

**The Faculty of Engineering  
Department of Architecture and the Built Environment**

*Institute of Sustainable Energy Technology*

# **NATURAL VENTILATION EFFECT OF TRADITIONAL TURKISH ARCHITECTUREAL ELEMENT “CUMBA” IN LOW-RISE DWELLINGS**

**A QUANTITATIVE STUDY**

**By**

**Yusuf Cihat AYDIN**  
*BArch, Architecture*

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## ABSTRACT

Global warming and increasing energy demands are significant challenges for all countries. Sharply increasing population and fossil-based energy generation have been causing CO<sub>2</sub> emissions and numerous social, economic and environmental problems.

Energy saving is the most practical and realistic way to decrease global CO<sub>2</sub> emissions and energy demands to achieve a sustainable future. Energy efficiency will also have a key role in future to sustain the affordability of energy demand with sustainable sources. It is known that dwellings energy consumption, particularly heating and cooling loads have considerable part of the global energy demand. Therefore, it is reasonable to underline the importance of domestic heating and cooling loads for sustainable future particularly cooling load have key role, which are expected to increase in future due to global warming. Passive strategies developed over thousands of years have great potential for widespread use to decrease dwellings' energy demands with low-cost and low maintenance demand compared to high-tech strategies. On accounts of this, it is reasonable to claim that passive strategies have an important role to play in a sustainable future.

This pioneering study evaluates the natural ventilation effect of a common traditional Turkish architectural element called *Cumba* in low-rise dwellings to investigate the functionality and applicability of this historical solution to decrease modern domestic energy demand with passive strategies. This study contributes to the development of new advance passive strategies and enhances dwellings' energy efficiency with an existing but neglected low-cost passive strategy. This grounded theory, quantitative method study evaluates the research hypothesis that “Cumba may have significant contribution on natural ventilation and decrease building cooling loads” with positivist paradigm, objectivist ontology and empirical epistemology. The research hypothesis is tested on a benchmark building selected as a result of case study on 111 different traditional Turkish architectural samples to define the most common traditional Turkish house typology. Natural ventilation effect of Cumba was tested with the benchmark building with and without Cumba under 40 different CFD simulations and 20 different conditions, with 8 different wind directions, 3 different wind velocities with 2 different wind directions each; 3 different window widths with 2 different wind directions each; and 2 different Echotect energy simulations were performed to assess the influence of Cumba on building cooling loads.

This study finds that Cumba is an effective and economical passive cooling strategy that can potentially decrease dwellings' energy demand, contributing to existing knowledge about advanced natural ventilation strategies and traditional Turkish architecture, filling the gap with a functioning traditional Turkish architectural element, enlarging existing academic knowledge and Turkish architectural development.

*Keywords: Natural ventilation, Traditional Turkish architecture, Cumba, Energy consumption, Building Cooling loads, CFD.*

## PREFACE

I have been feeling responsibility about rising environmental issues as an architect as well as an environmentalist. During my undergraduate education and professional life I have always worked to contribute to environmentally friendly and sustainable architecture.

I believe that I can contribute and develop eco-friendly architecture with academic works as well as my architectural designs and constructions. I do believe the contribution on environmental issues will be quite limited with my designs and constructions, because my life is limited and I am aware that the life of modern constructions is also limited. Therefore, as an architect I want to contribute to sustainable architecture and a sustainable future with my academic works more than my designs and constructions, because academic contributions will join the global knowledge pool, which will exist as long as the human race.

This study, based on my independent research, will form the basis of my PhD about “Low-cost passive strategies” and will enhance my skills in eco-friendly architecture in future. I aim to publish this study and contribute to the architectural field in my country and future academic researches about traditional Turkish architecture. The findings of this study will be presented in numerous conferences in Turkey. Therefore, I conduct this research with the awareness of this opportunity and responsibility.

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- My family, for their great support and encourage during this toughest times in my life.

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LIST OF EQUATIONS

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} = 0$$

$$\frac{\partial}{\partial x} \left[ (\mu_l + \mu_t) \left( \frac{\partial U}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ (\mu_l + \mu_t) \left( \frac{\partial U}{\partial y} \right) \right]$$

$$= \rho \left( U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} \right) + \frac{\partial p}{\partial x}$$

$$\frac{\partial}{\partial x} \left[ (\mu_l + \mu_t) \left( \frac{\partial V}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ (\mu_l + \mu_t) \left( \frac{\partial V}{\partial y} \right) \right]$$

$$= \rho \left( U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} \right) + \frac{\partial p}{\partial y}$$

Navier- Stokes equations (1)

$$y^+ = \frac{u_\tau y_p}{\nu}$$

Dimensionless wall distance (2)

$$u_\tau = \sqrt{\frac{\tau_w}{\rho}}$$

Friction velocity (m/s) (3)

$$u^+ = \frac{U_T}{u_\tau}$$

Dimensionless fluid speed (4)

$$\frac{\partial(\rho U_j H_i)}{\partial x_j} - \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu}{\sigma} + \frac{\mu_t}{\sigma_t} \right) \left( \frac{\partial H_i}{\partial x_j} \right) \right] = q$$

Energy equation (5)

$$Q = v \cdot A$$

Volumetric flow rate (6)

$$A = W \cdot H$$

Cross-sectional vector surface area (7)

LIST OF SYMBOLS

A	Cross-sectional vector
H	Air flow inlet height (m)
$H_i$	The specific enthalpy
l	Direction ( J/kg)
Q	Volumetric flow rate ( $m^3/s$ )
q	The volumetric heat production/dissipation rate ( $W/m^3$ )
Re	Reynolds number
T	Absolute air temperature (K)
$u^+$	Dimensionless fluid speed
$u_\tau$	Friction velocity (m/s)
$\nu$	Kinematic viscosity of air ( $m^2/s$ )
W	Air flow inlet width (m)
y	Distance form wall (m)
$y^+$	Dimensionless wall distance
$y_p$	Distance from the centre point P of the wall-adjacent cell to the wall (m)
$\alpha_P$	Robin coefficient
$\mu_l$	Laminar viscosity
$\mu_t$	Turbulent dynamic viscosity
$\rho$	Density of air ( $kg/m^3$ )
$\varphi$	Wind direction angle (Degree)

## ABBREVIATIONS

2D :	Two dimensional
3D :	Three dimensional
CFD :	Computational fluid dynamics
CO <sub>2</sub> :	Carbon dioxide
DNS :	Direct Numerical Simulation
HVAC :	Heating ventilation and air conditioning
IPPC :	Intergovernmental panel on climate change
LES :	Large Eddy Simulation
PCM:	Phase changed materials
RANS:	Reynolds Averaged Navier Stokes
UN :	United nations
WEO :	World energy outlook

# PART 1: BACKGROUND

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Part 1 aims to give reader fundamental background about traditional Turkish house design and CFD to enable a comprehensive understanding of the rest of the study.

## CHAPTER 1: INTRODUCTION AND BACKGROUND

Since prehistoric ages humans have needed safe and comfortable living spaces. Living space design developed over thousands of years with trial and error and the best techniques being preserved and passed on from generation to generation, contributing to occupant comfort with passive strategies. However, during the 20<sup>th</sup> century, the development of Heating Ventilation and Air Conditioning (HVAC) systems precipitated the abandonment of time-honoured passive techniques worldwide. Thus, modern occupants are largely dependent on artificial air conditioning systems and energy to achieve comfort.

After the 1970s oil crisis, non-renewable energy generation became a crucial issue for the environment as well as political and economic considerations (*i.e. increasing oil prices and CO<sub>2</sub> emissions*). Increasing awareness about global warming and increasing climate change-related natural catastrophes caused all countries to take note. National and international agreements (*e.g. the Kyoto protocol and Rio agreement*) concerning decreasing CO<sub>2</sub> emissions and energy consumption has created commitments and challenges for all countries (*IPPC, 2014*). Considering domestic energy consumption, particularly heating and cooling loads, comprise a considerable part of global energy demand, it is reasonable to claim that energy efficient and climate responsible dwellings with advanced passive strategies, may play a key role in attenuating global energy consumption. Traditional buildings are great sources for understanding the ancient passive strategies, which is fundamental for the development of modern advanced passive strategies to build a more sustainable future. Although high technology renewable energy generation is rapidly developing, considering the limited efficiencies, time and location dependences and high cost, energy saving form the backbone of sustainable future living and building design.

This study aims to analyse the natural ventilation effect of a widely used traditional Turkish architectural element known as “Cumba” with a quantitative approach. The Cumba (also known as a *Şahniş*) can simplified as an extension of the first or upper floors, covered by windows on three different facades. However, some variants exist with windows on only two or one facades (**see Fig. 1.1**).

Cumba is widely observed in Turkey, Balkans, Greece and Middle east (*Küçükerman, 2007; Eldem, 1984*). Although there are slight differences in building plan characteristics, all traditional dwellings share fundamental characteristics of Turkish architecture (*Essad, 1909*).

A review of related literature revealed that no empirical study has been conducted concerning the function of Cumba before. Considering functionality and cost effectiveness were important factors in traditional architecture, it is reasonable to claim that any traditional architectural element widely used in very different climates and locations should have important functions to justify such distribution. Considering the physical characteristics of Cumba and non-scientific (popular and experiential) claims about its functions, Cumba may have potential to contribute natural ventilation effect.

This study is mainly based on 40 different CFD simulations on the defined benchmark building, which was selected as a case study for 111 different traditional houses to test the research hypothesis, which is “Cumba contributes to domestic natural ventilation, and decreases building cooling loads”.

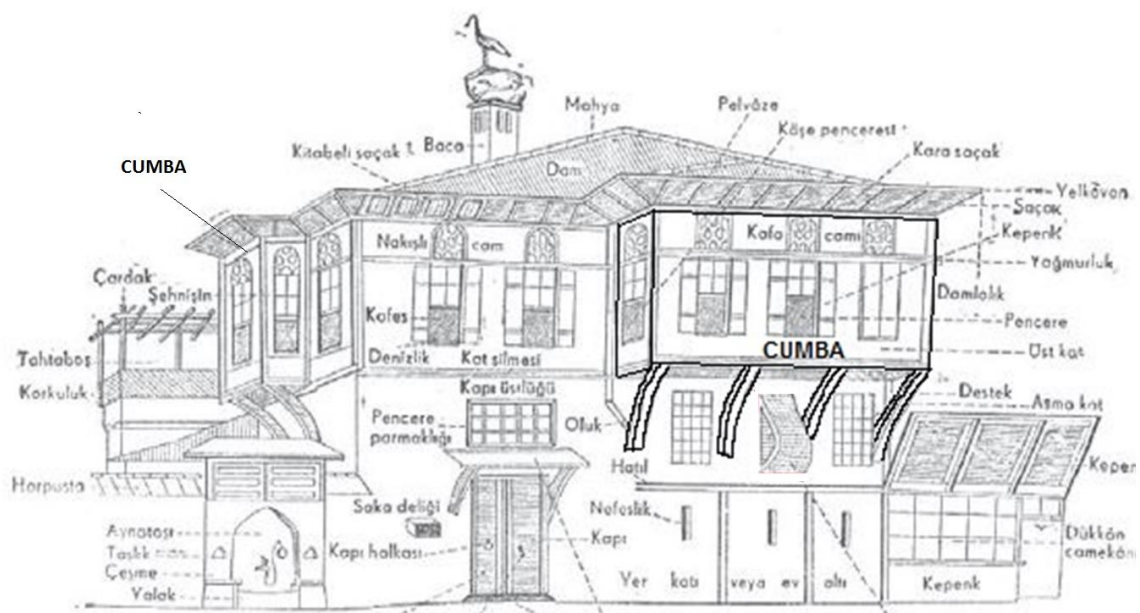


Figure 1.1: Illustration of Cumba and traditional Turkish house components (*Arseven, 1983*)

In addition, this study contributed two Echotect energy simulations to assess the potential energy saving with the existence of Cumba, if the hypothesis is valid. Using grounded theory approach, this qualitative study was conducted with a positivist paradigm, objectivist ontology and empirical epistemology to maximize the reliability and validity of the study.

This study is important as a seminal work scientifically investigating the natural ventilation effect of Cumba, with the potential to contribute to existing knowledge about advanced natural ventilation strategies and traditional Turkish architecture, filling the gap in existing literature and potentially contributing to passive cooling strategies with far-ranging implications for occupational comfort and health, structural lifespan and the mitigation of global warming (due to decreased energy demand for cooling).

### **1.1 Problem Statement**

Global warming, specifically increasing energy demand and CO<sub>2</sub> emissions, poses the most critical global issue that the world has encountered. The increase in the global population since the mid-20<sup>th</sup> century and increasing aspirational lifestyles worldwide have produced sharply increasing energy demand, which has crucial social, economic, health and environmental implications. Every fifteen seconds the world population increases by one person (net), which means world population will increase by approximately 180 people in the time it takes to read this study (**U.S.A. CWPC, 2014**). The UN estimates that the world population will reach 10.6 billion in 2050 (**UN, 2004**). Increasing population triggers increasing energy demand as well as food and water supply, garbage management, natural sources management and migration issues.

Increasing energy demand is one of the major problems of modern societies, because currently 82% of global energy demand is met by non-renewable energy sources (**WEC-WERS, 2013**). Fossil fuel-based energy generation is the major reason for CO<sub>2</sub> emissions, which contributes to the greenhouse effect, which in turn causes global warming and climate change.

Climate change is such a crucial issue because it fundamentally affects all ecosystems and life, including humans. Since the 1980s a growing body of evidence has illustrated the growing impacts of global warming and its consequences, in specific climate-related disasters such as increased flooding to more general underlying indicators (*i.e. increased global ambient temperature, 20% increased atmospheric CO<sub>2</sub> level, 86.3% extended ozone hole, 152 cubic kilometres of melted Antarctic ice and 17cm rising sea levels*) (**NASA, 2014; Ozone Watch, 2014**). Studies shows that the number of calamite-related natural catastrophes has almost tripled since 1980 (**UN-UNISDR, 2012**). The increasing number and intensity of climate-related natural disasters causes severe economic, social and health issues (*i.e. deaths, severe property damages, epidemics and migration*).

Considering the World Energy Outlook 2013 report, global primary energy demand is expected to increase 15% by 2035, which will significantly boost CO<sub>2</sub> emissions and global warming (**WEO, 2013**). In addition to this, a 3.6°C average global ambient temperature rise is expected over the long-term (**WEO, 2012**). Considering the predictions it is reasonable to claim that global warming and the number and intensity of the climate-related natural calamities will significantly increase (*i.e. floods, tornados, droughts and scarcity*). Natural disasters have the potential to cause global issues such as mass migration, conflicts for control of natural resources, and non-habitability of formerly habitable areas (*e.g. due to rising sea levels or desertification*).

Although it is predicted that 31% of global energy production will generated from renewable sources in 2035, 69% of energy production will still depend on non-renewable sources (**WEO, 2012**); any increase in the proportion of renewable energy is likely to be offset by rising use of electricity, thus a smaller proportion of energy being produced from fossil fuels in 2035 may still represent an increase in the amount of energy produced from such fuels, and thus a net gain in greenhouse gas emissions and global warming.

Therefore, although diversification and the promotion of renewable energy use is essential, the most realistic and efficient way to decrease the use of fossil fuels is to address the problem at the root by decreasing energy demand. According to the World Energy Council Case Study, 34% of global energy is consumed by dwellings (**WECCS, 2010**), mainly building heating and cooling loads. According to the National Academies report, domestic heating and cooling loads have comprised more than 40% of total building energy demand in 2006 (**N.A, 2014**). IPCC worst-case carbon emission scenario (A1F1) predictions for the USA claim that, there will be a 50% increase in building cooling loads in California due to rising temperatures and demographic factors (**Xu et. Al, 2014**).

Studies and predictions show that cooling loads will have much more influence on energy demand in the near future. The outcomes of several studies show that building cooling loads can be reduced with appropriate natural ventilation strategies (**Hiranoa et al., 2005**). Several qualitative and quantitative studies in different countries (*i.e. the USA, France and India*) illustrate that traditional buildings have better thermal performance and improved occupant comfort compared to modern structures (**Cantin et al., 2009; Dili et al., 2010**). In contrast, the European Energy Agency claims regarding household energy consumption that modern European buildings have 22% less energy consumption compared with dwellings built before 1985 (**EEA, 2001**), however the majority of existing literature claims that traditional buildings have better thermal performance. Therefore, in light of available data it is reasonable to claim that learning from traditional architecture and advancing existing passive strategies, particularly passive cooling strategies, may significantly decrease global energy demand. It is reasonable to underline potential energy savings and CO<sub>2</sub> emission attenuation with appropriately designed buildings, particularly in fast-growing countries (*i.e. china, India, Brazil and Turkey*)

The research problem is thus to investigate the use of passive cooling strategies using traditional architectural elements in the context of increasing energy demand in dwellings and its predicted consequences, supported by extensive research. In the light of the mentioned research problem the study aim is defined in following section.

## 1.2 Research Aim

The primarily aim of this pioneering study is to assess the natural ventilation effect of the Cumba in low-rise dwellings and test the research hypothesis (*i.e. Cumba contributes to natural ventilation and decreases low-rise dwellings' cooling load*) with an empirical quantitative approach. This study aims to learn from history and create a basis for the development of existing natural ventilation strategies to decrease building cooling loads and energy consumption. Cumba has the potential to contribute to natural ventilation and occupant comfort. However, no previous research has been done about the natural ventilation effect of Cumba before. The secondary aim of this grounded theory study is to fill the gap and contribute to existing knowledge about natural ventilation, the function of Cumba and traditional Turkish houses. Assessment of the natural ventilation effect of Cumba has the potential to create a basis for advancing existing natural ventilation strategies and passive strategies for decreasing domestic cooling loads, consequently decreasing CO<sub>2</sub> emissions. With publication and conferences this study is also aiming to underline the potentials of existing passive strategies for sustainable future.

To achieve the research aim objectives and scope of the work should be clearly defined. The objectives and scope of the study mentioned in following section.

## 1.3 Objectives and Scope

To achieve the aim of the study, objectives and limitations are defined as described below.

### 1.3.1 Objectives

- Define the most common traditional Turkish house and Cumba typology to select a benchmark building for CFD simulations.
- Test the influence of 8 different wind directions on natural ventilation effect of Cumba with the benchmark building (*i.e. north, northeast, northwest, south, southeast, southwest, east and west*).

- Test the influence of three different wind speeds with two different directions on the natural ventilation effect of Cumba with the benchmark building (*i.e. 0.5 m/s, 1.5 m/s and 2.5 m/s north wind, 0.5 m/s, 1.5 m/s and 2.5 m/s northwest wind*).
- Test the influence of three different wind speeds with two different directions on the natural ventilation effect of Cumba with the benchmark building (*i.e. 70 cm, 80 cm, 90cm window widths with north wind and 70 cm, 80 cm, 90cm window widths with northwest wind*).
- Define the overall natural ventilation effect of Cumba according to CFD simulations under three different main conditions.
- According to CFD simulation outcomes, test the benchmark building cooling loads with the energy simulation program Echotect.

### 1.3.2 Limitations

- Considering mesh cell number limitations in student licensed CFD program (*i.e. 500.000*) and time limitations, simulations were performed on 2D models.
- Energy simulations performed according to the overall average natural ventilation contribution if it existed.
- Considering time limitations, and avoiding the external influences, the benchmark building was tested as an isolated building, where environmental disturbances (*i.e. landscape, urban area*) on fluid flow were not taken into account in CFD studies to clearly understand the natural ventilation effect of Cumba.
- It was assumed that in the benchmark building all windows are open and all doors are close during the simulations. Variants in window and door opening combinations requires another separate research, which is considerably time demanding.

## 1.4 Methodology

There are various research methods available to conduct a research (*i.e. qualitative, quantitative and mixed methods*). **Given (2008)** defines quantitative method as: “*Quantitative method relies on empirical analysis of a subject via experiments including statistical, numerical and simulation-based investigations*”. **Olds et. al (2005)** defines qualitative method as: “*Qualitative method is based on textual data such as secondary data, interviews, ethnographies and surveys*”. **Maxcy (2003)** defines Mixed-method as:” *Mixed-method study combines both qualitative and quantitative approaches to achieve a comprehensive understanding about the subject, and the researcher develops the research on pragmatic grounds*”.

The link between methodology, research paradigm and research question is important for achieving high quality academic research. The research problem and research question constitute the core of the research, while the research problem is defined as the field of research. The research question has a key role to narrow the specific topic to give the researcher adequate focus on a specific aim. The research aim can be understood on the most basic level as obtaining an answer to the research question. Therefore, it is reasonable to say research problem, question and aim are the fundamental pillars of the research structure.

Based on the research question, a methodology is devised to achieve the aim. In this study quantitative method is best suited because no secondary data exists about the research topic; all research is based on primary numerical data and experiments. Qualitative or mixed-method research is possible, interweaving experiential (qualitative) data from residents of traditional Turkish houses to understand their personal experiences of the natural ventilation effect of Cumba. It is also possible to compare the outcomes of both experimental simulation-based primary numerical outcomes and interviews. However in this point the research paradigm has a key role to select the most suitable methodology for achieving the research aim.

The research paradigm mainly concerns the researcher’s perspective on the research problem. The study paradigm is positivist, with objectivist ontology, whereby the researcher is observing phenomena in the real world, held to exist independent of human perception.

It is believed that the positivist paradigm is best suited to this study, rather than the interpretivist paradigm, because it is believed that the results obtained with human perception can vary and do not reflect absolute fact. Absolute fact can be obtained in an objective, positivist and scientific manner, purified from the errors and variations of human perception. Empirical epistemology is more suited to this research, which aims to test a research hypothesis using quantifiable data obtained by experimentation for replication and generalisation. As a grounded theory research, this study is deductive, which follows a path through theory to observation rather than inductive, which follows a path through observation to theory. The research methodology is summarised in **Table 1.1**.

**Table 1.1:** Summary of research methodology

<b>Research problem</b>	Increasing energy demand in dwellings
<b>Research question</b>	Does cumba contribute to natural ventilation ?
<b>Research aim</b>	Analysis of the natural ventilation effect of Cumba for obtaining fundamental data to contribute passive cooling strategies and energy demand attenuation for dwellings.
<b>Research hypothesis</b>	Cumba contributes to natural ventilation and decreases low-rise dwellings’ cooling load.
<b>Research method</b>	Quantitative
<b>Research paradigm</b>	Positivist
<b>Ontology</b>	Objective
<b>Epistemology</b>	Empirical
<b>Logic method</b>	Deductive

Research structure is as important as research methodology. The following section presents a broader perspective and information about the rest of the study.

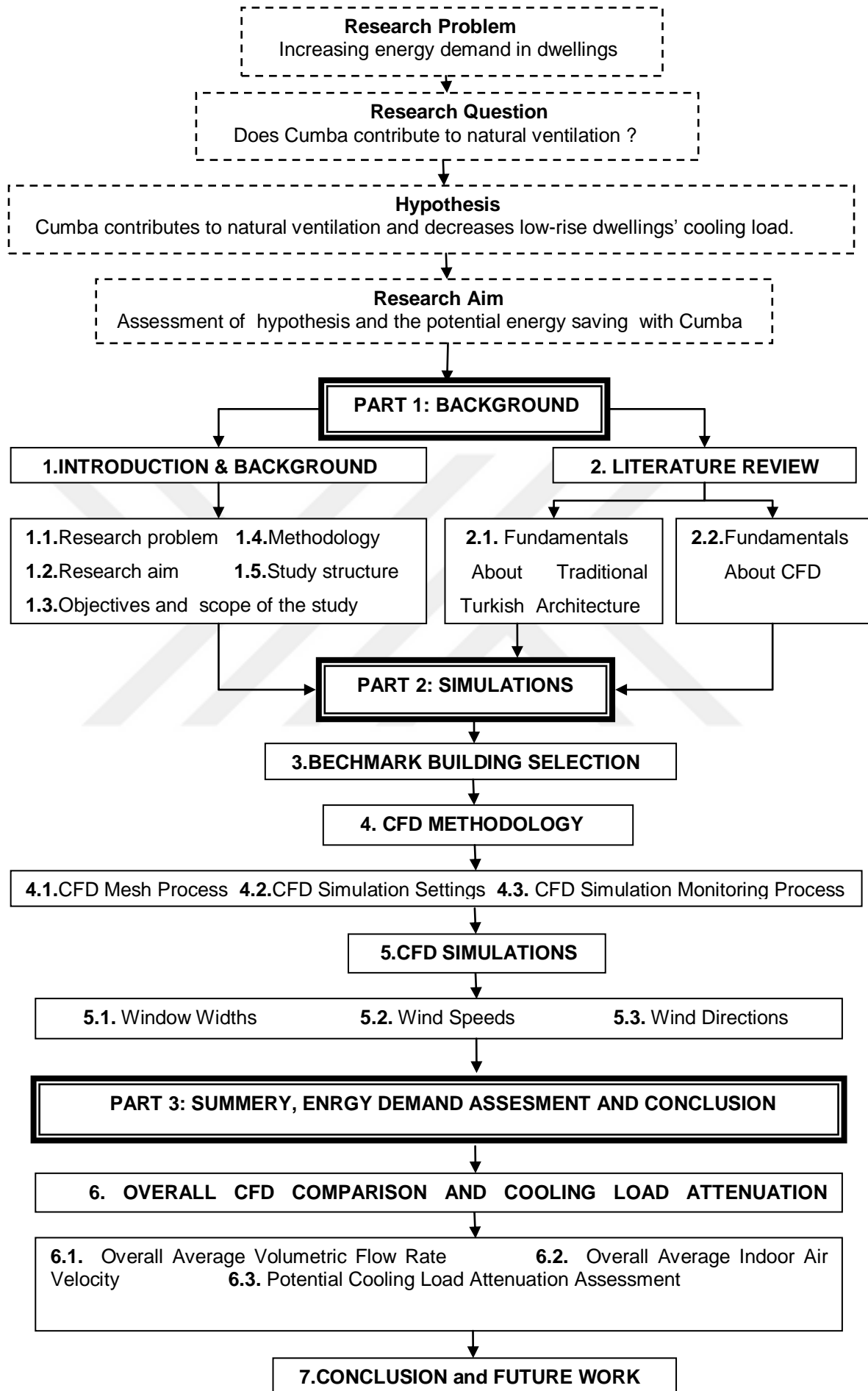
## 1.5 Research Structure

Study structure divided in three main parts. A detailed summary is given in next page

- Part one provides reader required background information about the fundamentals of this study (*i.e. study aim, method*) and the fundamental knowledge about CFD and traditional Turkish architecture.
- Part two is completely based on quantitative method empirical analysis, which tested study hypothesis in a positivist manner, via CFD simulations. Part two provides details about simulation outcomes.
- Part three concludes the findings of this study, summarising the salient outcomes of the research. Part three summarises all CFD simulation results to provide the reader with a clearer and broader perspective of the overall CFD simulation results. In addition, part three extends the study with energy simulations and asses the influence of Cumba on building cooling loads and energy saving. Also part three presents a suggested conceptual design to guide future studies

Overall Study structure is summarised in following page to provide reader boarder perspective about the study. In addition to this following chapter provides reader fundamental knowledge for the rest of the study.

# NATURAL VENTILLATION EFFECT OF “CUMBA” IN LOW RISE DWELLINGS



## CHAPTER 2: LITERATURE REVIEW

This literature review aims to focus on two main subjects (*i.e. traditional Turkish architecture and CFD*) to provide fundamental knowledge for the reader to understand the rest of the study better.

As mentioned previously, no research has been conducted to investigate the natural ventilation effect of Cumba before. Therefore, the literature review contains research about more broad and fundamental knowledge (*i.e. fundamentals of traditional Turkish architecture and development*).

### 2.1 Fundamentals of Traditional Turkish Architecture

Culture can be defined as the sum of material and spiritual values, which is a dynamic concept transferred from generation to generation and evolving with new conditions and time. This section aims to give the reader the necessary infrastructure about the traditional Turkish domestic architecture, particularly as observed in Anatolia, Rumelia and the Balkans, which have their own characteristics with the development over 500 years (**Cansever, 2002; Eldem, 1984**) (see Fig. 2.1).



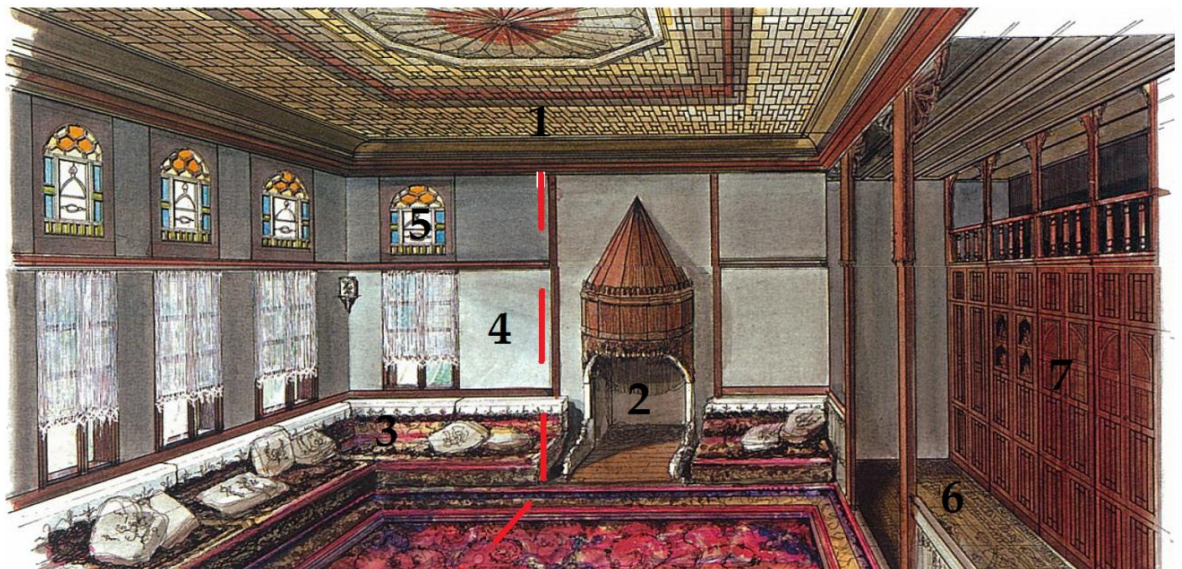
**Figure 2.1:** Notable areas of traditional Turkish domestic architecture

Traditional Turkish houses design ultimately originates from the nomadic period in the steppes of Central Asia. Nomadic Turks constantly migrated due to the inhabitable and harsh climatic conditions of Middle Asia steppes, using relatively lightweight and portable tents as living units, constructed with a light wood structure and covered with felt (see **Fig. 2.2**).

