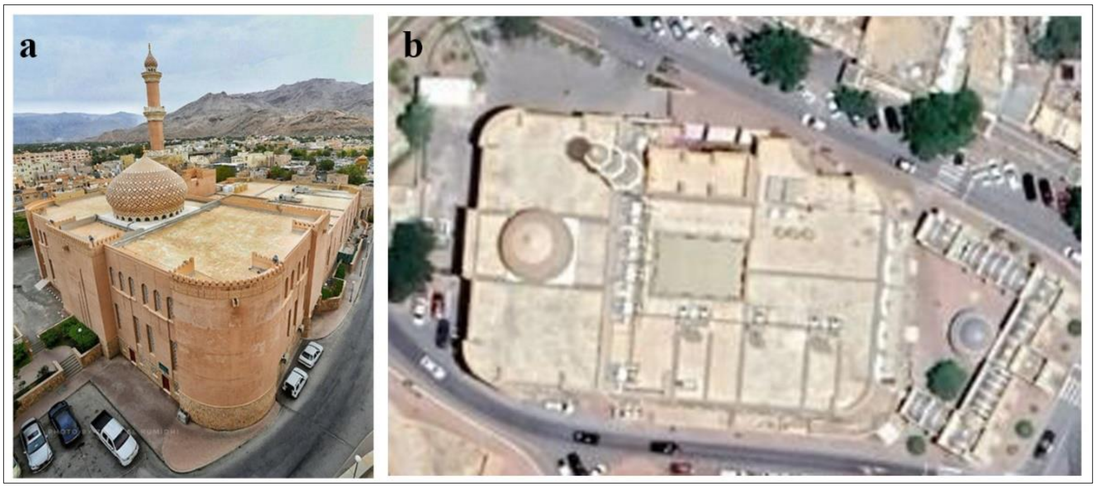


Figure 3.2. a) South-west view of the mosque b) Master Plan of the mosque [42].

The mosque has two main parts. The first part represents the old building while an extension has been added to the old building in the 1980s. The building is slightly oriented from the north-south axis. The Qibla direction faces the west direction of the building. The mosque has two main entrances from the north direction. The prayers firstly enter the extended part which is also used for praying and then can enter the old part of the mosque from four interior doors- Figure 3.3. The extension has fixed glass windows from the east direction with four Islamic pattern arches shape while the south direction of the building has five operable windows with a small window-wall Ratio (WWR). The main construction material of the building (the old and the new built) is clay. It is worth to mention that the buildings surrounding the mosque are traditional markets that are predominantly traditional style buildings and contain Islamic decorations and inscriptions, and are low in height, containing two floors. The height of the surrounding buildings ranges between 7 to 8 meters.

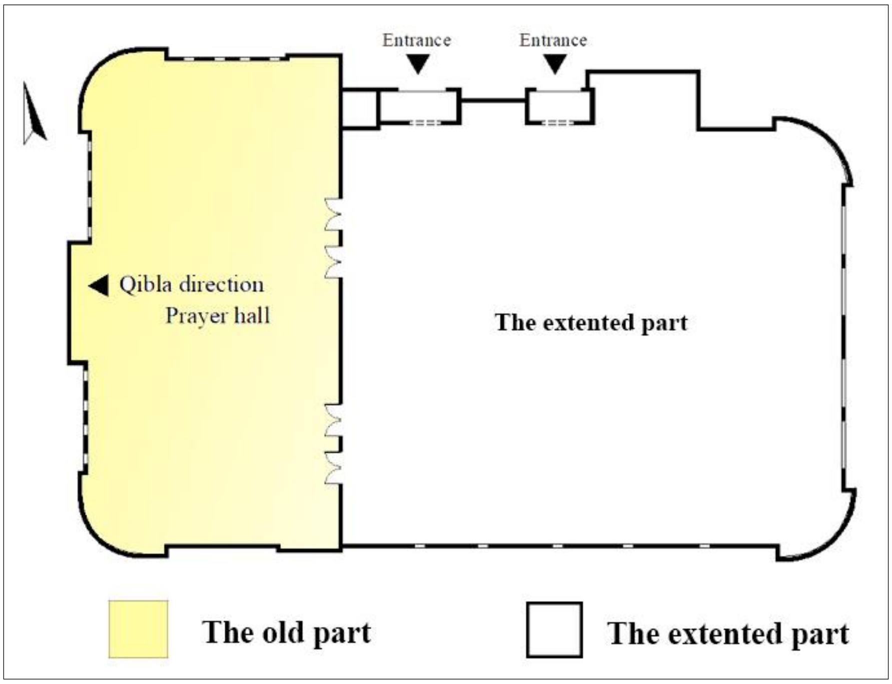


Figure 3.3. The Ground floor of the mosque.

Following the collected data from various sources such as drawings, documents, google maps and the available information, the case study was modelled using Autodesk Revit (3D BIM software) and the required information were assigned to the model as shown in Figure 3.4.

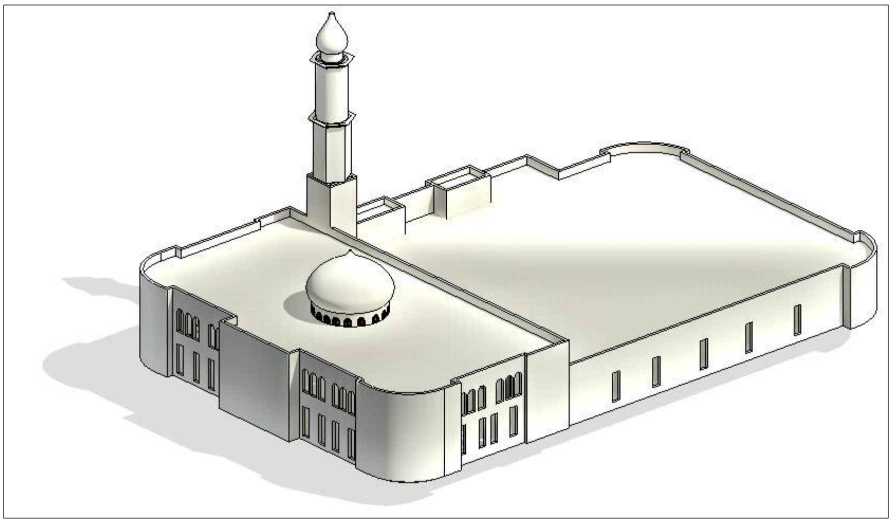


Figure 3.4. The mosque model in Autodesk Revit.

3.2. METHOD

This section describes the method and the procedure of the research in general. An overview of the general workflow that was adopted in reaching the research results and conclusions will be introduced. In addition, the generation process of the Scenarios of wind catcher geometry, dimensions, internal partitions type will be explored.

3.2.1. Modelling and Simulation Tools

The research aims to examine the effect of several types of wind catcher geometry and internal blades on the indoor ventilation rate. For that reason, modeling the form of the case study and the suggested scenario with the available information is the initial decision for choosing the suitable tools. 3D modeling and CFD simulation can be performed by using BIM tools thanks to the development in that area. Recently, BIM tools integration has been developed to simulate air flow and thermal comfort for the produced BIM models [44]. Within this context, Autodesk Revit and Autodesk CFD were chosen to perform the scope of the study. The following describes these tools.

Revit is the most common 3D BIM program. Charles River Software created the first software in 1997. It was afterwards called Revit Technology Corporation in 2000 and was purchased by Autodesk in 2002. Autodesk Revit Architecture is used to create the

3D model, which aids in capturing and analyzing the most creative design thoughts. Revit Architecture also automatically generates every schedule, drawing sheet, 2D view, and 3D view from a single set of fundamental data while coordinating modifications as the project progresses. The decision-making for sustainable design, clash detection, and construction planning is supported by the information-rich models that Revit generates. Revit may assist designers in early conceptual design decision-making, assisting in the identification of the best approaches for designing energy-efficient buildings [45].

Revit also allows the model to be exported in different languages (i.e., gbXML, SAT) that are compatible with other software, and offers tools to evaluate and analyze building energy performance. In the study, Revit is used to develop the 3D models of the case study (base model and the Scenario) to be exported to Autodesk CFD using SAT format. This process accelerates the workflow thanks to the great integration and the flexible flow of information between the selected tools [46].

Engineers and analysts utilize computational fluid dynamics simulations produced by Autodesk CFD software to make informed predictions about the behavior of gases and liquids. Engineers can optimize system design using a variety of strong tools from Autodesk CFD software. For product design, simulate fluid flow, free surface movement, and thermal impact [46].

Autodesk CFD software is used by mechanical engineers who need fluid simulation to improve product performance. It is also used by HVAC system engineers who need BIM tools to simulate efficiency of their building HVAC designs. Architects also can get benefit from Autodesk CFD in examining the air flow through their building design and optimize the best solution regarding the opening ratio and location or other design parameters [44].

In the study, Autodesk CFD was used to calculate the air velocity at certain points in the base case and the suggested scenarios (before and after adding the wind catcher’s Scenarios).

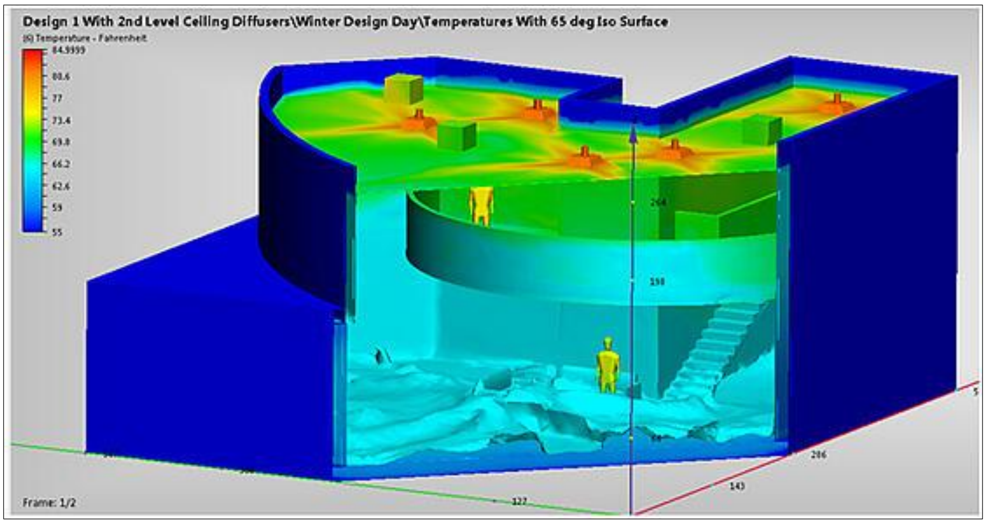


Figure 3.9. Example of CFD analysis using Autodesk CFD [46].

3.2.2. General Workflow

The methodology of the research depends on implementing a comparative analysis between the base case of the selected building (without wind catcher) and some successive scenarios of wind catcher geometries and their internal partition types. For that purpose, the existing case study was modelled by Autodesk Revit architecture with the available information to create the **3D BIM model** with the required spaces and openings information. The BIM model was created within Level of details equal to LOD150. Then, the Scenarios were also modelled in Revit. As a result, the 3D models of the case study and the Scenarios of different wind catcher's types were ready to be exported to Autodesk CFD with the required information such as location, the orientation, the input, and output of wind flow.

In the next step, each model was exported separately to Autodesk CFD using the SAT file format that is used to transfer the information from Revit to Autodesk CFD program. The models were then prepared in the CFD simulation program by **assigning material** for the building components as "Brick" and for the input boundaries and space volumes as "Air" with their thermal properties. The **boundary conditions** were assigned to the models as "Input: Air Velocity" with magnitude equal to 2.36 m/s from south and southwest direction (The prevailing wind average velocity and direction in Nizwa) and "output: Pressure" equal to 0 Pa. As for the buildings surrounding the mosque, they are dominated by the traditional architectural character, with a height of about 7-8 meters, and this does not affect the air current because the wind catcher is higher than the surrounding buildings, and for this reason it can be considered that the surrounding buildings are negligible.

Then the models were set to initial condition and auto sized in the CFD simulation program and were ready to be solved with air flow settings- **See Appendix A.**

It is worth mentioning that the models of wind catchers were developed according to some criteria such as the gross area that were fixed in all scenarios to be 16 m^2 while the thicknesses of wind catcher external walls and roofs also fixed in all scenarios to be 0.2 meter as well as the height of wind catchers in all scenarios is 15.5 meter from the ground floor. In addition, the direction of wind is from south and south-west direction which is compatible with the prevailing wind direction in Nizwa city with 2.36 m/s magnitude. Within this context, the analysis period can be considered as annual where the average of prevailing wind was calculated depending on the monthly wind speed data mentioned in section 3.2.1.

The last step represents the **CFD simulations**. For the purpose, the setting of solving CFD simulation was determined to 100 iterations to gain reliable results for the comparative analysis.

The results were limited to **air flow** (air velocity) with exclusion of heat transfer and thermal comfort factors in the CFD settings. This was because that the research purpose is limited to comparing the natural ventilation rate before and after adding the wind catcher Scenarios. As a result, the models (the base case and the Scenarios) were simulated with the basics of **Computational Fluid Dynamics** CFD to get the air velocity at all points in the created volumes- **See appendix B and C.**

For systematic comparison process, **three points (A, B, C)** were selected to be compared in the base model and the Scenario. The location of these points was considered as a reference for all models to achieve the purpose of the study. **Point A** location is at the opening of the wind catcher where the wind first hits the internal partition. **Point B** location is above the water bond at the bottom of the wind catcher before entering the indoor space. Whereas **Point C** location is inside the extended space of the mosque to examine the effect of wind catcher Scenario on the indoor ventilation rate. Finally, the results were compared at these points (A, B, C) and discussed. Conclusions and future studies were drawn and connected to the previous studies and findings. Figure 3.11 illustrates the location of the reference points.

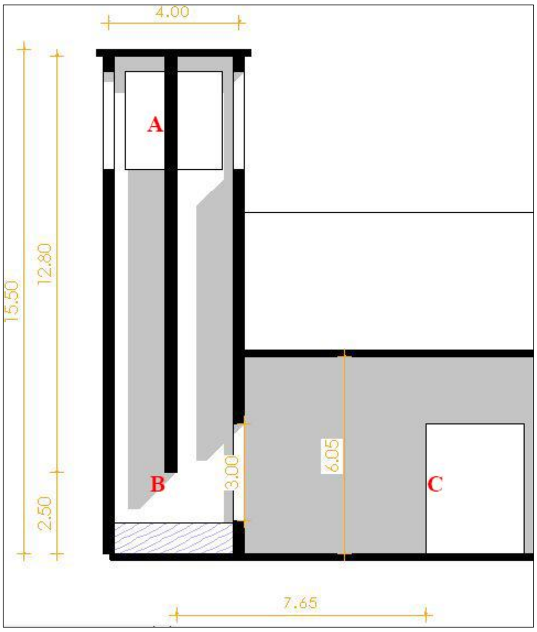


Figure 3.11. Location of reference points.

Figure 3.10 illustrates the general workflow development of the study.

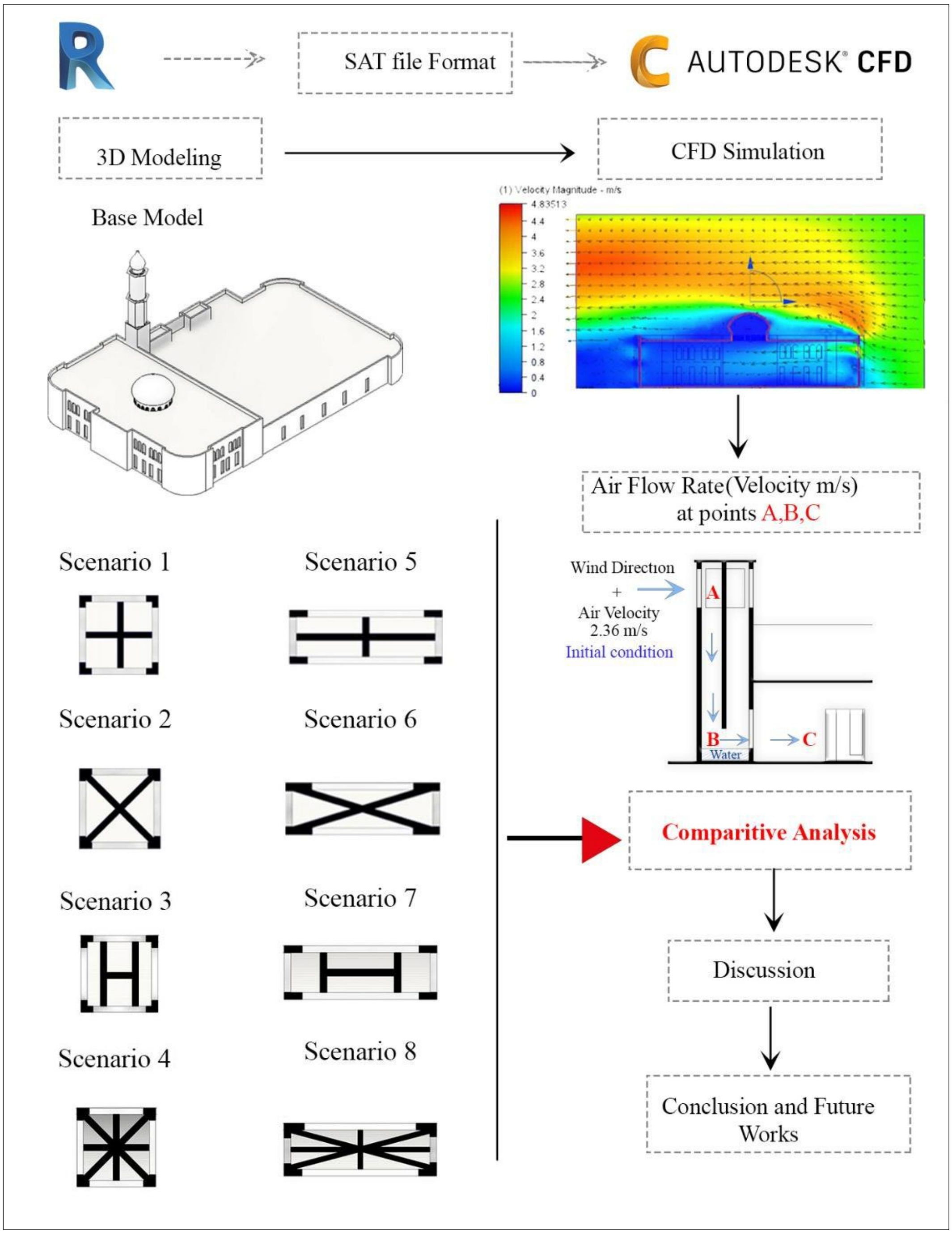


Figure 3.10. General workflow of the study.

3.2.3. Generation of Wind Catcher Scenarios

Since the main purpose of the study is to examine the effect of wind catcher on natural ventilation rate in hot-arid regions, it was essential to determine various Scenario of wind catcher geometry and internal partitions. The study assumes some scenarios of wind catchers with some fixed and variable parameters. Some parameters were **fixed** such as wind catcher height, location, the opening ratio of wind catcher and the gross area of wind catcher. In addition, all wind catchers were suggested to be in a four-sided direction. In this context, the **variables** were also determined as wind catcher geometry (Square and Rectangular) and type of internal partitions (+ type X, H, and X+ composed (Star) type).

It is also worth mentioning that the location and height of the wind catcher were determined after the CFD simulation of the existing case where the highest magnitude of air velocity was investigated as shown in Figure 3.12. The location of the wind catcher was determined to be at the southern façade of the building and in middle distance while the height of the wind catcher was fixed to be 15.50 meters from the ground floor level. The following explains the suggested solutions and properties for the added wind catchers.

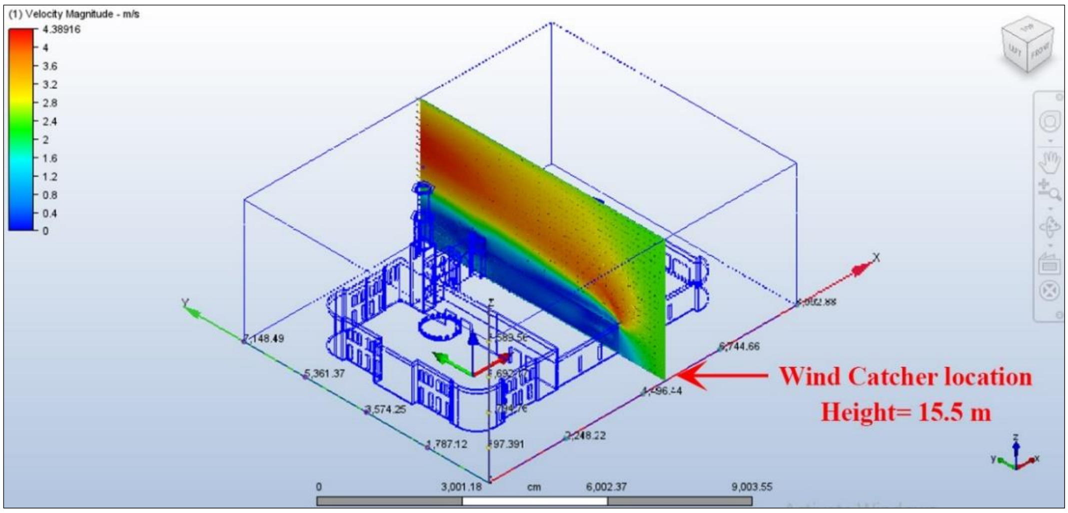


Figure 3.12. The highest air velocity magnitude height and location

3.2.3.1. Scenario 1

In this Scenario, the type of wind catcher geometry was Square with 4 x 4 meters dimensions. The openings in this Scenario were four directional wind catchers with 3 x 3 meters dimensions in all directions. In addition, the type of internal partitions was **+ type** as shown in Figure 3.13.