Many fundamental similarities can be observed between the archetypal Turkish tent and Turkish houses (i.e. *hearth, sitting areas, rooms correlation with common areas (Sofa)*) (see Fig. 2.2 and 2.3). As in Turkish tents, in traditional Turkish houses all rooms are designed as separate living units linked to a common area called the Sofa (see Fig. 2.4.). Sofa and rooms correlations have significant characteristic similarities with nomadic Turkish tents and common area. As seen in Fig 2.5, Turkish tents are ordered around the Sofa common area, around which separate independent living units radiate (see Fig. 2.4).



Figure 2.2: Turkish tent illustrations

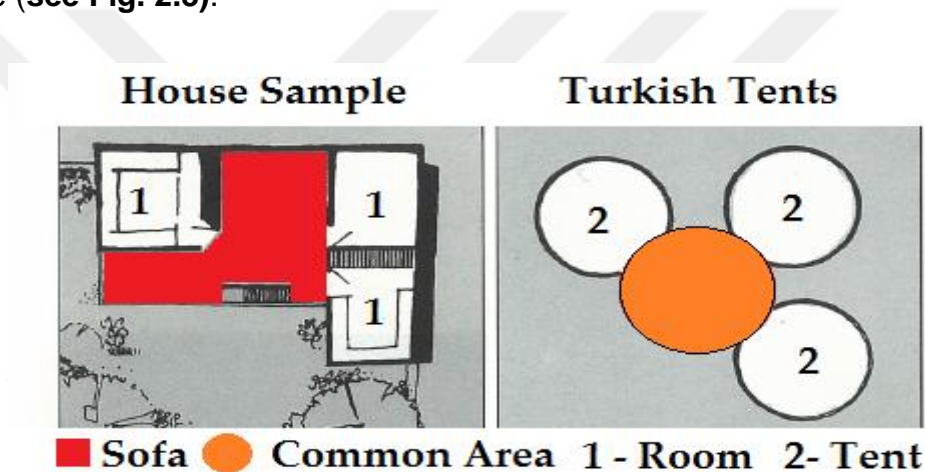


— — — Cumba beginning illustration line

- |                      |                       |                              |
|----------------------|-----------------------|------------------------------|
| 1 -Decorated Ceiling | 3-Raised Seating Area | 5- Stained Glass Top Windows |
| 2- Hearth            | 4- Cumba              | 6- Low Level Corridor        |
|                      |                       | 7- Cupboards and Bath        |

Figure 2.3: Traditional Turkish house main room illustration(modified from Küçükerman, 1978).

The independent living areas are the main room of family units and thus they have better ornaments (*i.e. decorative ceilings, stained top glasses*) and bigger areas, being generally used to host guests and being reserved as the living spaces of senior members of family, such as elders (**Cansever, 2002**). The majority of rooms have a hearth and a raised sitting area; the hearth is used for heating and cooking, as in the Turkish tent. In addition, the majority of traditional Turkish house rooms have a private bath behind the cupboard. Thus, all rooms function as separate house units that provide all the needs of a family unit independent of the rest of the house structure (see Fig. 2.3).

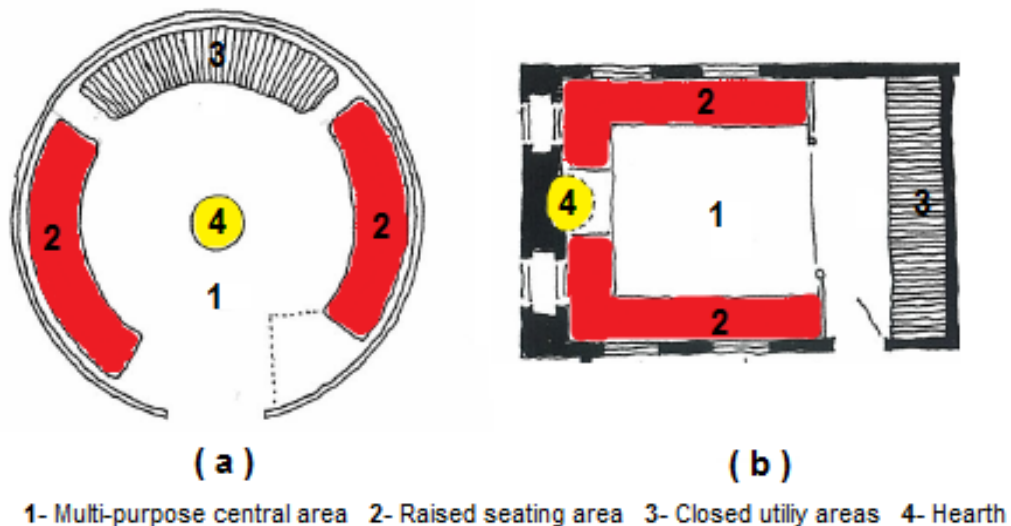


**Figure 2.4:** Similar relations between nomadic and settled period living spaces (modified from Küçükerman, 1978)



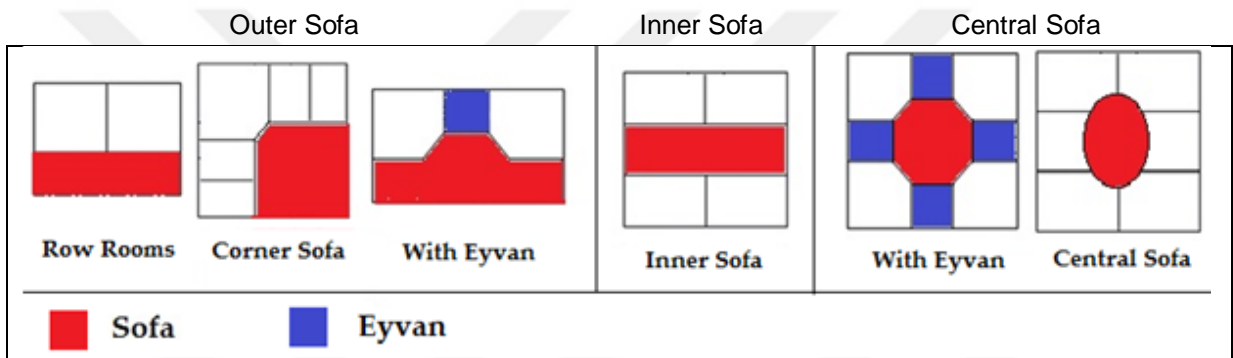
**Figure 2.5:** Turkish tents and clan arrangement

**Fig. 2.6** illustrates further similarities between Turkish tents and rooms in traditional Turkish houses (*i.e. raised sitting areas and design, multipurpose central area, closed utility areas and hearth elements*). As with the tent, flexibility is another important characteristic of the Turkish house. When the family grow, new rooms can easily be added to the house or houses can be easily separated owing to the Sofa (**Fig. 2.4**). A Turkish house plan consists of rooms aligned around the Sofa (**Günay, 1999**); the Sofa is the main distinctive element that creates dwellings characteristics because room plan typology shows no distinctions, but room-Sofa correlations can vary significantly, therefore Turkish house plan typologies are classified according to Sofa characteristics. **Eldem (1984)** categorized Turkish house plan typology under 36 different Sofa arrangements. However, in this study Turkish house plan typology were simplified to six subheadings under three main headings (*i.e. outer Sofa, Inner Sofa and Central Sofa*) to avoid confusion (**see Fig.2.7**). Plan types are defined according to the Sofa location and the existence of an Eyvan, which can be simply defined as a semi-open place, generally raised from the floor level, used as a sitting area.

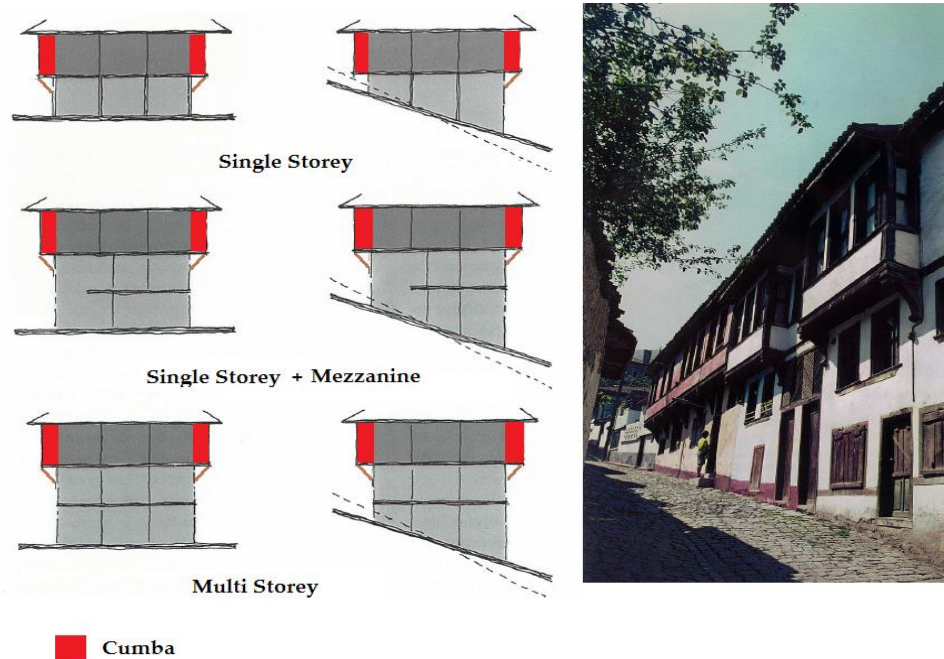


**Figure 2.6:** Similarities between Turkish tent and house (a) Tent plan (b) Room plan (modified from Küçükerman, 1978)

As seen in **Fig 2.8**, ground floors vary according to topography or user demand (e.g. *stable or storage*), but top floors reflect all the mentioned traditional Turkish house characteristics. In addition to this, ground floors provide required privacy from the street and prevent visual contact between the exterior and interior; privacy is important in both Turkish and Islamic culture. Another main characteristic of Turkish houses is the development of the building from the interior to exterior, which means form follows function. Dwelling plans can easily be estimated from the building exterior, where generally rooms are extended with Cumba (see **Fig. 2.9**).



**Figure 2.7:** Traditional Turkish house plan typologies



**Figure 2.8:** Floor characteristics and interaction between surrounding (modified from **Küçükerman, 1978**)

Although Cumba is a widespread (one might say ubiquitous) architectural element in traditional Turkish architecture (see Fig. 2.9), surprisingly there have been no empirical studies dedicated to them. This study assesses the natural ventilation effect of Cumba, via CFD simulations. Considering CFD is a program that demands a high technical background, the following section outlines the fundamentals of CFD to enable an enhanced understanding of the research undertaken in this study.

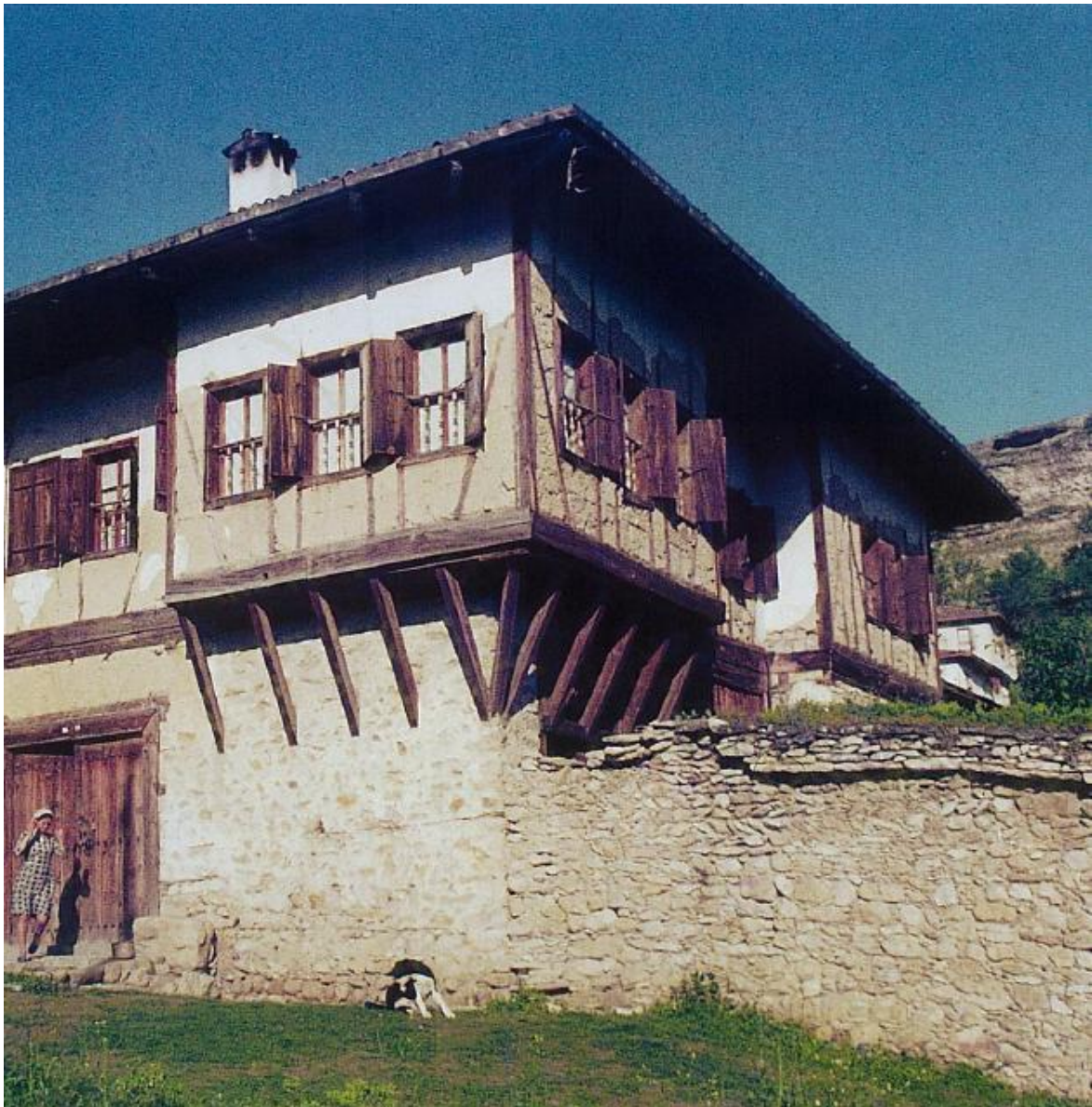


Figure 2.9: Traditional Turkish house and Cumba illustration

## 2.2 Fundamentals of CFD

Extensive research has been conducted concerning CFD for this study, due to the researcher hitherto having insufficient background about CFD and fluid mechanics. This section explains the fundamentals of CFD that underpin the rest of the study.

CFD can simply be defined as a simulation program that allows the user to solve numerical fluid flow problems. **Anderson (1995)** defined CFD as: “*The art of replacing the integrals or the partial derivatives (as the case may be) in the Navier-Stokes equations by discretized algebraic forms, which in turn are solved to obtain numbers for the flow field values at discrete points in time and/or space*”. Navier-Stokes equations for laminar flow can be expressed as:

$$\begin{aligned}
 \frac{\partial U}{\partial x} + \frac{\partial U}{\partial y} &= 0 \\
 \frac{\partial}{\partial x} \left[ (\mu_l + \mu_t) \left( \frac{\partial U}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ (\mu_l + \mu_t) \left( \frac{\partial U}{\partial y} \right) \right] \\
 &= \rho \left( U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} \right) + \frac{\partial p}{\partial x} \\
 \frac{\partial}{\partial x} \left[ (\mu_l + \mu_t) \left( \frac{\partial V}{\partial x} \right) \right] + \frac{\partial}{\partial y} \left[ (\mu_l + \mu_t) \left( \frac{\partial V}{\partial y} \right) \right] \\
 &= \rho \left( U \frac{\partial V}{\partial x} + V \frac{\partial V}{\partial y} \right) + \frac{\partial p}{\partial y},
 \end{aligned} \tag{1}$$

Where  $\mu_l$  is laminar viscosity,  $\mu_t$  is turbulent dynamic viscosity,  $\rho$  is density  $U$  and  $V$  represent the mean velocity components parallel and normal to the wall,  $\alpha P$  is Robin coefficient for  $U$  and  $K$  is boundary conditions (**Nazif et al., 2014**).

CFD provides user an important opportunity to perform numerical experiments, which allows users to conduct parametric studies. However, there are particular advantages (*i.e. cost and time efficient, allows assessment of 1:1 scale models*) and disadvantages (*i.e. reliability issues, high expertise requirement, sensitivity to settings, numerical limitations*) that should considered (**Anderson, 1995**). Considering the mentioned disadvantages, CFD simulations should be validated, preferably by wind tunnel tests or other CFD studies validated by wind testing.

It should also be taken into account that many sensitive parameter settings and appropriate space discretization (mesh) generation have significant importance to obtain reliable CFD simulations.

### 2.2.1. Fundamentals of high quality CFD mesh generation process

As well as many sensitive numbers of parameters, settings appropriate space discretization (mesh) is important to obtain accurate simulation results. **Blocken (2014)** defines the space discretization as: “*Replacing the spatial continuum by a finite number of points or cells (the grid) where the numerical values of the variables will be determined*”. Mesh generation is one of the most crucial and time consuming part of CFD simulation process. Mesh quality and compliance with model requires significant attention for boosting the reliability of simulations. The importance of the mesh quality is extensively reported in several studies. **Hirsch (2007)** highlights the importance of the mesh quality as: “*Grid generation and grid quality are essential elements of the whole discretization process. Not only is grid generation today a most critical element in the cost of running CFD simulations, but more importantly, the accuracy of the obtained numerical results is critically dependent on mesh quality.*”

CFD simulation’s accuracy is not only related with the size of the mesh but it also related to the form of the mesh. The most appropriate mesh decision can vary according the models physical properties (*i.e. rounded or angular*) and flow type (*i.e. laminar or turbulent flow*).

CFD mesh is distinguished between “Structured grid” and “Unstructured grid”. Structured grid can simply defined as a grid with regular typology. In contrast unstructured grid is grid with irregular typology (**see Fig. 2.10**). There are several studies mentioned if simulation model is suitable structure grid is more reliability Compared with unstructured grid.

Also mesh can distinguished as “uniform grid” and “non-uniform grid”. Uniform grid mesh is a type of space discretization that has equal distance between all grid lines. Uniform grid mesh is highly uncommon. Uniform grid is not suitable for obtaining accuracy in particularly turbulent flow simulation, because higher grid resolution is needed in areas of large flow gradients (see Fig. 2.11). Different grid resolution demand is important to deal with the near wall modelling in CFD. Far away from the wall the large flows structures are observed. However large flow structures cannot exist close to the wall, where at some point turbulence vanishes and laminar viscous layer is observed. The structure of the turbulent boundary layers can be defined under two different main regions, outer layer and inner layer. The outer layer consists of fully turbulent flow with large flow gradients, while the inner layer consists of three sub layers, namely log-law layer, buffer layer and linear sub-layer (viscous layer) (see Fig. 2.11).

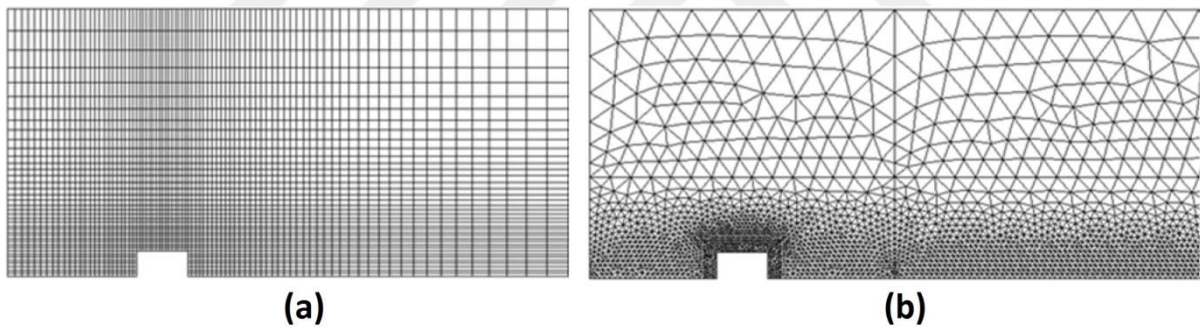


Figure 2.10: (a) structured grid sample (b) unstructured grid sample

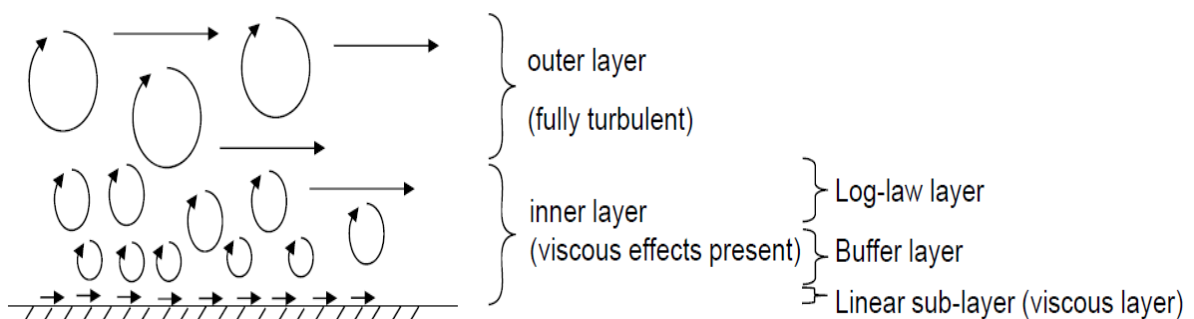


Figure 2.11: Structure of the turbulent boundary layer

Each layer has specific characteristics. Linear sub-layer (viscous layer) observed close to the wall surface has a viscous effect dominating flow, while log-law layer turbulent effect is clearly dominant and in buffer layer more or less viscous and turbulent flow dominance is equal. Many turbulence models, particularly k-ε ones, are only valid for high-Reynolds number flow or turbulence core flow but not for adjacent to wall surface, where viscous effects is dominant. Therefore different treatment is necessary for different layer, which have different flow characteristics. Obtaining the different treatments for different layers and flow characteristics is not possible with uniform grid mesh, that's why uniform grid mesh is not suitable for turbulent flow simulations (**CFD Manual**).

In contrast with uniform grid, non-uniform grid space discretization has different distances between grid lines. To maximize the simulation accuracy non-uniform grid mesh is suggested, whereby grid line distances get narrowed around the 2D or 3D model boundaries, because as mentioned in **Fig. 2.11** far from the wall boundary large flow gradients are observed and larger cells are necessary to calculate with higher accuracy. In **Figure 4.10a,b** grid illustrations are good examples for non-uniform grid.

Considering there is different flow behaviours in different flow layers (**see Fig. 2.11**) different treatments needs in those layers (*i.e. inner later, outer layer*). For obtaining high reliability in the simulations it is important to define the height of each later and the distance between model surface and the first mesh cells distance. There are two important dimensionless quantities required which called dimensionless wall distance ( $y^+$ ) and dimensionless fluid speed ( $u^+$ ) to define the mesh quality according to universal law of the wall to achieve high reliability.

The first dimensionless quantity calls as dimensionless wall distance ( $y^+$ ) value, which is defined as:

$$y^+ = \frac{u_\tau y_P}{\nu} \quad (2)$$

$$u_{\tau} = \sqrt{\frac{\tau_w}{\rho}} \quad (3)$$

Where  $y^+$  is dimensionless wall distance,  $u_{\tau}$  is the friction velocity (m/s) which based on the wall shear stress,  $y_P$  the distance from the centre point P of the wall (see Fig. 2.12),  $\nu$  is the kinematic viscosity  $\tau_w$  (Pa) and air density  $\rho$  ( $\text{kg/m}^3$ ).

In CFD simulations the most common two near-wall region fluid flow modelling, which known as wall function and low-Reynolds number modelling was illustrated in Figure 2.12. Preference between these two options may vary according to which boundary layer at the wall surface is take in account (*i.e. fully turbulent outer layer, logarithmic layer, buffer layer and linear-sub (viscous) layer*) (White, 1974; Wilcox, 1998). When the detailed viscous effect influence is important or if the study particularly focus on inner layer, low Reynolds number modelling is more suitable for obtaining high accuracy.

Second dimensionless quantity calls as dimensionless fluid speed ( $u^+$ ) value, which is defined as:

$$u^+ = \frac{U_{\tau}}{u_{\tau}} \quad (4)$$

Where  $u^+$  is dimensionless fluid speed  $U_{\tau}$  is fluid speed parallel to the wall and  $u_{\tau}$  is friction velocity (m/s).

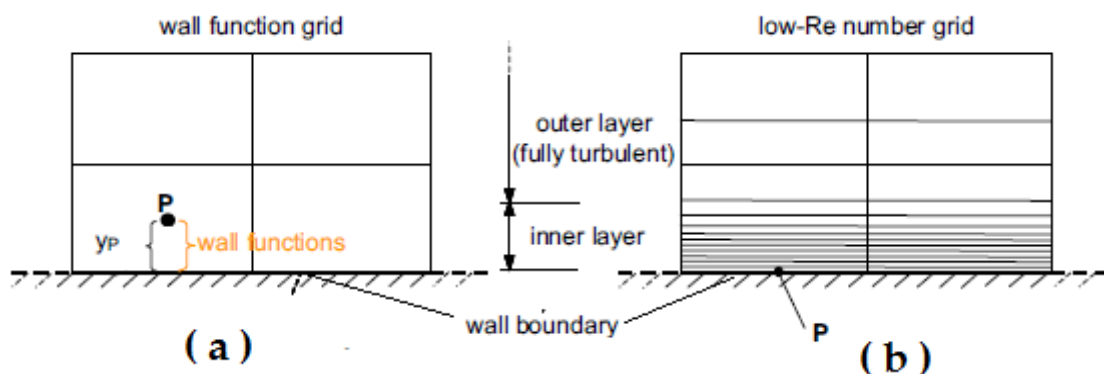
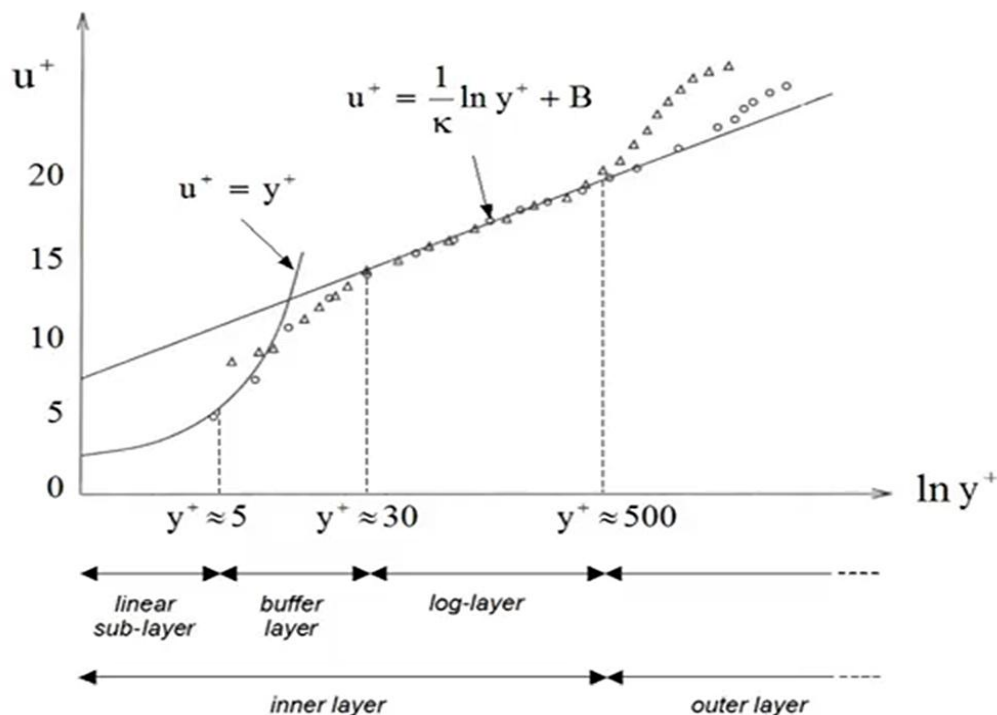


Figure 2.12: Wall boundary grid representation. (a) wall function grid (b) low-Re number grid (Blocken, et.al, 2009)

When dimensionless fluid speed ( $u^+$ ) value and dimensionless wall distance ( $y^+$ ) value are known, the most appropriate  $y^+$  value can be decided with using universal law of the wall, as illustrated in **Figure 2.13**. If the sub-layer (viscous) or buffer layer is target and dimensionless fluid speed is equal to dimensionless wall distance then when checking the mesh quality  $y^+$  value should be between 5 and 30. Or as another limits  $y^+ < 4$  preferably  $y^+ = 1$ . If simulations focus on log-layer then when checking the mesh quality  $y^+$  value should be between 30 and 500. If simulations focus on outer layer where the fully turbulent zone then  $y^+$  value should be greater than 500.