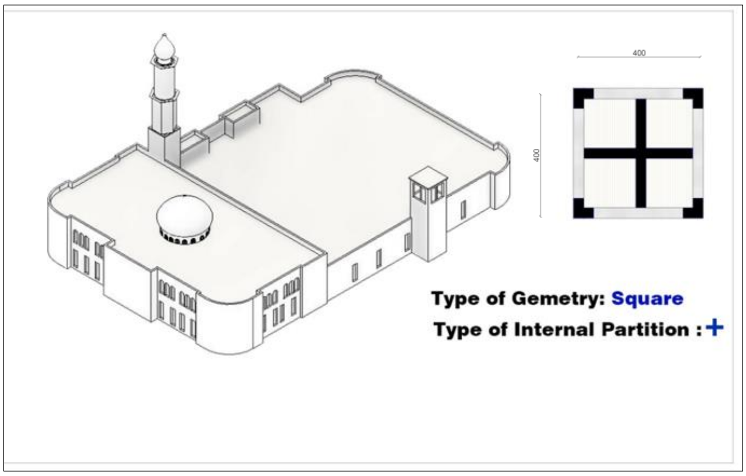


Figure 3.13. Scenario 1 representation.

3.2.3.2. Scenario 2

In this Scenario, the type of wind catcher geometry was Square with 4 x 4 meters dimensions. The openings in this Scenario were four directional wind catchers with 3 x 3 meters dimensions in all directions. In addition, the type of internal partitions was **X type** as shown in Figure 3.14.

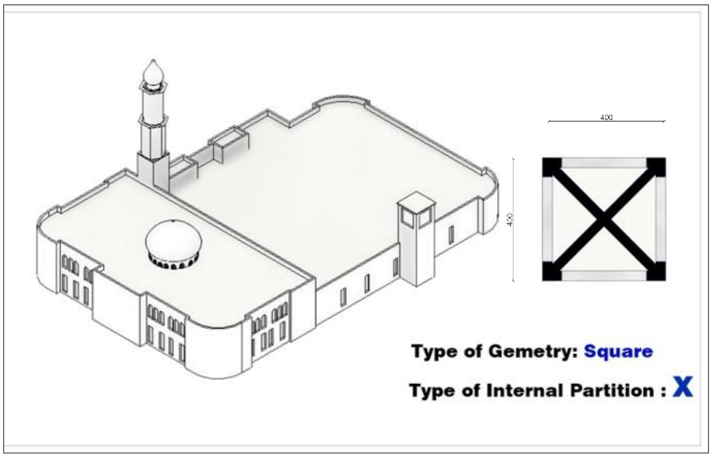


Figure 3.14. Scenario 2 representation

3.2.3.3. Scenario 3

In this Scenario, the type of wind catcher geometry was Square with 4 x 4 meters dimensions. The openings in this Scenario were four directional wind catchers with 3 x 3 meters dimensions in all directions. In addition, the type of internal partitions was **H type** as shown in Figure 3.17.

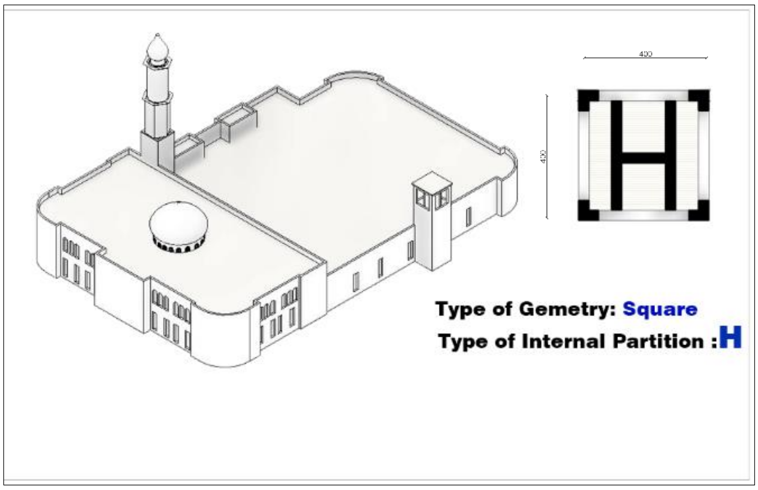


Figure 3.15. Scenario 3 representation

3.2.3.4. Scenario 4

In this Scenario, the type of wind catcher geometry was Square with 4 x 4 meters dimensions. The openings in this Scenario were four directional wind catchers with 3 x 3 meters dimensions in all directions. In addition, the type of internal partitions was **X and + composed (Star) type** as shown in Figure 3.18.

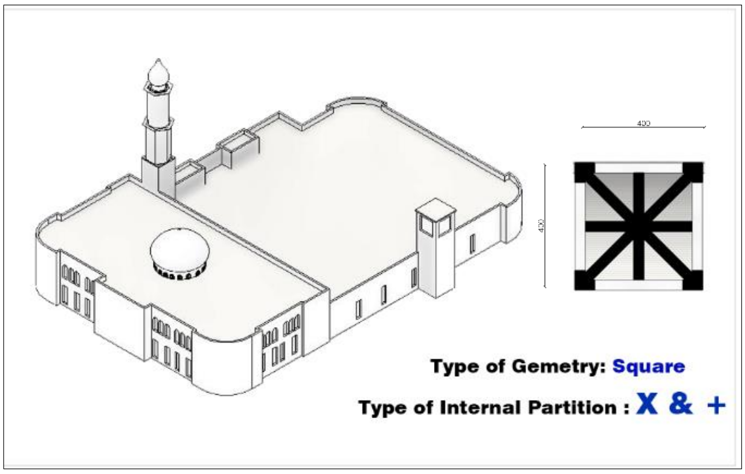


Figure 3.16. Scenario 4 representation

3.2.3.5. Scenario 5

In this Scenario, the type of wind catcher geometry was Rectangular with 2 x 8 meters dimensions. The openings in this Scenario were four directional wind catchers with 6 x 1.5 meters dimensions in the south and north directions and 4.5 x 2 meters in the west and east directions. In addition, the type of internal partitions was **+ type** as shown in Figure 3.15.

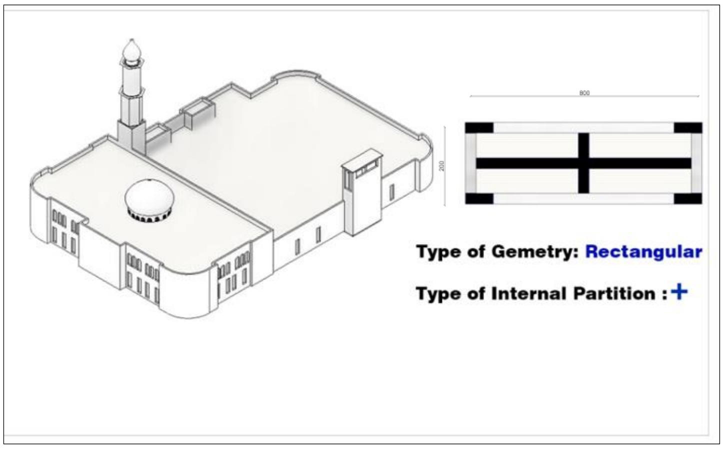


Figure 3.17. Scenario 5 representation.

3.2.3.6. Scenario 6

This Scenario introduces rectangular type of wind catcher geometry with 2 x 8 meters dimensions. The openings in this Scenario were four directional wind catchers with 6 x 1.5 meters dimensions in the south and north directions and 4.5 x 2 meters in the west and east directions. In addition, the type of internal partitions was **X type** as shown in Figure 3.16.

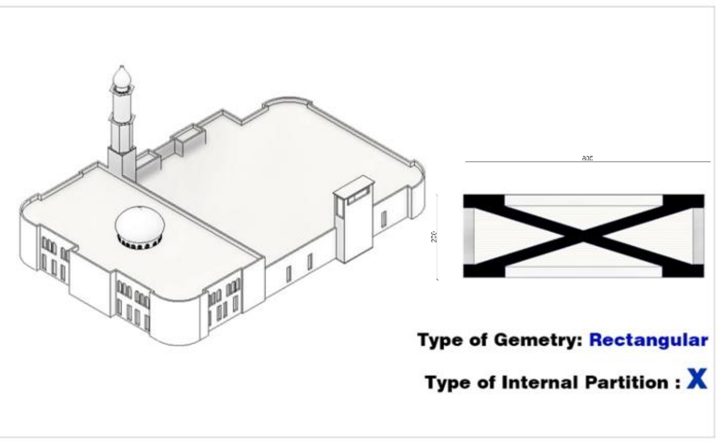


Figure 3.18. Scenario 6 representation.

3.2.3.7. Scenario 7

This Scenario introduces rectangular type of wind catcher geometry with 2 x 8 meters dimensions. The openings in this Scenario were four directional wind catchers with 6 x 1.5 meters dimensions in the south and north directions and 4.5 x 2 meters in the west and east directions. In addition, the type of internal partitions was **H type** as shown in Figure 3.19.

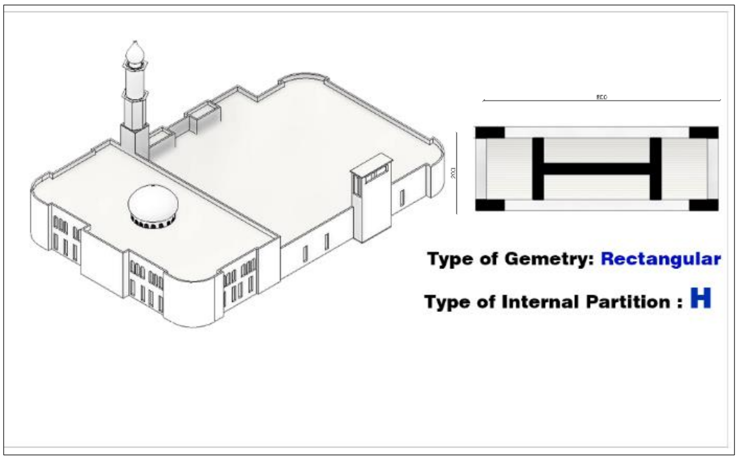


Figure 3.19. Scenario 7 representation

3.2.3.8. Scenario 8

The final Scenario represents rectangular type of wind catcher geometry with 2 x 8 meters dimensions. The openings in this Scenario were four directional wind catchers with 6 x 1.5 meters dimensions in the south and north directions and 4.5 x 2 meters in the west and east directions. In addition, the type of internal partitions was **X and + composed (Star) type** as shown in Figure 3.20.

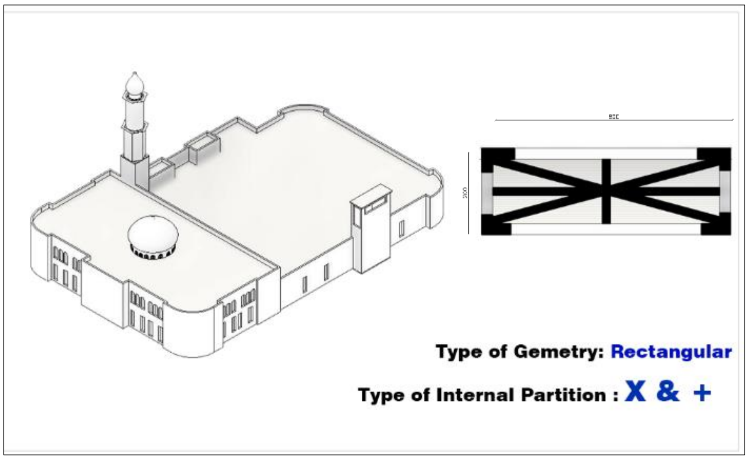


Figure 3.20. Scenario 8 representation

PART 4

RESULTS AND DISCUSSION

This part explores the CFD simulation results of building’s existing situation as well as the Scenarios after adding different scenarios of wind catchers. The general workflow described in Section 3.2.1 was implemented to the research assumptions. In addition, this part includes an analysis and discussion section where the results are compared for the base model of the existing building and the Scenario of wind catchers.

4.1. CFD SIMULATION RESULTS

The results will be explored in terms of air velocity (m/s). For the study, analytical plane’s locations were determined to be able to calculate the air velocity at specific points. Figure 4.1 illustrates the locations of the analytical planes where the results assessed and compared. The analytical plane 1 crosses all the openings at the ground floor and locates in horizontally position at 2 meters height from the ground floor level. Whereas analytical plane 2 crosses the wind catcher location through the indoor space of the extension part of the mosque until the north entrance of the building.

As mentioned, points A, B, and C were determined on analytical plane 2 to conduct the comparison process for the research Scenarios. Figure 4.2 illustrates the location of these points that will be used as reference points to all study Scenarios.

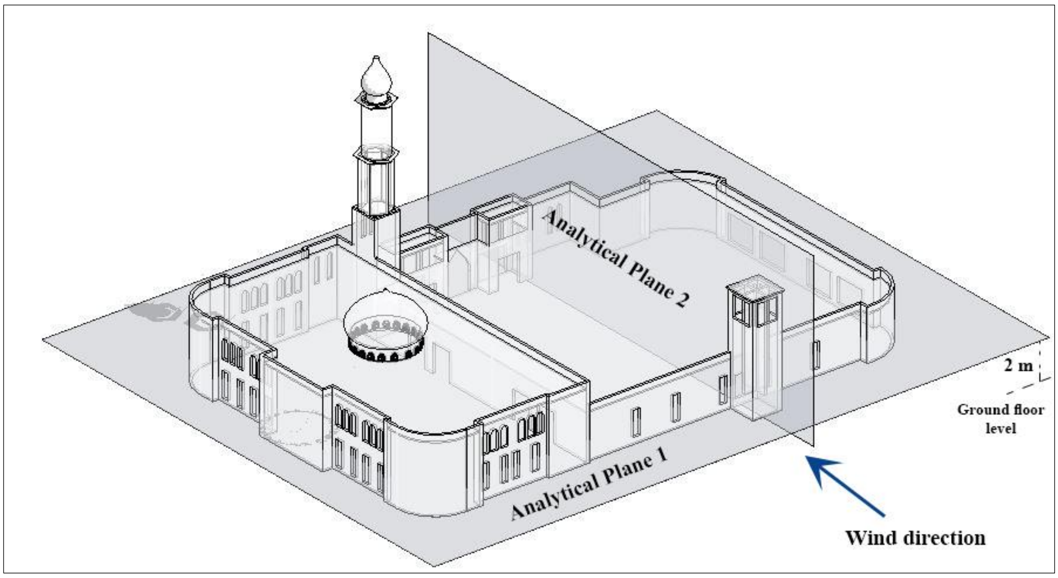


Figure 4.1. The location of the analytical planes.

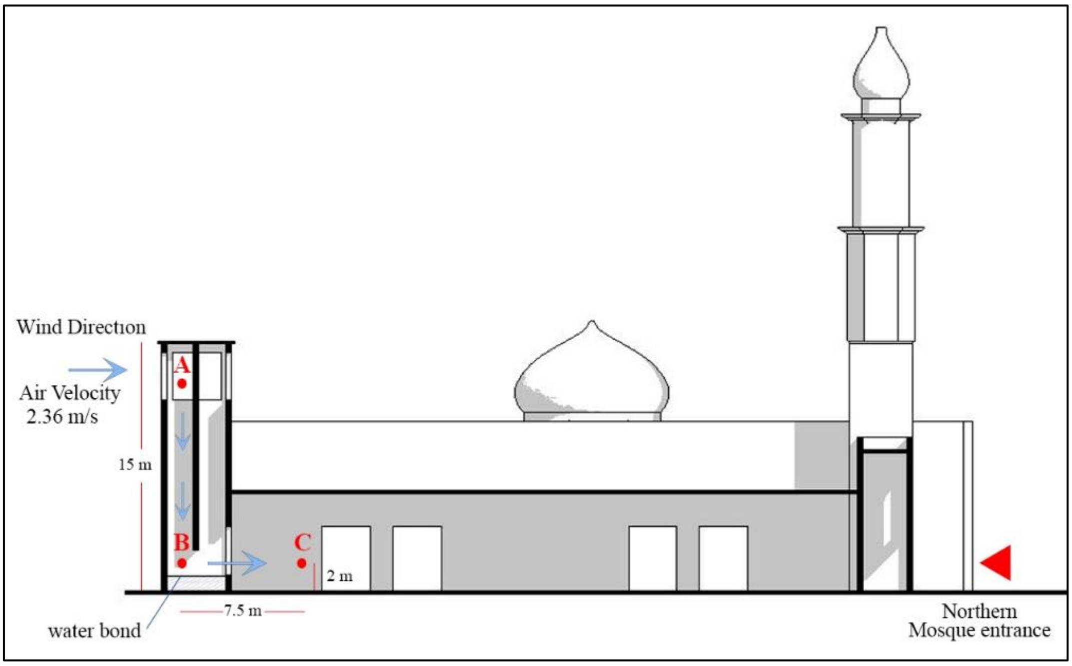


Figure 4.2. The location of reference points on analytical plane 2.

4.1.1. Base Model Results

The base model results showed that the average indoor air velocity at analytical plane 1 is **0.327872** m/s- Figure 4.3 (b). At the analytical plane 2, point A and B do not exist in the base model whereas the air velocity at point C was 0.333508 m/s as shown in Table 4.1 and Figure 4.3 (c) respectively.

Table 4.1. The results of base model

	Analytical plane 1 Avg. air velocity m/s	**Analytical plane 2**		
		Point A	Point B	Point C
Base Model	0.327872	-------	--------	0.333508

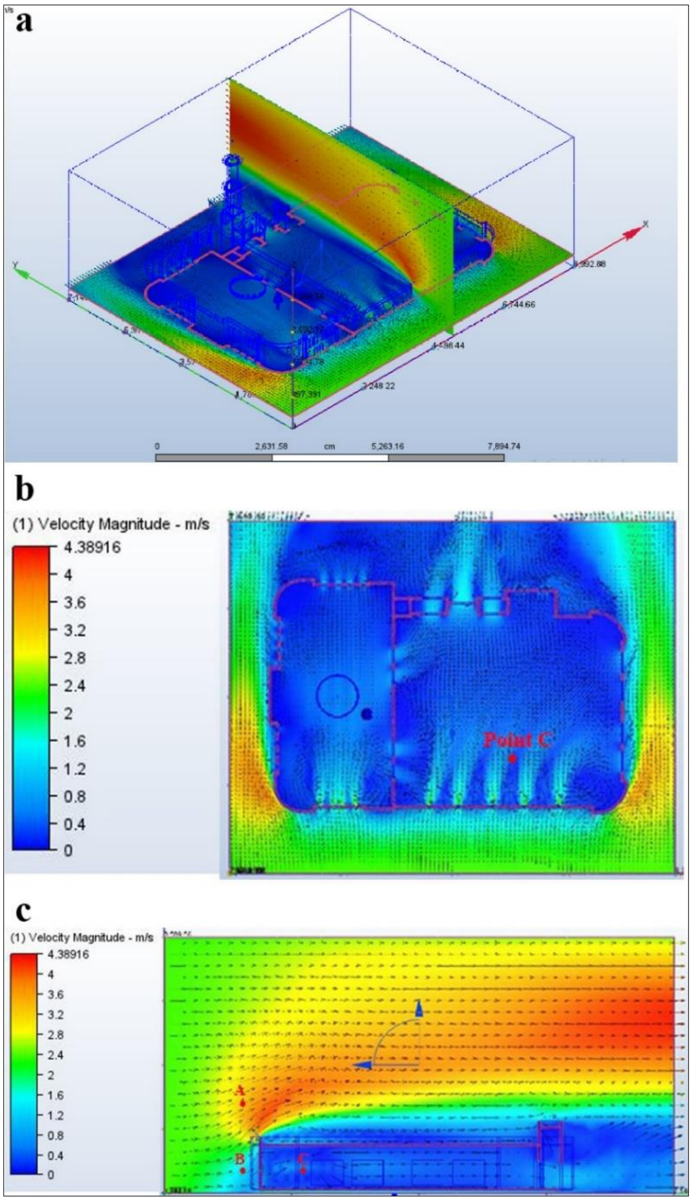


Figure 4.3. (a) CFD simulation of base model (b) Analytical plane 1 results (c) Analytical plane 2 results.