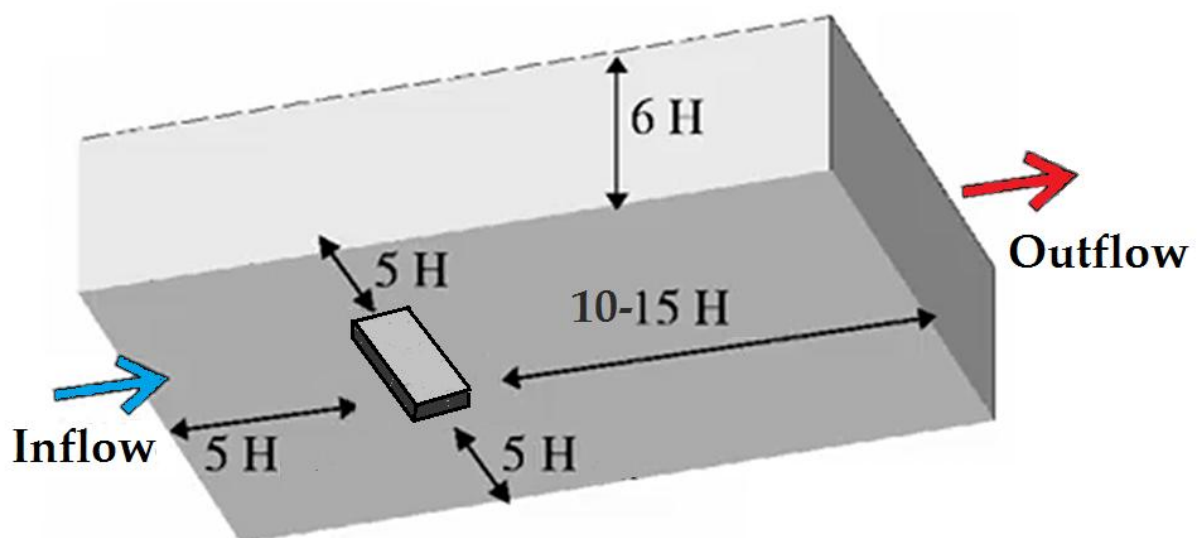
Simulation domain sizing is as important as mesh quality to achieve high reliability on CFD simulations. Some guidelines were published for achieving maximum possible accuracy with CFD simulation. Those guidelines were prepared according to studies compared with real wind tunnel tests to obtain the minimum domain sizing ratios. If the domain is not sufficiently large then Venturi effect may be observed, which can significantly influence the results.



**Figure 2.13:** Universal law of the wall illustration

According to those guideline studies, computational domain size should sufficiently large and the blockage ratio should be less than 3%. The minimum distances between building model and inflow domain boundaries at upwind area and edges of the building suggested  $5H$  away from the building, where  $H$  is building height. In 3D CFD simulations the distance between top of the building and the domain boundaries are recommended to set minimum  $6H$  height. The distance between outlet boundaries and building suggested to set minimum  $10H$  (**Franke et al., 2007; Shirasawa et al., 2003; Mochida et al., 2002; Tominaga et al., 2008**). However the downstream zone is controversial, although the majority of the studies claims  $10H$  is adequate. **Franke (2006)** recommended the minimum distance as  $15H$  (see **Fig. 2.14**).

Beside the mesh quality and domain size, another important point is simulation method. The three most popular approaches are Direct Numerical Simulation (DNS), Large Eddy Simulation (LES) and Reynolds Averaged Navier Stokes (RANS). DNS models solve the exact Navier-Stokes equation completely, therefore they are extremely time consuming and require extremely fine mesh. LES models solve filtered Navier-Stokes equation, whereby only large eddies are solved and small ones are modelled. LES models are not as exact as DNS but they need less time.



**Figure 2.14:** Suggested minimum distances between building and domain boundaries

RANS models solve the averaged Navier-Stokes equation, whereby only mean flow is solved and all eddies are modelled. RANS models are not exact and less accurate compared with LES and particularly DNS, but they are applicable and significantly less time consuming (**Blocken, 2014**).

In the light of the information mentioned in this chapter, the following chapter contains CFD simulations to assess the natural ventilation effect of Cumba.



# PART 2: CFD SIMULATIONS

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Part 2 covers the simulation preparation process, simulation methodology, and simulation results. This part aims to give reader transparent information about the study, to provide repeatability of this empirical study by other researchers, and make visible the possible user related CFD settings errors to maximizing the reliability of this study for future studies.

### CHAPTER 3: BENCHMARK BUILDING SELECTION

This chapter aims to inform the reader about the benchmark building decision process before CFD simulations were performed. A case study was conducted on 111 existing traditional Turkish house plans obtained from reliable sources.

#### 3.1. Case Study for Defining the Benchmark Building

It is reasonable to underline the importance of defining benchmark building and the most common parameters, because considering variables (*i.e. Cumba parameters, environmental conditions, room-Sofa relation and climate*) have considerable influence of natural ventilation effect of Cumba.

Therefore, although not part of the main focus of this research project, a case study was conducted on 111 different Turkish house plans to define the most common Turkish house plan typology and Cumba parameters. This case study is also important for contributing to existing literature, because there no previous research considered the most common traditional Turkish house plan typology and parameters. To increase reliability, all sample buildings were selected in different books containing scaled plans and sections, elevations, photos and location details. It should be considered that selected sample buildings were built after the 18<sup>th</sup> century and locations were not homogenous, Therefore, the 111 buildings are not representative of all Turkish house typologies. However, considering that this study requires generalized parameters and plan typologies to define and test the most common Cumba typology, 111 sample buildings in 27 different cities was deemed appropriate to obtain adequate reliability for the demands of this study. The case study data regarding the 111 different sample buildings can be seen in details in Appendix. (**See Appendix**)

#### 3.2 Benchmark Building Location Decision

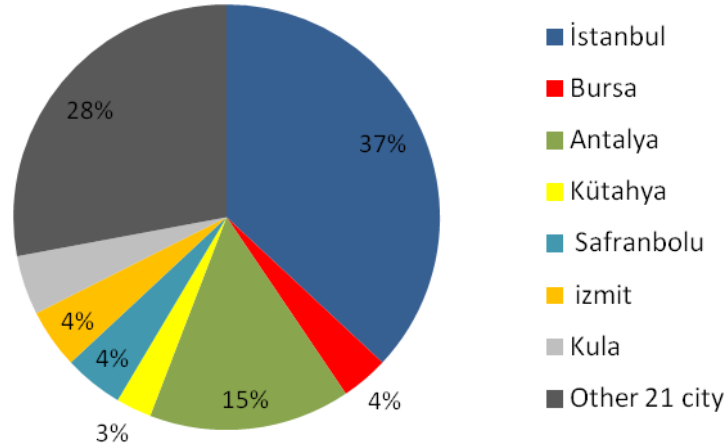
Defining the benchmark building location is important for obtaining the environmental conditions (*i.e. outdoor temperature, average wind velocity*), which have an important influence on simulations accuracy.



**Table 3.1** illustrates the number of sample buildings in 27 different cities. As seen in **Table 3.1**, 41 of the 111 sample buildings are located in Istanbul (37%) (see **Graph 3.1**). Considering the data, Istanbul’s climatic conditions were used during the CFD simulations in following chapters.

### 3.3 Benchmark Building Plan Typology Decision

111 sample buildings were categorized under five different categories to obtain the most common traditional Turkish house plan typology. As mentioned in chapter 2 there are 36 different categories for traditional Turkish houses, but in this study the plan typologies were simplified under five main categories to avoid confusion. It was observed that 57 of 111 buildings have internal Sofa with Cumba plan typology (see **Table 3.2**). In addition to this, plan typology decision study results show that the vast majority of sample buildings have Cumba.



**Graph 3.1:** Percentage-based categorization of the sample traditional buildings according to locations

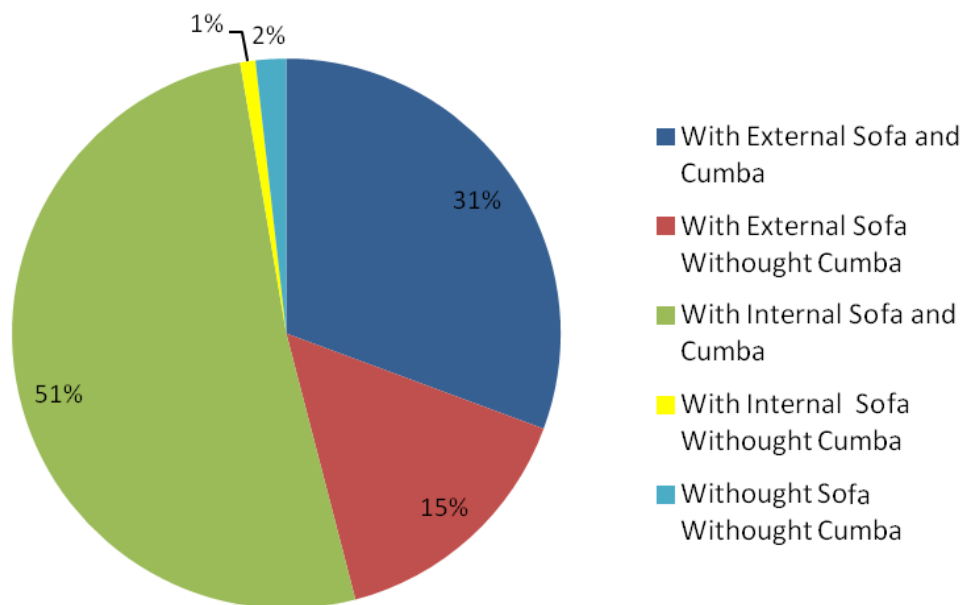
**Table 3.2:** Sample building plan typology categorization

Total	With External Sofa and Cumba	With External Sofa Without Cumba	With Internal Sofa and Cumba	With Internal Sofa Without Cumba	Without Sofa and Cumba
111	34	17	57	1	2

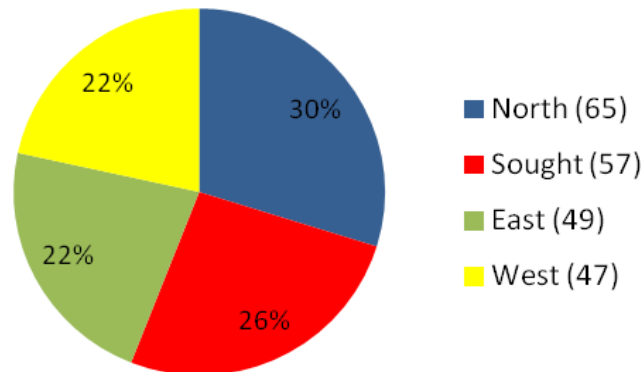
Considering the consequences of the study conducted on 111 buildings, 82% of sample buildings have Cumba. Therefore, it is reasonable to say that this study also supports the existing literature, which claims that Cumba is a widely used architectural element in traditional Turkish houses (**see Graph 3.2**).

### 3.4 Benchmark Building Cumba Orientation Decision

Defining the most common Cumba orientation is also important because it may give clues about its natural ventilation characteristics. However, it should be considered that the sample buildings are located in 27 different cities and different locations, thus they can be expected to be oriented with reference to varying wind directions according to local and regional conditions (*i.e. landscape, urban texture, microclimate*). Although the reliability of this study is controversial, it is believed that the outcomes of this study may give important clues about characteristics of Cumba.



**Graph 3.2:** Percentage of sample buildings plan typology categorization



**Graph 3.3:** Percentages of Cumba directions

It was observed that Cumba directions of 111 sample buildings have almost the same ratios, with only a 7% difference observed between the major and minor orientations (**see Graph 3.3**). Considering there is no dominant Cumba direction, this finding is crucial for the rest of the study for comparison with the simulation outputs, which test the wind direction influence on the natural ventilation effect of Cumba.

The sample buildings' Cumba directions are almost the same as the north direction-oriented Cumba samples, which comprised the majority (30%) the 111-structure sample (**see Graph 3.3**). In addition to this, as seen in **Graph 3.3**, 111 sample buildings have 218 Cumbas, thus it can be seen that each building has an average of 2 Cumbas.

### 3.5 Benchmark Building Parameters Decision

111 sample building parameters (*i.e. room area, number of rooms and window width*) were analysed as shown in **Table 3.3**. According to parametric study it was observed that small rooms' areas vary between 6.3 m<sup>2</sup> and 40 m<sup>2</sup> and main room areas vary between 15 m<sup>2</sup> to 56 m<sup>2</sup>. The average and most common small and main room areas defined as 18 m<sup>2</sup> and 23.3 m<sup>2</sup> respectively. It was observed that sample buildings have a minimum of two rooms and a maximum of fourteen, and the vast majority of sample buildings have four rooms. Minimum window width was detected as 0.6 m and maximum 1 m. The average window rate was detected as 0.8 m.

As a result, the most common traditional Turkish house properties are defined and given in **Table 3.4**. According to results of the study, the majority of sample buildings locates in Istanbul and have 4 rooms. The smallest room varies between 11-20 m<sup>2</sup> and the main room area between 21-30 m<sup>2</sup>. The most common window width was defined as 0.8 m (**see Table 3.4**) The sample building, which best fit the motioned properties in **Table 3.4** was selected between the 111 sample building as a benchmark building. **Figure 3.2** illustrates the selected benchmark building plans of 111 building according to case study.

**Table 3.3:** Overall parameter comparison for 111 sample buildings

	Minimum m <sup>2</sup>	Maximum m <sup>2</sup>	Average m <sup>2</sup>	Number of 0-10 m <sup>2</sup>	Number of 11-20m <sup>2</sup>	Number of 21-30 m <sup>2</sup>	Number of 31-40 m <sup>2</sup>	Number of > 41 m <sup>2</sup>
Small Room m <sup>2</sup>	6.25	40	18	11	64	36	2	
Main Room m <sup>2</sup>	15	56	28.3		19	56	23	13
	Minimum Room Number	Maximum Room Number	Average Room Number	Number of Room (2-4)	Number of Room (5-7)	Number of Room (8-10)	Number of Room (11-13)	Number of Room (14)
Room Number	2	14	4	75	28	6	1	1
	Minimum (m)	Maximum (m)	Average (m)	Number of 0.6 (m)	Number of 0.7 (m)	Number of 0.8 (m)	Number of 0.9 (m)	Number of 1 (m)
Window Weight (m)	0.6	1	0.8	6	33	52	19	14

**Table 3.4:** The most common traditional Turkish house parameters

Location Priority	Room Number	Small Room m <sup>2</sup>	Main Room m <sup>2</sup>	Window Weight (m)	Window Height (m)
Istanbul	4	11-20m <sup>2</sup>	21-30 m <sup>2</sup>	0.8	1.5

Although all rooms are considered in simulations to be oriented northwest and northeast rooms as a focus room, because those rooms are the most suitable rooms for testing the natural ventilation effect of Cumba. The case study of 111 samples showed that there are 3 types of Cumbas commonly used (see Fig 3.3). The building’s northwest room is a sample of one facade Cumba. However, the vast majority of Cumba have windows on 3 different facades (Fig 3.3a), then the second most common Cumba type have windows on 4 different facades (Fig 3.3b). It was also observed that Cumba with windows on single facade are quite rare compared with other Cumba types (Fig 3.3c). Therefore, the benchmark building northwest room Cumba was modified by adding 0.8 cm windows on east and west facades and converting from single facade windows Cumba to three facade windows to test the most common Cumba types (see Fig 3.2a).

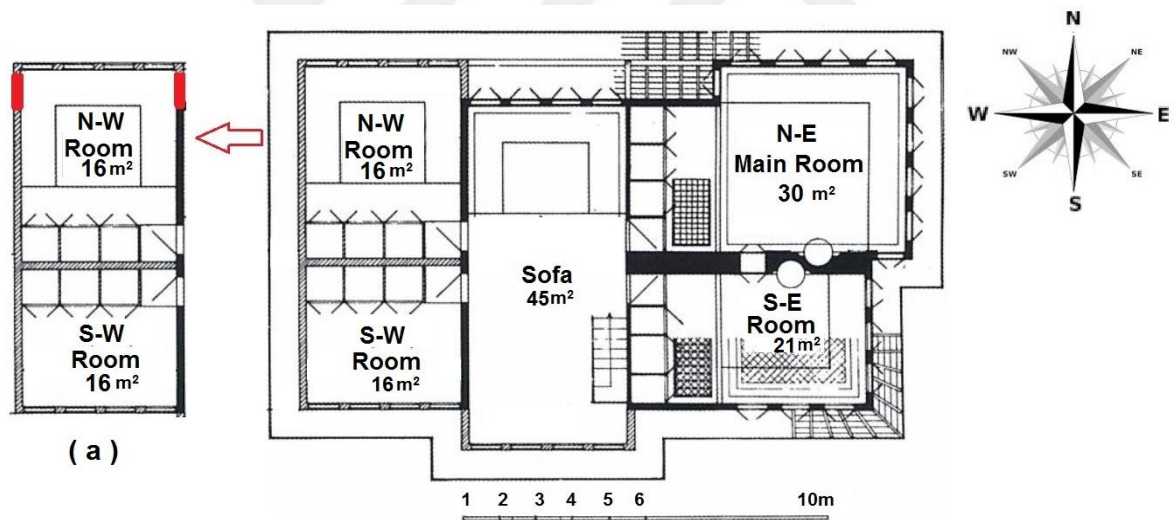


Figure 3.2: Benchmark building plan Cumba modification illustration (Talya, 2007)

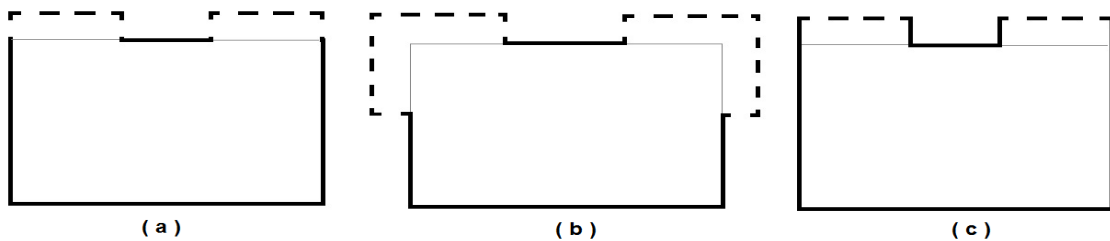
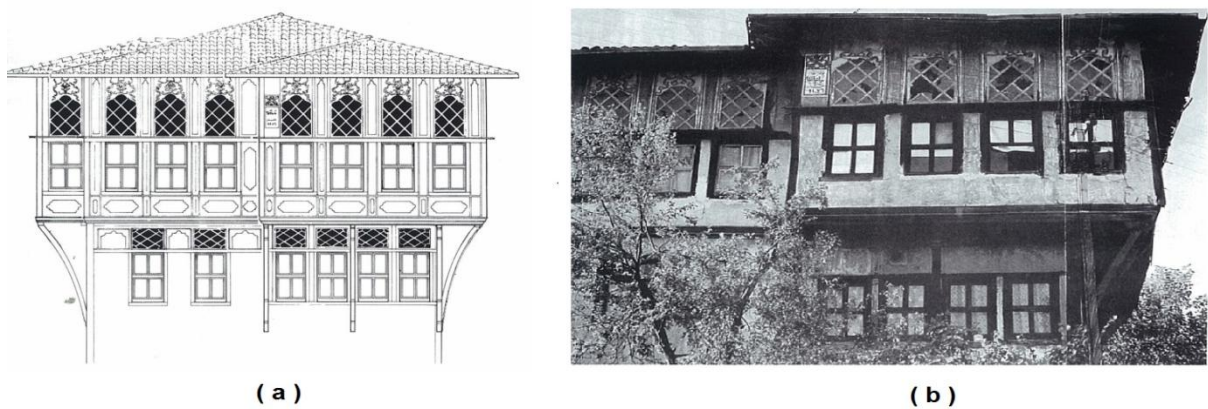
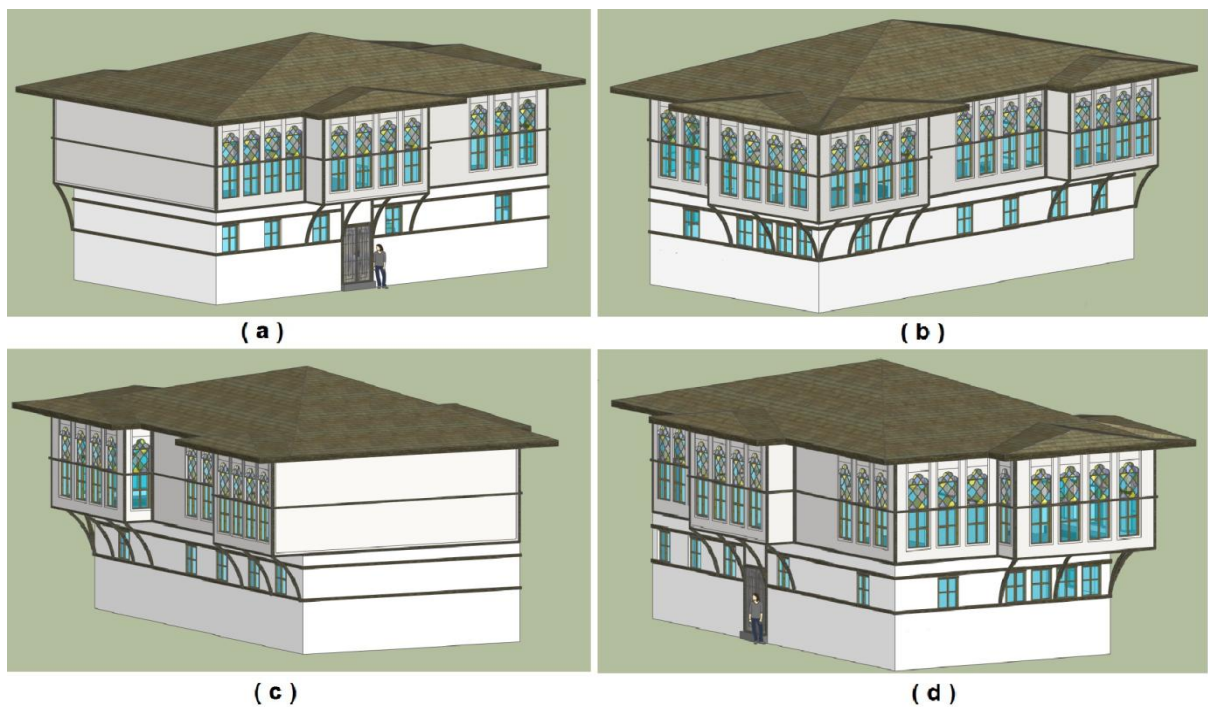


Figure 3.3: Most common type of Cumba (a) 3 side Cumba, (b) 4 side Cumba, (c) 1 side Cumba

**Fig. 3.3** and **Fig 3.4** illustrate the benchmark building elevation and photo. Benchmark building scaled plan, elevation and photo is crucial to obtain better understanding of benchmark building by both reader and researcher in advance benchmark building 3D model was carried out. **Figure 3.5** illustrates the benchmark building perspective from four different directions. As shown in **Figure 3.5** there are three Cumba available in benchmark building, where in northwest, northeast rooms and Sofa.

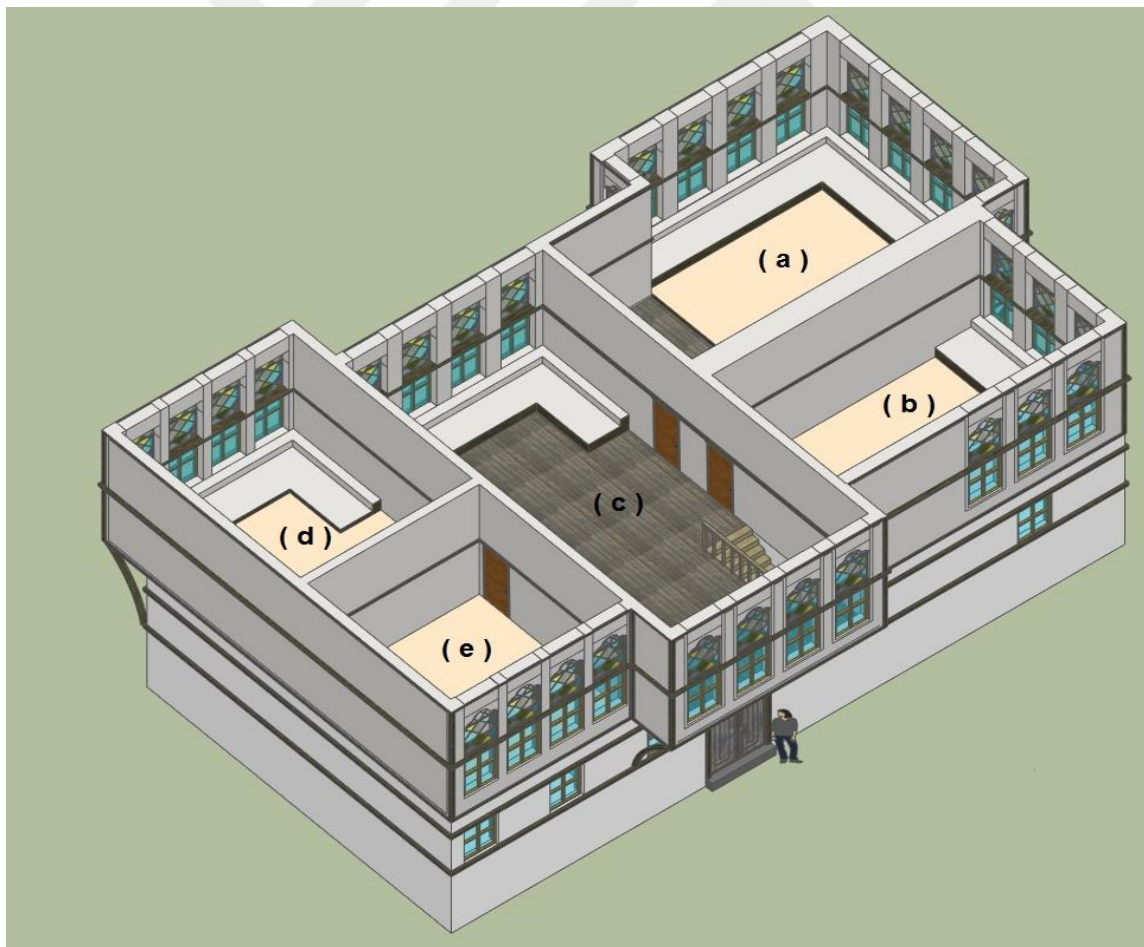


**Figure 3.4:** Benchmark building elevation and photo(Talya, 2007)



**Figure 3.5:** Benchmark building 3D perspective(a) southwest (b) northeast (c) northwest (d) southeast

**Figure 3.6** illustrates the interior perspective of benchmark building. It should be considered that the 3 model shows raised sitting areas as furnishings, but other furnishings like fixed cupboards are not modelled. It is important to underline that the study carried out on 111 different sample buildings included sitting areas particularly located in Cumbas. This observation is one of the supporting points of the research hypothesis, because it may be claimed that considering sitting areas are fixed in Turkish architecture, sitting areas particularly located relative to Cumbas may contribute to occupant comfort. It should be mentioned that the CFD model used in simulations did not contain any kind of furnishing; simulations were performed on the room without any obstacles. After deciding the benchmark building and parameters, natural ventilation effect of Cumba is tested with CFD simulations. Following chapter provides the CFD methodology, which informs reader about simulation conditions.



**Figure 3.6:** Benchmark building 3D interior illustration (a) N-e room 30 m<sup>2</sup> (b) S-e room 21 m<sup>2</sup> (c) Sofa 45m<sup>2</sup> (d) n-w room 16 m<sup>2</sup> (e) n-w room 16 m<sup>2</sup>

## CHAPTER 4: CFD METHODOLOGY

In the framework of positivist paradigm and objective ontology, this chapter explains the CFD simulations settings and simulation conditions, to provide repeatability and give opportunity to assess the reliability of this pioneering study with a transparent process.