4.1.2. Scenario 1 Results

The Scenario of adding square wind catcher with internal partitions + type was implemented to the case study. The results showed that the average indoor air velocity at analytical plane 1 is **0.437706** m/s. At analytical plane 2, the air velocity at point A, point B and point C were 1.93586, 1.17032, and 0.647451 m/s respectively as shown in Table 4.2. Figure 4.4 represents the results at analytical plane 1 and 2 in graphical way.

Table 4.2. The results of Scenario 1.

	Analytical plane 1	**Analytical plane 2**		
	Avg. air velocity m/s	Point A	Point B	Point C
Scenario 1	0.437706	1.93586	1.17032	0.647451
				

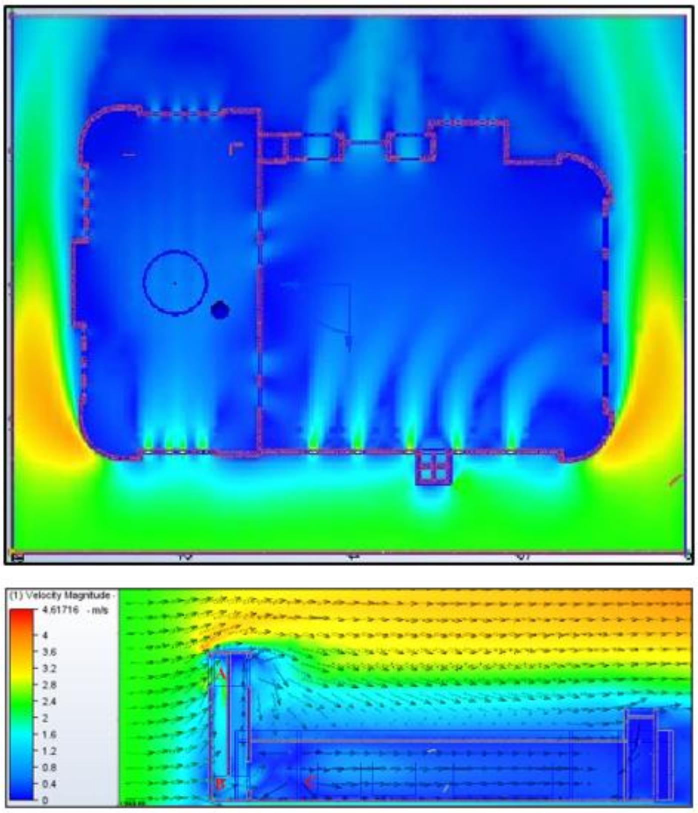


Figure 4.4. The results of air velocity at analytical plane 1 and 2 for Scenario 1.

4.1.3. Scenario 2 Results

The Scenario of adding square wind catcher with internal partitions X type was implemented to the case study. The results showed that the average indoor air velocity at analytical plane 1 is **0.457457** m/s. At analytical plane 2, the air velocity at point A, point B and point C were 2.19658, 1.73654, and 0.671595 m/s respectively as shown in Table 4.3. Figure 4.5 represents the results in graphical way.

Table 4.3. The results of Scenario 2.

	Analytical plane 1	**Analytical plane 2**		
	Avg. air velocity m/s	Point A	Point B	Point C
Scenario 2	0.457457	2.19658	1.73654	0.671595
				

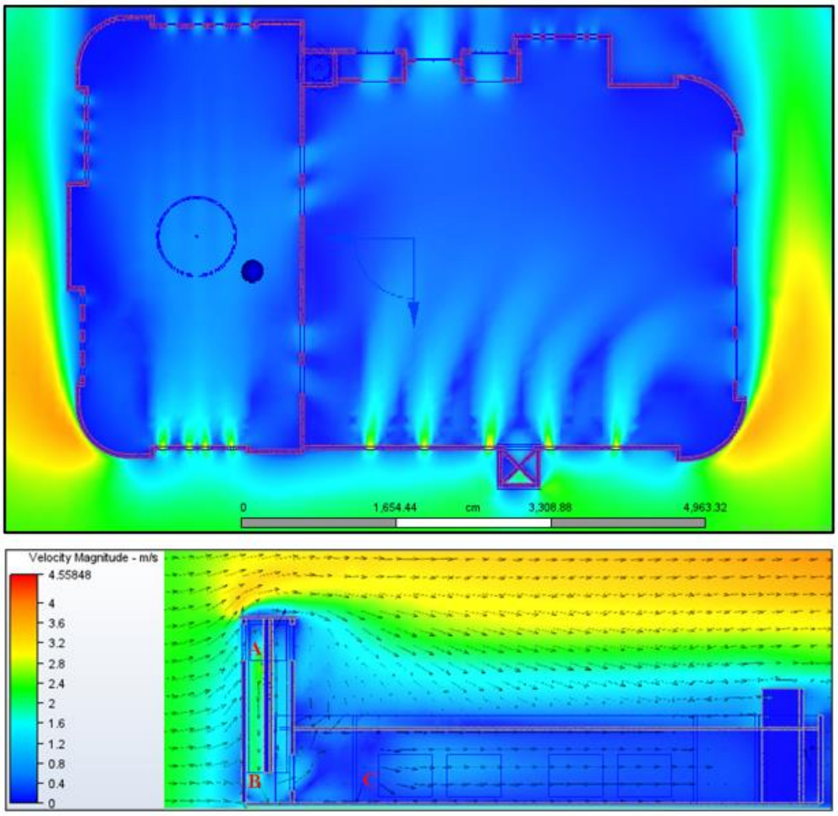


Figure 4.5. The results of air velocity at analytical plane 1 and 2 for Scenario 2.

4.1.4. Scenario 3 Results

The Scenario of adding square wind catcher with internal partitions H type was implemented to the case study. The results showed that the average indoor air velocity at analytical plane 1 is **0.424831** m/s. At analytical plane 2, the air velocity at point A, point B and point C were 1.36687, 0.93963, and 0.608448 m/s respectively as shown in Table 4.4. Figure 4.6 represents the results at analytical plane 2 in graphical way.

Table 4.4. The results of Scenario 3.

	Analytical plane 1 **Avg. air velocity m/s**	Analytical plane 2		
		Point A	Point B	Point C
Scenario 3	0.424831	1.36687	0.93963	0.608448
				

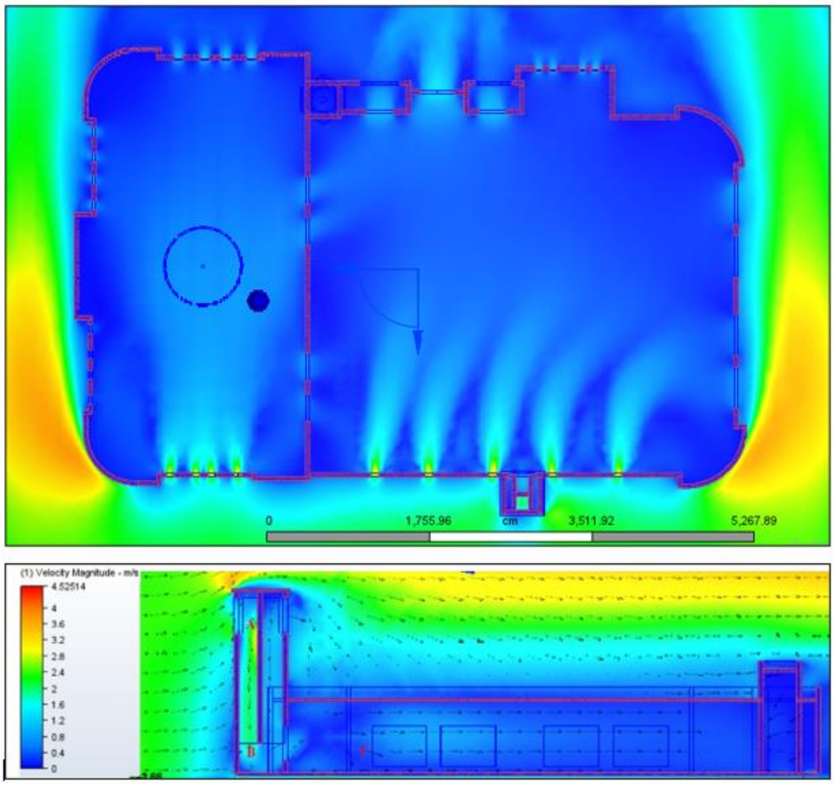


Figure 4.6. The results of air velocity at analytical plane 1 and 2 for Scenario 3.

4.1.5. Scenario 4 Results

The Scenario of adding square wind catcher with internal partitions X and + composed (Star) type was implemented to the case study. The results showed that the average indoor air velocity at analytical plane 1 is **0.353678** m/s. At analytical plane 2, the air velocity at point A, point B and point C were 1.77605, 1.04921, and 0.693379 m/s respectively as shown in Table 4.5. Figure 4.7 represents the results at analytical plane 1 and 2 in graphical way.

Table 4.5. The results of Scenario 4.

	Analytical plane 1	Analytical plane 2		
	Avg. air velocity m/s	Point A	Point B	Point C
Scenario 4	0.353678	1.77605	1.04921	0.693379
				

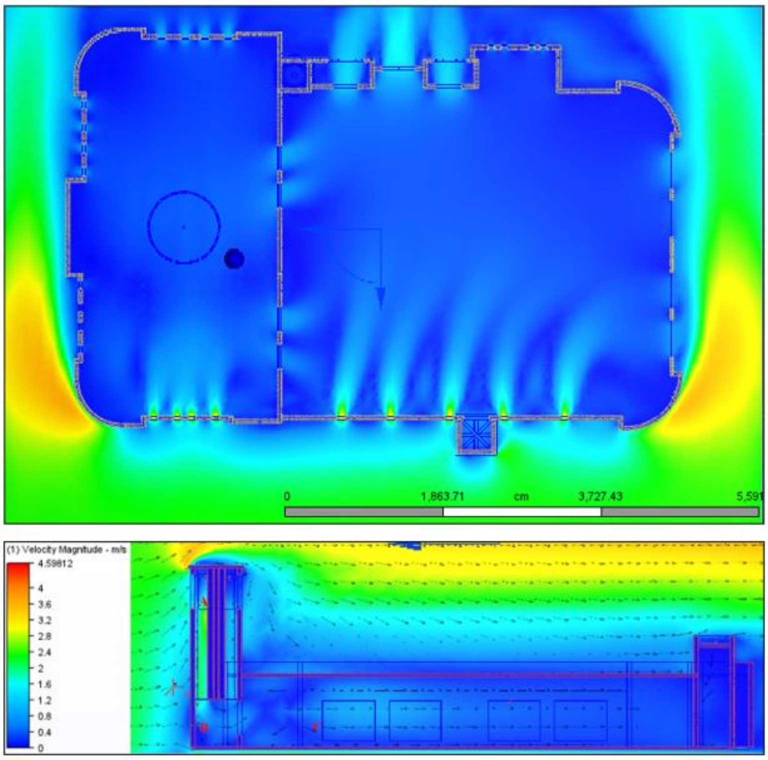


Figure 4.7. The results of air velocity at analytical plane 1 and 2 for Scenario 4.

4.1.6. Scenario 5 Results

The Scenario of adding rectangular wind catcher with internal partitions + type was implemented to the case study. The results showed that the average indoor air velocity at analytical plane 1 is **0.384847** m/s. At analytical plane 2, the air velocity at point A, point B and point C were 2.09220, 0.87805, and 0.414143 m/s respectively as shown in Table 4.6. Figure 4.8 represents the results in graphical way.

Table 4.6. The results of Scenario 5.

	Analytical plane 1	**Analytical plane 2**		
	Avg. air velocity m/s	Point A	Point B	Point C
Scenario 5	0.384847	2.09220	0.87805	0.414143
				

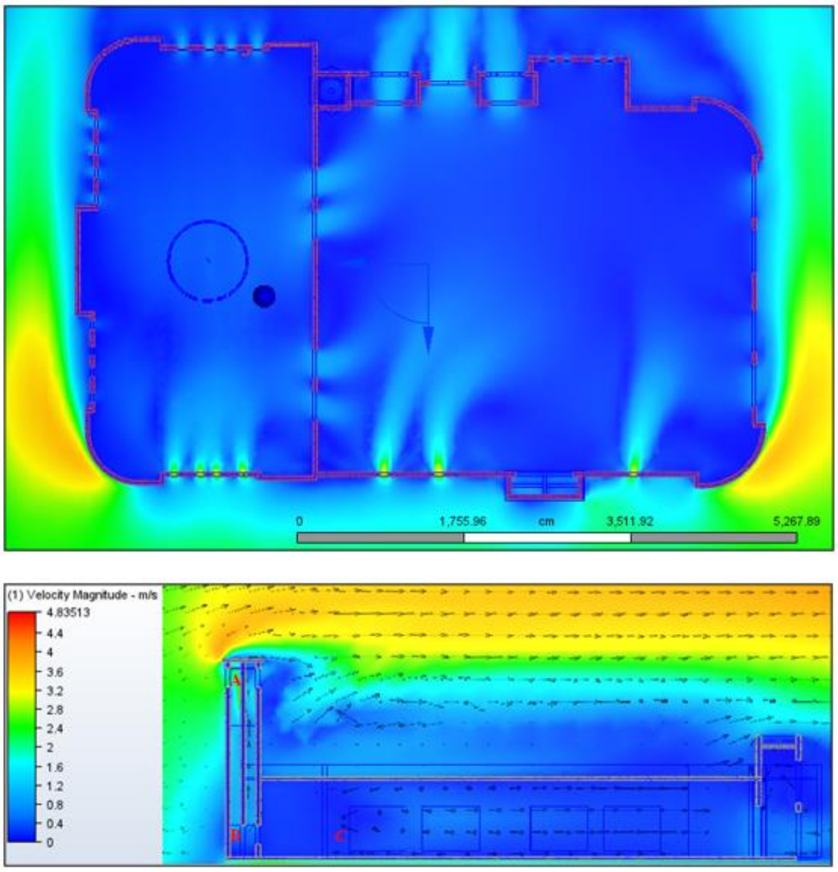


Figure 4.8. The results of air velocity at analytical plane 1 and 2 for Scenario 5.

4.1.7. Scenario 6 Results

The Scenario of adding rectangular wind catcher with internal partitions X type was implemented to the case study. The results showed that the average indoor air velocity at analytical plane 1 is **0.384214** m/s. At analytical plane 2, the air velocity at point A, point B and point C were 1.74059, 1.13777, and 0.434472 m/s respectively as shown in Table 4.7. Figure 4.9 represents the results in graphical way.

Table 4.7. The results of Scenario 6.

	Analytical plane 1	Analytical plane 2		
	Avg. air velocity m/s	Point A	Point B	Point C
Scenario 6	0.384214	1.74059	1.13777	0.434472
				

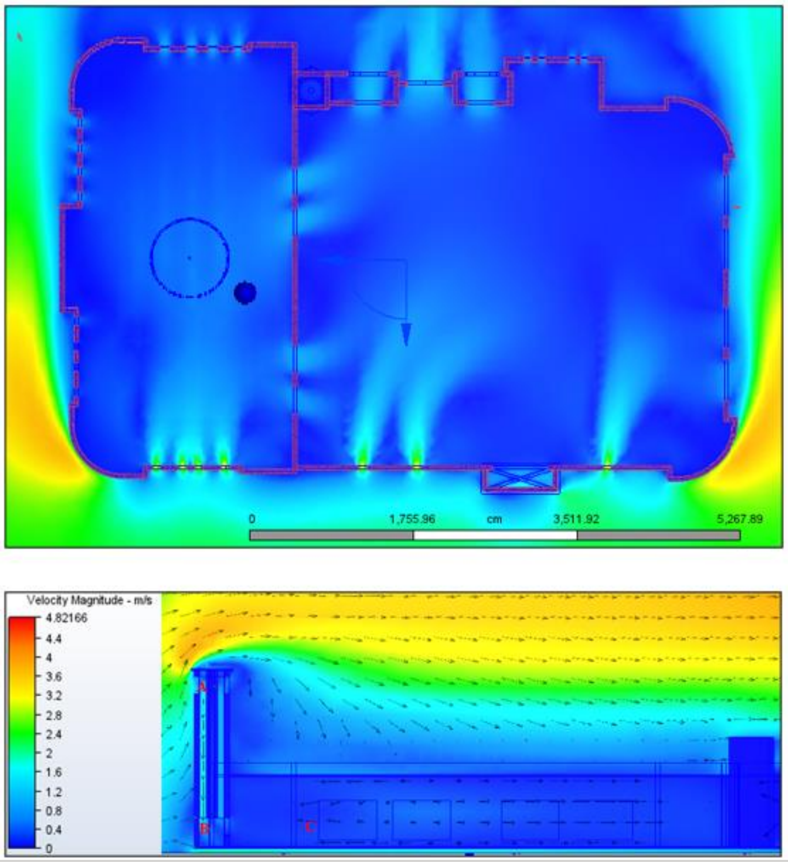
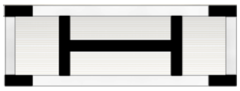


Figure 4.9. The results of air velocity at analytical plane 1 and 2 for Scenario 6.

4.1.8. Scenario 7 Results

The Scenario of adding rectangular wind catcher with internal partitions H type was implemented to the case study. The results showed that the average indoor air velocity at analytical plane 1 is **0.334773** m/s. At analytical plane 2, the air velocity at point A, point B and point C were 1.82871, 1.63752, and 0.35850 m/s respectively as shown in Table 4.8. Figure 4.10 represents the results in graphical way.

Table 4.8. The results of Scenario 7.

	Analytical plane 1 **Avg. air velocity m/s**	Analytical plane 2		
		Point A	Point B	Point C
Scenario 7	0.334773	1.82871	1.63752	0.35850
				

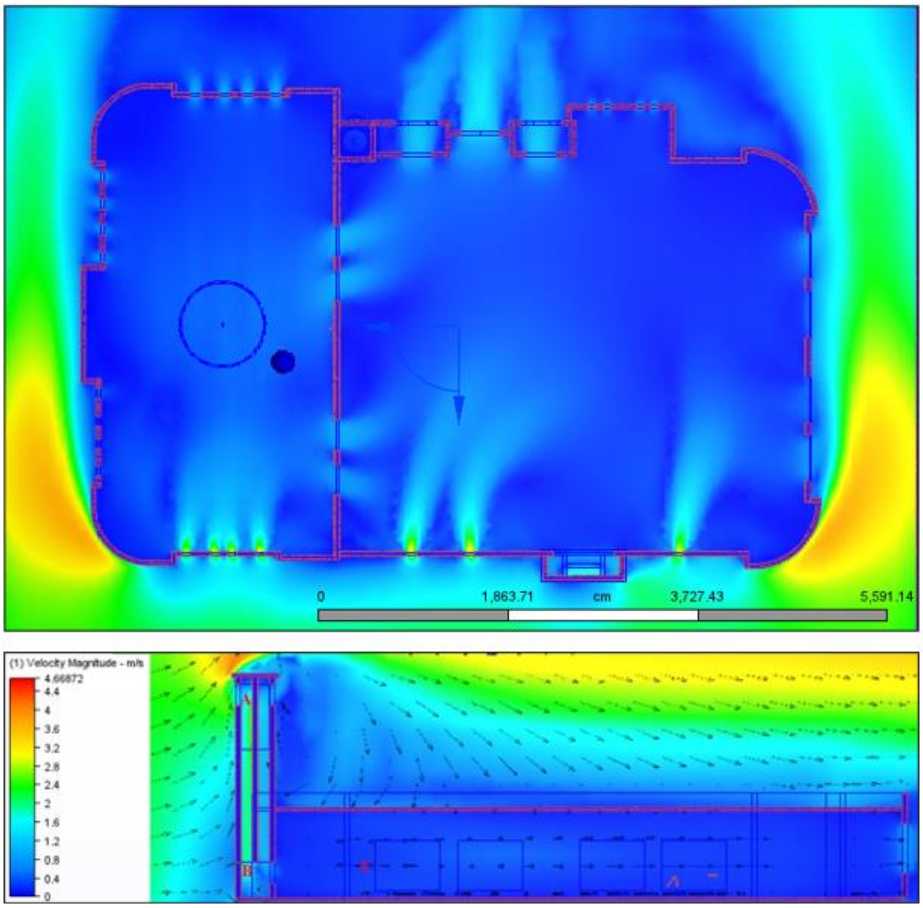


Figure 4.10. The results of air velocity at analytical plane 1 and 2 for Scenario 7.

4.1.9. Scenario 8 Results

The Scenario of adding rectangular wind catcher with internal partitions X and + composed (Star) type was implemented to the case study. The results showed that the average indoor air velocity at analytical plane 1 is **0.337485** m/s. At analytical plane 2, the air velocity at point A, point B and point C were 1.37705, 0.833321, and 0.400911 m/s respectively as shown in Table 4.9. Figure 4.11 represents the results in a graphical way.

Table 4.9. The results of Scenario 8.

	Analytical plane 1 **Avg. air velocity m/s**	Analytical plane 2		
		Point A	Point B	Point C
Scenario 7	0.337485	1.37705	0.833321	0.400911
				

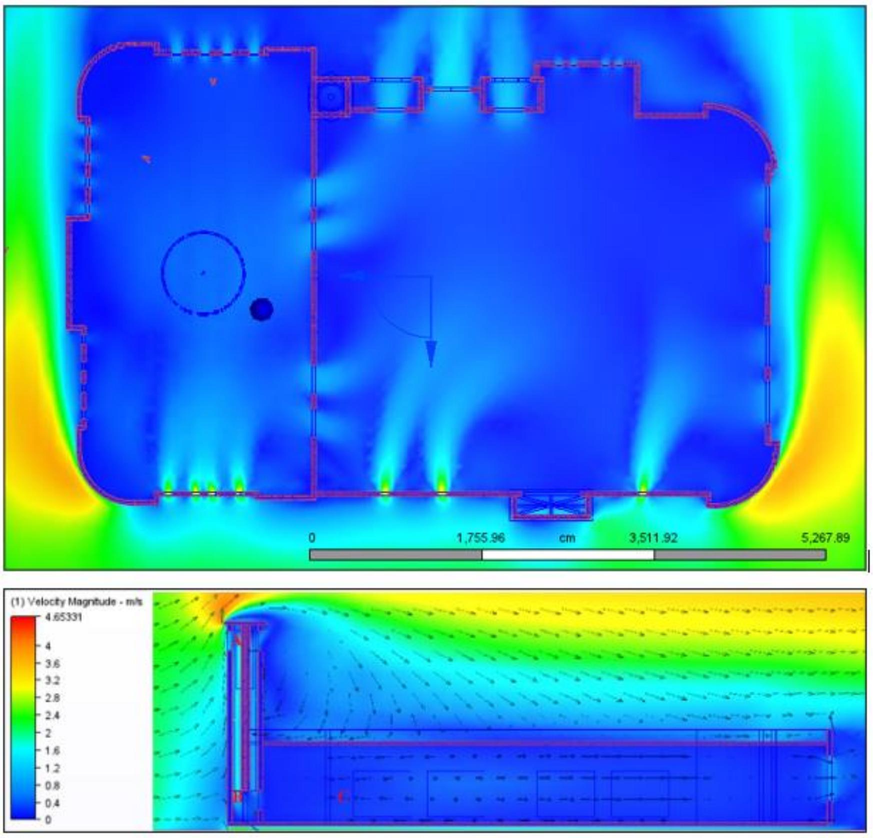


Figure 4.11. The results of air velocity at analytical plane 1 and 2 for Scenario 8.

4.2. ANALYSES AND DISSCUSION

This section includes the comparative analysis of the CFD simulation of analytical plane 1 and 2 in the base model and the Scenarios of the study. The results will be compared in terms of air velocity m/s at analytical model 1 for all assumptions. Additionally, the air velocity at points A, B, and C will be compared in all cases. The results will be discussed and connected to the previous studies to conclude the effect of using wind catcher and its properties on the indoor ventilation rate in the study area.

Analyses of results at analytical plane 1: The results showed that all the wind catcher Scenarios increased the average of air velocity at analytical plane 1 compared to the base case. Within this context, the square geometry of the wind catcher with X type internal partitions achieved the highest ventilation rate at analytical plane 1. In this scenario, the average of air velocity increased from 0.327872 m/s in the base model to 0.457457 m/s.

Compared to the base model, the square geometry of wind catcher with + type and H type internal partitions also increased the ventilation rate up to 0.437706 m/s and 0.424831 m/s, respectively. The square geometry has a better effect on the overall ventilation rate in the building. However, the Square X+ composed (Star) type has less effect on increasing the overall ventilation rate from the other square types.

On the other side, the rectangular geometry of the wind catcher with X, +, and H types also increased the ventilation rate compared to the base model results at analytical plane 1. However, this increase is less than the square geometry as shown in Figure 4.12. In addition, it can be noticed from the results of rectangular geometry Scenarios that the X and + internal partition types increased the overall ventilation rates more than the H and X+ Scenarios. The lowest improvement has been achieved by the Rectangular H type internal partition where the air velocity increased from 0.327872 m/s to only 0.334773 m/s as shown in Figure 4.12.

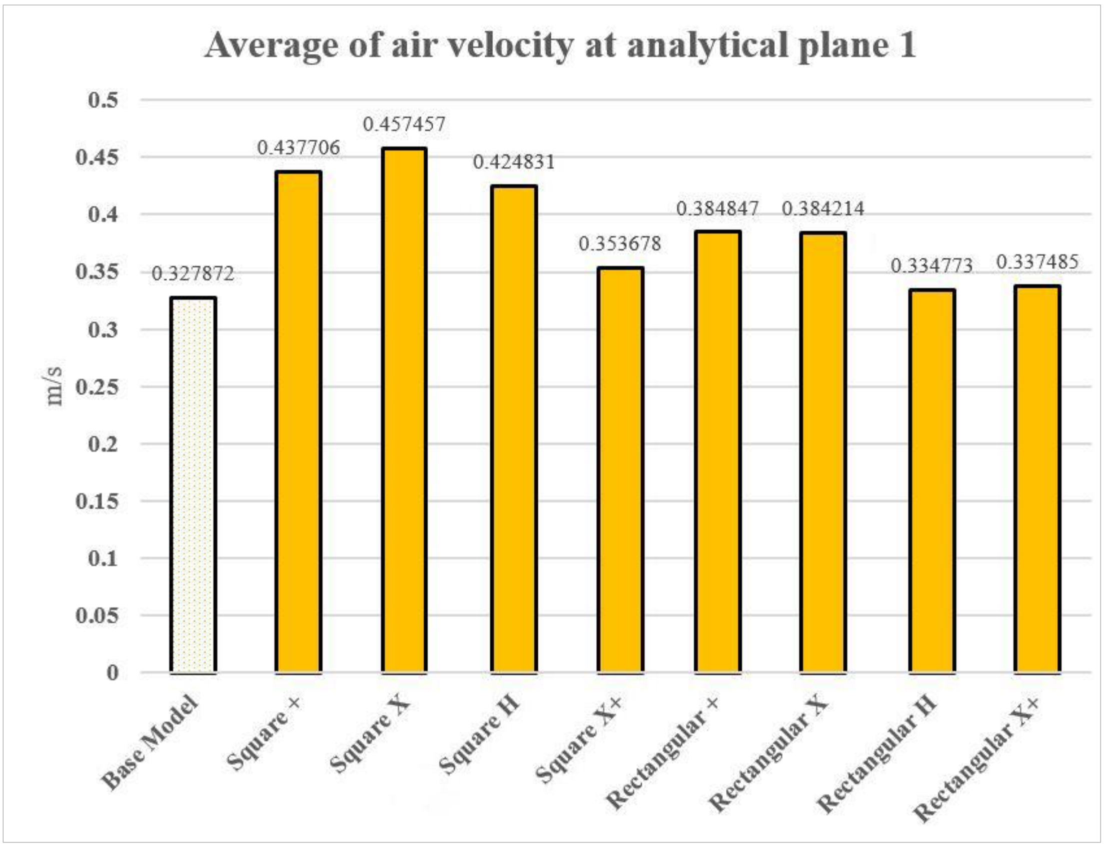


Figure 4.12. The results of average air velocity at analytical plane 1.

Analyses of results at analytical plane 2: The data comparison at Point A, as mentioned, point A represents the reference point where **the wind hits the internal partition at the top of the wind catcher**. The air velocity (m/s) was calculated at this point for all cases. The results showed that the highest air velocity at point A achieved at square geometry type with X type of internal partitions with 2.19658 m/s while the square geometry type with H type internal partitions achieved the lowest air velocity at that point with 1.36687 m/s among all Scenarios.

For the rectangular geometry Scenarios, the + type internal partitions achieved the highest air velocity among the Scenarios at point A with 2.0922 m/s while the rectangular X+ composed (Star) type achieved the lowest air velocity at point A among the rectangular geometry Scenarios as shown in Figure 4.13.

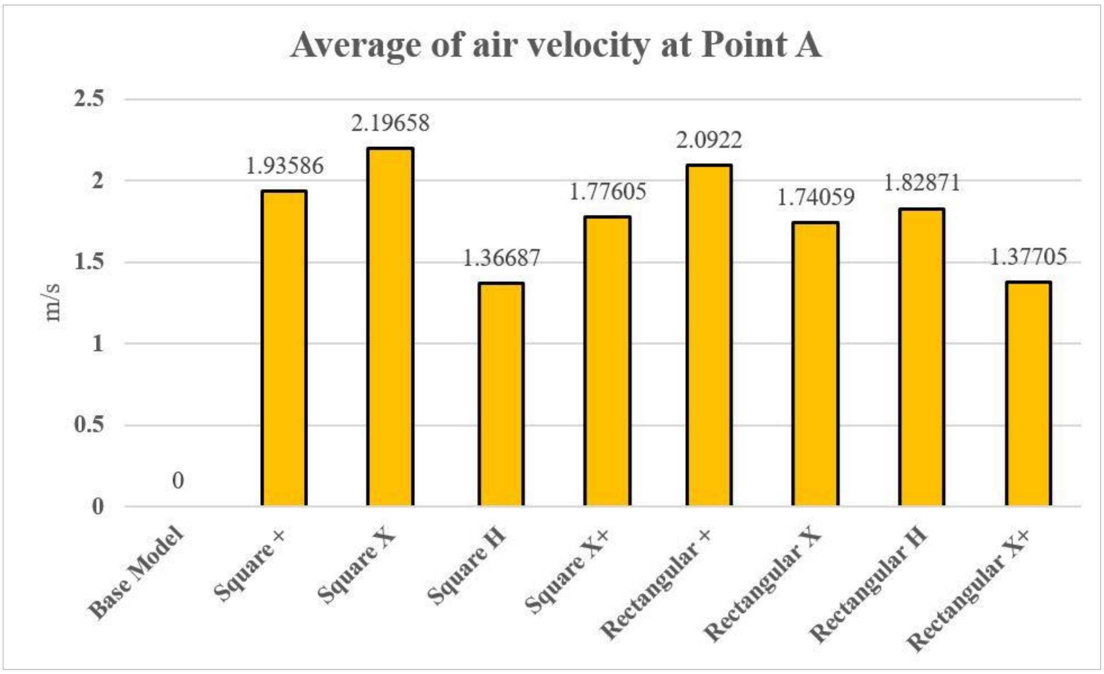


Figure 4.13. The results of air velocity at Point A.

The data comparison at Point B: Point B represents the reference point above the water bond at the bottom of the wind catcher **where the wind passes over the water surface before entering the indoor space**. The air velocity at this point was calculated and compared for all cases of wind catcher Scenarios. The results showed that the highest air velocity at point B achieved at square geometry with X type of internal partitions with 1.73654 m/s while the lowest air velocity achieved at adding rectangular geometry of wind catcher with X+ composed (Star) type of internal partitions with 0.833321 m/s.

It is worth mentioning that using the rectangular H type achieved results slightly like the square X type of wind catcher at point B as shown in Figure 4.14. These results could give a good indication that the square geometry X type of internal partitions has the best impact on the ventilation rate, however, the most important results can be assessed at point C that represents the reference point of indoor space and will be explored in the followings.

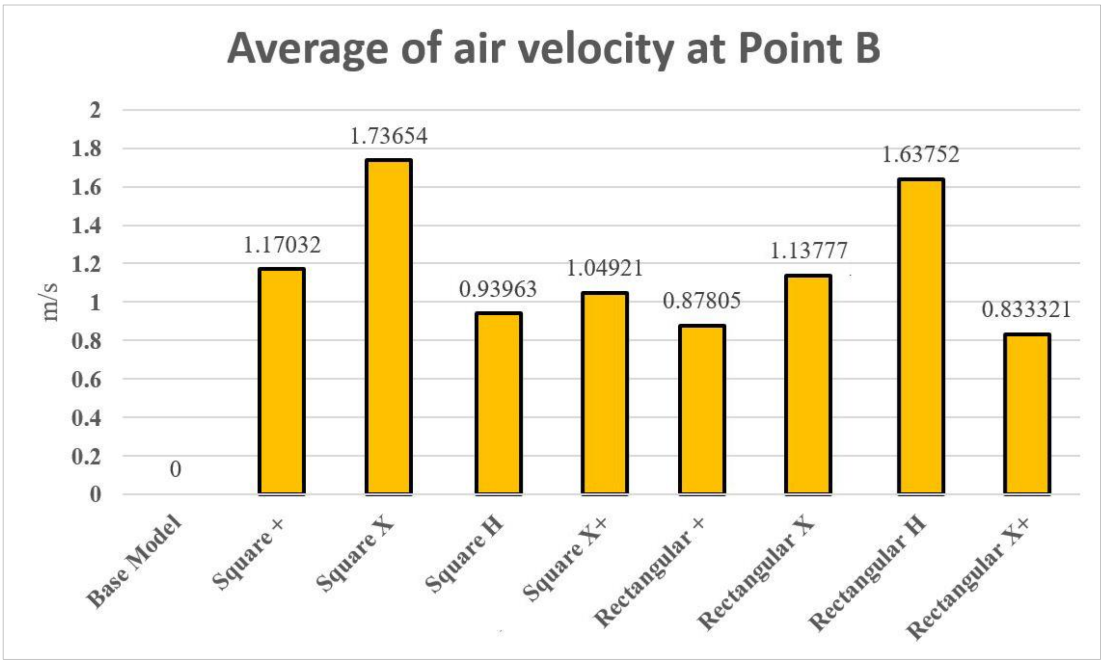


Figure 4.14. The results of air velocity at Point B.

The data comparison at Point C: Point C represents a reference point for evaluating air velocity and the indoor ventilation rate for the base model and the Scenarios. This point is located 2 meters above the ground floor level at analytical plane 2 and 4 meters from the external wall where the wind starts to enter the indoor space (7.5 meters away from point B) as mentioned in section 4.1 and shown in Figure 4.2.

The results of air velocity at this point for the base model and the study Scenarios were considered as the final assessment of the study because of the sensitivity of this point and its direct effect on the indoor occupant’s comfort. Consequently, the results at point C showed that the square geometry of X+ composed (Star) type had achieved the highest air velocity with 0.424831 m/s while the Rectangular H type achieved the lowest value at this point with 0.35850 m/s. Consequently, all the wind catcher Scenarios had positive effect on the ventilation rates as shown in Figure 4.15, however, square geometry with X+ composed (Star) and the X type of internal blades achieved the highest air velocity among the other Scenarios. An improvement up to 51.90% and 50.34% has been achieved in these Scenarios respectively compared to the base model result at point C (from 0.333508 to 0.693379 and 0.671595 m/s respectively).

For the rectangular Scenarios, the results showed that the air velocity at point c increased compared to the base model but by less magnitudes than the square Scenarios. For example, the Rectangular X type achieved 23% improvement in air velocity (from 0.333508 to 0.434472 m/s) while the Rectangular **+** type achieved 19% improvement in the ventilation rate (from 0.333508 to 0.414143 m/s) as shown in Figure 4.15. Therefore, it can be concluded that the rectangular X type improves the ventilation rate more than the rectangular + type in the study area while the rectangular X+ and H types increased the air velocity with less magnitudes at point C among the rectangular geometry Scenarios.

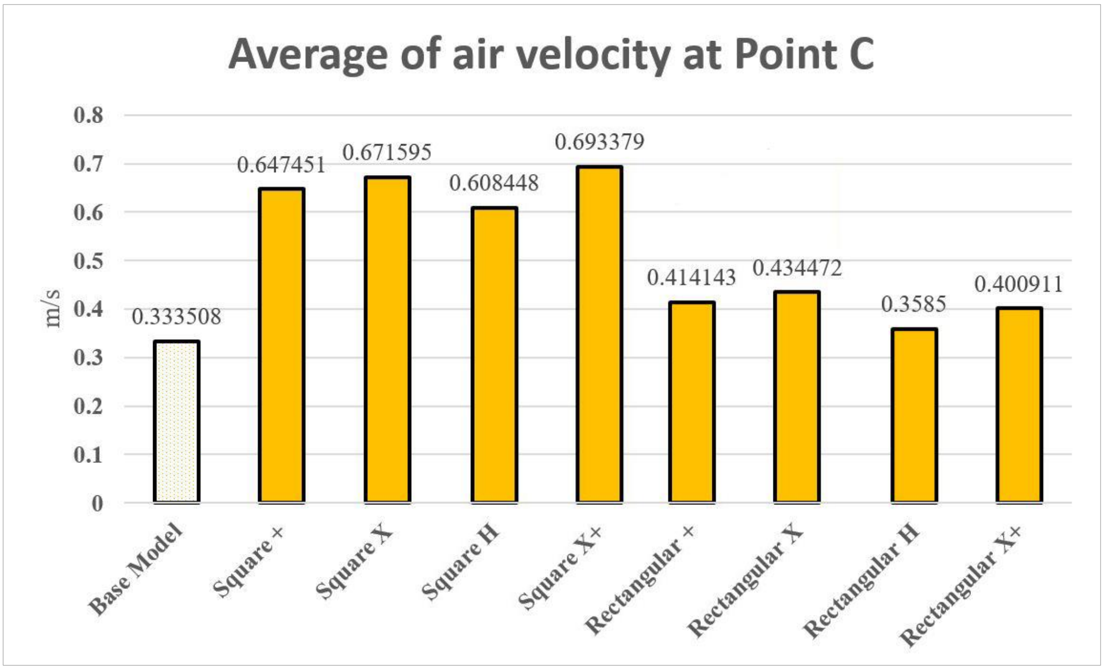


Figure 4.15. The results of air velocity at Point C.

In general, it can be concluded that the composition between X and + internal partitions achieved the best improvement in the square geometry while the only X type achieved more improvement than the only + type in the square geometry scenarios. Nevertheless, the composition between X and + is not the best solution for rectangular scenarios. In this context, only the X type and only the + type of internal partitions achieved more improvement in indoor ventilation rate than the composed (Star) type. Additionally, the H type of internal partitions achieved more improvement in the square geometry than the rectangular geometry, however, it achieved the least magnitude compared to the other square geometry scenarios.

Accordingly, it can be concluded that the square geometry scenario is a better solution approach for wind catchers in Nizwa region than the rectangular shape scenarios. In addition, the X or + type of internal partitions or their composition scenarios are the best approach than the H type internal partition approach at the early design stages in Nizwa region. The following part will draw the general conclusions of the research.

PART 5

CONCLUSION

The research proposed investigating the effectiveness of using wind catchers as a passive cooling strategy in a hot-dry region. The research was conducted in Nizwa city in Oman through a mosque building. The methodology was based on establishing different Scenarios of wind catcher typology to be applied to the existing case study. The study in that context supposed testing the scenarios that could give an indication for architects and designers in hot-arid zones to adopt wind catcher principles as a passive cooling technique in their future projects. For that purpose, wind catcher scenarios are related to parameters of the geometry and internal partitions while other design parameters were fixed for all cases. For example, the height of wind catcher, the construction materials, the opening ratio, as well as the gross area of the suggested wind catchers were fixed. In that context, square and rectangular plan-based shapes were selected with certain dimensions and examined. In addition, Scenarios including a variety of X, +, and H blade types were selected. In summary, a total of eight scenarios were generated and examined. CFD analysis was conducted for the existing case and the generated Scenarios to obtain the indoor ventilation rate in term of air velocity (m/s). Results were obtained, extracted, presented, and compared to determine the best solutions for the study area.

The results were concentrated on the impact of wind catcher’s typology on the indoor ventilation rates of buildings. For the purpose, an internal point was selected represented by point C to compare the air velocity at that point. The results presented and compared. Figure 5.1 illustrates the results in descending order to catch up the best solutions from the Scenarios.