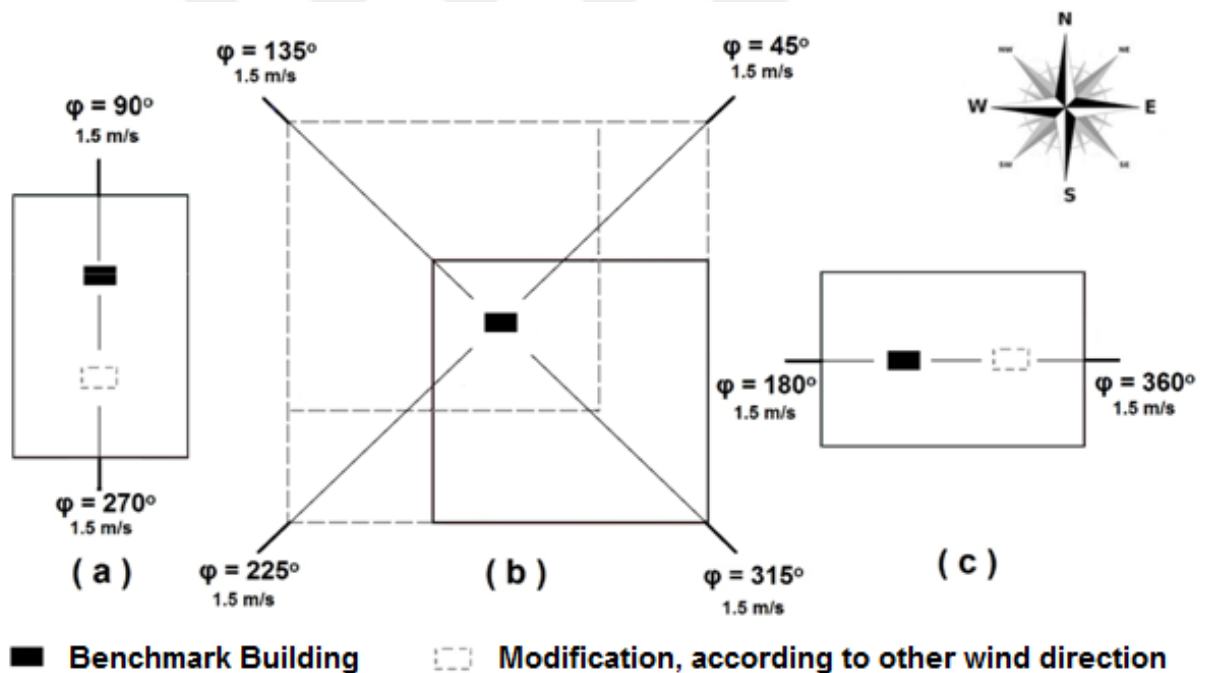
### 4.1. CFD Mesh Process

The recommended domain boundaries size were set as minimum values ( $10H$  between building and outlet boundaries and  $5H$  from inlet to and corner boundaries) (see Fig. 2.14), which is mentioned in the guidelines due to time and CFD student licence cell number limitation (*i.e.* 500.000 cells). As seen in Figure 4.1, the benchmark building is two-storey, and each floor is 4 m in height. Considering the roof height is 1.5 m, the building's total height ( $H$ ) was defined as 9.5 m. CFD mesh domain size was modified according to eight different wind directions according to wind blow direction, because the minimum boundary distances should be rearranged according to wind coming in at an angular direction to obtain minimum recommended boundary distances (see Fig. 4.2).



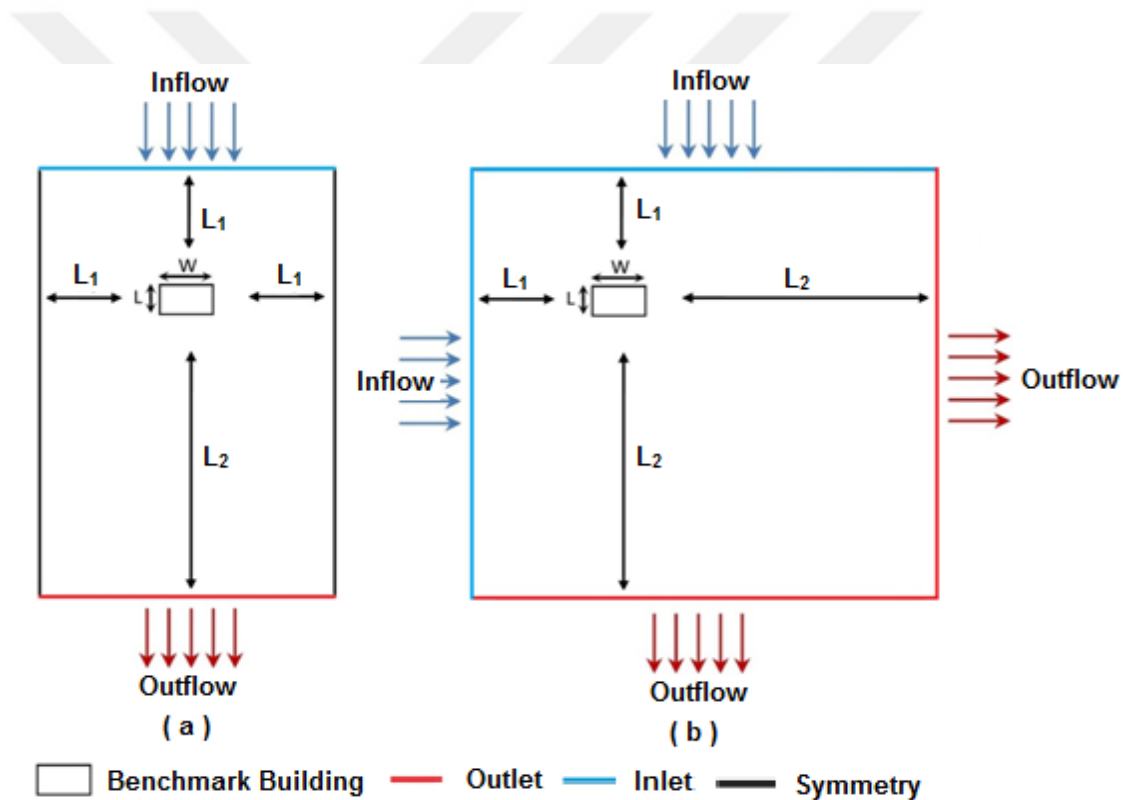
Figure 4.1: Benchmark building total height ( $H$ ) definition

CFD mesh boundary conditions and dimensions for direct (*i.e. east, west, north, south*) and angular (*i.e. northeast, northwest, southwest, southeast*) wind directions are illustrated in **Fig 4.3** and **Table 4.1**. Boundary conditions have considerable importance as well as domain size to achieve high reliability in CFD simulations. As seen in **Fig. 4.2**, domain air inlet is defined as “Inlet”, air outlet define as “outlet” and in **Fig. 4.2 (a)**, parallel boundaries to wind flow is defined as “symmetry”. The importance of symmetrical boundary conditions has been reported in several papers (**Blazek, 2006; Lanzafame et. Al., 2013, 2014**). Symmetry boundary conditions avoid non-slip conditions and viscosity on domain boundary surfaces. If the required surfaces were not defined as symmetrical, then Solver calculates those boundaries as a wall with shear slip conditions and viscosity, which influences the fluid flow and speed, consequently decreasing the reliability of the simulations.



**Figure 4.2:** Domain modification according to wind directions where  $\phi$  is wind direction angle  
**(a)** For  $90^\circ - 270^\circ$  **(b)** For  $45^\circ - 135^\circ - 225^\circ - 315^\circ$  **(c)** For  $180^\circ - 360^\circ$

In addition to this some researches show that domain geometry also influences CFD simulations' accuracy, therefore two different domain types were tested, cylindrical and rectangular domains. Some studies show that cylindrical domains have considerable advantages (*i.e.* 15.2% better accuracy, less number of cell demand, provide opportunity to test different wind directions with one mesh domain) (Mirzaei et al., 2013) Firstly, considering the mentioned study, limited time and required number of simulations tested with eight different wind directions, cylindrical domain were preferred (Fig. 4.4c, d).

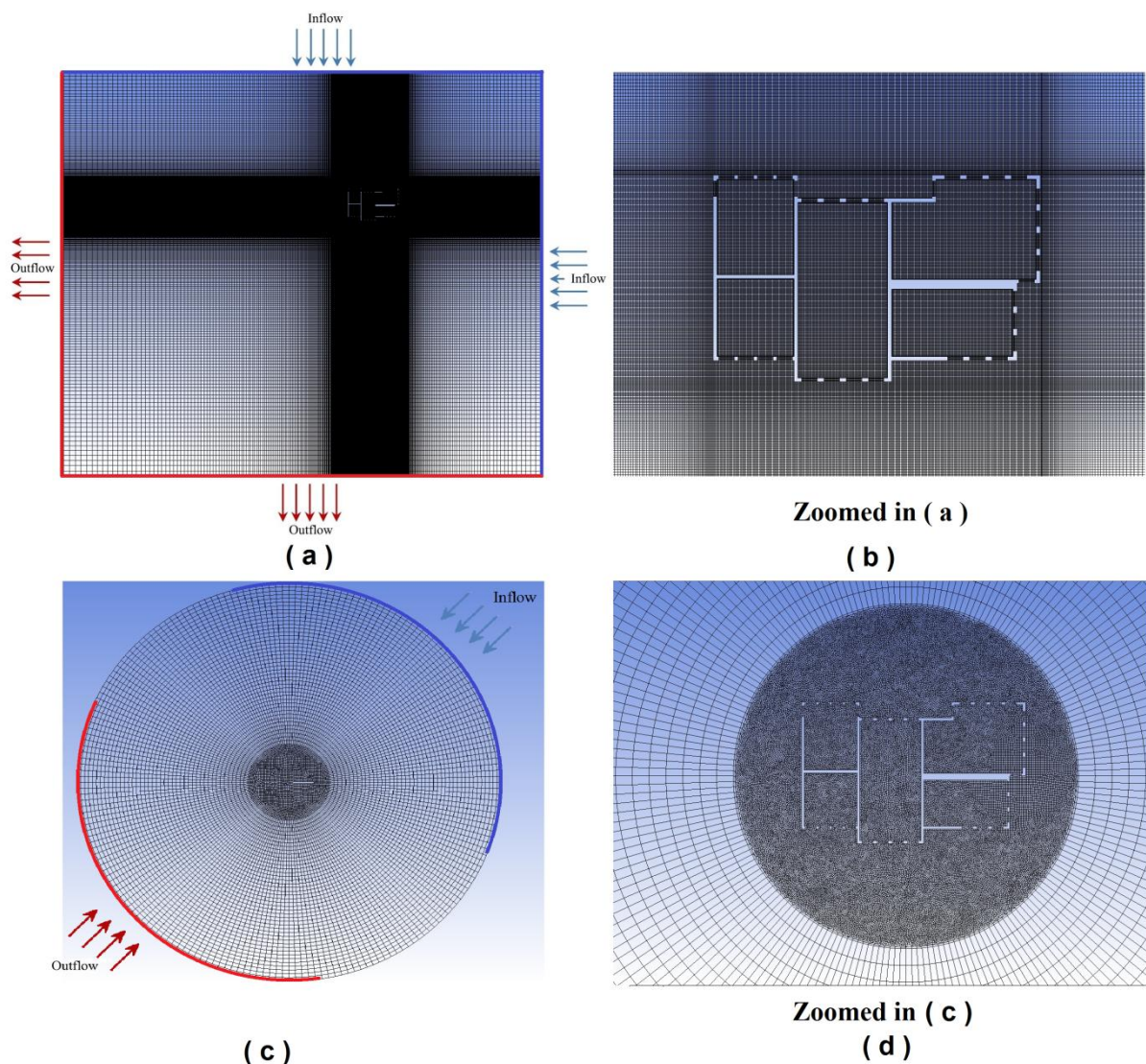


**Figure 4.3:** Domain size illustration (a) For 90° – 180° – 270° – 360° flow direction (b) For 45° – 135° – 225° – 315° flow direction

**Table 4.1:** Domain size and building size

$W = 16.8 \text{ m}$
$L = 10.7 \text{ m}$
$H = 9.5 \text{ m}$
$L_1 = 5H = 47.5 \text{ m}$
$L_2 = 10H = 95 \text{ m}$

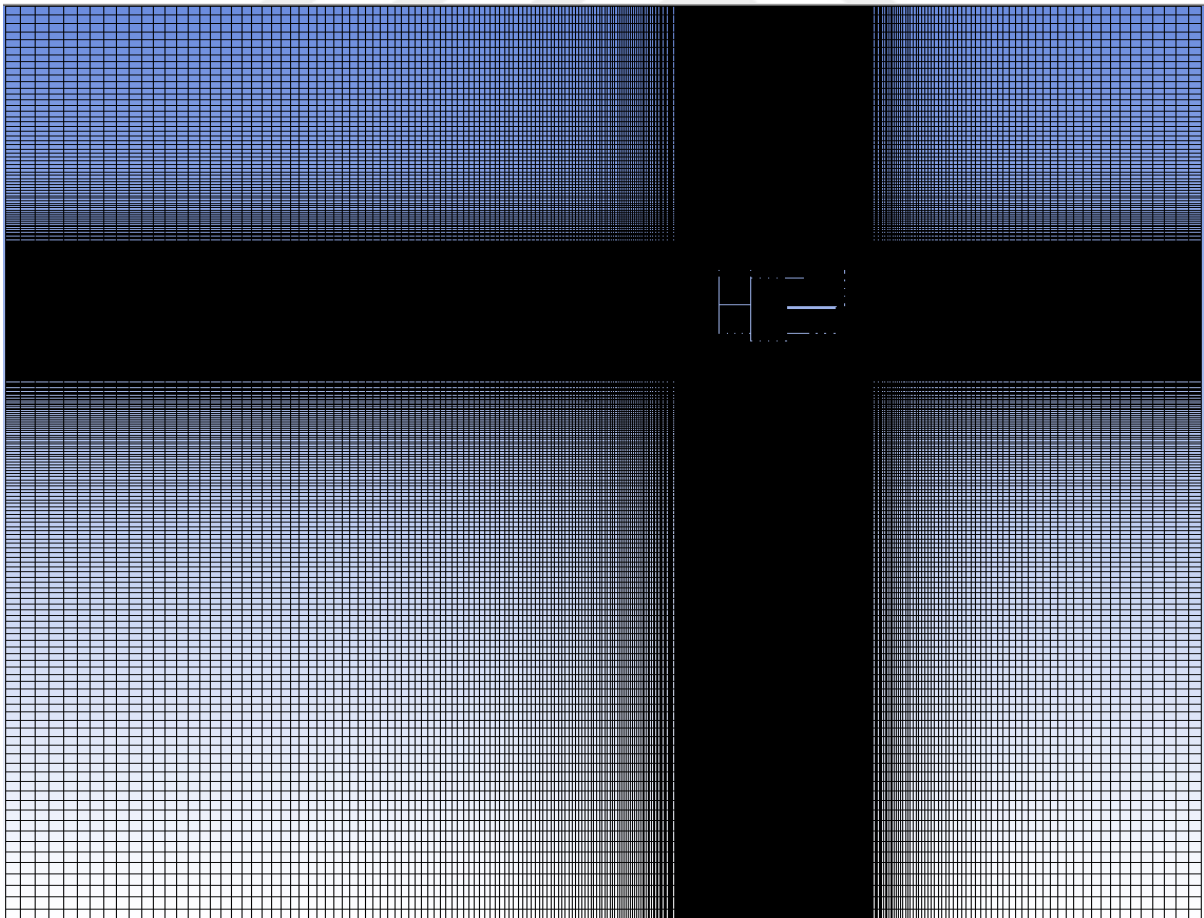
However, due to the multi-part structure of the benchmark building, structured grid and adequate mesh quality, particularly minimum orthogonal quality and  $y^+$  value, could not be obtained with cylindrical domain due to lack of experience. Therefore rectangular domain was preferred in this study to obtain structured mesh with high mesh quality (see Fig. 4.4a, b). For obtaining heist possible mesh quality quadrilateral cell types were used with rectangular domain. To achieve maximum mesh quality with minimum orthogonal quality (*i.e.* = 1) mesh was carefully done with avoiding distortion of cells and obtained all cell angles equal to  $90^\circ$ .



**Figure 4.4:** Simulation mesh domain experimental analysis (a) Rectangular full domain, (b) Rectangular domain building surroundings, (c) Cylindrical full domain, (d) Cylindrical domain building surroundings

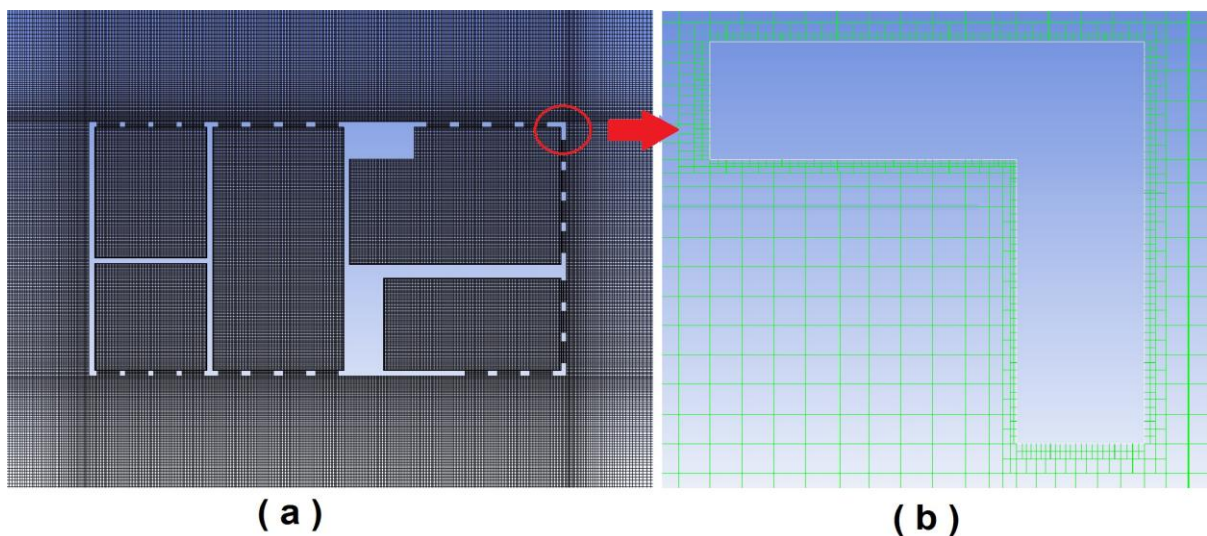
As seen in **Figure 4.5**, grid resolution were arrange higher in regions where large flow gradients are expected to capture the turbulences in inner layer and increase the accuracy of the CFD simulation outcomes. Bios type mapped mesh was used to obtain higher resolution around the building external boundaries and close surroundings to calculate inner layer with high accuracy with very fine mesh around the building close surroundings. Gradually increasing mesh cell distances were set to calculate outer layer with high accuracy (**see Fig. 4.5**).

In addition to this some studies underline the necessity to number of cells between fluid passages. It is recommended at least 10 cells across passages. Therefore when the mesh size were defining window widths were take account and even with the minimum window width (i.e. 0.7 m) the number of cells keep more than 10 cells. (**Franke, 2007**)

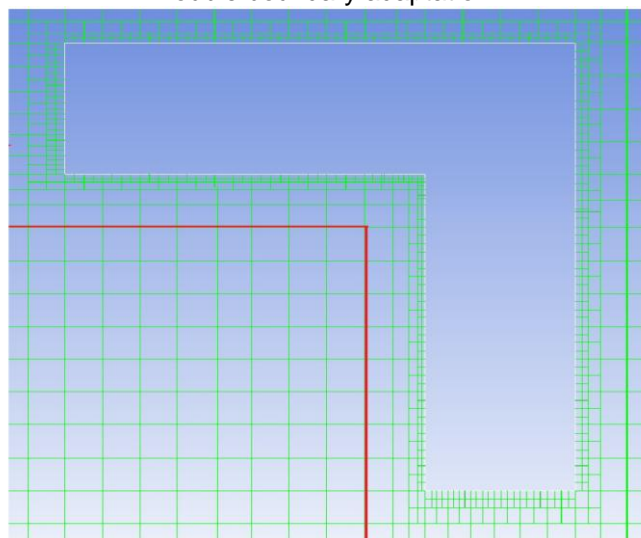


**Figure 4.5:** Preferred overall domain mesh grid resolution illustration

Double boundary adaptation was made to maximize the mesh quality with higher grid resolution with very fine mesh around the building walls, because largest flow gradients observed around the building walls (see Fig. 4.6). Beside boundary adaptation, building interior mesh was separated by 0.1 m from all interior building walls and with bios mapped mesh technique cell sizes get smaller near the wall and reach the finer mesh with close surrounding of building walls to provide smoother transition between cells. Building interior mesh separation was shown with red line, where cell sizes get smaller gradually after separation line (see Fig. 4.7).



**Figure 4.6:** Rectangular domain grid resolution (a) Rectangular domain building surroundings (b) Double boundary adaptation.



- Mesh boundary

**Figure 4.7:** Rectangular domain special building interior mesh separation (detail from building northeast corner; see Figure 4.6).

As a consequence of all those mesh studies  $Y^+ = 1$  was obtained with majority of simulations. However, in some simulations  $y^+$  was  $> 1$ , particularly with the simulations 2.5 m/s wind speed and angular wind direction conditions. However, in all simulations  $y^+ \leq 2$  in all conditions. For  $y^+$  adaptation average values 76 for benchmark building with Cumba and 81 for benchmark without Cumba. Better  $y^+$  (i.e. 30  $y^+$  adaptation value and  $y^+ = 1$ ) could not obtained due to cell limitations of student licensed CFD (i.e. 500.000).

#### 4.2. CFD Simulation Settings

Simulations were performed with Reynolds Averaged Navier Stokes (RANS) method equations. Considering the time demand LES model did not preferred. As a turbulent scheme K- $\epsilon$  model was employed. In addition to this Second order discretization schemes were used. Near-Wall Treatments was set as “enhanced wall treatment” because K- $\epsilon$  models are not appropriate for calculating the near wall flow. Enhanced wall treatment provide smooth transition in inner layer (i.e. between sub-layer and log-law layer) (see Fig. 4.2). However, Enhanced wall treatment requires very fine mesh near wall boundaries. Very fine mesh was obtained with bios type mapped mesh technique and double boundary adaptation. Energy equations and gravity influence were also added simulation equations to increase the CFD simulations accuracy.

Energy simulations can defined with the equation:

$$\frac{\partial(\rho U_j H_i)}{\partial x_j} - \frac{\partial}{\partial x_j} \left[ \left( \frac{\mu}{\sigma} + \frac{\mu_t}{\sigma_t} \right) \left( \frac{\partial H_i}{\partial x_j} \right) \right] = q \quad (5)$$

Where,  $H_i$  is the specific enthalpy in I direction (J/kg), T is absolute air temperature (K) and q is the volumetric heat production/dissipation rate (W/m<sup>3</sup>) (Gan, 2011).

Integrating energy equation is important, because particularly thermal differences have significant influence on fluent density and viscosity, which considerably influence the fluid flow behaviour and speed. Operation temperature decision was taken according to Istanbul's annual average temperature (*i.e.* 14°C). Operational temperature was set as 287.15 K where equal to Istanbul annual average temperature (14°C). Inlet velocity was decided according to Istanbul average wind speed (*i.e.* 5.5 km/h). According to Istanbul weather data, inlet velocity was calculated as;

$$5.5 \text{ (km / h)} * 1000 \text{ (m)} / 3600 \text{ (s)} = 1.5 \text{ m/s}$$

Therefore inlet velocity magnitude was taken as 1.5 m/s. As a stable values all wind velocities were taken 1.5 m/s and with 80 cm window with. Also for maximizing the simulations reliability gravity acceleration value was taken as -9.81 m/s<sup>2</sup> to y direction. Convergence absolute criteria were set as 10<sup>-6</sup> for energy equation and 10<sup>-5</sup> for all equations (**see Table 4.2**). Simulations were continued for an average of 270,000 iterations but the convergence point was not reached. Considering the simulations iteration graphs are quite linear and time is limited simulations were stopped around 270,000 iterations before reaching the convergence point. Simulation technical settings details are given in **Table 4.2** with all details.

NATURAL VENTILLATION EFFECT OF “CUMBA” IN LOW RISE DWELLINGS

**Table 4.2:** Simulation settings overall summary information for all 40 simulations

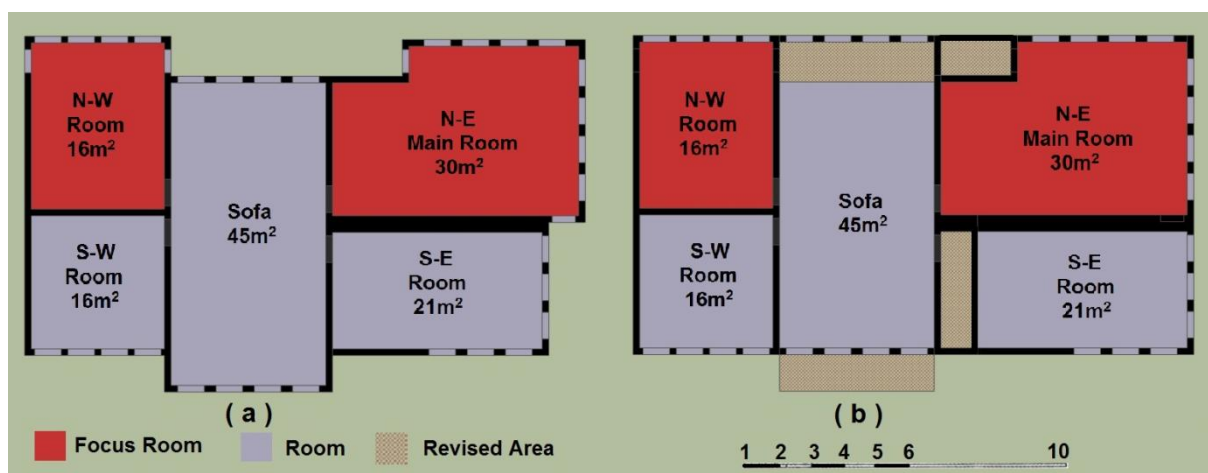
<b>GENERAL:</b>	-Pressure-Based Solver Type, -Steady Time, -Absolute Velocity Formulation, -Gravity Influence was activated, where $y = 9.81 \text{ m/s}^2$
<b>MODELS :</b>	-Viscous – Standard k-epsilon, -Enhanced Wall Treatment -Energy equations activated
<b>MATERIALS- FLUID- AIR PROPERTIES :</b>	-Density: 1.225 kg/m <sup>3</sup> -Specific Heat: 1006.43 j/kg-k, -Thermal Conductivity: 0.0242 w/m-k, -Viscosity: 1.78 kg/m-s.
<b>BOUNDARY CONDITIONS :</b>	-Magnitude and Direction Velocity Speciation Method, -Intensity and Viscosity Ratio Turbulence speciation Method, -5% Turbulent Intensity, -10 Turbulent Viscosity Ratio, -287.15 k Inlet Air Temperature.
<b>ITERATION NUMBER :</b>	<b>-Min :</b> 250.000 <b>- Max :</b> 310.000 <b>- Average :</b> 270.000
<b>ITERATION NUMBER AFTER BOUNDARY ADAPTATION:</b>	250.000 + 10.000
<b>SOLUTION METHODS :</b>	-Simple Pressure-Velocity Coupling Scheme, -Spatial Discretization, -Last squares Cell Based Gradient, -Standard Pressure, -Second Order Upwind Momentum, -First order Upwind Turbulent Kinetic energy, -First order Upwind Turbulent Dissipation rate
<b>CONVERGENCE ABSOLUTE CRITERIA FOR :</b>	-Continuity : 10 <sup>-5</sup> -x-Velocity : 10 <sup>-5</sup> -y-Velocity : 10 <sup>-5</sup> -Energy : 10 <sup>-6</sup> -k : 10 <sup>-5</sup> -Epsilon : 10 <sup>-5</sup>
<b>DIMENSIONLESS WALL DISTANCE ADAPTATION (Y+)</b>	<b>-Min :</b> 49 <b>- Max :</b> 124 <b>- Average :</b> 78
<b>DIMENSIONLESS WALL DISTANCE (Y+)</b>	$1 \leq y^+ \leq 2$
<b>MINIMUM ORTHOGONAL QUALITY :</b>	1
<b>MESH MAXIMUM ASPECT RATIO :</b>	<b>-Min :</b> 5.8 <b>-Max :</b> 7.1 <b>-Average :</b> 6.4
<b>MESH SIZE (Cell number) :</b>	<b>-Min :</b> 292298 <b>-Max :</b> 489612 <b>-Average :</b> 374764

### 4.3 CFD Simulation Monitoring Process

As shown in **Figure 4.8**, northwest and northeast rooms were defined as focus rooms where the number of indoor air velocity measurement points are arranged significantly more intensive Compared with other rooms to maximize the accuracy of focus rooms indoor air speed. Benchmark building with and without Cumba room areas where kept same. For converting benchmark building to without Cumba sample just rooms were moved and required areas were filled as not affect the fluid flow and change the room area (**see Fig 4.8**).

As shown in **Figure 4.9**, building indoor velocity was measured with 282 points. Point numbers vary according to room areas and being focus room. First focus rooms northwest room and northeast room indoor velocity was measured with 63 points and 114 points respectively. Other rooms’ measurement points numbers and details can be seen in **Figure 4.9** and **Table 4.3**. In addition to this, 200 rake measurement points arrange at focus rooms windows to measuring the average air speed passing through each window (**see Fig 4.9**). The average wind speed passing through the windows is required for volumetric flow rate calculation for each rooms.

Volumetric flow rate is required to energy simulations to assess the influence of Cumba natural ventilation effect on building cooling loads if Cumba have any contribution on neural ventilation.



**Figure 4.8:** Benchmark building with and without Cumba for average indoor air speed and volumetric flow rate monitoring process

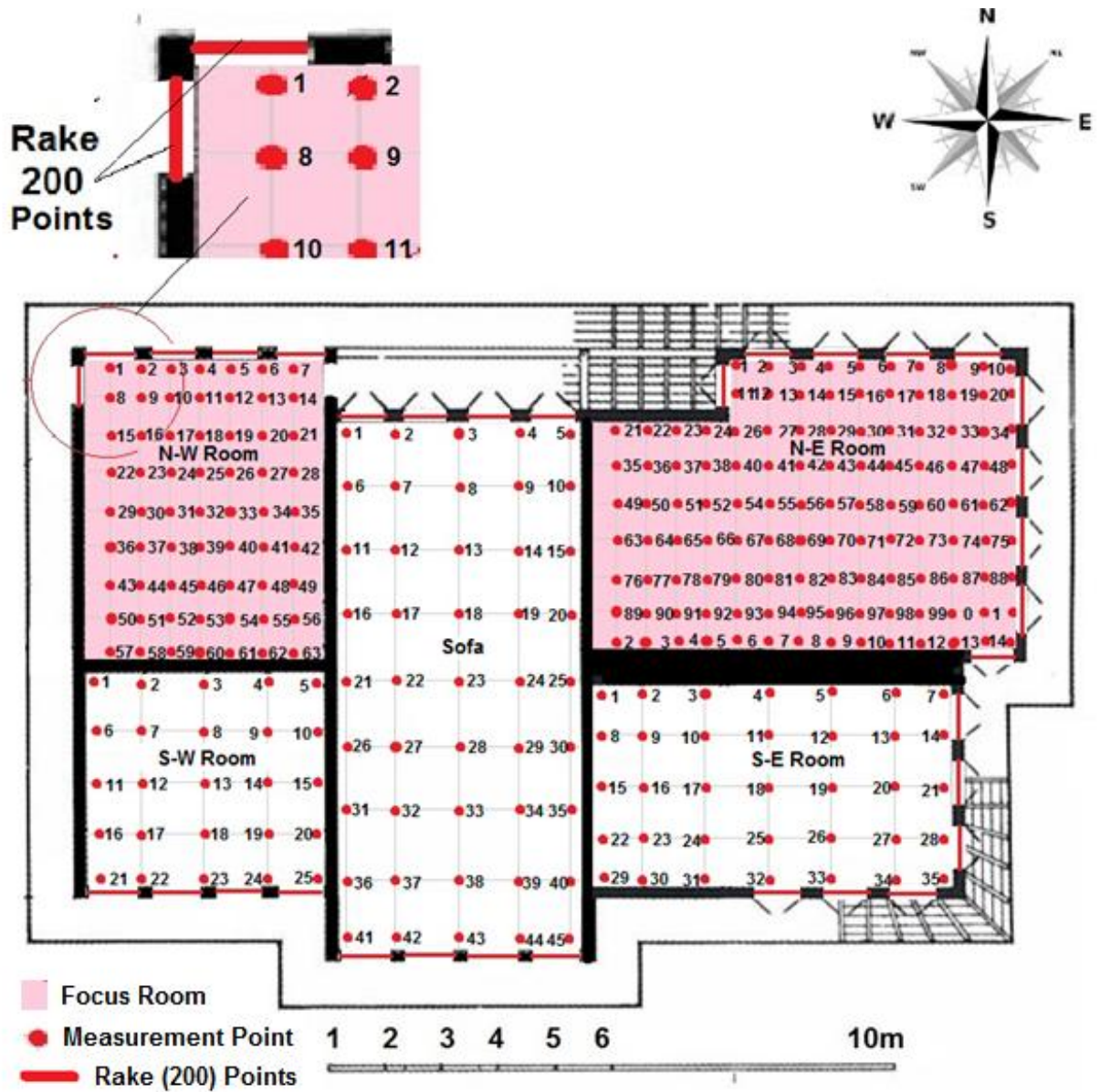


Figure 4.9: Benchmark building sensor and rake location illustrations

Table 4.3: Benchmark building sensor and rake information

	N-W Room	N-E Room	S-W Room	S-E Room	Sofa
Room Sensor Number	63	114	25	35	45
Room Area	16 m2	30 m2	16 m2	21 m2	45 m2
Window Rake Number	200	200			

## CHAPTER 5: CFD SIMULATIONS

This section contains the CFD simulations outcomes. The natural ventilation effect of Cumba was tested on the benchmark building with and without Cumba under 40 different 2D CFD simulations and 20 different conditions, with eight different wind directions (*i.e. north, northwest, northeast south, southwest, southeast, west and east*), three different wind velocities (*i.e. 0.5 m/s, 1.5 m/s, 2.5 m/s*) with two different wind directions each (*i.e. north, northwest*) and three different window widths (*i.e. 70 cm, 80 cm, 90 cm*) with two different wind directions (*i.e. north, northwest*). CFD simulations are monitored and assessed under five main concepts (*i.e. outdoor air flow pattern, Indoor air flow pattern, Indoor average air velocity, Volumetric flow tare, Indoor pressure characteristics*). Indoor air velocity was obtained with 282 air speed sensor points and volumetric flow rate was obtained via 3200 air speed sensor points where, 200 points locates in each focus room windows.

Volumetric flow rate is obtained with fallowing equations:

$$Q = v \cdot A \text{ (6)}$$

Where, Q is volumetric flow rate, v is flow velocity and A is cross-sectional vector surface area.

$$A = W \cdot H \text{ (7)}$$

Where, A is cross-sectional vector surface area, W is air flow inlet width and H is air flow inlet height

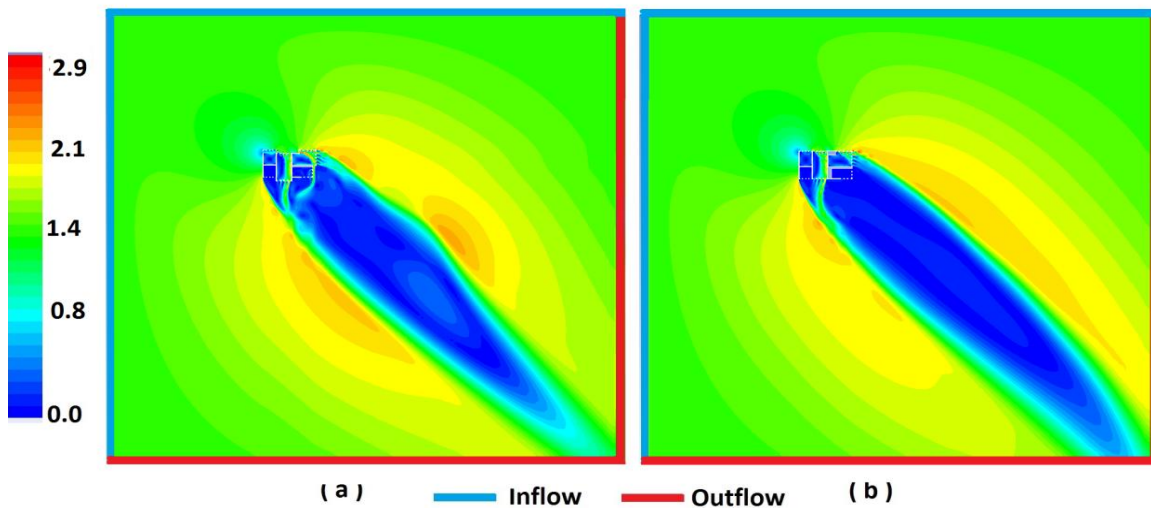
Considering all simulation normal conditions were defined as 80 cm window width and 1.5 m/s wind speed, simulations under this conditions is addressed in wind direction influence section but not in the wind speed and window width sections. However, window with section and wind speed section, mentioned those simulations outcomes with overall comparisons part at the end of each sections, where summary all simulations with overall averaged graphs.

### 5.1. The Influence of window Width on Natural Ventilation Effect of Cumba

In this section the influence of three different window widths (*i.e.* 70 cm, 80 cm and 90 cm) with two different directions (*i.e.* north and northwest) on natural ventilation effect of Cumba is analysed with CFD simulations.

#### 5.1.1 70 cm window width influence under northwest wind direction

As seen in **Fig 5.1**, Cumba cause considerable variations on outdoor air flow pattern Compared with benchmark building without Cumba. The benchmark building outdoor air flow pattern is compared with benchmark building without Cumba. The northeast room Cumba directs the northwest wind through the south facade opening and lets the air flow through the negative pressure zone in downstream zone, which also causes 900% average indoor air velocity acceleration in southeast room (**Table 5.2**) (see **Fig 5.1** and **5.2**).



**Figure 5.1:** Benchmark with 70 cm window width and northwest wind outdoor air flow characteristic  
**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba

In addition to this the existence of Cumba increase northeast and northwest room volumetric flow rate  $3.3 \text{ m}^3/\text{s}$  (68.6%) and  $2.5 \text{ m}^3/\text{s}$  (493.5%) respectively (see Table 5.1 and 5.2). The significant contribution of Cumba on average indoor air speed and volumetric flow rate can be explained with the pressure simulations results. As seen in Fig. 5.3 There is approximately 4 Pascal pressure attenuation was observed in northeast room. The pressure attenuation reason can be explained by, Cumba causing Venturi effect, which decreases pressure, increases indoor air flow speed and contributes to natural ventilation in the room (see Fig 5.3).

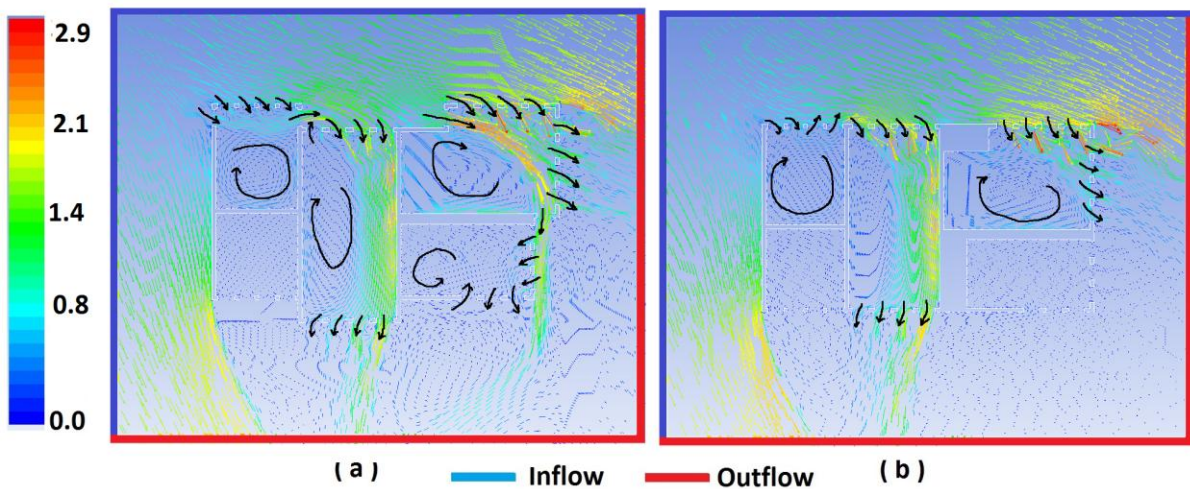


Figure 5.2: Benchmark with 70 cm window width and northwest wind indoor air flow characteristic (a) Benchmark with Cumba (b) Benchmark without Cumba

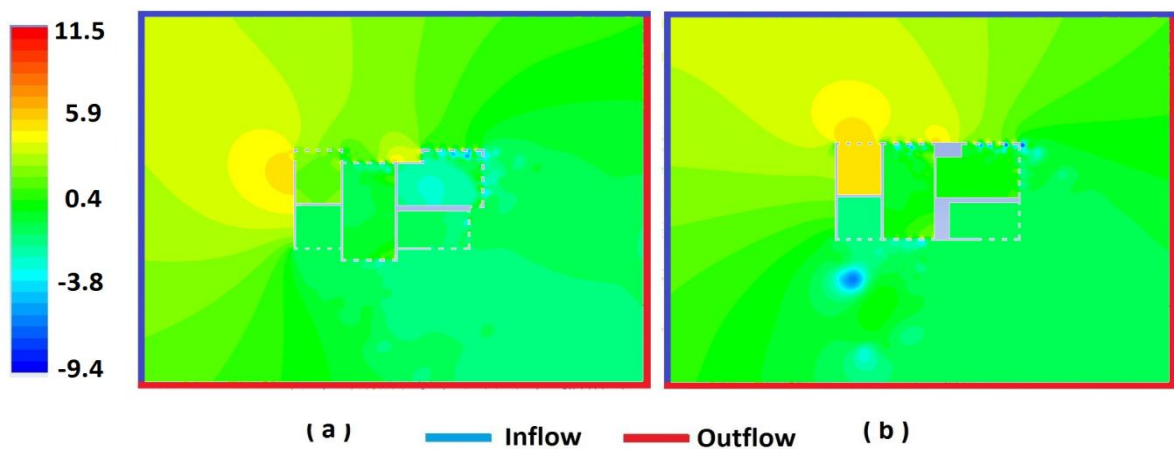


Figure 5.3: Benchmark with 70 cm window width and northwest wind pressure characteristic (a) Benchmark with Cumba (b) Benchmark without Cumba

In addition to this, similar to northwest room, there is approximately 5 Pascal pressure attenuation observed in northwest room indoor (see Fig 5.3).

**Table 5.1:** Benchmark with 70 cm window width and northwest wind simulation results (a) Results for benchmark building with Cumba (b) Results for benchmark building without Cumba

Room	Focus Room	Room Area (m2)	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag. ( m/s)	Volumetric Flow Rate ( m <sup>3</sup> /s)
Sofa		45	28	3.4	0.7	1.10	
N - E	X	30	64	3.6	0.03	1.08	8.2
N - W	X	16	35	2.4	0.06	0.85	3.0
S - E		22	15	0.8	0.2	0.39	
S - W		16	16	0.5	0.04	0.15	
( a )							
Sofa		45	28	2.9	0.2	1.36	
N - E	X	30	64	2.2	0.02	0.74	4.9
N - W	X	16	35	0.5	0.02	0.21	0.5
S - E		22	15	0.1	0.02	0.06	
S - W		16	16	0.2	0.05	0.12	
( b )							

**Table 5.2:** Benchmark with 70 cm window width and northwest wind simulation comparison results for benchmark building with and without Cumba

Room	Focus Room	Max. Velocity Mag. Difference ( % )	Min. Velocity Mag. Difference ( % )	Volumetric Flow Rate Difference ( % )
Sofa		17.2	250.0	
N - E	X	63.6	50.0	68.6
N - W	X	380.0	200.0	493.5
S - E		700.0	900.0	
S - W		150.0	-20.0	

5.1.1.2. 70 cm window width influence under north wind direction

As seen in Fig 5.4, there is no big difference observed for outdoor air speed around benchmark building with and without Cumba except the air flow through Sofa is slightly stronger in sample without Cumba, and it slightly influences the air flow velocity at the downstream zone (see Fig. 5.4 b).

Cumba creates Venturi effect in northwest room due to air flow through east window to west window (Fig. 5.5), which increased northwest room volumetric flow rate 4.4 m<sup>3</sup>/s (253%) and northwest room average indoor air velocity is 0.17 m/s increased with Cumba (see Table 5.3 and 5.4). Similarly, northeast room indoor velocity (39.6%) and volumetric flow rate (253%) increased (see Table 5.4).

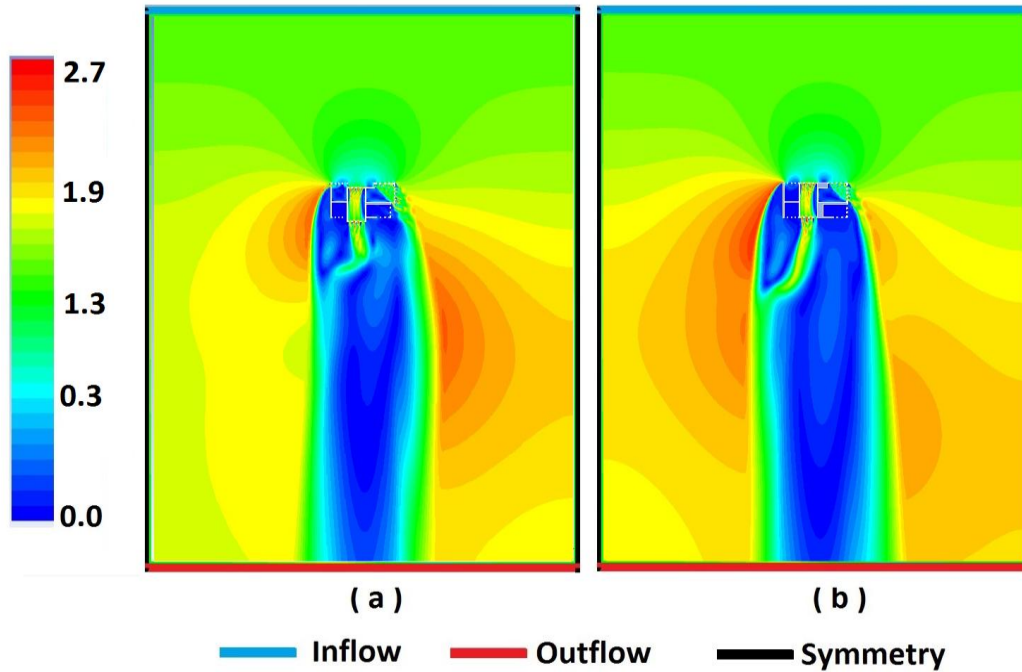


Figure 5.4: Benchmark with 70 cm window width and north wind outdoor air flow characteristic (a) Benchmark with Cumba (b) Benchmark without Cumba

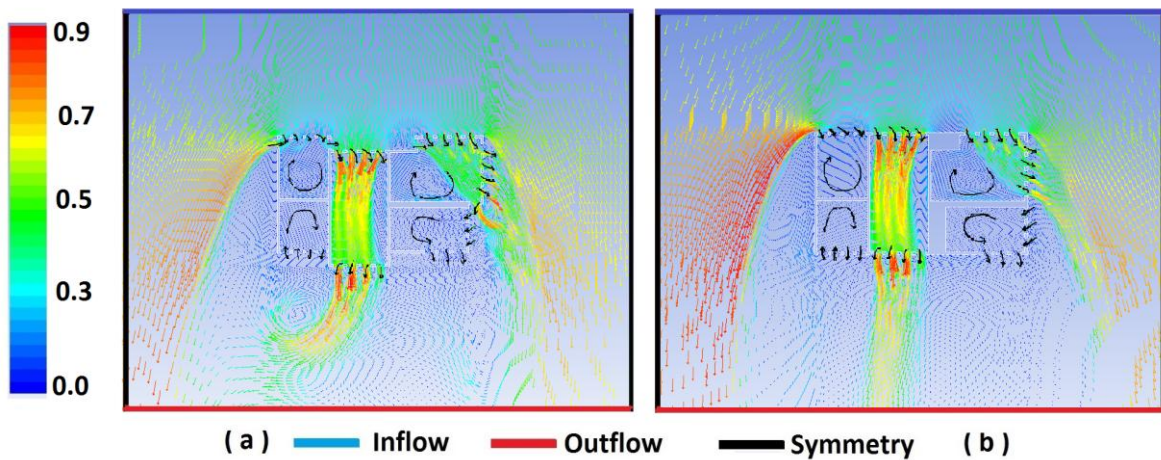


Figure 5.5: Benchmark with 70 cm window width and north wind indoor air flow characteristic (a) Benchmark with Cumba (b) Benchmark without Cumba

**Table 5.3:** Benchmark with 70 cm window width and north wind simulation results

Room	Focus Room	Room Area (m <sup>2</sup> )	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag. ( m/s)	Volumetric Flow Rate ( m <sup>3</sup> /s)
Sofa		45	28	0.05	1.8	0.70	
N - E	X	30	64	1.4	0.04	0.60	6.1
N - W	X	16	35	0.4	0.03	0.12	2.1
S - E		22	15	0.2	0.02	0.08	
S - W		16	16	0.1	0.02	0.05	
<b>( a )</b>							
Sofa		45	28	1.8	0.06	0.72	
N - E	X	30	64	1.9	0.01	0.43	1.7
N - W	X	16	35	0.3	0.01	0.11	0.3
S - E		22	15	0.06	0	0.04	
S - W		16	16	0.03	0	0.02	
<b>( b )</b>							

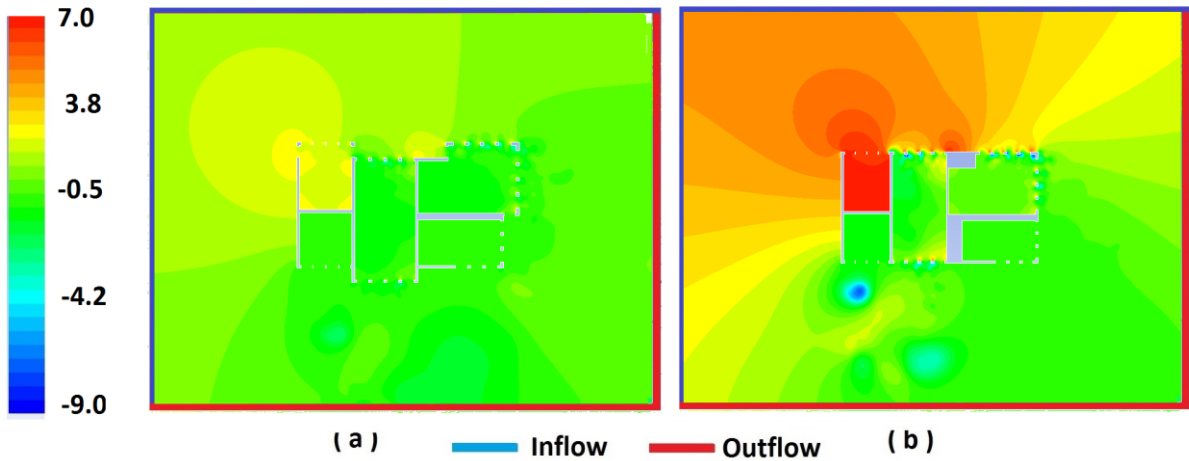
**(a)** Results for benchmark building with Cumba **(b)** Results for benchmark building without Cumba

**Table 5.4:** Benchmark with 70 cm window width and north wind simulation results for benchmark building with and without Cumba

Room	Focus Room	Max. Velocity Mag. Difference ( % )	Min. Velocity Mag. Difference ( % )	Ave. Velocity Mag. Difference ( % )	Volumetric Flow Rate Difference ( % )
Sofa		-97.2	2900.0	-1.7	
N - E	X	-26.3	300.0	39.6	253.0
N - W	X	33.3	200.0	6.2	629.7
S - E		233.3	0.0	74.0	
S - W		233.3	0.0	134.1	

### 5.1.3 The influence of 90 cm window with under northwest wind direction

There is no significant indoor and outdoor air flow pattern difference was observed between 70 cm and 90 cm window width with northwest wind direction simulation, for seeing the air flow patterns see **Fig 5.1** and **Fig 5.2**. However there is significant pressure difference was detected. Particularly in northwest room without Cumba sample there is approximately 5 Pascal higher pressure was observed (**see Fig 5.6**). As seen in **Table 5.5** existence of Cumba cause 0.16 m/s average indoor air velocity acceleration in northeast room. A significant contribution was also observed on 2.3 m<sup>3</sup>/s (254.9%) volumetric flow rate on northwest room (**see Table 5.5 and 5.6**).



**Figure 5.6:** Benchmark with 90 cm window width and northwest wind pressure characteristic  
**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba

**Table 5.5:** Benchmark with 70 cm window width and north wind simulation results

Room	Focus Room	Room Area (m2)	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag. ( m/s)	Volumetric Flow Rate ( m³/s)
Sofa		45	28	2.3	0.03	1.00	
N - E	X	30	64	2.3	0.03	0.92	7.8
N - W	X	16	35	0.9	0.06	0.39	3.2
S - E		22	15	0.2	0.04	0.08	
S - W		16	16	0.1	0	0.03	
<b>( a )</b>							
Sofa		45	28	3.3	0.2	1.86	
N - E	X	30	64	2.2	0.03	0.76	7.4
N - W	X	16	35	0.5	0.02	0.18	0.9
S - E		22	15	0.1	0.02	0.07	
S - W		16	16	0.2	0.01	0.09	
<b>( b )</b>							

**(a)** Results for benchmark building with Cumba **(b)** Results for benchmark building without Cumba

**Table 5.6:** Benchmark with 70 cm window width and north wind simulation results for benchmark building with and without Cumba

Room	Focus Room	Max. Velocity Mag. Difference ( % )	Min. Velocity Mag. Difference ( % )	Ave. Velocity Mag. Difference ( % )	Volumetric Flow Rate Difference ( % )
Sofa		-30.3	-85.0	-46.4	
N - E	X	4.5	0.0	21.2	4.9
N - W	X	80.0	200.0	120.7	254.9
S - E		100.0	100.0	27.4	
S - W		-50.0	-100.0	-65.0	

5.1.4 The influence of 90 cm window with under north wind direction

There is no considerable difference on was observed between indoor and outdoor air flow pattern between 70 cm and 90 cm window width with north wind direction simulation. Therefore both indoor and outdoor air patens can be seen in **Fig 5.4** and **Fig 5.5**. As seen in **Table 5.8** the most considerable difference was observed in northwest room average indoor speed and volumetric flow rate where northwest room average indoor air speed increased 0.16 m/s (270.6%) and volumetric flow rate increased 0.7 m<sup>3</sup>/s (419.5%) with the presence of Cumba. Also there is 291.5% average indoor speed acceleration is stands out (**see Table 5.7 and 5.8**).

**Table 5.7:** Benchmark with 70 cm window width and north wind simulation results

Room	Focus Room	Room Area (m2)	Number of Sensors	Max. Velocity Mag.( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag.( m/s)	Volumetric Flow Rate ( m3/s)
Sofa		45	28	1.7	0.07	0.93	
N - E	X	30	64	1.7	0.03	0.70	4.2
N - W	X	16	35	0.5	0.05	0.22	0.9
S - E		22	15	0.3	0.09	0.14	
S - W		16	16	0.2	0	0.06	
<b>( a )</b>							
Sofa		45	28	1.9	0.1	1.09	
N - E	X	30	64	1.8	0.01	0.53	3.0
N - W	X	16	35	0.1	0	0.06	0.2
S - E		22	15	0.3	0.05	0.16	
S - W		16	16	0.06	0	0.02	
<b>( b )</b>							

(a) Results for benchmark building with Cumba (b) Results for benchmark building without Cumba

**Table 5.8:** Benchmark with 70 cm window width and north wind simulation results for benchmark building with and without Cumba

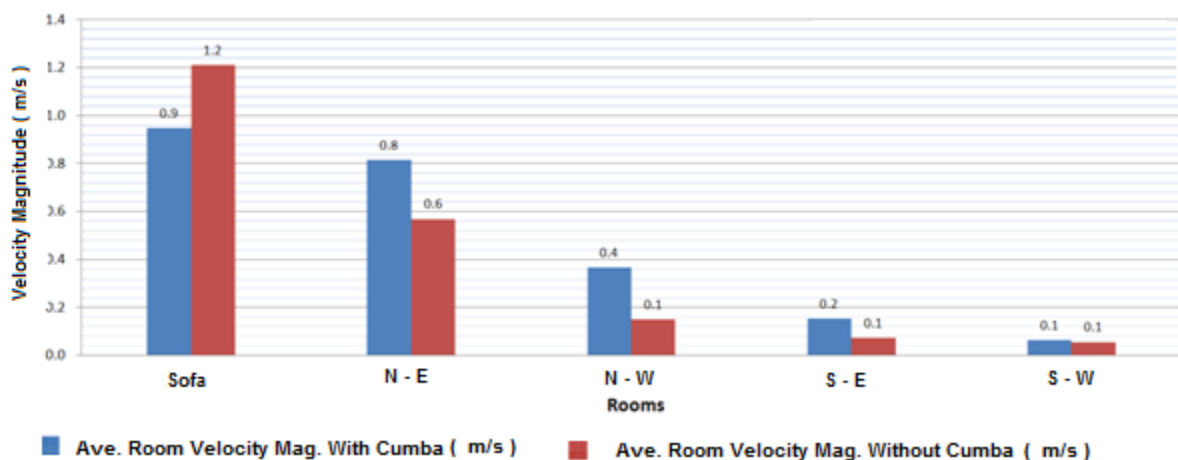
Room	Focus Room	Max. Velocity Mag. Difference ( % )	Min. Velocity Mag. Difference ( % )	Ave. Velocity Mag. Difference ( % )	Volumetric Flow Rate Difference ( % )
Sofa		-10.5	-30.0	-14.8	
N - E	X	-5.6	200.0	33.8	40.4
N - W	X	400.0	0.0	270.6	419.5
S - E		0.0	80.0	-10.9	
S - W		233.3	0.0	291.5	

5.1.5 Window width influence overall summary and comparison

For assessing the different window widths’ influence on natural ventilation effect of Cumba under different wind directions with a broader and clearer perspective, all results simulation outcomes were summarised and compared with graphs.