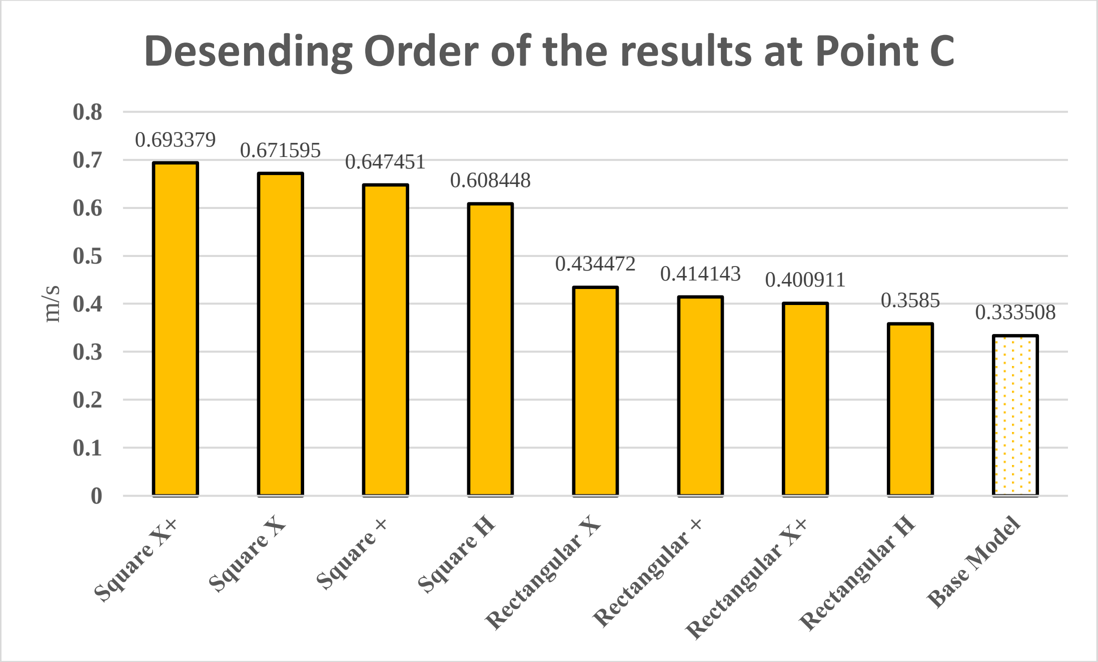


Figure 5.1. Descending order of the results at Point C compared to the base model.

The improvement of the indoor ventilation rate for each Scenario compared to the base case (without a wind catcher) is also presented.

the following statements can be concluded from Table 5.1:

1. Square shape wind catcher with + type internal partitions achieved up to 48.48% improvement in indoor ventilation rate in hot-arid regions compared to the existing case (without wind catcher).

2. Square shape wind catcher with X type internal partitions achieved up to 50.34% improvement in indoor ventilation rate in hot-arid regions compared to the existing case. This represents the maximum efficiency of wind catcher typology in the study area.

3. Rectangular shape wind catcher with + type internal partitions achieved up to 19.47% improvement in indoor ventilation rate in hot-arid regions compared to the existing case.

4. Rectangular shape wind catcher with X type internal partitions achieved up to 23.24% improvement in indoor ventilation rate in hot-arid regions compared to the existing case.

5. A square shape wind catcher with H type internal partitions achieved up to 45.18% improvement in indoor ventilation rate in hot-arid regions compared to the existing case.

6. Square shape wind catcher with X and + composed (Star) type internal partitions achieved up to 51.90% improvement in indoor ventilation rate in hot-arid regions compared to the existing case.

7. Rectangular shape wind catcher with H type internal partitions achieved only up to 6.97% improvement in indoor ventilation rate in hot-arid regions compared to the existing case. This represents the minimum efficiency of wind catcher typology in the study area.

8. Rectangular shape wind catcher with X and + composed (Star) type internal partitions achieved up to 16.81% improvement in indoor ventilation rate in hot-arid regions compared to the existing case.

In general, it is a good approach to adopt wind catchers as a passive cooling technique to building design in the Nizwa region. From the research results, all the Scenarios increased the indoor air velocity which could be enough indication of improving the ventilation rate inside the building. In addition, it can be concluded that square shape of wind catcher plan is better solution in improving building indoor ventilation rate or increasing the indoor air velocity in Nizwa climate. Another conclusion could be drawn that the X+ composed (Star) type and X type of internal partition of wind catchers is better than the + and H pattern in Nizwa region. This result is completely opposite to what is common in the Iranian city Yazd where the + internal pattern shape with blades perpendicular to each other are the most dominated [26].

It is worth mentioning that the conclusion is based on the limited Scenarios in this study. Hence, more investigations could be conducted supposing other different Scenarios. Within this context, the researcher recommends the followings for future investigations:

1. Choosing wind catchers with more different geometric forms and internal partitions for measurement of wind catcher potentials.

2. Examining the effect of wind catcher building materials on the indoor thermal comfort conditions in the study area could be performed in future studies to get more reliable results and guarantee indoor comfortable conditions.

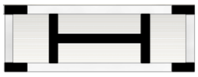
3. Considering more design parameters in wind catcher options such as the height of the wind catcher, the opening ratio, the design and the numbers of the internal blades, the control elements, the construction materials as well as the technology in modern wind catchers design and manufacture.

4. Developing parametric modeling and simulation workflow to include as much as possible of wind catcher design parameters could accelerate and facilitate examining the impact of wind catcher's typology on ventilation rate as well as thermal comfort conditions at the same time.

5. Studying the reasons for the difference between the average wind speed at the three selected points within the wind catcher (point A, point B, and point C).

6. the scope of the performance analysis can be extended by adding heat transfer and thermal comfort factors in the CFD settings.

Table 5.1. Comparing the indoor ventilation rate results of the wind catcher Scenarios with the existing model.

Scenario	**Description**	**Representation**	**Indoor Ventilation Rate (m/s)** (@ Point C)	**Improvement (%)**
Exist model	**Without wind catcher**	**----------------**	**0.333508**	**----------------**
S 1	Square shape wind catcher with + type internal partitions		0.647451	48.48%
S 2	Square shape wind catcher with X type internal partitions		0.671595	50.34%
S 3	Square shape wind catcher with H type internal partitions		0.608448	45.18%
S 4	partitions Square shape wind catcher with X and + composed (Star) type internal partitions		0.693379	51.90%
S 5	Rectangular shape wind catcher with + type internal partitions		0.414143	19.47%
S 6	Rectangular shape wind catcher with X type internal		0.434472	23.24 %
S 7	Rectangular shape wind catcher with H type internal partitions		0.35850	6.97%
S 8	Rectangular shape wind catcher with X and + composed (Star) type internal partitions		0.400911	16.81%

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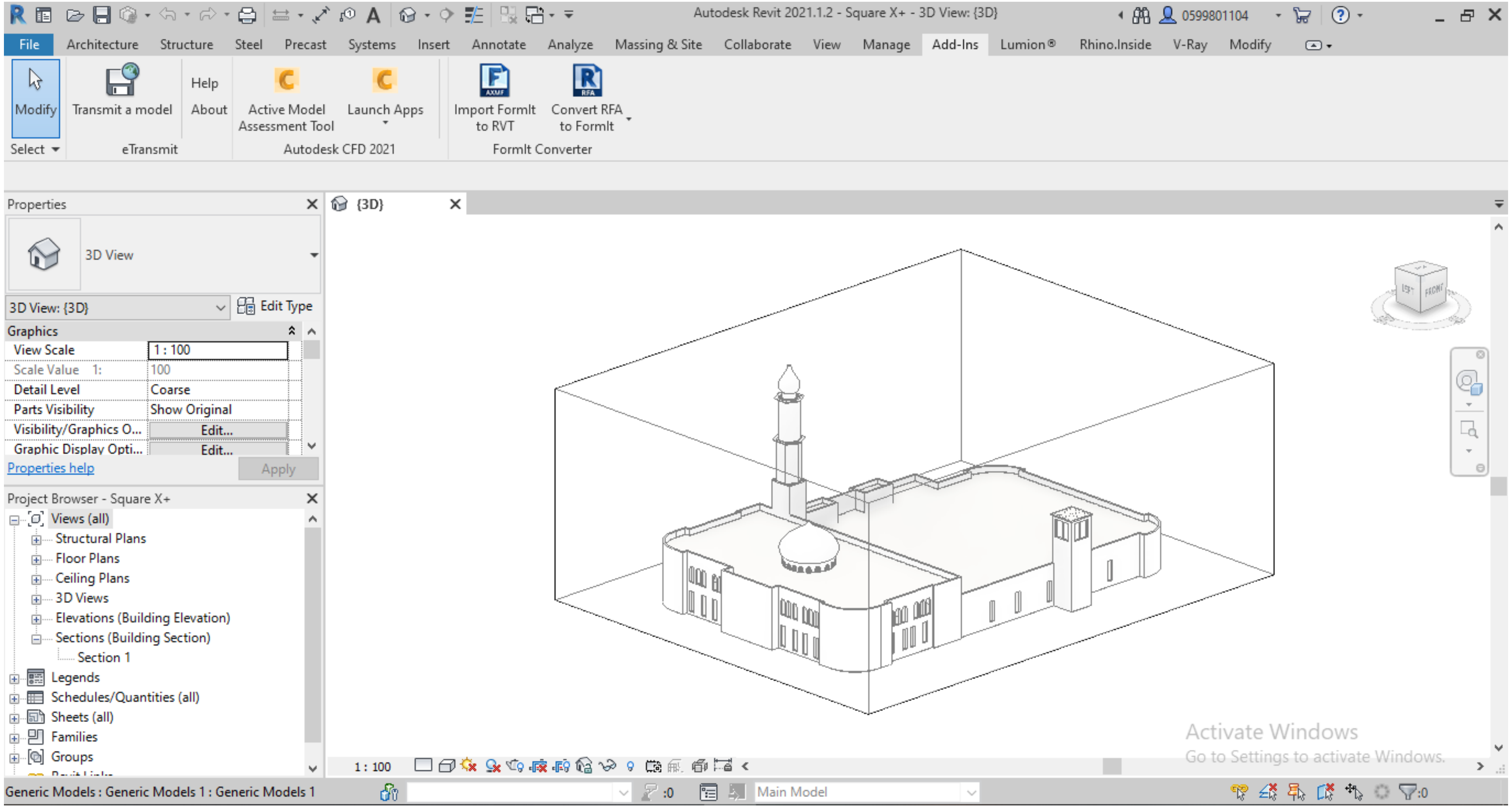
APPENDIX A.

BIM-CFD WORFLOW



Autodesk Revit 2021.1.2 - Square X+ - 3D View: {3D}

View Scale: 1 : 100
Scale Value 1: 100
Detail Level: Coarse
Parts Visibility: Show Original

Generic Models : Generic Models 1 : Generic Models 1

Figure Appendix A.1. Exporting the 3D BIM model from Revit to Autodesk CFD.

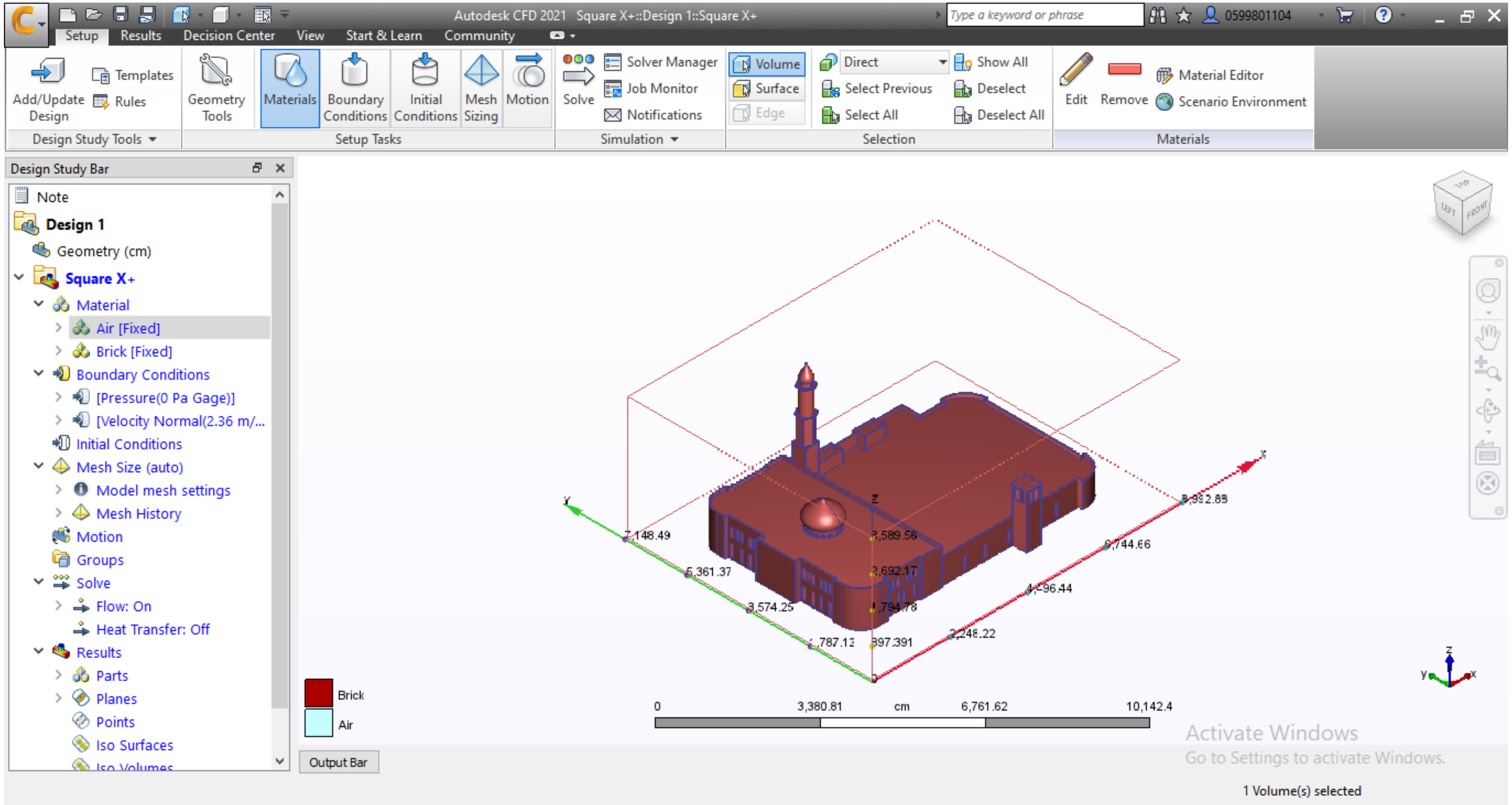


Figure Appendix A.2. Assigning materials (Brick) to model in Autodesk CFD.

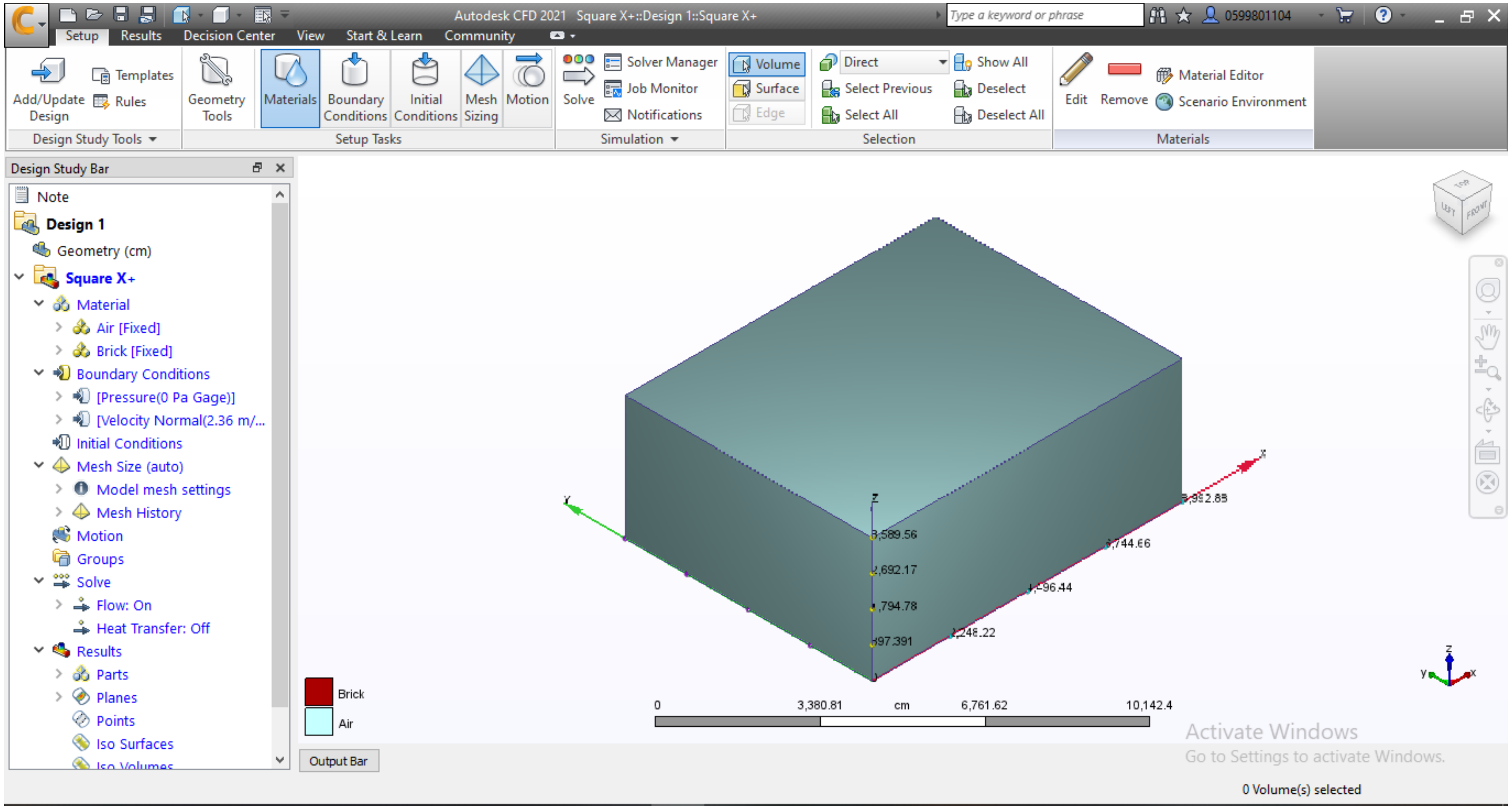
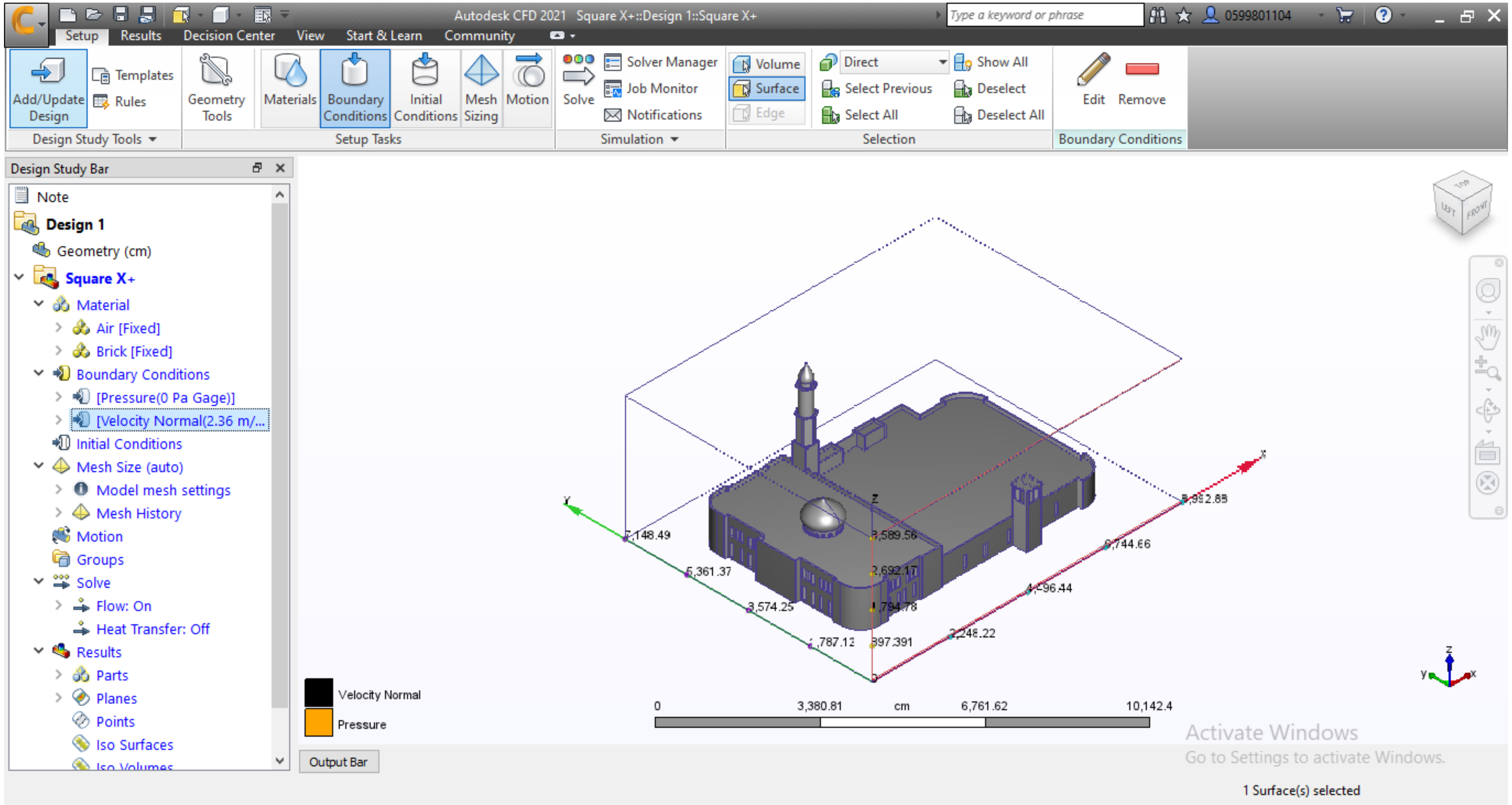


Figure Appendix A.3. Assigning materials (Air) to model in Autodesk CFD.