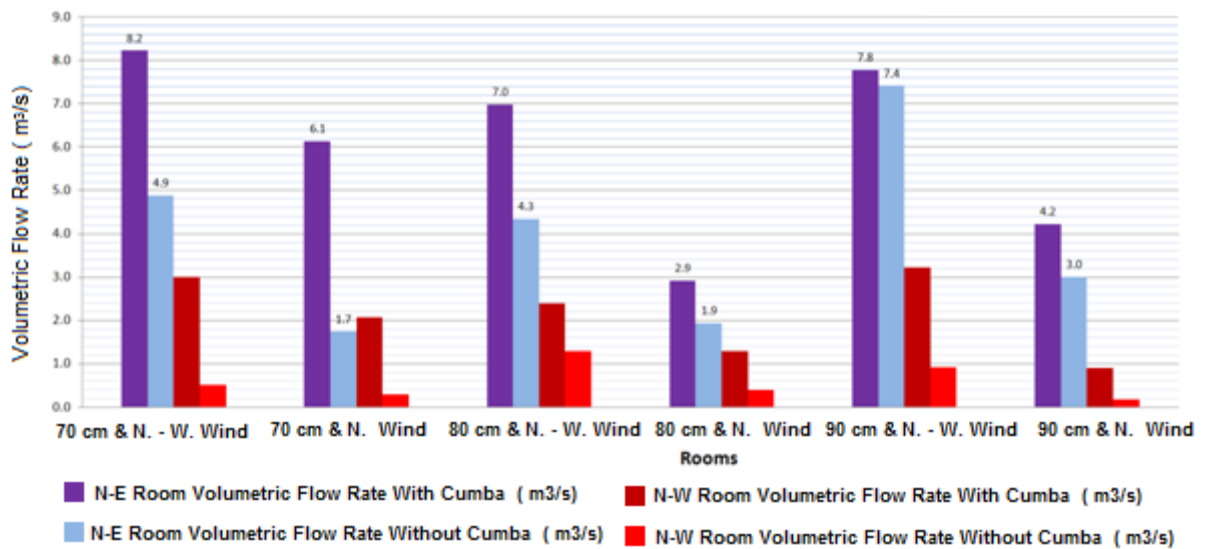
**Graph 5.1** shows the influence of window width on overall average indoor air velocity for each room. **Graph 5.1** indicates the average values for both north and northwest wind direction conditions. As seen in **Graph 5.1** existence of Cumba significantly contribute all rooms average indoor velocity except Sofa. The biggest Cumba average indoor air velocity contribution observed in northwest room with 0.3 m/s acceleration. In contrast the presence of Cumba 0.3 m/s decrease the average indoor air speed in Sofa (see **Graph 5.1**).

The window width influence on focus rooms volumetric flow rate under different wind directions (*i.e. north, northwest*) is shown in **Graph 5.2**. As clearly seen Cumba significantly contribute the focus rooms volumetric flow rate. The biggest Contribution with 630% rise is observed northwest room with 70cm window width under north wind flow (see **Graph 5.3**). The minimum volumetric flow rate contribution (*i.e. 0.4 m<sup>3</sup>/s, where 5% difference*) was observed in northeast room with 90cm window width under northwest wind direction (see **Graph 5.2 and 5.3**).

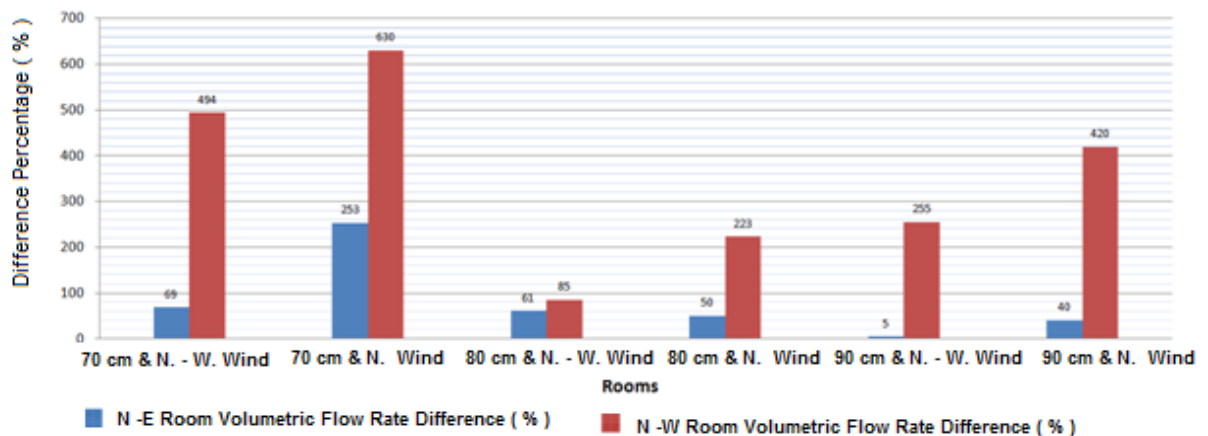


**Graph 5.1:** Overall window width influence on average indoor air velocity

The biggest volumetric flow rate differences, which caused by Cumba is observed in northwest room (see Graph 5.3). The reason can be explained by the room plan. Northwest room without Cumba have windows on only one facade, but northwest room with Cumba have windows on three facade, which provides separate room air inlet and outlet. However in northwest room without Cumba air access and leave the room on same facade which disturb both room air access and leave. Therefore, the existence of Cumba significantly contribute the northwest room volumetric flow rate.



Graph 5.2: Overall window width influence on volumetric flow rate

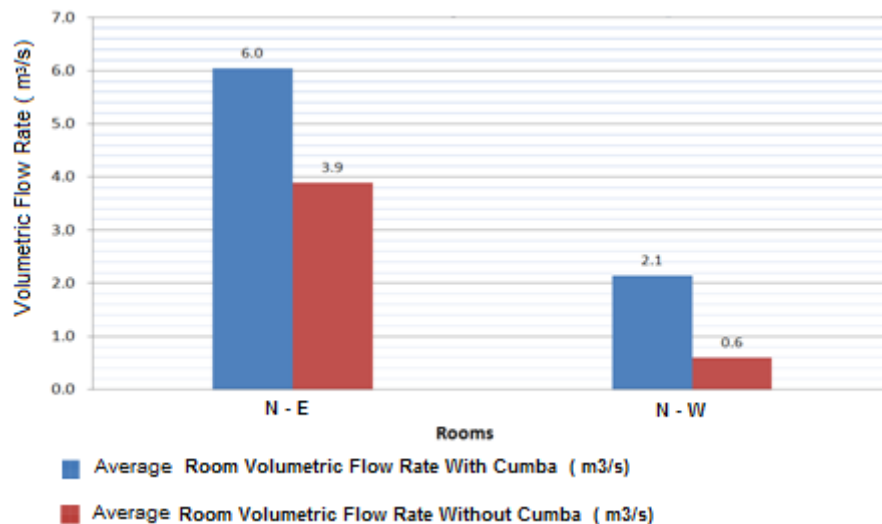


Graph 5.3: Overall average volumetric flow rate difference percentages

To examine the influence of wind direction on Cumba natural ventilation effect clearly, all window width influence under different wind directions, results summarised and compared. As depicted in **Graph 5.4**, the influence of window widths on overall average volumetric flow rate was summarised to make outcomes more clear. As clearly seen in **Graph 5.4** the existence of Cumba contributes the focus rooms volumetric flow rates as 2.1 m<sup>3</sup>/s (53.8%) to northeast room and 1.5 m<sup>3</sup>/s (250%) northwest room. It can be concluded that the existence of Cumba contributes to the focus rooms' average 1.8 m<sup>3</sup>/s.

**5.2. The Influence of Wind Speed on Natural Ventilation Effect of Cumba**

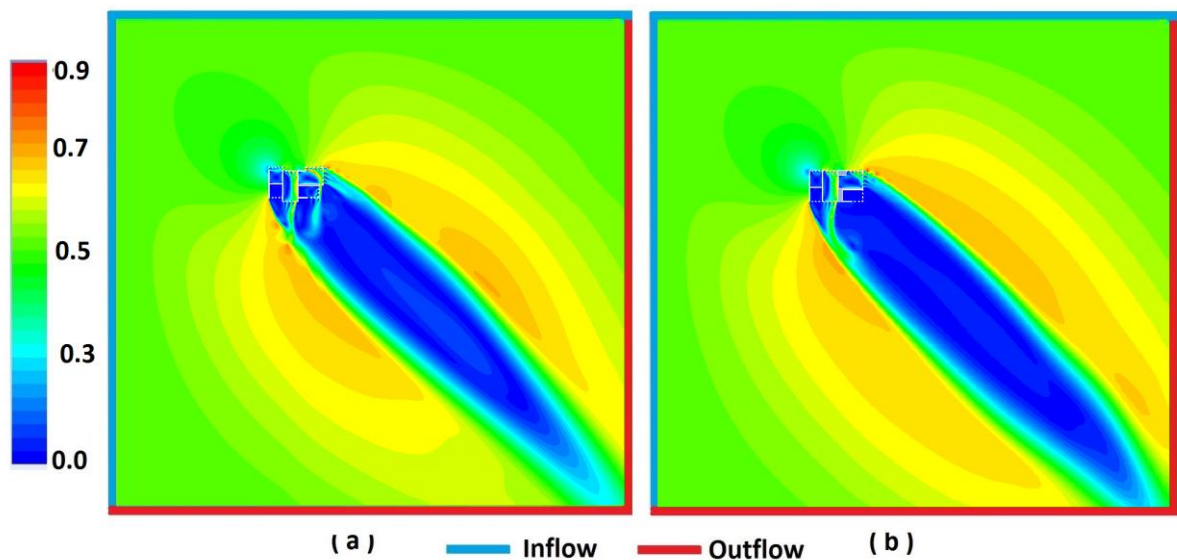
The influence of three different wind speed (*i.e.* 0.5m/s, 1.5m/s and 2.5 m/s) with two different direction (*i.e.* north and northwest) on natural ventilation effect of Cumba was analysed with CFD simulations. 1.5 m/s wind speed simulations are mentioned in the influence of wind direction section but not in this section, because all the sable variables are 1.5 m/s wind speed and 80 cm window width.



**Graph 5.4:** Overall volumetric flow rate average results for all conditions

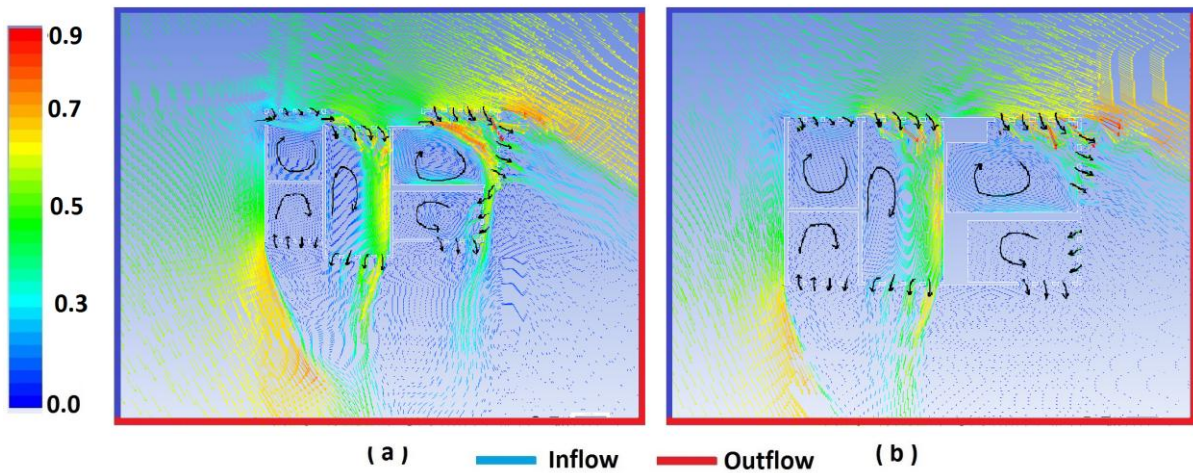
5.2.1 Northwest wind with 0.5 m/s wind speed

As seen in **Fig 5.7**, northwest room significantly influence the outdoor air flow pattern, under northwest wind direction conditions with 0.5 m/s wind speed. In **Fig 5.7a** and **Fig 5.8** it can be seen northeast room Cumba direct the northwest wind to negative pressure zone in downstream negative pressure area and 311.7% accelerate the air speed at southeast room (**see Table 5.10**). In addition to this the existence of Cumba increase northeast and northwest room volumetric flow rate 0.9 m<sup>3</sup>/s (61.1%) and 0.7 m<sup>3</sup>/s (85.2%) respectively (**see Table 5.9 and 5.10**).



**Figure 5.7:** Northwest wind with 0.5 m/s wind speed outdoor air flow characteristic

**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba



**Figure 5.8:** Northwest wind with 0.5 m/s wind speed indoor air flow characteristic  
**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba

**Table 5.9:** Northwest wind with 0.5 m/s wind speed simulation results

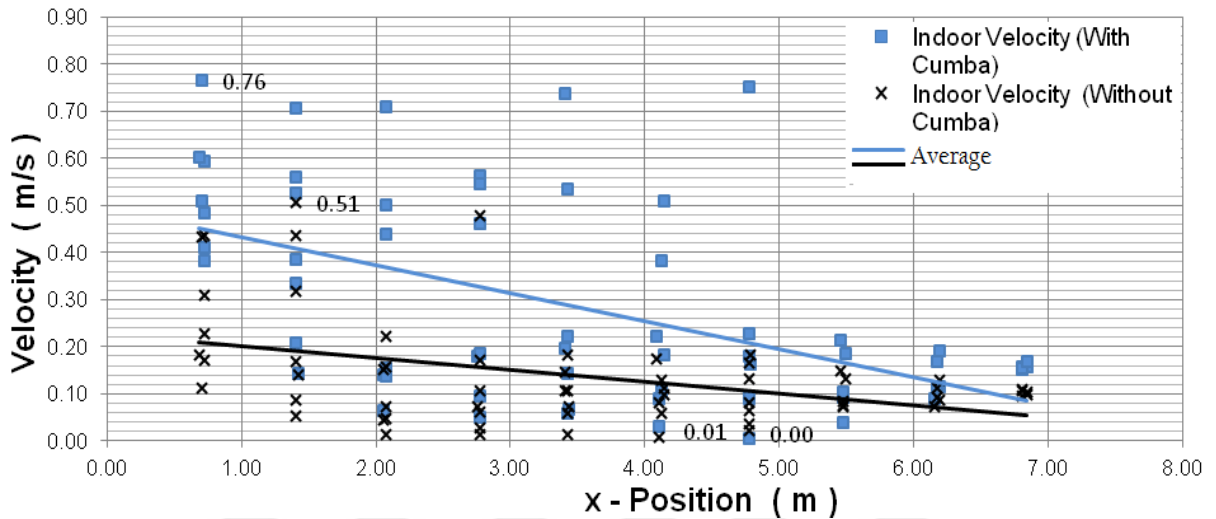
Room	Focus Room	Room Area (m <sup>2</sup> )	Number of Sensors	Max. Velocity Mag.( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag.(m/s)	Volumetric Flow Rate ( m <sup>3</sup> /s)
Sofa		45	28	0.7	0.01	0.27	
N - E	X	30	64	0.8	0	0.28	2.3
N - W	X	16	35	0.3	0.02	0.11	0.7
S - E		22	15	0.2	0.01	0.07	
S - W		16	16	0.8	0.01	0.03	
<b>( a )</b>							
Sofa		45	28	0.7	0.03	0.32	
N - E	X	30	64	0.5	0.01	0.14	1.4
N - W	X	16	35	0.2	0.01	0.07	0.3
S - E		22	15	0.06	0	0.02	
S - W		16	16	0.05	0.01	0.02	
<b>( b )</b>							

**(a)** Results for benchmark building with Cumba **(b)** Results for benchmark building without Cumba

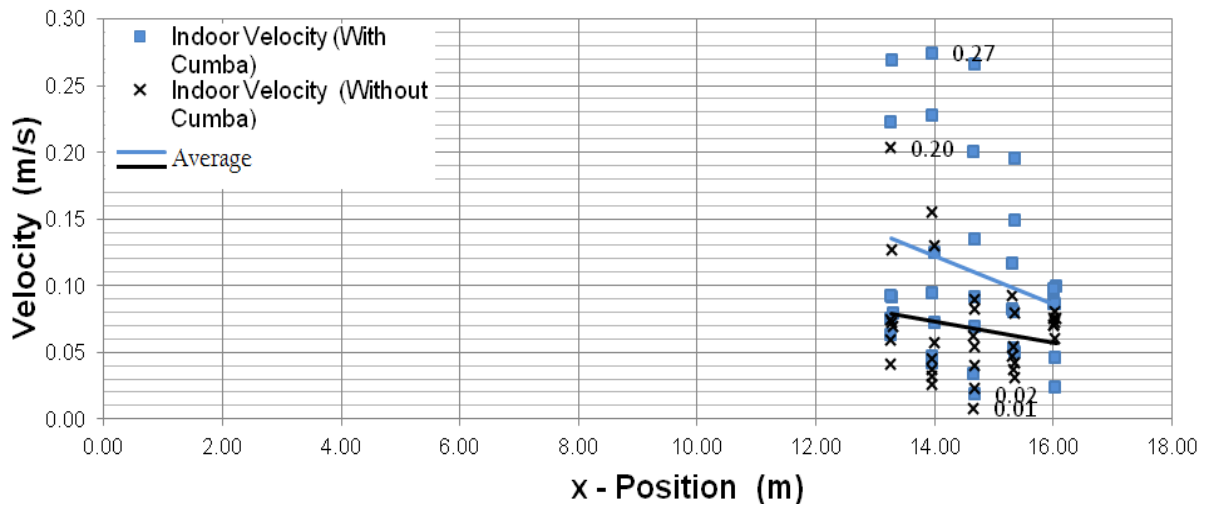
**Table 5.10:** Percentage based difference between northwest wind with 0.5 m/s wind speed simulation results for benchmark building with and without Cumba

Room	Focus Room	Max. Velocity Mag. Difference ( % )	Min. Velocity Mag. Difference ( % )	Ave. Velocity Mag. Difference ( % )	Volumetric Flow Rate Difference ( % )
Sofa		0.0	-66.7	-15.7	
N - E	X	60.0	-100.0	104.2	66.4
N - W	X	50.0	100.0	62.5	127.8
S - E		233.3	0.0	311.7	
S - W		1500.0	0.0	14.0	

As seen in both focus room’s average indoor velocity characteristic according to x-position, both room have similar characteristics, where average indoor air speed is decreased with increasing x-position (see Graph 5.6 and Graph 5.7).



Graph 5.5: Northeast room with and without Cumba indoor velocity



Graph 5.6: Northwest room with and without Cumba indoor velocity

5.2.2 Northwest wind with 2.5 m/s wind speed

There were no outdoor and indoor air pattern differences observed between northwest wind with 2.5 m/s and 0.5 m/s wind speed. Both indoor and outdoor air patens can be seen in **Fig 5.7** and **Fig 5.8**. As seen in **Table 5.10** and **Table 5.12** when the wind speed increased from 0.5 m/s to 2.5 m/s the volumetric flow rate difference between benchmark building with and without Cumba is decreased, whereby the difference 66.4% in northeast room with 0.5 m/s wind sped the difference decrease to 53.3% in 2.5 m/s wind speed (see **Table 5.10** and **Table 5.12**). Similarly the volumetric flow rate contribution of Cumba decreased from 127.8% to 115.5% when the wind velocity increased from 0.5 m/s to 2.5 m/s (see **Table 5.10** and **Table 5.12**).

**Table 5.11:** Northwest wind with 2.5 m/s wind speed simulation results

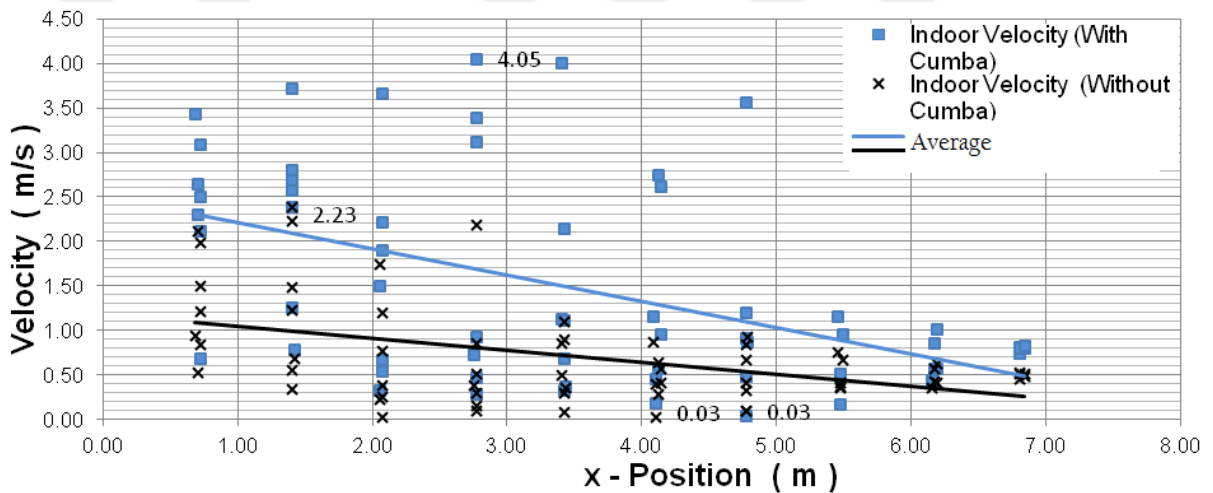
Room	Focus Room	Room Area (m2)	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag. ( m/s)	Volumetric Flow Rate ( m3/s)
Sofa		45	28	3.3	0.05	1.38	
N - E	X	30	64	4.1	0.03	1.46	10.9
N - W	X	16	35	1.5	0.09	0.64	4.4
S - E		22	15	0.6	0.09	0.28	
S - W		16	16	0.2	0.04	0.10	
( a )							
Sofa		45	28	3.4	0.1	1.56	
N - E	X	30	64	2.4	0.03	0.70	7.1
N - W	X	16	35	0.8	0.04	0.40	2.1
S - E		22	15	0.4	0.03	0.09	
S - W		16	16	0.2	0.01	0.10	
( b )							

(a) Results for benchmark building with Cumba (b) Results for benchmark building without Cumba

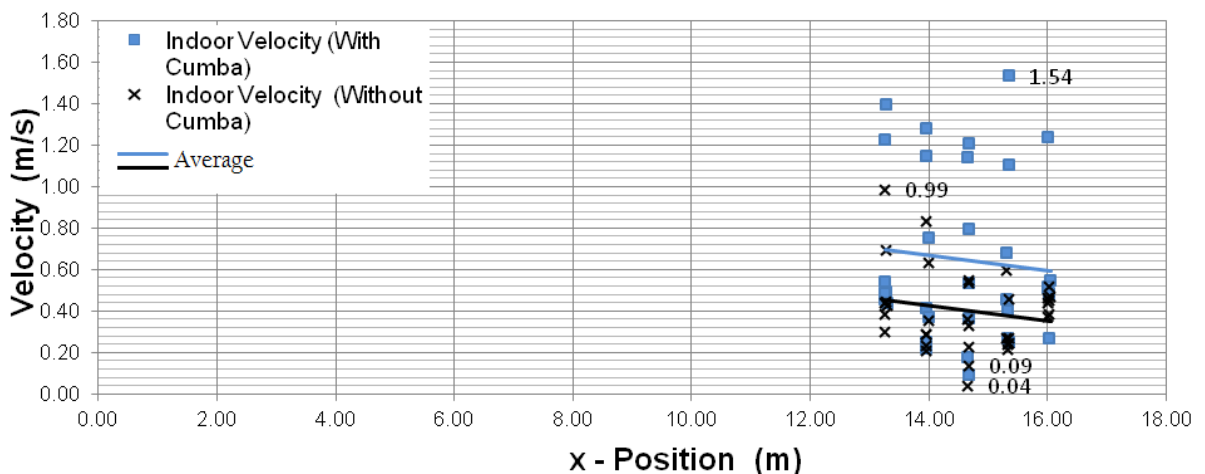
**Table 5.12:** Percentage based difference between northwest wind with 2.5 m/s wind speed simulation results for benchmark building with and without Cumba

Room	Focus Room	Max. Velocity Mag. Difference ( % )	Min. Velocity Mag. Difference ( % )	Ave. Velocity Mag. Difference ( % )	Volumetric Flow Rate Differences ( % )
Sofa		-2.9	-50.0	-11.4	
N - E	X	70.83	0.00	107.12	53.3
N - W	X	87.5	125.0	60.2	115.5
S - E		50	200	223.91	
S - W		0.0	300.0	4.7	

The greatest average indoor air velocity contribution, which Cumba cause is observed in southeast room (i.e. 0.19 m/s (223.9%)) (see Table 5.11) It was observed, for both focus rooms, the indoor average air velocity characteristic are same in both 0.5 m/s, 1.5 m/s and 2.5 m/s wind speed conditions, where there is an inverse proportion between x- position and average indoor velocity. It was observed wind speed and average indoor velocity have direct proportion, where 1 m/s wind speed acceleration, cause almost 1 m/s average indoor air velocity increase (see Graphs 5.5, 5.6, 5.7, and 5.8).



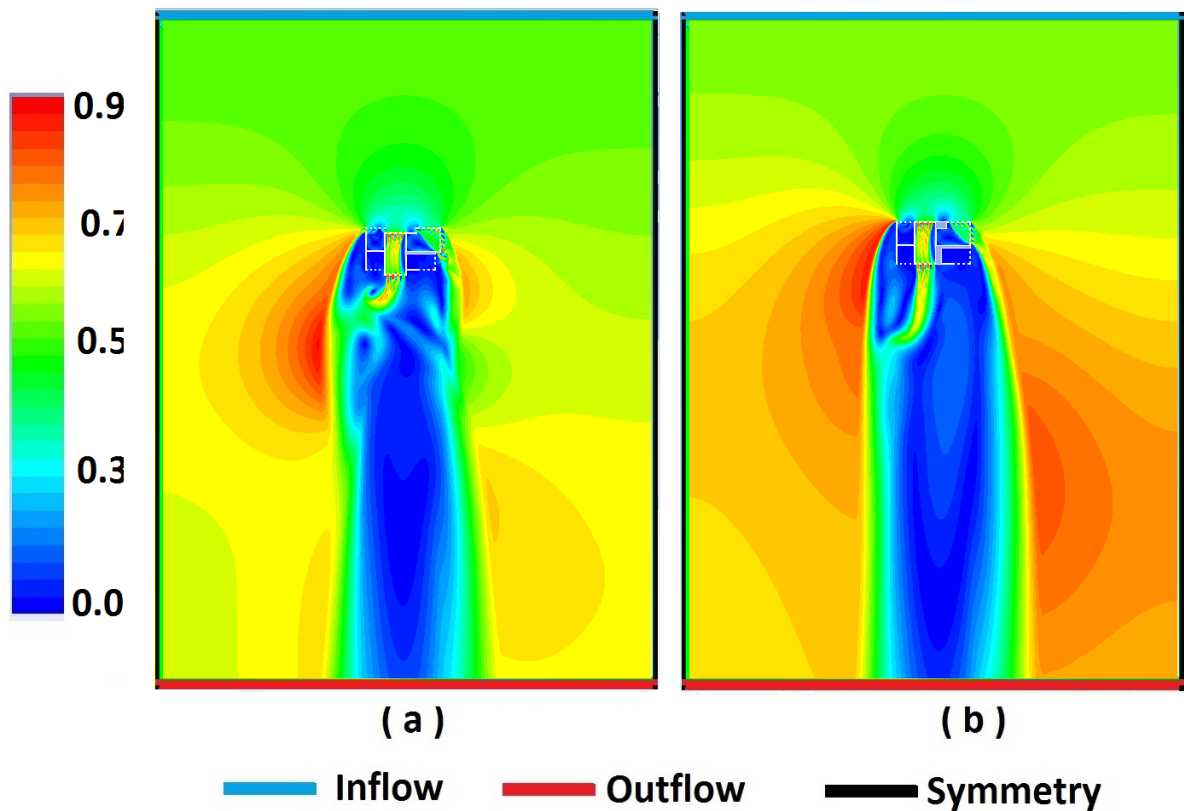
Graph 5.7: Northeast room with and without Cumba indoor velocity



Graph 5.8: Northwest room with and without Cumba indoor velocity

5.2.3 North wind with 0.5 m/s wind speed

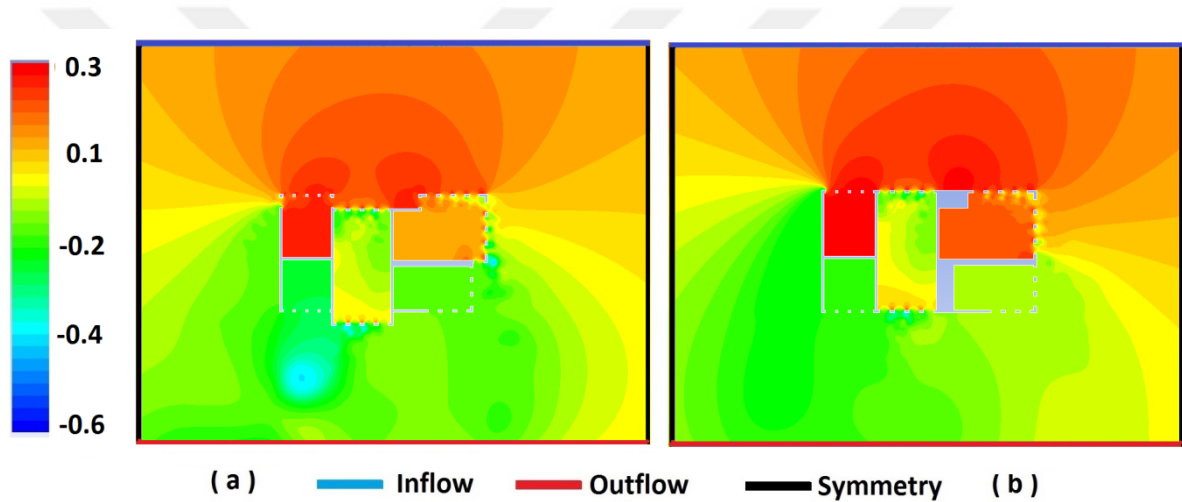
There is a considerable wind speed acceleration in external flow was observed with benchmark building without Cumba, under north 0.5 m/s north wind conditions (**Fig. 5.9**). The reason can be explained by, benchmark building without Cumba behave as obstacle for wind, therefore wind speed is increase at east and west sides of building. However, in contrast, benchmark building with Cumba let the air left the room due to extra windows opened through east, west and south side and this decrease the stress on building (**Fig. 5.9 and 5.10**).



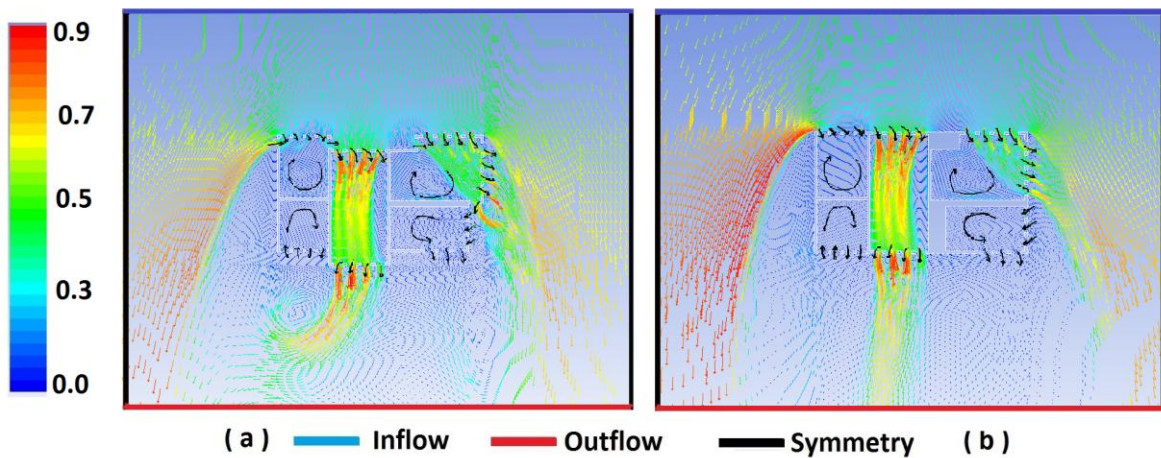
**Figure 5.9:** North wind with 0.5 m/s wind speed outdoor air flow characteristic

(a) Benchmark with Cumba (b) Benchmark without Cumba

The reason why can explain better with pressure simulation results. As seen in **Fig. 5.10**, particularly, northwest room indoor pressure is significantly decreased with Cumba, northwest room pressure decreased approximately from 0.2 Pascal to 0.1 Pascal (see **Fig. 5.10**). Similar to 1.5 m/s wind speed conditions it was observed that Cumba create Venturi effect in northwest room with east and west windows (**Fig. 5.11**), which increased northwest room volumetric flow rate 0.4 m<sup>3</sup>/s (266%) (see **Table 5.13 and 5.14**). In addition to this there is significant average indoor velocity contribution was observed with 574.3% increase in southwest room (see **Table 5.14**).



**Figure 5.10:** North wind with 0.5 m/s wind speed pressure characteristic  
**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba



**Figure 5.11:** North wind with 0.5 m/s wind speed indoor air flow characteristic  
**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba

**Table 5.13:** North wind with 0.5 m/s wind speed simulation results

Room	Focus Room	Room Area (m2)	Number of Sensors	Max. Velocity Mag.( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag.( m/s)	Volumetric Flow Rate ( m3/s)
Sofa		45	28	0.7	0.03	0.41	
N - E	X	30	64	0.6	0.0	0.24	1.0
N - W	X	16	35	0.3	0.01	0.08	0.5
S - E		22	15	0.05	0	0.03	
S - W		16	16	0.07	0.01	0.03	
<b>( a )</b>							
Sofa		45	28	0.7	0.01	0.42	
N - E	X	30	64	0.5	0	0.16	0.6
N - W	X	16	35	0.1	0.01	0.04	0.1
S - E		22	15	0.08	0.01	0.02	
S - W		16	16	0.01	0	0.00	
<b>( b )</b>							

**(a)** Results for benchmark building with Cumba **(b)** Results for benchmark building without Cumba

**Table 5.14:** Percentage based difference between north wind with 0.5 m/s wind speed simulation results for benchmark building with and without Cumba

Room	Focus Room	Max. Velocity Mag. Difference ( % )	Min. Velocity Mag. Difference ( % )	Ave. Velocity Mag. Difference ( % )	Volumetric Flow Rate Difference ( % )
Sofa		0.0	200.0	-2.3	
N - E	X	20.00	0	48.98	65.6
N - W	X	200.0	0.0	92.4	266.0
S - E		-37.5	-100	22.54	
S - W		600.0	0	574.3	

#### 5.2.4 North wind with 2.5 m/s wind speed

There were no outdoor and indoor air pattern difference observed between north wind with 2.5 m/s and 0.5 m/s wind speed. Therefore, outdoor and indoor air pattern can be seen in **Fig 5.9** and **Fig 5.11**. It was observed that particularly in northwest room, Cumba have significant natural ventilation contribution with 18 m<sup>3</sup> /s volumetric flow rate increase (409.8%) (**see Table 5.15 and Table 5.16**).

In addition to this average indoor air velocity is 197.4% accelerated in northwest room with the existence of Cumba. Similarly 0.7 m<sup>3</sup>/s the volumetric flow rate contribution (32%) can also observed wit Cumba presence of Cumba (**see Table 5.15 and Table 5.16**).

**Table 5.15:** North wind with 2.5 m/s wind speed simulation results

Room	Focus Room	Room Area (m2)	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag. ( m/s)	Volumetric Flow Rate ( m3/s)
Sofa		45	28	3.7	0.2	2.10	
N - E	X	30	64	3.1	0.05	1.20	4.7
N - W	X	16	35	1.2	0.1	0.45	2.2
S - E		22	15	0.3	0.02	0.12	
S - W		16	16	0.1	0.01	0.03	
<b>( a )</b>							
Sofa		45	28	3.5	0.06	2.03	
N - E	X	30	64	3.1	0.02	0.87	3.5
N - W	X	16	35	0.5	0.02	0.15	0.4
S - E		22	15	0.3	0.08	0.16	
S - W		16	16	0.1	0.01	0.04	
<b>( b )</b>							

**(a)** Results for benchmark building with Cumba **(b)** Results for benchmark building without Cumba

**Table 5.16:** Percentage based difference between north wind with 2.5 m/s wind speed simulation results for benchmark building with and without Cumba

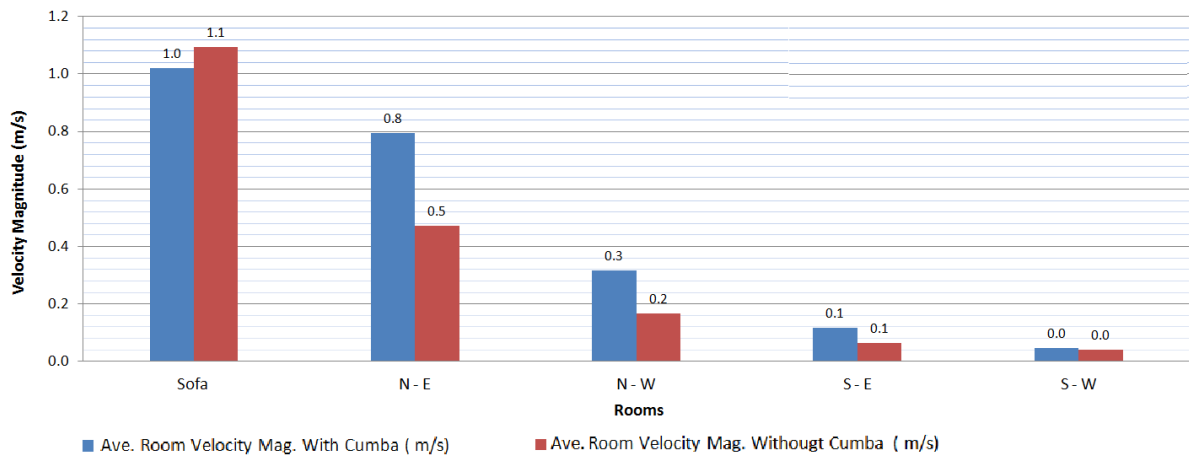
Room	Focus Room	Max. Velocity Mag. Difference ( % )	Min. Velocity Mag. Difference ( % )	Ave. Velocity Mag. Difference ( % )	Volumetric Flow Rate Difference ( % )
Sofa		5.7	233.3	3.4	
N - E	X	0.0	150.0	37.8	32.0
N - W	X	140.0	400.0	197.4	409.8
S - E		0.0	-75.0	-25.6	
S - W		0.0	0.0	-2.8	

### 5.2.5 Wind speed overall summary and comparison

All wind speed simulation results summarised and compared to examine the influence of wind direction on Cumba natural ventilation effect with a wider perspective.

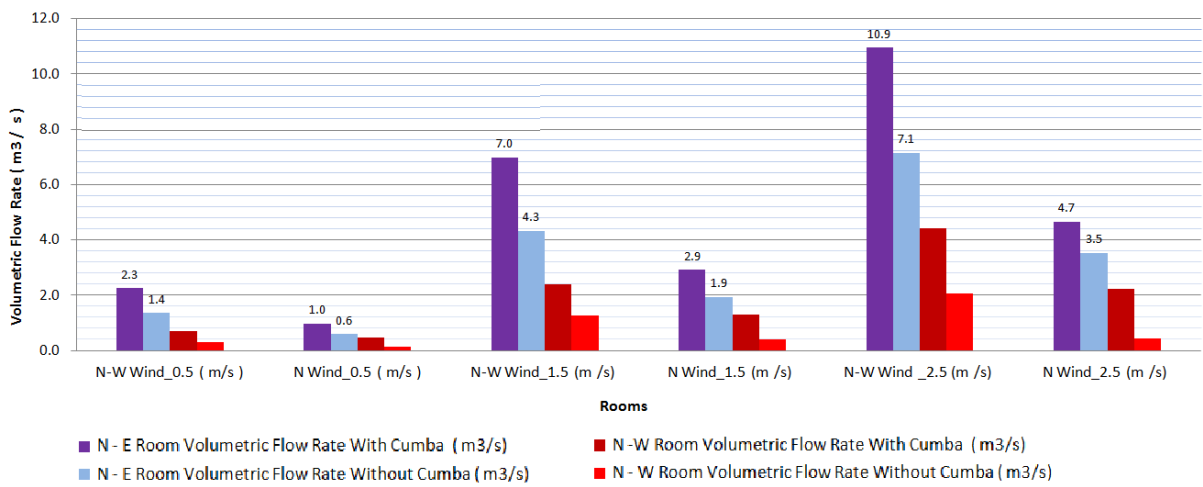
As depicted in **Graph 5.9**, similar with window width simulation results, in all 3 different wind speeds with 2 two wind directions all rooms average indoor velocity is contributed by presence of Cumba except Sofa. It was observed that existence of Cumba cause 0.1m/s overall speed attenuation in Sofa.

However at focus rooms overall average indoor air speed is 0.3 m/s increased in northeast room and 0.1 m/s increased in northwest room with existence of Cumba (see **Graph 5.9**). For each wind speed, overall wind speed influence on Cumba natural ventilation effect is also compared for focus room’s volumetric flow rate (see **Graph 5.10 and 5.11**). With Cumba a significant volumetric flow rate contribution was observed for all wind speeds and directions (see **Graph 5.10**). The biggest volumetric flow rate contribution was observed on northwest room under 2.5 m/s north wind conditions, where 409.8% volumetric flow rate acceleration was observed (see **Graph 5.11**) Minimum contribution was observed as 32% in northeast room with 2.5 m/s north wind direction.

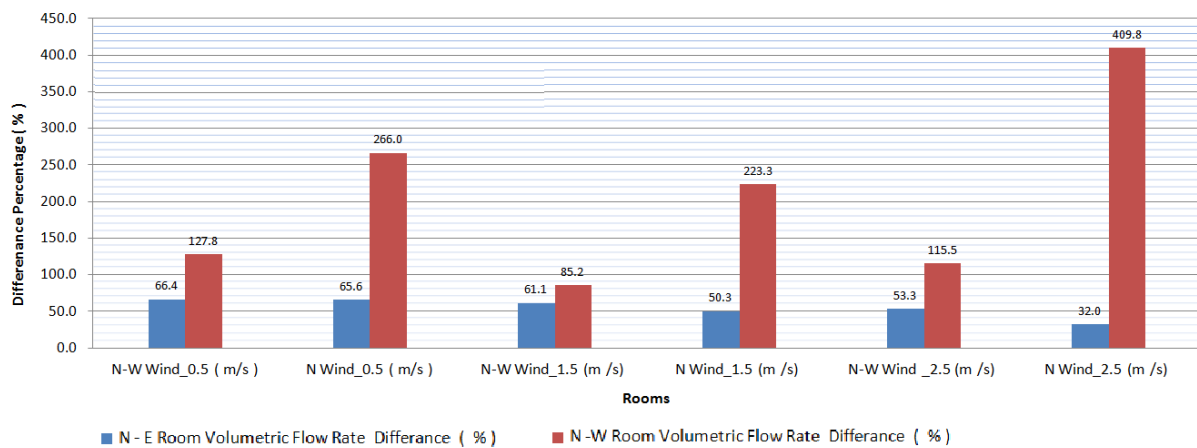


**Graph 5.9:** Overall wind speed influence on average indoor air velocity

In conclusion, as seen in the summary graphs, Cumba have considerable natural ventilation contribution in all wind speeds and directions. **Graph 5.12** illustrates focus rooms (i.e. *northeast and northwest*) room average volumetric flow rate, which cover volumetric flow rates averages for total 3 wind speed wind two directions. As seen in **Graph 5.12**, Cumba contribute the volumetric flow rate average 1.6 m<sup>3</sup>/s for northeast room and 1.1 m<sup>3</sup>/s for northwest room in all wind speeds.

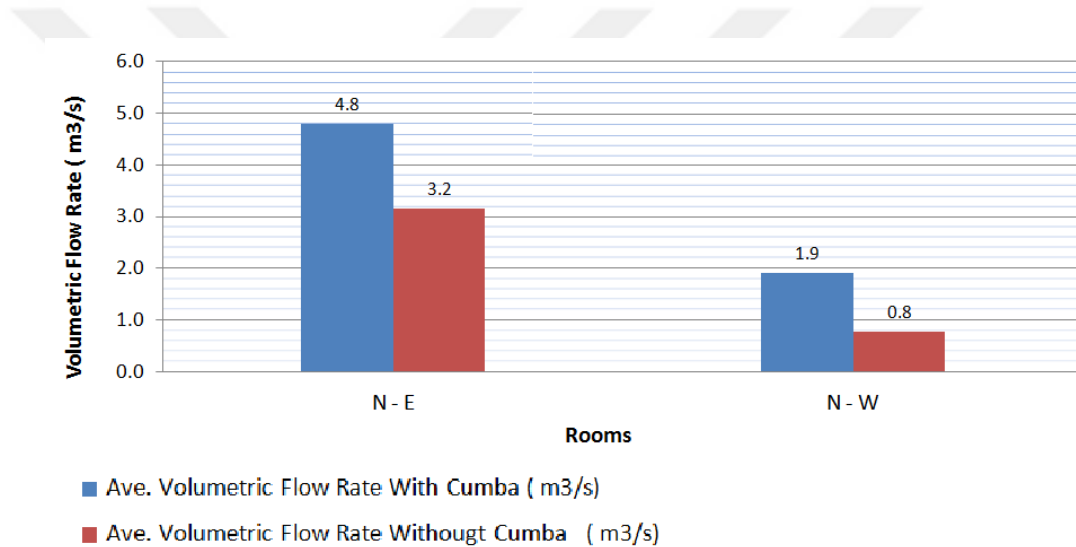


**Graph 5.10:** Overall wind direction influence on volumetric flow rate



**Graph 5.11:** Overall volumetric flow rate average difference percentages

**Graph 5.12** illustrates the existence of Cumba contributes the focus rooms volumetric flow rates as 1.6 m<sup>3</sup>/s (53.8%) to northeast room and 1.1 m<sup>3</sup>/s (137.5%) northwest room. The existence of a Cumba contributes to the focus rooms’ average volumetric flow rate in total 1.4 m<sup>3</sup>/s (see **Graph 5.12**). Compared with window width and wind speed influence on natural ventilation effect of Cumba, it is seen that window width has more natural ventilation effect of Cumba, because the overall average volumetric flow rate was 1.8 m<sup>3</sup>/s window with influence but wind speed influence is observed 1.4 m<sup>3</sup>/s (see **Graph 5.4 and 5.12**).



**Graph 5.12:** Overall volumetric flow rate average results for all wind directions averages for focus rooms

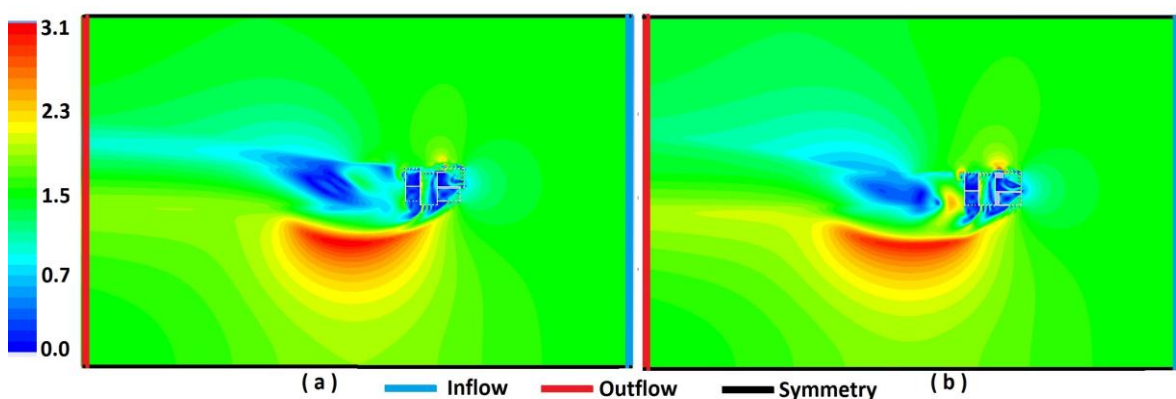
### 5.3. The Influence of Wind Direction on Natural Ventilation Effect of Cumba

In this section the influence of eight different wind directions (*i.e. north, northwest, northeast, south, southwest, southeast, east and west*) influence on natural ventilation effect of Cumba was analysed with CFD simulations. During all simulations wind speed and widow speed is fixed with 1.5 m/s and 80cm respectively.

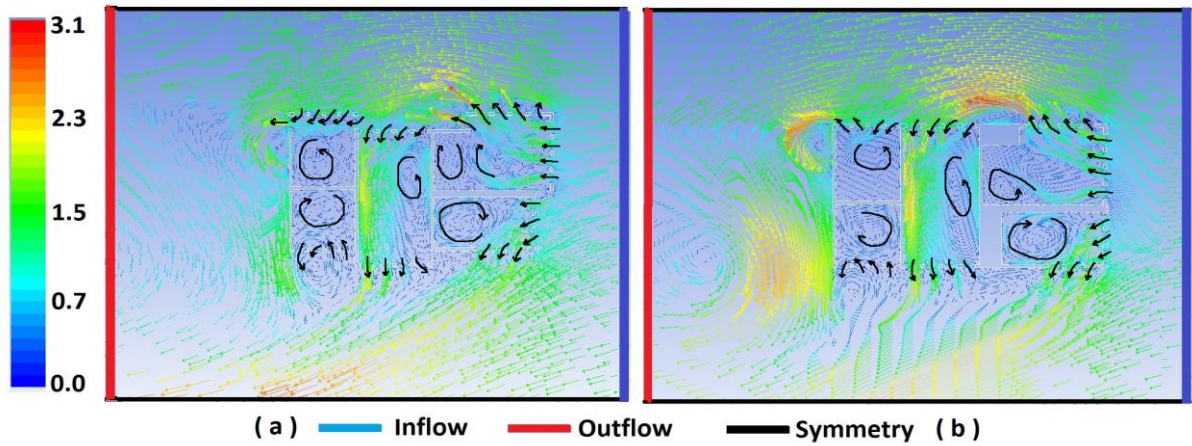
### 5.3.1 East wind

**Fig. 5.11** depicts the outdoor air flow pattern around the building. Larger negative pressure zone in downstream zone was observed with Cumba (**Fig.5.12a**). Also in sample without Cumba there was a higher velocity area was observed in east side of Sofa north wall (**see Fig. 5.12b**). Benchmark building indoor air flow patterns are illustrated in **Fig 5.13**. In general there is no significant air flow patter difference was observed between benchmark building with and without Cumba, except for northwest room with Cumba (**Fig 5.13a**). As seen **Fig 5.13a** the presence of Cumba created Venturi effect, which caused a vortex and acceleration in the northwest room.

**Table 5.17** indicates the indoor air speed and volumetric flow rates. In general the average indoor air velocity is higher in benchmark building with Cumba accept Sofa and southeast room (**Table 5.17a,b**). Particularly northwest room volumetric flow rate is almost three times increased with Cumba. Although, northeast room with Cumba volumetric flow rate is increased  $1.1 \text{ m}^3/\text{s}$  as well, the difference is not as much as northwest room volumetric flow rate variation (**see Table 5.17**). Room indoor air speed and volumetric flow rate difference percentages were addressed in **Table 5.18**. For benchmark building with Cumba, there is 9.2% average indoor air velocity attenuation was observed in Sofa (**see Table 5. 18**).



**Figure 5.12:** East wind outdoor air flow characteristic  
**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba



**Figure 5.13:** East wind indoor air flow characteristic  
 (a) Benchmark with Cumba (b) Benchmark without Cumba

**Table 5.17:** East wind simulation results

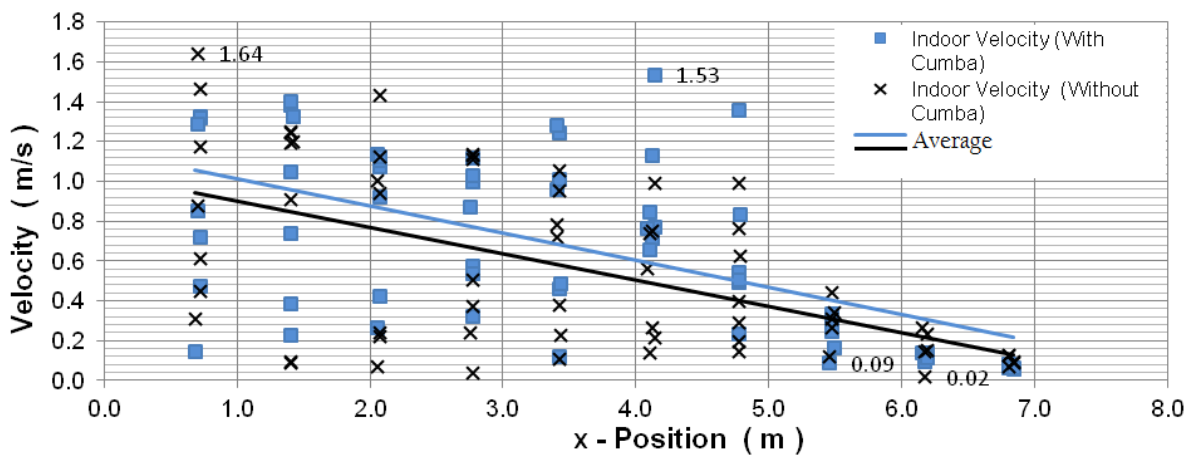
Room	Focus Room	Room Area (m <sup>2</sup> )	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag. ( m/s)	Average Velocity Mag. ( m/s)	Volumetric Flow Rate ( m <sup>3</sup> /s)
Sofa		45	28	2.1	0.1	0.94	
N - E	X	30	64	1.5	0.06	0.67	6.5
N - W	X	16	35	0.9	0.07	0.30	3.0
S - E		22	15	1.3	0.1	0.56	
S - W		16	16	0.5	0.09	0.27	
<b>( a )</b>							
Sofa		45	28	2.3	0.1	1.03	
N - E	X	30	64	1.6	0.07	0.56	5.4
N - W	X	16	35	0.7	0.06	0.23	1.2
S - E		22	15	1.1	0.09	0.56	
S - W		16	16	0.4	0.06	0.25	
<b>( b )</b>							

(a) Results for benchmark building with Cumba (b) Results for benchmark building without Cumba

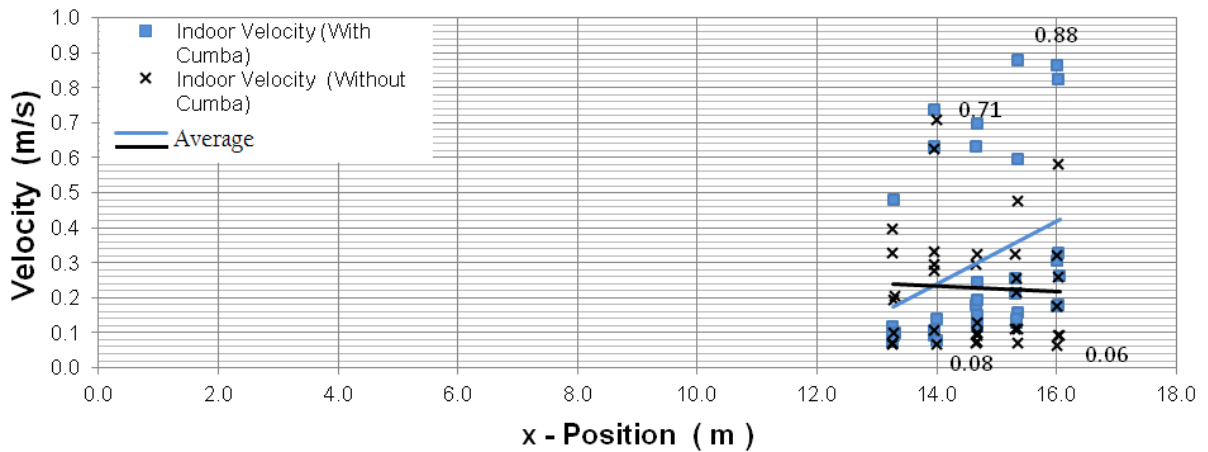
**Table 5.18:** Percentage based difference between east wind simulation results for benchmark building with and without Cumba

Room	Focus Room	Max. Velocity Mag. Difference ( % )	Min. Velocity Mag. Difference ( % )	Ave. Velocity Mag. Difference ( % )	Volumetric Flow Rate Difference ( % )
Sofa		-8.7	0.0	-9.2	
N - E	X	-6.3	-14.3	17.9	19.6
N - W	X	28.6	16.7	30.6	152.8
S - E		18.2	11.1	-0.7	
S - W		25.0	50.0	5.5	

The reason can be explained by inflow wind direction and the air flow path with Cumba. Wind is coming from east side of the benchmark building and Cumba direct the wind through northwest room east window, which create blockage with air and influence the Sofa air inlet, this decrease the Sofa indoor air speed (see Fig 5.13). The significant average indoor air velocity variation was observed in northwest room with Cumba. The 30.6% increase (see Table 5. 18) in northwest room indoor speed can explained by the Cumba creating one more extra outlet, therefore the room average air velocity is considerably increased with sample with Cumba (see Fig 5.13). The biggest difference was observed in northwest room volumetric flow rate with Cumba, where the volumetric flow rate of 152.8% increased due to Venturi effect caused by Cumba (see Table 5. 18). CFD indoor measurement points results are also compared in Graph 5.13 and Graph 5.14. Northeast room average air flow speed have similar characteristic and Cumba accelerate the indoor average air speed (see Graph 5.13). However, northwest room average indoor velocity characteristic change with Cumba. For without Cumba sample the indoor velocity is decreased with increasing x- position, but in contrast with Cumba indoor average air velocity increasing wit increasing x- position (see Graph 5.14). The different average indoor air speed characteristic may explain with the occurred vortex with Cumba, where it accelerate the air speed at back part of the room (see Fig 5.13).