Note
Design 1
Geometry (cm)
Square X+
- Material
  - Air [Fixed]
  - Brick [Fixed]
- Boundary Conditions
  - [Pressure(0 Pa Gage)]
  - [Velocity Normal(2.36 m/...
- Initial Conditions
- Mesh Size (auto)
  - Model mesh settings
  - Mesh History
- Motion
- Groups
- Solve
  - Flow: On
  - Heat Transfer: Off
- Results
  - Parts
  - Planes
  - Points
  - Iso Surfaces
  - Iso Volumes

1 Surface(s) selected

Figure Appendix A.4. Assigning boundary conditions to model in Autodesk CFD.

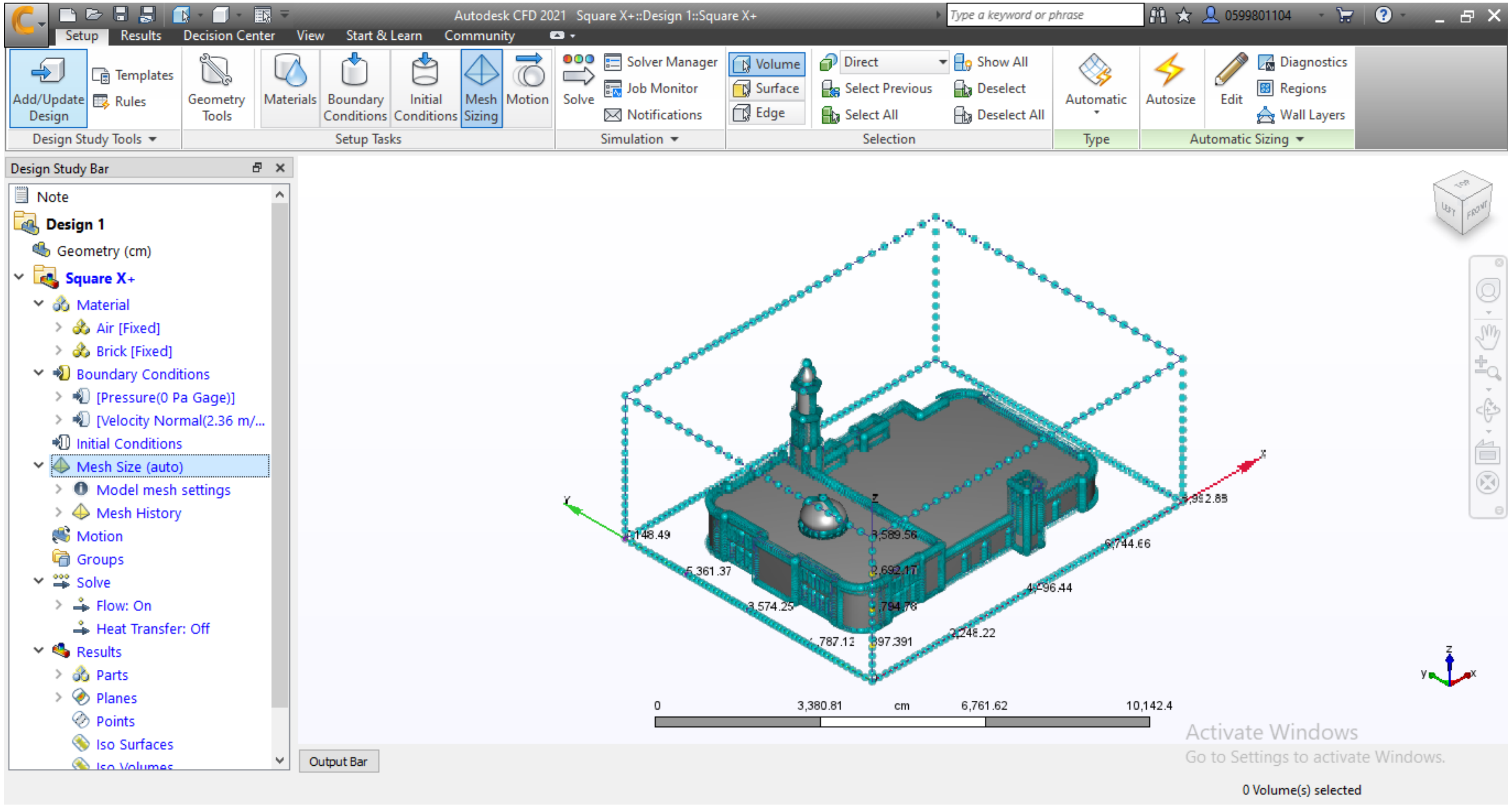
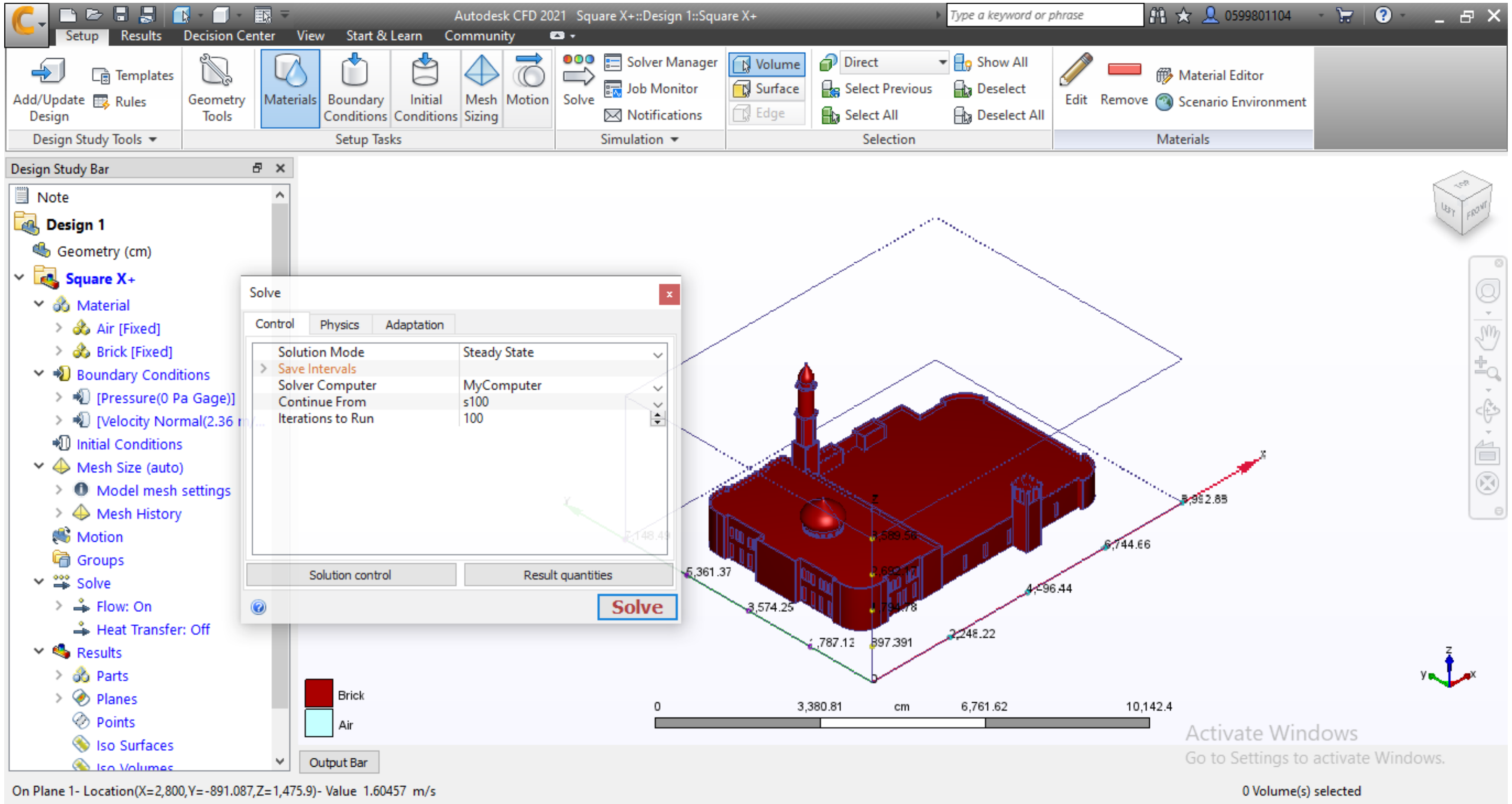


Figure Appendix A.5. Auto sizing the mesh to the BIM model in Autodesk CFD.

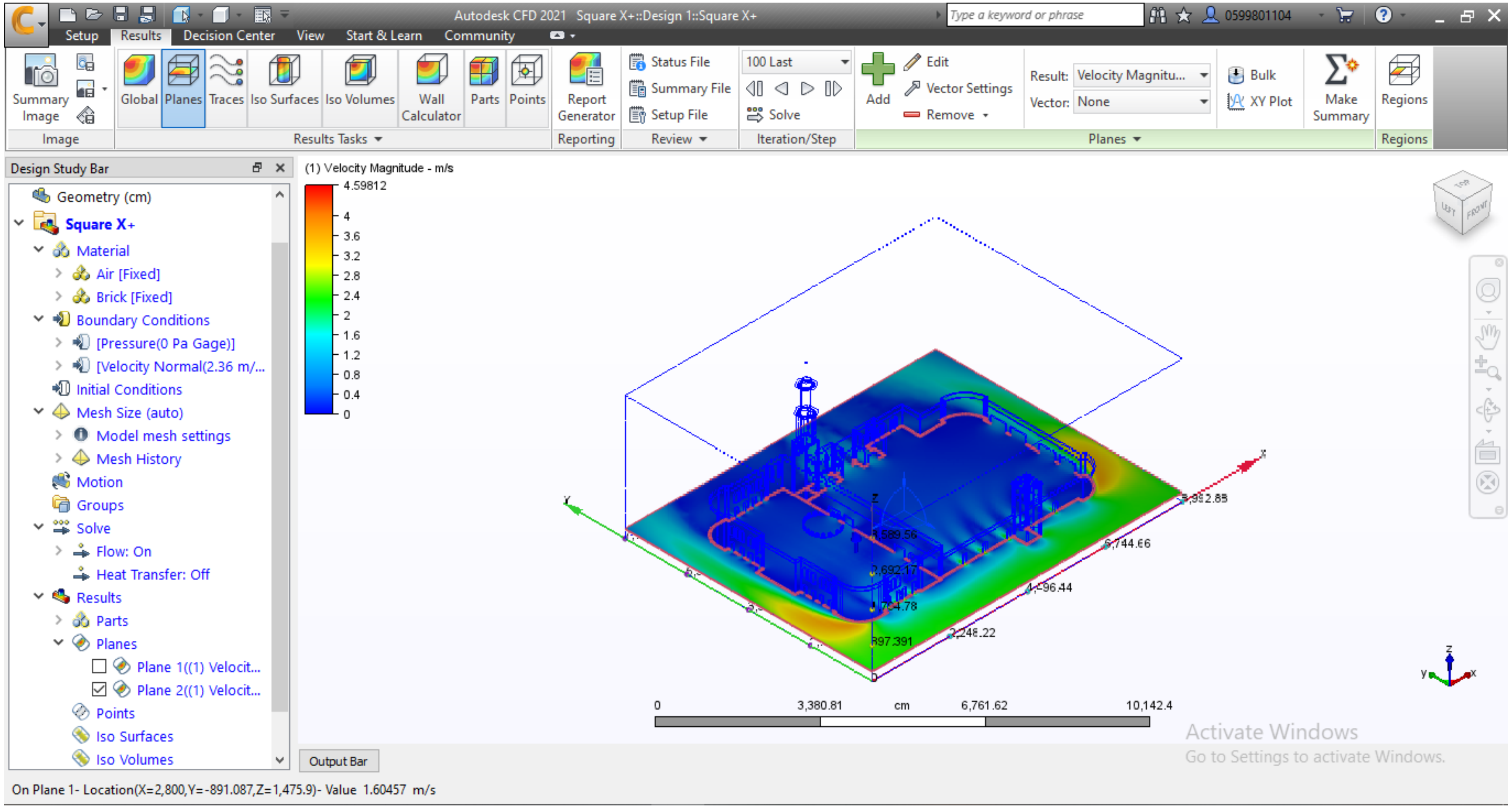


Solution Mode: Steady State
Save Intervals
Solver Computer: MyComputer
Continue From: s100
Iterations to Run: 100

On Plane 1- Location(X=2,800,Y=-891.087,Z=1,475.9)- Value 1.60457 m/s

0 Volume(s) selected

Figure Appendix A.676. CFD simulation solve settings in Autodesk CFD.



Result: Velocity Magnitu...

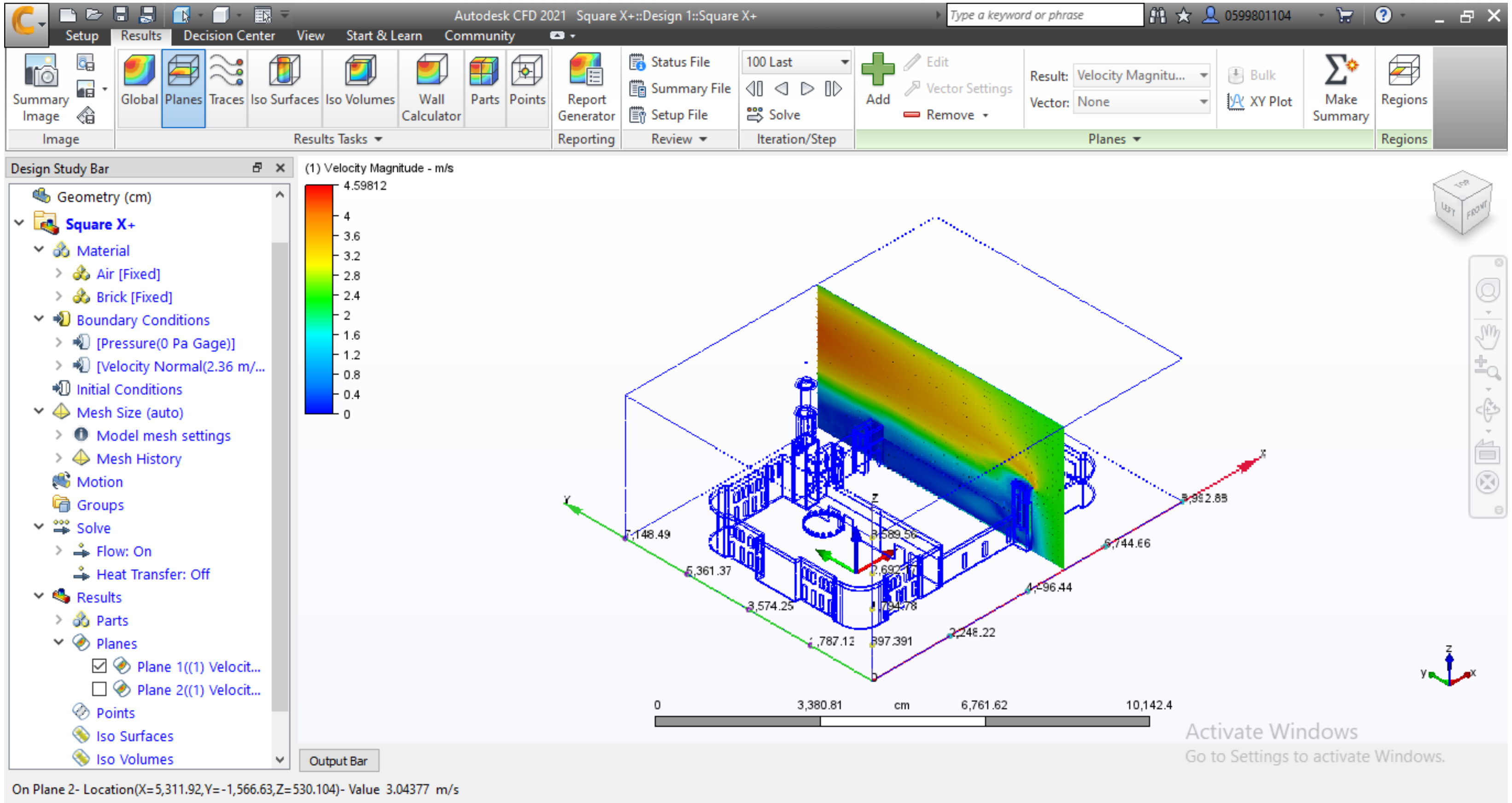
Vector: None

☐ Plane 1((1) Velocit...

☑ Plane 2((1) Velocit...

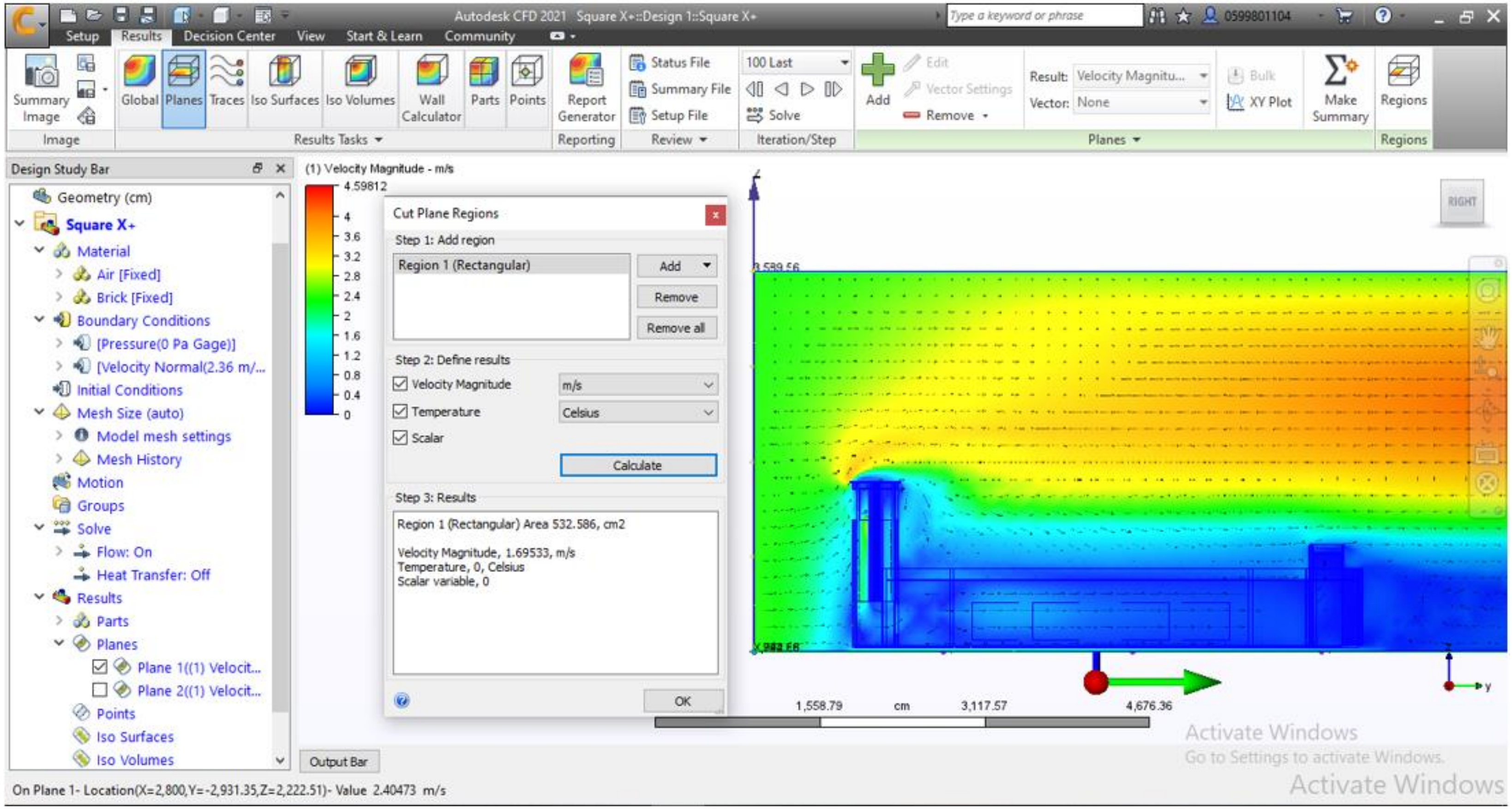
On Plane 1- Location(X=2,800,Y=-891.087,Z=1,475.9)- Value 1.60457 m/s

Figure Appendix A.7. Visualizing CFD simulation results at analytical plane 1.



On Plane 2- Location(X=5,311.92,Y=-1,566.63,Z=530.104)- Value 3.04377 m/s

Figure Appendix A.8. Visualizing CFD simulation results at analytical plane 2.



Cut Plane Regions

Step 1: Add region

Region 1 (Rectangular)

Step 2: Define results

☑ Velocity Magnitude m/s

☑ Temperature Celsius

☑ Scalar

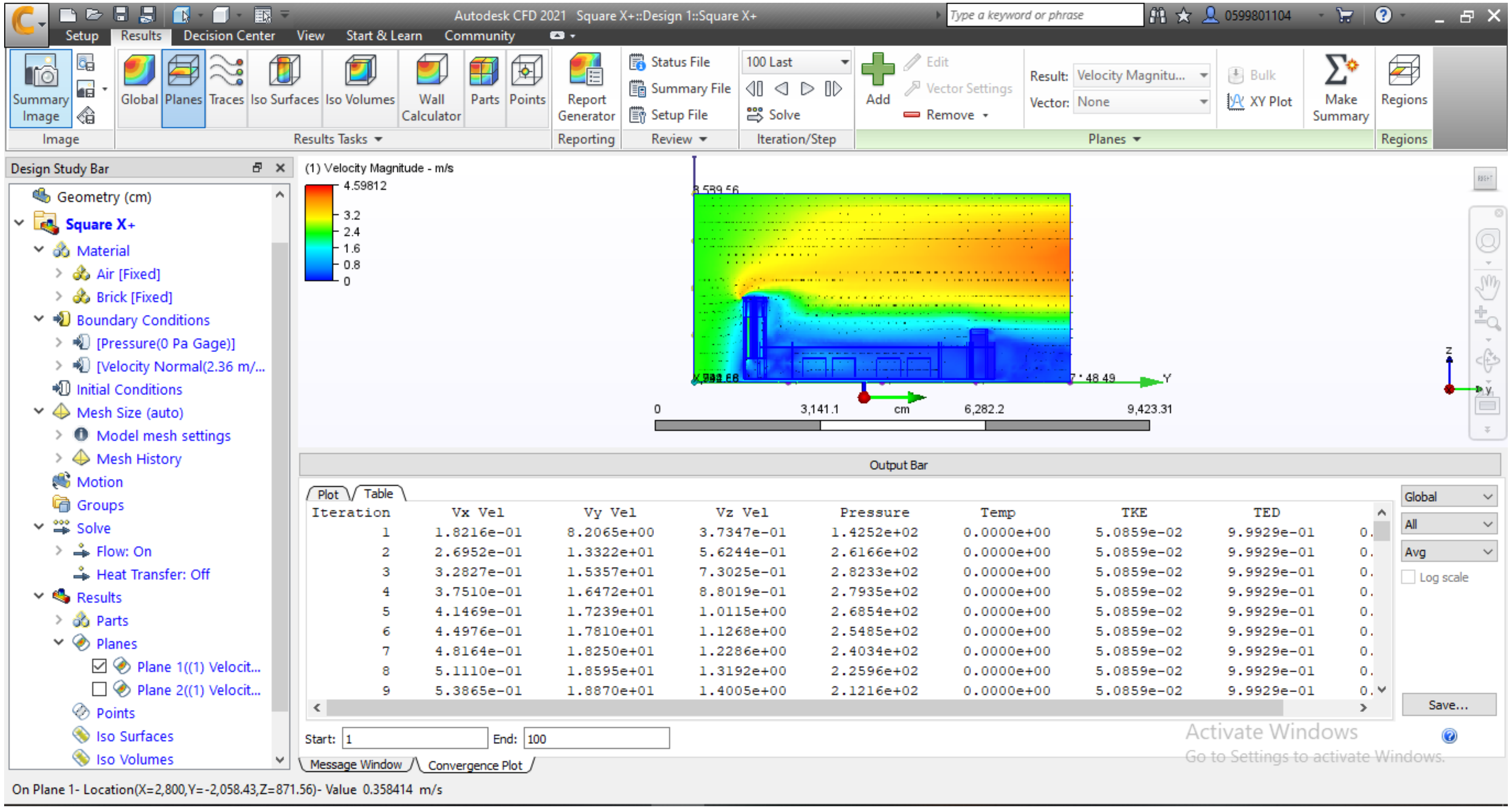
Step 3: Results

```
Region 1 (Rectangular) Area 532.586, cm2

Velocity Magnitude, 1.69533, m/s
Temperature, 0, Celsius
Scalar variable, 0
```

On Plane 1- Location(X=2,800,Y=-2,931.35,Z=2,222.51)- Value 2.40473 m/s

Figure Appendix A.9. Calculating air velocity (m/s) at the selected points.

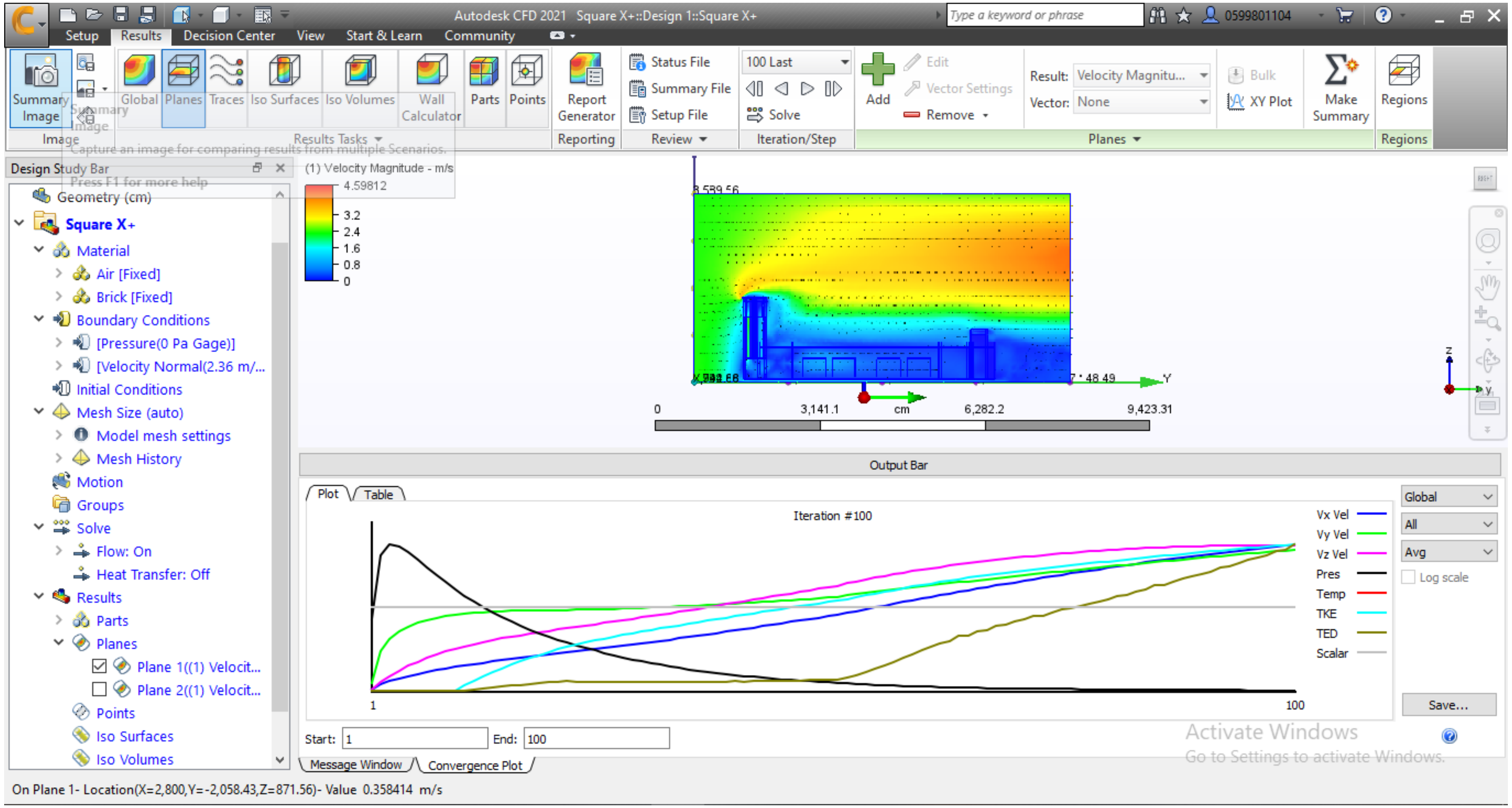


```
Iteration    Vx Vel      Vy Vel      Vz Vel      Pressure    Temp        TKE         TED
        1  1.8216e-01  8.2065e+00  3.7347e-01  1.4252e+02  0.0000e+00  5.0859e-02  9.9929e-01  0.
        2  2.6952e-01  1.3322e+01  5.6244e-01  2.6166e+02  0.0000e+00  5.0859e-02  9.9929e-01  0.
        3  3.2827e-01  1.5357e+01  7.3025e-01  2.8233e+02  0.0000e+00  5.0859e-02  9.9929e-01  0.
        4  3.7510e-01  1.6472e+01  8.8019e-01  2.7935e+02  0.0000e+00  5.0859e-02  9.9929e-01  0.
        5  4.1469e-01  1.7239e+01  1.0115e+00  2.6854e+02  0.0000e+00  5.0859e-02  9.9929e-01  0.
        6  4.4976e-01  1.7810e+01  1.1268e+00  2.5485e+02  0.0000e+00  5.0859e-02  9.9929e-01  0.
        7  4.8164e-01  1.8250e+01  1.2286e+00  2.4034e+02  0.0000e+00  5.0859e-02  9.9929e-01  0.
        8  5.1110e-01  1.8595e+01  1.3192e+00  2.2596e+02  0.0000e+00  5.0859e-02  9.9929e-01  0.
        9  5.3865e-01  1.8870e+01  1.4005e+00  2.1216e+02  0.0000e+00  5.0859e-02  9.9929e-01  0.
```

Start: 1 End: 100

On Plane 1- Location(X=2,800,Y=-2,058.43,Z=871.56)- Value 0.358414 m/s

Figure Appendix A.10. CFD simulation results for the 100 iterations.



Autodesk CFD 2021 Square X+::Design 1::Square X+

100 Last

Result: Velocity Magnitu...

Vector: None

Global

All

Avg

Start: 1 End: 100

On Plane 1- Location(X=2,800,Y=-2,058.43,Z=871.56)- Value 0.358414 m/s

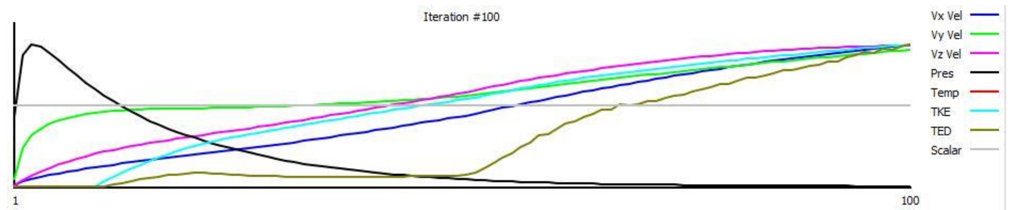
Figure Appendix A.11. Plot of the CFD simulation for the 100 iterations.

APPENDIX B.

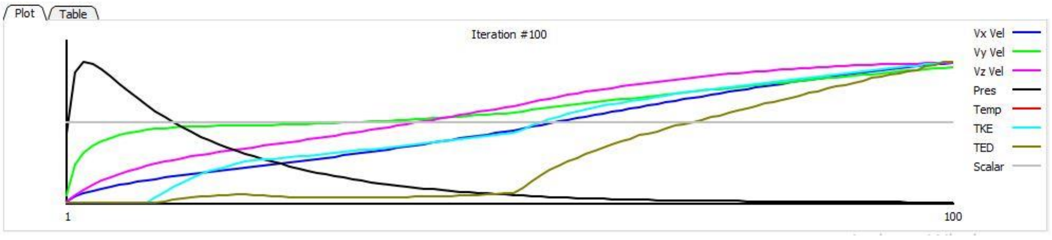
PLOT OF THE AIR FLOW RESULTS

Table Appendix B. 1. Air flow plot representation results for the base model and the Scenarios through 100 iteration.

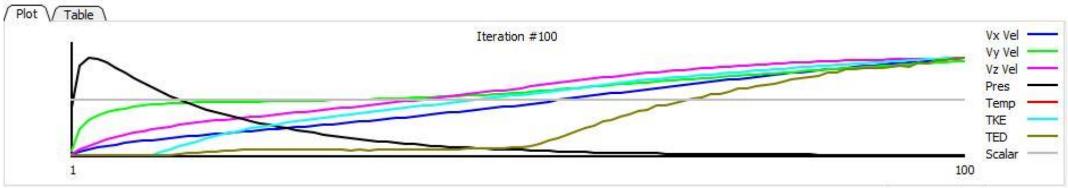
Base model Results- Without wind catchers



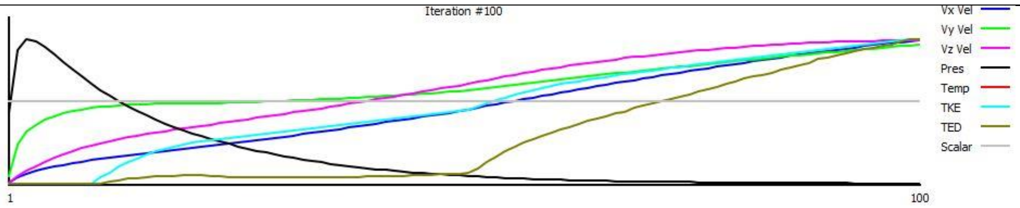
Scenario 1 Results- Square +



Scenario 2 Results- Square X



Scenario 3 Results- Square H



Scenario 4 Results- Square X+

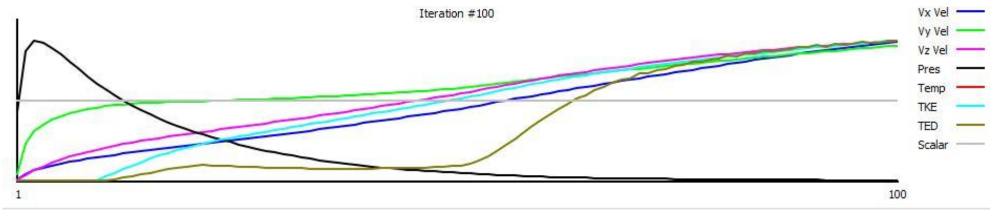
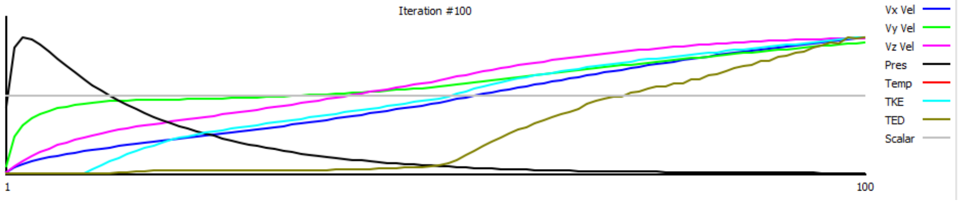
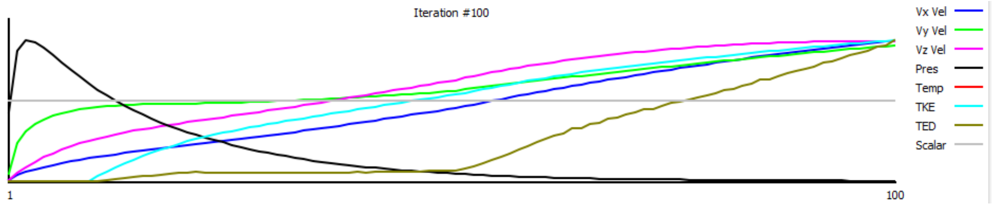


Table Appendix B. 1. (Coninues)

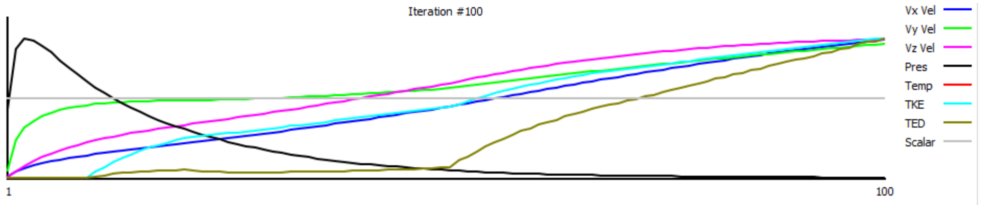
Scenario 5 Results- Rectangular +



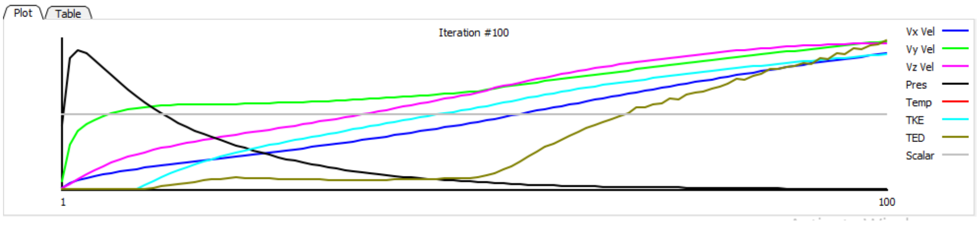
Scenario 6 Results- Rectangular X



Scenario 7 Results- Rectangular H



Scenario 8 Results- Rectangular X+



APPENDIX C.

EXAMPLE OF AIR FLOW NUMERICAL RESULTS

Table Appendix C. 1. Air flow numerical results for the base model through 100 iteration.

Iteration	Vx Vel	Vy Vel	Vz Vel	Pressure	TKE	TED
1	0.180016	8.14585	0.293456	136.873	0.0482093	0.999325
2	0.243558	13.1977	0.412926	249.897	0.0482093	0.999325
3	0.28536	15.1722	0.520863	268.51	0.0482093	0.999325
4	0.321874	16.2418	0.621892	264.727	0.0482093	0.999325
5	0.35459	16.9746	0.713101	253.816	0.0482093	0.999325
6	0.384666	17.5191	0.795096	240.402	0.0482093	0.999325
7	0.412688	17.9385	0.868987	226.36	0.0482093	0.999325
8	0.439024	18.268	0.935913	212.545	0.0482093	0.999325
9	0.463946	18.5297	0.996916	199.352	0.0482093	0.999325
10	0.487664	18.739	1.0529	186.949	0.0482093	0.999325
11	0.510341	18.9069	1.10461	175.394	34.3972	69.2474
12	0.532102	19.0413	1.15266	164.68	62.0175	154.131
13	0.553045	19.1486	1.19755	154.772	91.5594	284.251
14	0.573262	19.2336	1.23971	145.619	116.156	386.955
15	0.592814	19.3002	1.27948	137.165	139.05	520.128
16	0.611771	19.3514	1.31714	129.354	165.422	616.598
17	0.630175	19.3897	1.35294	122.132	185.41	679.197
18	0.648086	19.4173	1.38706	115.449	203.529	819.825
19	0.665527	19.4358	1.41967	109.258	221.105	850.845
20	0.682545	19.4465	1.45091	103.518	241.636	916.91
21	0.699164	19.4507	1.48089	98.1901	256.237	986.401
22	0.716374	19.4698	1.51149	93.1074	269.377	960.588
23	0.734005	19.4957	1.54259	88.2489	281.267	933.666
24	0.752028	19.5258	1.57412	83.607	293.569	895.571
25	0.770413	19.5592	1.60602	79.1801	306.732	860.142
26	0.789187	19.5955	1.63834	74.9714	317.227	823.68
27	0.808354	19.6344	1.67103	70.9767	327.052	794.824
28	0.82791	19.6759	1.70409	67.1951	337.42	782.45
29	0.847836	19.7199	1.73753	63.624	347.387	739.226
30	0.868146	19.7666	1.77136	60.258	358.424	740.399
31	0.888813	19.8159	1.80559	57.0904	368.017	724.532
32	0.909876	19.868	1.8402	54.1142	377.728	706.875
33	0.931298	19.923	1.87524	51.3226	386.584	709.674
34	0.953084	19.9809	1.9106	48.7045	396.914	704.724
35	0.975217	20.0418	1.94632	46.2506	406.234	686.799
36	0.997652	20.1058	1.98238	43.9523	415.589	691.768

Table Appendix C. 1. (Continues)

Iteration	Vx Vel	Vy Vel	Vz Vel	Pressure	TKE	TED
37	1.0204	20.1729	2.01874	41.8014	424.447	699.756
38	1.04345	20.2431	2.0554	39.792	434.611	688.977
39	1.06679	20.3164	2.09232	37.9126	443.658	690.249
40	1.09038	20.3928	2.12947	36.1545	452.47	704.196
41	1.11421	20.4723	2.16684	34.5118	461.234	704.266
42	1.13834	20.5544	2.20426	32.9722	470.91	709.752
43	1.16265	20.6398	2.24184	31.5375	479.581	717.809
44	1.18719	20.7279	2.27943	30.1957	488.47	707.224
45	1.21189	20.819	2.31674	28.9437	497.031	735.913
46	1.23675	20.9119	2.3543	27.763	506.344	739.645
47	1.26171	21.0078	2.39172	26.6638	514.876	748.638
48	1.28689	21.1059	2.42904	25.634	522.992	754.954
49	1.31226	21.2059	2.46598	24.6651	531.259	795.798
50	1.33752	21.3084	2.50238	23.761	540.634	793.076
51	1.36304	21.4121	2.53868	22.9072	548.641	828.604
52	1.39702	21.6394	2.5904	21.8287	557.874	999.432
53	1.4295	21.8375	2.63825	20.9051	569.277	1255.97
54	1.46132	22.0224	2.68385	20.0684	580.444	1611.44
55	1.4927	22.199	2.72689	19.2951	591.482	1990.27
56	1.52376	22.3721	2.76943	18.6064	603.222	2296.67
57	1.55452	22.5418	2.81027	17.971	614.059	2754.71
58	1.585	22.7092	2.84972	17.4017	623.883	2981.55
59	1.61532	22.8744	2.88809	16.8795	635.165	3487.01
60	1.64535	23.0381	2.92497	16.3903	644.336	3618.77
61	1.67517	23.2007	2.96093	15.9471	653.565	3985.45
62	1.70451	23.3619	2.9957	15.5405	662.839	4280.24
63	1.73369	23.5221	3.02936	15.1646	671.044	4436.11
64	1.76268	23.6809	3.06197	14.8148	679.07	4718.47
65	1.79136	23.8392	3.09361	14.4954	687.428	4954.29
66	1.81972	23.9962	3.12419	14.1983	695.651	5228.58
67	1.84766	24.1524	3.15395	13.9243	702.351	5223.4
68	1.87537	24.3078	3.18293	13.671	710.036	5614.12
69	1.90269	24.4623	3.21101	13.4357	717.508	5547.1
70	1.9297	24.616	3.23821	13.218	724.121	5620.17
71	1.95629	24.7686	3.26496	13.0128	730.149	5860.17
72	1.98258	24.9203	3.29064	12.8212	736.443	5830.99
73	2.00851	25.0713	3.31569	12.6427	743.846	6055.04
74	2.03413	25.2213	3.33989	12.4733	749.502	6207.52
75	2.05933	25.3704	3.36335	12.3145	754.868	6233.48

Table Appendix C. 1. (Continues)

Iteration	Vx Vel	Vy Vel	Vz Vel	Pressure	TKE	TED
76	2.08415	25.5186	3.38597	12.1662	762.195	6522.87
77	2.1086	25.6659	3.40779	12.0254	767.213	6610.03
78	2.1326	25.8121	3.4289	11.8923	773.615	6743.25
79	2.15628	25.9574	3.44923	11.7671	779.99	6981.63
80	2.17953	26.1017	3.46871	11.647	785.979	7016.17
81	2.20239	26.2448	3.48734	11.5319	790.408	7196.31
82	2.22489	26.387	3.50511	11.4206	798.087	7433.87
83	2.24701	26.528	3.52205	11.3147	802.25	7403.41
84	2.26869	26.668	3.53805	11.212	806.909	7580.69
85	2.28991	26.8068	3.55319	11.113	813.783	7719.52
86	2.31066	26.9444	3.56747	11.0166	818.964	7911.34
87	2.33096	27.0809	3.5808	10.9234	822.397	7909.72
88	2.35084	27.2163	3.59318	10.8335	829.75	8066.42
89	2.37026	27.3506	3.6047	10.7454	833.912	8249.39
90	2.38914	27.4837	3.61535	10.6595	838.775	8331.21
91	2.4076	27.6156	3.62512	10.5765	844.81	8487.33
92	2.42537	27.7464	3.63385	10.4971	849.152	8487.48
93	2.44284	27.8762	3.64193	10.4187	853.315	8827.29
94	2.45984	28.0047	3.64933	10.3411	860.938	8983.06
95	2.47632	28.1323	3.65607	10.2655	865.252	9140.18
96	2.49243	28.2587	3.66206	10.1909	868.13	9101.26
97	2.50799	28.3881	3.66741	10.1167	875.631	9366.84
98	2.52327	28.5164	3.67319	10.0776	880.352	9333.64
99	2.53769	28.637	3.67672	9.99816	884.038	9537.51
100	2.55172	28.7582	3.67998	9.92295	890.59	9705.7

Table Appendix C. 2. Air flow numerical results for Scenario 4 (Square X+) through 100 iteration.

Iteration	Vx Vel	Vy Vel	Vz Vel	Pressure	TKE	TED
1	0.182156	8.20647	0.373467	142.523	0.050859	0.999287
2	0.269524	13.3219	0.562436	261.662	0.050859	0.999287
3	0.328273	15.3568	0.730251	282.325	0.050859	0.999287
4	0.375104	16.4718	0.880194	279.349	0.050859	0.999287
5	0.414691	17.2391	1.01154	268.535	0.050859	0.999287
6	0.449757	17.8099	1.12683	254.85	0.050859	0.999287
7	0.481638	18.2497	1.22862	240.341	0.050859	0.999287
8	0.511104	18.5952	1.3192	225.96	0.050859	0.999287
9	0.538654	18.8699	1.40048	212.155	0.050859	0.999287
10	0.564628	19.0897	1.474	199.131	0.050859	0.999287
11	0.589276	19.2663	1.541	186.964	36.2548	57.1655
12	0.612781	19.4081	1.60249	175.661	65.5278	122.209
13	0.635293	19.5219	1.65928	165.192	96.727	220.327
14	0.656926	19.6125	1.71204	155.509	123.09	302.621
15	0.677768	19.684	1.76131	146.559	147.821	407.46
16	0.697904	19.7398	1.80754	138.283	176.025	496.993
17	0.697904	19.7823	1.85111	130.628	198.039	561.719
18	0.73629	19.8137	1.89229	123.542	218.038	673.437
19	0.754637	19.8357	1.93136	116.977	237.635	725.66
20	0.772472	19.8498	1.96852	110.889	259.828	779.762
21	0.789821	19.8573	2.00394	105.238	275.961	861.634
22	0.80781	19.8801	2.03987	99.8532	291.015	868.285
23	0.826192	19.9098	2.07602	94.7055	305.238	862.266
24	0.844935	19.9438	2.11233	89.7836	319.007	865.809
25	0.863996	19.9812	2.1488	85.0884	334.18	863.49
26	0.883384	20.0214	2.18545	80.6193	345.867	846.146
27	0.903085	20.0643	2.22231	76.3766	357.381	843.257
28	0.923105	20.1098	2.25944	72.3597	368.828	840.417
29	0.943417	20.158	2.29694	68.5663	379.89	834.047
30	0.964004	20.2089	2.3348	64.99	391.507	827.809
31	0.98489	20.2624	2.37306	61.6242	402.502	833.664
32	1.00607	20.3189	2.41175	58.4593	412.85	826.982
33	1.02755	20.3782	2.45086	55.4869	422.814	828.249
34	1.04929	20.4405	2.49038	52.6983	433.341	833.944
35	1.07127	20.5059	2.53038	50.0853	443.595	836.593
36	1.09348	20.5744	2.57082	47.6379	453.798	844.155

Table Appendix C. 2. (Continues)

Iteration	Vx Vel	Vy Vel	Vz Vel	Pressure	TKE	TED
37	1.11592	20.646	2.61169	45.3465	463.322	841.155
38	1.13859	20.7208	2.65295	43.2023	473.136	847.882
39	1.16142	20.7988	2.6946	41.1963	482.942	857.271
40	1.18446	20.8797	2.73657	39.318	492.976	872.345
41	1.20765	20.9635	2.77877	37.5593	502.255	864.978
42	1.23111	21.0505	2.82125	35.9188	511.676	880.065
43	1.25461	21.1401	2.86389	34.3776	520.921	897.035
44	1.27828	21.2329	2.90665	32.9424	530.642	903.009
45	1.30197	21.3283	2.94954	31.5943	540.001	917.18
46	1.32589	21.4261	2.99241	30.3311	549.255	941.293
47	1.34987	21.5268	3.03318	29.1537	558.495	950.074
48	1.37404	21.6346	3.07849	28.0669	567.453	970.593
49	1.39819	21.7369	3.12006	27.0143	576.445	998.123
50	1.42238	21.8424	3.15522	26.0239	585.961	1017.01
51	1.4468	21.9574	3.20378	25.1418	594.909	1043.1
52	1.47989	22.189	3.26539	23.9498	604.773	1188.3
53	1.5114	22.3896	3.32	22.9144	616.23	1394.26
54	1.5423	22.5789	3.37078	21.9981	628.624	1644.59
55	1.57252	22.7608	3.41967	21.1689	640.147	1940.24
56	1.60242	22.9386	3.46691	20.4162	652.752	2291.73
57	1.63204	23.1127	3.51225	19.7277	664.676	2598.28
58	1.66141	23.2847	3.55594	19.1043	675.884	2955.62
59	1.6905	23.4541	3.59808	18.5274	687.356	3258.17
60	1.71937	23.6221	3.63847	18.002	698.309	3614.4
61	1.74795	23.7888	3.67734	17.516	707.705	3891.35
62	1.77619	23.9539	3.71439	17.0719	717.943	4190.74
63	1.80412	24.1179	3.75016	16.6594	727.648	4365.65
64	1.83182	24.2809	3.78462	16.2803	736.056	4840.01
65	1.85931	24.4429	3.8177	15.9305	744.818	4851.46
66	1.88655	24.6041	3.84943	15.6075	753.494	5273.89
67	1.91354	24.764	3.8799	15.3067	761.459	5352.68
68	1.94027	24.9228	3.90703	15.0277	769.847	5714.48
69	1.96697	25.0878	3.93934	14.7951	777.687	5845.84
70	1.99319	25.2425	3.96505	14.5448	784.929	6143.27
71	2.01919	25.3979	3.99046	14.3111	792.567	6276.61
72	2.04496	25.5527	4.01502	14.0945	800.297	6601.57
73	2.07046	25.7066	4.0386	13.8924	806.639	6644.47
74	2.09569	25.8596	4.06111	13.7025	813.454	6850.98
75	2.12061	26.0115	4.08263	13.5234	821.27	7183.05

Table Appendix C. 2. (Continues)

Iteration	Vx Vel	Vy Vel	Vz Vel	Pressure	TKE	TED
76	2.14526	26.1625	4.10315	13.3544	827.386	7295.04
77	2.16952	26.3127	4.12279	13.1962	833.276	7481.74
78	2.19346	26.4619	4.14132	13.0454	840.177	7666.35
79	2.21712	26.6097	4.15879	12.9016	846.526	7901.04
80	2.2405	26.7566	4.17531	12.7653	852.483	8056.31
81	2.26347	26.9025	4.19069	12.6343	859.383	8338.07
82	2.28619	27.0472	4.20506	12.5088	865.967	8462.78
83	2.30846	27.1909	4.21845	12.3884	870.95	8698.25
84	2.33036	27.3334	4.23078	12.2731	877.54	8949.09
85	2.35192	27.4749	4.24206	12.1614	885.087	9326.69
86	2.373	27.6151	4.25222	12.0521	890.232	9344.53
87	2.39375	27.7541	4.26147	11.9462	895.592	9545.8
88	2.41407	27.8922	4.2698	11.8436	901.089	9853.42
89	2.43405	28.029	4.27712	11.7438	907.874	10103.9
90	2.45357	28.1649	4.28346	11.6469	913.542	10289.9
91	2.4727	28.2993	4.2889	11.5515	918.28	10486.3
92	2.49124	28.4328	4.29341	11.4598	924.382	10844.6
93	2.50941	28.565	4.29704	11.3688	929.027	10896.9
94	2.52706	28.696	4.29982	11.2805	934.615	11238.9
95	2.54421	28.826	4.30194	11.1936	941.121	11547.7
96	2.56096	28.9549	4.30341	11.1081	945.74	11696.8
97	2.5772	29.0825	4.30402	11.0222	950.414	11906.7
98	2.59294	29.209	4.30418	10.9392	956.159	12262.4
99	2.60835	29.3343	4.30361	10.8588	960.336	12388.7
100	2.6233	29.4588	4.30257	10.7799	967.562	12904.1

Table Appendix C. 3. Air flow numerical results for Scenario 7 (Rectangular H) through 100 iteration.

Iteration	Vx Vel	Vy Vel	Vz Vel	Pressure	TKE	TED
1	0.177336	8.277	0.341268	140.066	0.052681	0.999261
2	0.269639	13.3625	0.504801	256.197	0.052681	0.999261
3	0.328988	15.3757	0.655363	276.188	0.052681	0.999261
4	0.37437	16.4782	0.792455	273.234	0.052681	0.999261
5	0.411912	17.2368	0.914005	262.645	0.052681	0.999261
6	0.444788	17.8012	1.02175	249.252	0.052681	0.999261
7	0.474491	18.2361	1.11769	235.052	0.052681	0.999261
8	0.501872	18.5777	1.20371	220.971	0.052681	0.999261
9	0.527441	18.849	1.28142	207.447	0.052681	0.999261
10	0.551552	19.0659	1.35217	194.681	0.052681	0.999261
11	0.574459	19.2399	1.41705	182.748	58.0459	845.089
12	0.596347	19.3794	1.47694	171.654	104.545	1784.87
13	0.617359	19.4909	1.53258	161.374	153.735	2544.06
14	0.637604	19.5793	1.58454	151.862	190.298	3122.87
15	0.65716	19.6488	1.63331	143.064	221.374	3518.04
16	0.676108	19.7025	1.67931	134.927	258.934	3914.09
17	0.694502	19.743	1.72285	127.398	283.955	4136.45
18	0.712384	19.7723	1.76421	120.426	305.057	4399.8
19	0.729802	19.7924	1.80359	113.964	326.366	4601.01
20	0.746782	19.8045	1.8412	107.971	352.507	4709.59
21	0.763363	19.8099	1.87718	102.406	368.069	4838.46
22	0.780677	19.8327	1.9138	97.1079	378.868	4466.3
23	0.798418	19.8621	1.95074	92.0415	387.208	4114.17
24	0.816488	19.8958	1.98796	87.1982	396.872	3856.79
25	0.834864	19.9326	2.02548	82.5777	408.72	3660.63
26	0.853585	19.9723	2.06328	78.1797	416.755	3531.44
27	0.872657	20.0145	2.10143	74.0057	424.077	3451.71
28	0.891873	20.059	2.14	70.0534	433.232	3442.1
29	0.911495	20.106	2.17891	66.3217	443.356	3408.96
30	0.931493	20.1557	2.21825	62.8027	452.986	3444.72
31	0.951845	20.208	2.258	59.4897	462.166	3484.57
32	0.972521	20.263	2.2982	56.3739	472.506	3526.66
33	0.993539	20.3209	2.33887	53.449	483.212	3598.57
34	1.01482	20.3817	2.38003	50.7063	492.208	3666.29
35	1.03636	20.4454	2.42166	48.135	501.982	3749.01
36	1.05816	20.5121	2.46371	45.7262	512.03	3877.81

Table Appendix C. 3. (Continues)

Iteration	Vx Vel	Vy Vel	Vz Vel	Pressure	TKE	TED
37	1.08016	20.5819	2.5062	43.4725	521.507	3926.14
38	1.10239	20.6546	2.54914	41.3629	531.941	4067.18
39	1.12482	20.7303	2.59241	39.3861	542.188	4152.82
40	1.1474	20.8089	2.63607	37.539	551.042	4296.97
41	1.17014	20.8904	2.67999	35.8078	561.667	4402.86
42	1.19303	20.9749	2.72426	34.1894	571.692	4564.01
43	1.21596	21.062	2.76861	32.6762	581.084	4675.83
44	1.23898	21.1516	2.81311	31.2551	591.133	4874.81
45	1.26213	21.2436	2.85767	29.9254	600.509	5008.06
46	1.28539	21.3379	2.90201	28.6776	610.701	5205.39
47	1.30874	21.4345	2.94635	27.5066	619.889	5370.5
48	1.33205	21.5333	2.98932	26.4114	629.649	5605.92
49	1.35559	21.6391	3.03461	25.4115	639.374	5855.48
50	1.37896	21.7388	3.078	24.4284	649.86	6080.02
51	1.40234	21.8421	3.12053	23.5109	660.033	6379.33
52	1.4337	22.073	3.1833	22.3505	683.454	10225.4
53	1.46312	22.27	3.24001	21.347	710.981	12501.1
54	1.49217	22.4555	3.29289	20.4527	735.452	15554.6
55	1.5206	22.6318	3.34358	19.6314	762.337	18034.1
56	1.54906	22.8046	3.39283	18.8927	784.501	20438.3
57	1.57697	22.974	3.44053	18.2192	806.312	22755.3
58	1.60461	23.1401	3.48661	17.6024	824.651	24767.8
59	1.63206	23.3044	3.53093	17.0359	846.184	27057
60	1.65939	23.4669	3.57369	16.5126	861.374	28757.1
61	1.6865	23.6274	3.61505	16.0321	879.153	30657.9
62	1.71346	23.7866	3.65483	15.5844	895.574	32135.4
63	1.74024	23.945	3.69337	15.176	909.708	33550.9
64	1.76683	24.102	3.73061	14.7993	922.395	35370.8
65	1.79328	24.258	3.76662	14.4498	938.997	37044.2
66	1.81962	24.413	3.80153	14.1222	951.658	38342.7
67	1.8458	24.5673	3.8353	13.8193	966.369	39639.2
68	1.87174	24.7208	3.86801	13.5394	978.923	40833.9
69	1.89749	24.8735	3.89974	13.2767	990.155	42062.3
70	1.92317	25.0251	3.93034	13.0309	998.334	43047.9
71	1.94859	25.1759	3.95999	12.7992	1010.47	44504.9
72	1.97392	25.3259	3.98866	12.5838	1018.21	45253.1
73	1.99916	25.4749	4.0163	12.3785	1028.34	46771.4
74	2.02412	25.6233	4.04312	12.1869	1038.97	47761
75	2.04874	25.7702	4.0691	12.0032	1048.62	49233.2

Table Appendix C. 3. (Continues)

Iteration	Vx Vel	Vy Vel	Vz Vel	Pressure	TKE	TED
76	2.07333	25.9164	4.09405	11.8292	1059.36	50499.6
77	2.09779	26.0616	4.11809	11.6638	1073.04	52121.7
78	2.12204	26.2062	4.14132	11.5074	1081.19	52864.6
79	2.14607	26.3497	4.16361	11.3578	1092.82	54403.8
80	2.16983	26.4925	4.18518	11.2167	1103.13	55405.4
81	2.19337	26.6343	4.20573	11.0793	1113.47	57113.7
82	2.21669	26.7754	4.2255	10.9508	1124.72	57906.2
83	2.23984	26.9157	4.24433	10.8237	1136.9	59482.6
84	2.2627	27.0547	4.26205	10.7046	1143.84	60029.5
85	2.28525	27.1925	4.27898	10.5866	1155	61778.8
86	2.30754	27.3296	4.29501	10.4748	1165.41	62601.5
87	2.32945	27.4654	4.31007	10.3638	1175.92	64270.6
88	2.35106	27.6005	4.32441	10.2569	1187.07	65585.6
89	2.37239	27.734	4.33778	10.1505	1197.24	66634.1
90	2.3933	27.8667	4.35014	10.0487	1203.98	67844.1
91	2.41374	27.9983	4.36168	9.94853	1216.83	68923.3
92	2.43385	28.1288	4.37229	9.85126	1224.42	69924.2
93	2.45343	28.2582	4.382	9.75517	1232.51	71562.3
94	2.47284	28.3866	4.39087	9.66181	1242.51	72303.8
95	2.49186	28.5139	4.39913	9.57026	1251.81	73907.3
96	2.51054	28.64	4.40625	9.48365	1256.44	74790
97	2.5288	28.7652	4.41298	9.39772	1267.77	76783.4
98	2.54674	28.8892	4.41914	9.30996	1278.29	78383.6
99	2.56434	29.0122	4.42466	9.22589	1286.92	78391.8
100	2.58139	29.1342	4.42969	9.14145	1293.8	80275.5

RESUME

Ahmad Rateb ALHRAKI completed his primary and secondary education in the city of Aleppo- Syria. He completed high school education in Turkey. In 2016, he started undergraduate program at Gaziantep University-Turkey- Department of Architecture and graduated in 2020. After 2020 he moved to Karabük University to complete his master’s degree in architecture.