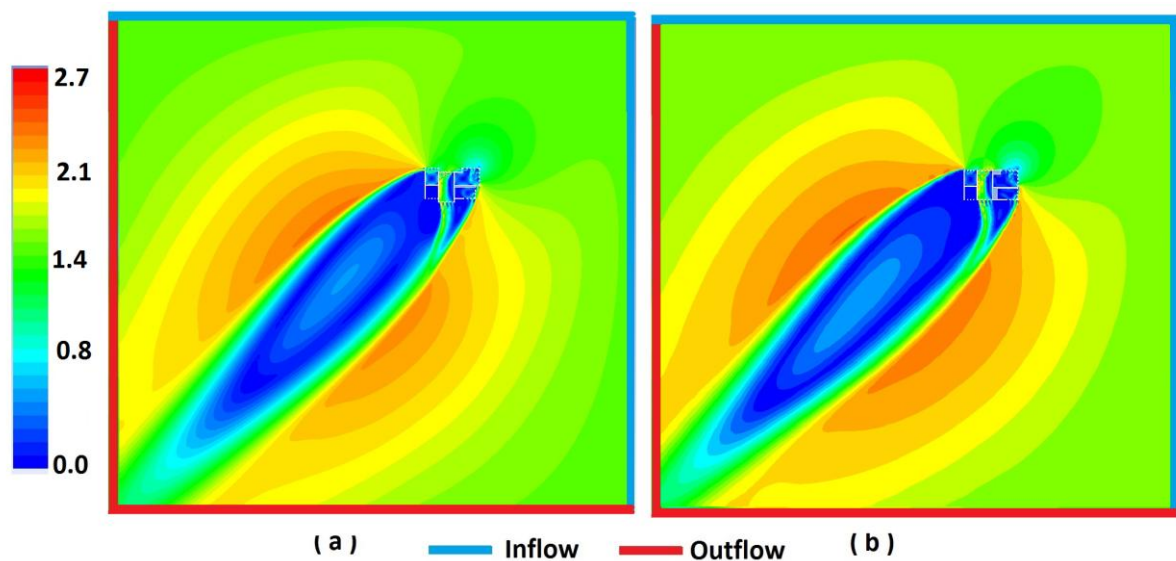
Graph 5.13: Northeast room with and without Cumba indoor velocity comparison



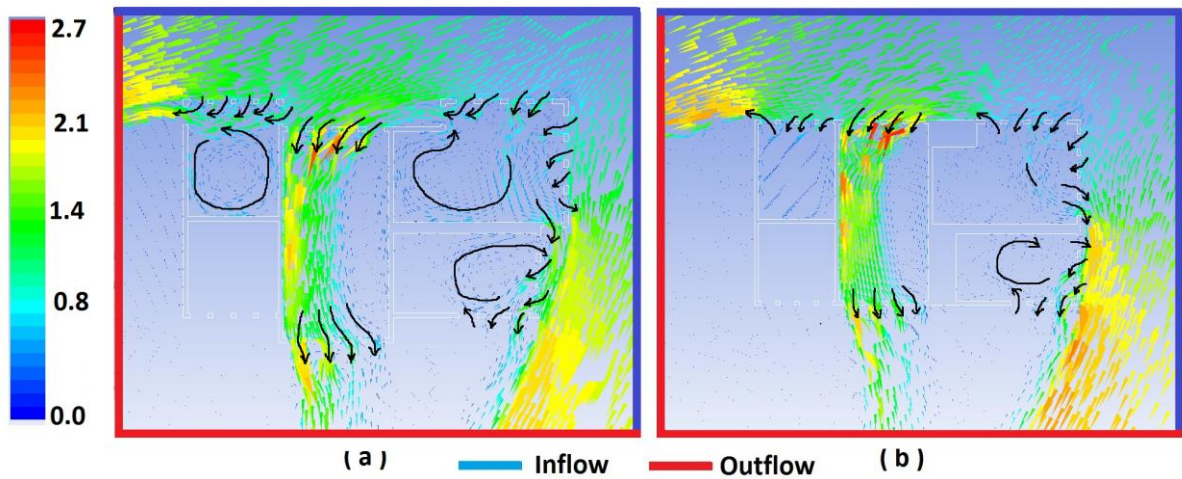
**Graph 5.14:** Northwest room with and without Cumba indoor velocity comparison

### 5.3.2 Northeast wind

There is no significant outdoor air flow pattern observed between the benchmark buildings with and without samples (see Fig 5.14). However, it is observed that speed of air and amount, which passing through the Sofa is slightly more in sample building without Cumba and this cause slight wind speed differences in downstream zone in benchmark building without Cumba sample (see Fig 5.14b). In Fig 5.15 it can be seen there is a vortex consist in northwest room and northeast room (Fig 5.15a), which cause 20m/s , 16 m/s average indoor air velocity acceleration respectively (see Table 5.19).



**Figure 5.14:** Northeast wind outdoor air flow characteristic  
**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba



**Figure 5.15:** Northeast wind indoor air flow characteristic  
**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba

**Table 5.19:** Northeast wind simulation results

Room	Focus Room	Room Area (m <sup>2</sup> )	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag. ( m/s)	Volumetric Flow Rate ( m <sup>3</sup> /s)
Sofa		45	28	2	0.1	0.92	
N - E	X	30	64	0.9	0.05	0.40	2.7
N - W	X	16	35	1.1	0.08	0.46	3.3
S - E		22	15	0.4	0.06	0.22	
S - W		16	16	0.4	0	0.04	
<b>(a)</b>							
Sofa		45	28	2	0.01	1.00	
N - E	X	30	64	0.7	0.03	0.24	1.3
N - W	X	16	35	0.7	0.01	0.26	1.1
S - E		22	15	0.5	0.04	0.19	
S - W		16	16	0.2	0	0.03	
<b>(b)</b>							

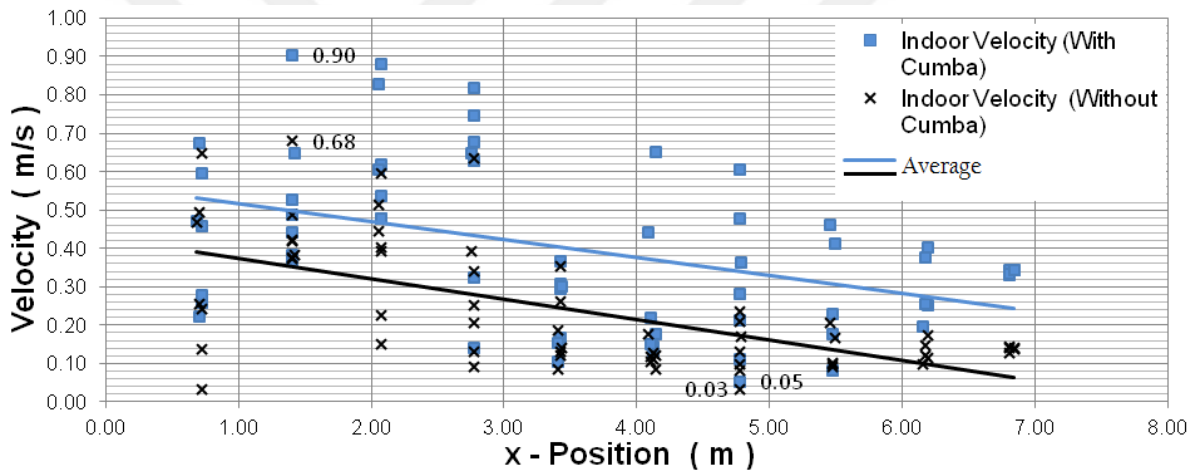
**(a)** Results for benchmark building with Cumba **(b)** Results for benchmark building without Cumba

**Table 5.20:** Percentage based difference between northeast wind simulation results for benchmark building with and without Cumba

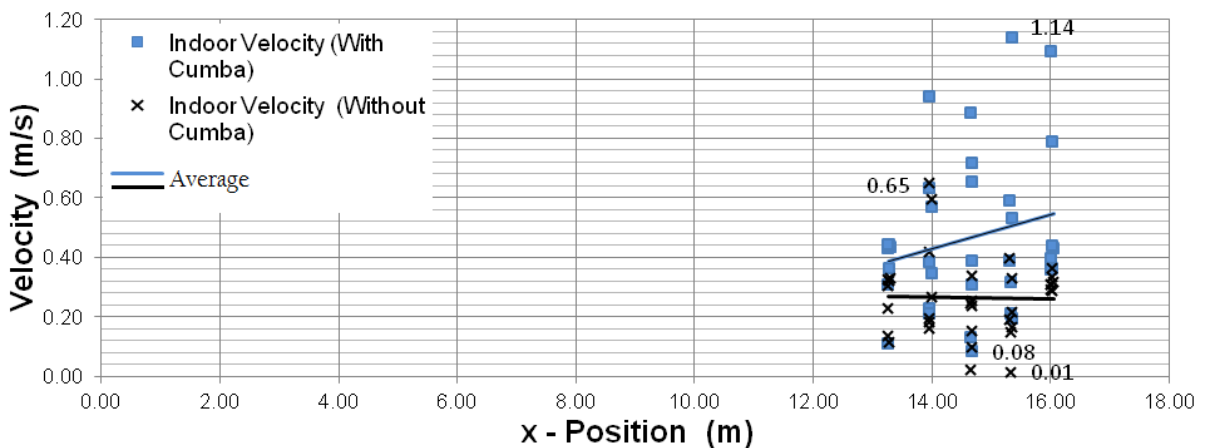
Room	Focus Room	Max. Velocity Mag. Difference (%)	Min. Velocity Mag. Difference (%)	Ave. Velocity Mag. Difference (%)	Volumetric Flow Rate Difference (%)
Sofa		0.0	900.0	-7.9	
N - E	X	28.6	66.7	66.1	113.8
N - W	X	57.1	700.0	76.1	201.9
S - E		-20.0	50.0	13.0	
S - W		100.0	0	37.3	

Similar to east wind direction results, the existence of Cumba cause 0.8 m/s indoor air speed attenuation in Sofa (see Table 5.19). In both northeast and northwest rooms Cumba contribute the volumetric flow rate 113.8% and 201.9% respectively (see Table 5.20). Similar to volumetric flow rate results, average indoor air velocity are increased 66.1% for northeast room and 76.1% for northwest room (see Table 5.20).

As seen in Graph 5.15 in northeast wind flow conditions, focus rooms indoor velocity characteristics where same as east wind flow where, velocity is decreased with increased x-position. Similar with east wind direction Cumba cause average indoor speed acceleration on northeast room (see Graph 5.16).



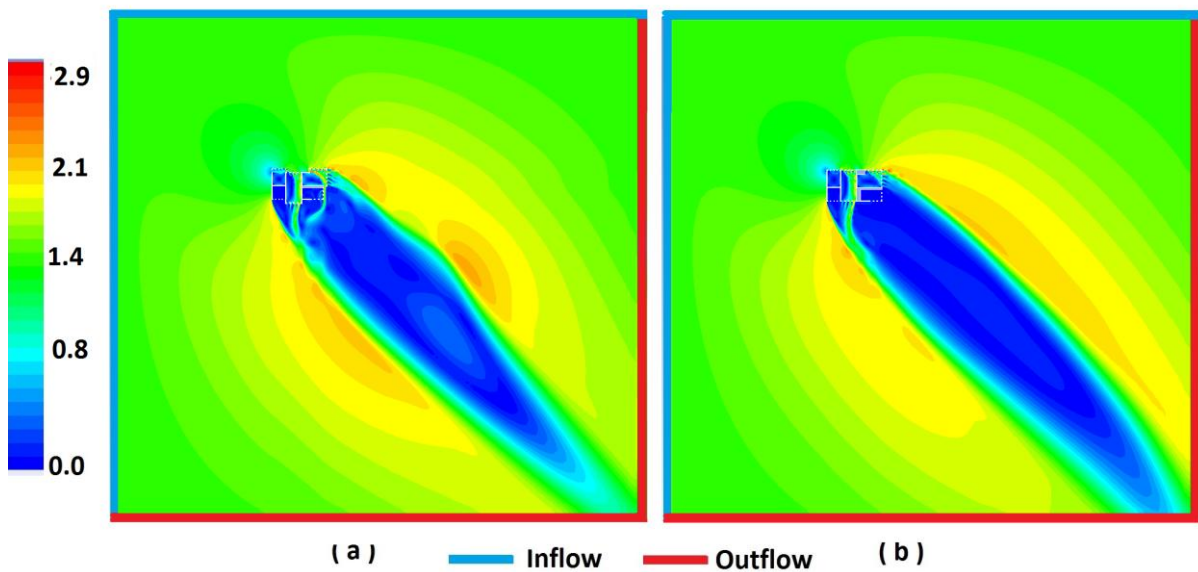
Graph 5.15: Northeast room with and without Cumba indoor velocity



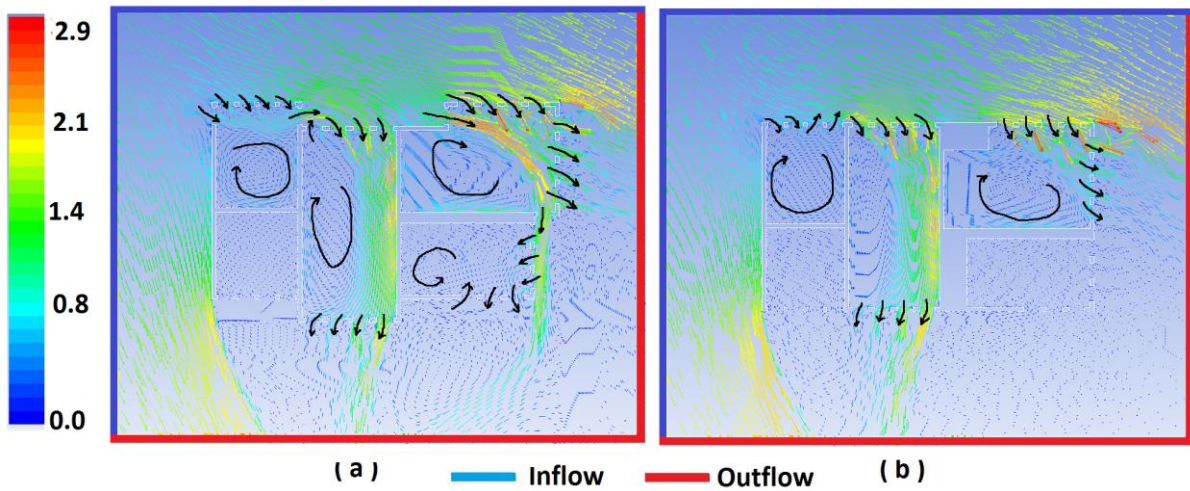
Graph 5.16: Northwest room with and without Cumba indoor velocity

5.3.3 Northwest wind

In contrast with previous two wind directions mentioned before, under northwest wind direction conditions there is a significant outdoor air flow pattern difference was observed between benchmark with and without Cumba samples (**Fig 5.16**). In **Fig 5.16a** it can be seen that the Cumba directs the northwest wind to negative pressure zone in downstream area and accelerates the air speed by 120% at the southeast room (see **Table 5.22**).

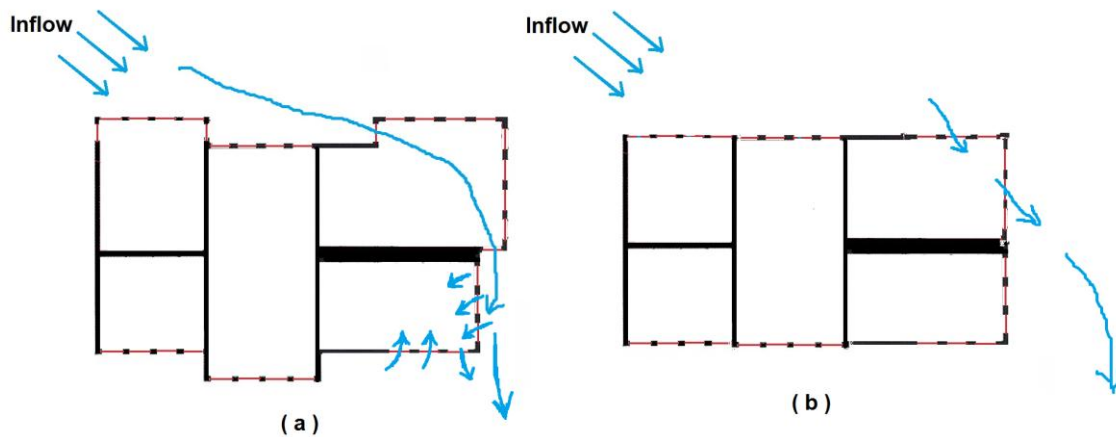


**Figure 5.16:** Northwest wind outdoor air flow characteristic  
 (a) Benchmark with Cumba (b) Benchmark without Cumba



**Figure 5.17:** Northwest wind indoor air flow characteristic  
 (a) Benchmark with Cumba (b) Benchmark without Cumba

In addition to this the existence of Cumba increase northeast and northwest room volumetric flow rate by  $2.7 \text{ m}^3/\text{s}$  (61.1%) and  $1.1 \text{ m}^3/\text{s}$  (85.2%) respectively (see **Table 5.21 and 5.22**). **Fig. 5.18** demonstrates the explanation for significant increase on indoor air speed and volumetric flow rate in southeast room. It was observed that Cumba cause significant wind flow pattern change in northwest room, it can be seen **Fig 5.16** and **5.17**. Cumba directs the northwest wind through the southeast room via northeast room south window (see **Fig 5.18**). The outdoor air flow pattern change cause significant contribution on southeast room natural ventilation.



**Figure 5.18:** Southeast room natural ventilation development explanation  
(a) With Cumba (b) Without Cumba

The influence of cumba on northeast room average indoor velocity can also clearly be seen in **Graph 5.17**, where although the average indoor velocity lines were parallel each other in previous wind direction conditions, with northwest wind direction average indoor velocity with cumba line decrease with increasing x-position sharper than average indoor velocity without cumba (**Graph 5.17**). In addition to this northwest room average indoor velocity with Cumba line characteristic is different than previous simulations, where velocity is decreasing with increasing x-position. This can be explained by the changing wind direction. In previous two simulations wind is coming from east side of the building but in this simulation wind is coming from northwest direction (**Fig 5.16**).

Table 5.21: Northwest wind simulation results

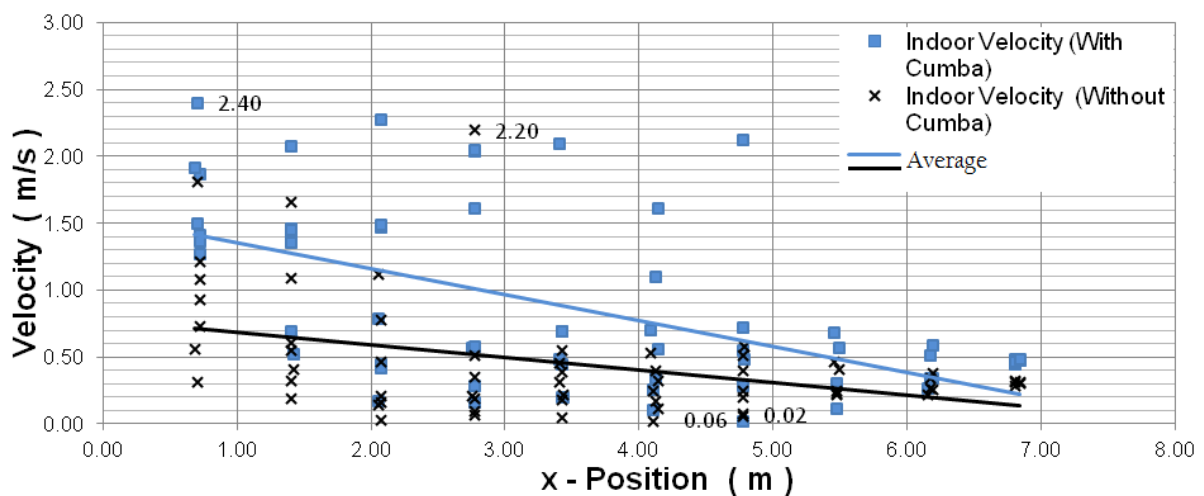
Room	Focus Room	Room Area (m2)	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag.(m/s)	Volumetric Flow Rate ( m <sup>3</sup> /s)
Sofa		45	28	2.1	0.04	0.83	
N - E	X	30	64	2.4	0.02	0.86	7.0
N - W	X	16	35	0.9	0.07	0.40	2.4
S - E		22	15	0.3	0.03	0.14	
S - W		16	16	0.1	0.02	0.06	
( a )							
Sofa		45	28	2.1	0.08	0.95	
N - E	X	30	64	2.2	0.02	0.45	4.3
N - W	X	16	35	0.6	0.02	0.23	1.3
S - E		22	15	0.2	0.03	0.06	
S - W		16	16	0.1	0.01	0.06	
( b )							

(a) Results for benchmark building with Cumba (b) Results for benchmark building without Cumba

Table 5.22: Percentage based difference between northwest wind simulation results for benchmark building with and without Cumba

Room	Focus room	Max. Velocity Mag. Difference (%)	Min. Velocity Mag. Difference (%)	Ave. Velocity Mag. Difference (%)	Volumetric Flow Rate Difference (%)
Sofa		0.0	-50.0	-12.5	
N - E	X	9.1	0.0	93.8	61.1
N - W	X	50.0	250.0	69.5	85.2
S - E		50.0	0.0	120.1	
S - W		0.0	100.0	0.4	

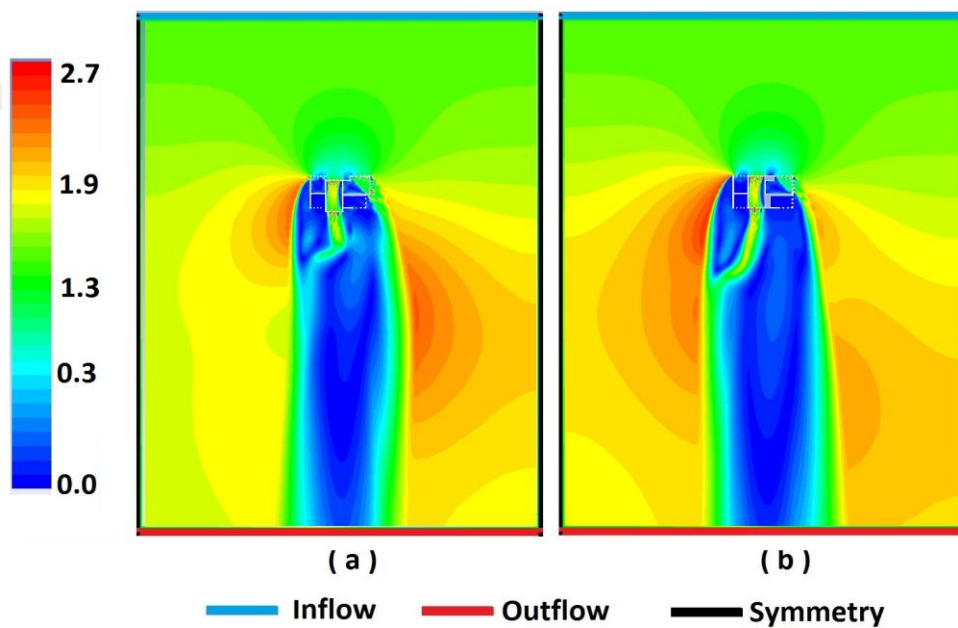
Graph 5.22 northeast room with and without Cumba indoor velocity



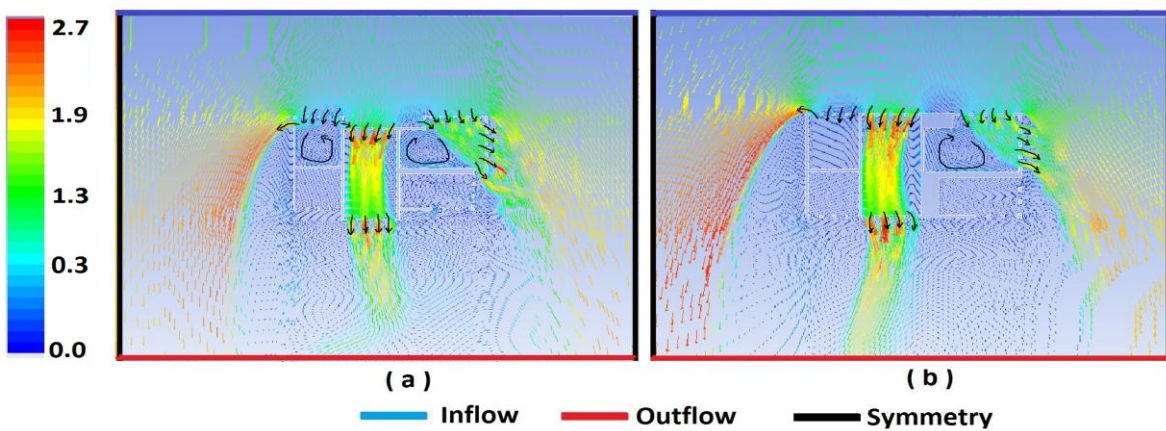
Graph 5.17: Northwest room with and without Cumba indoor velocity

5.3.4 North wind

As seen in **Fig. 5.19** wind flow through Sofa cause flow pattern and speed variations at downstream between benchmark building with and without Cumba. It was observed that Cumba create Venturi effect in northwest room (**Fig. 5.20**), which increased northwest room volumetric flow rate more than three times (223.3%) (**see Table 5.24**). Similarly northwest room average indoor air velocity is 0.12 m/s increased with Cumba (**see Table 5.23**).

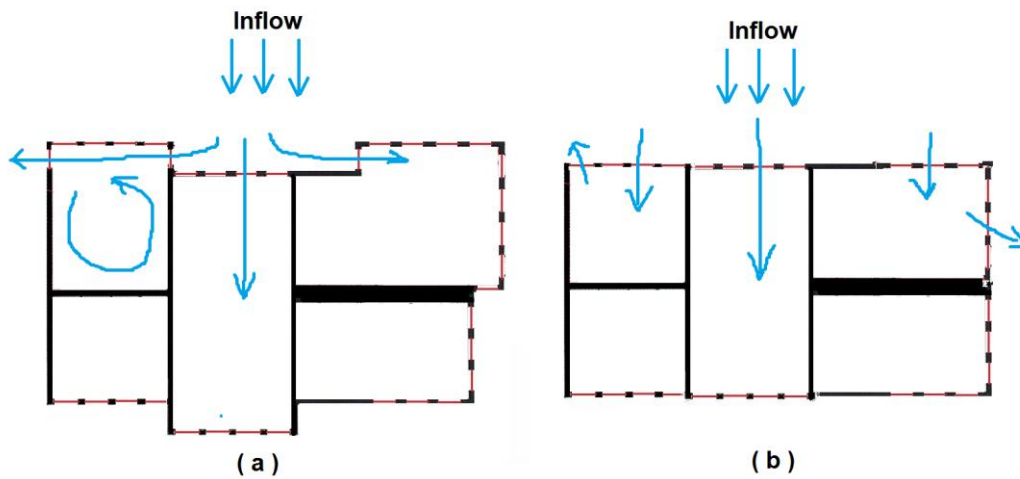


**Figure 5.19:** North wind outdoor air flow characteristic  
 (a) Benchmark with Cumba (b) Benchmark without Cumba



**Figure 5.20:** North wind indoor air flow characteristic  
 (a) Benchmark with Cumba (b) Benchmark without Cumba

The reason of significantly contributed natural ventilation on northwest room with Cumba was illustrated (Fig. 5.21) As seen in Fig. 5.21a north wind flow through east and west direction after hit the benchmark building north wall. Cumba Cause Venturi effect, where significantly accelerate the air flow and create suction effect in overall room and this cause significant contribution on both volumetric flow rate and average indoor air speed. In contrast at benchmark building without Cumba air access enter and left the room via north window, which significantly disturb the air circulation in the room (see Fig. 5.21 b).



**Figure 5.21:** North wind indoor air flow characteristic  
 (a) Benchmark with Cumba (b) Benchmark without Cumba

**Table 5.23:** North wind simulation results

Room	Focus Room	Room Area (m2)	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag. ( m/s)	Volumetric Flow Rate ( m3/s)
Sofa		45	28	2.2	0.2	1.13	
N - E	X	30	64	1.6	0.03	0.72	2.9
N - W	X	16	35	0.7	0.02	0.23	1.3
S - E		22	15	0.1	0.04	0.08	
S - W		16	16	0.09	0	0.03	
( a )							
Sofa		45	28	2.2	0.04	1.29	
N - E	X	30	64	1.8	0.02	0.51	1.9
N - W	X	16	35	0.4	0	0.11	0.4
S - E		22	15	0.2	0.1	0.05	
S - W		16	16	0.06	0.01	0.02	
( b )							

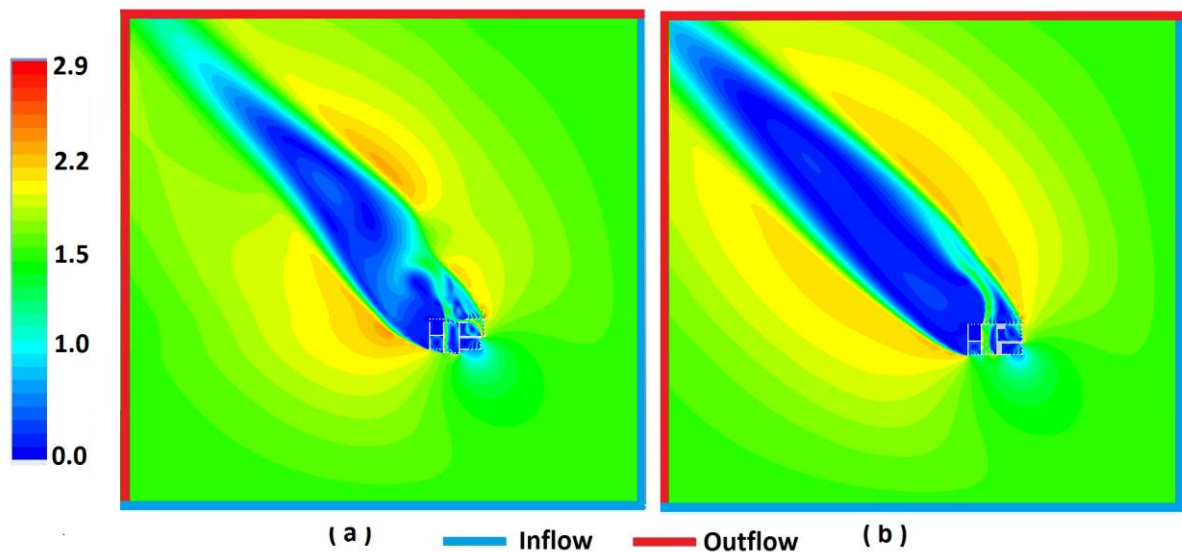
(a) Results for benchmark building with Cumba (b) Results for benchmark building without Cumba

**Table 5.24:** Percentage based difference between north wind simulation results for benchmark building with and without Cumba

Room	Focus Room	Max. Velocity Mag. Difference (%)	Min. Velocity Mag. Difference (%)	Ave. Velocity Mag. Difference (%)	Volumetric Flow Rate Difference (%)
Sofa			400.0	- 12.1	
N - E	X	- 11.1	50.0	39.2	50.3
N - W	X	75.0	0	114.3	223.3
S - E		- 50.0	- 60.0	68.3	
S - W		50.0	- 100.0	12.8	

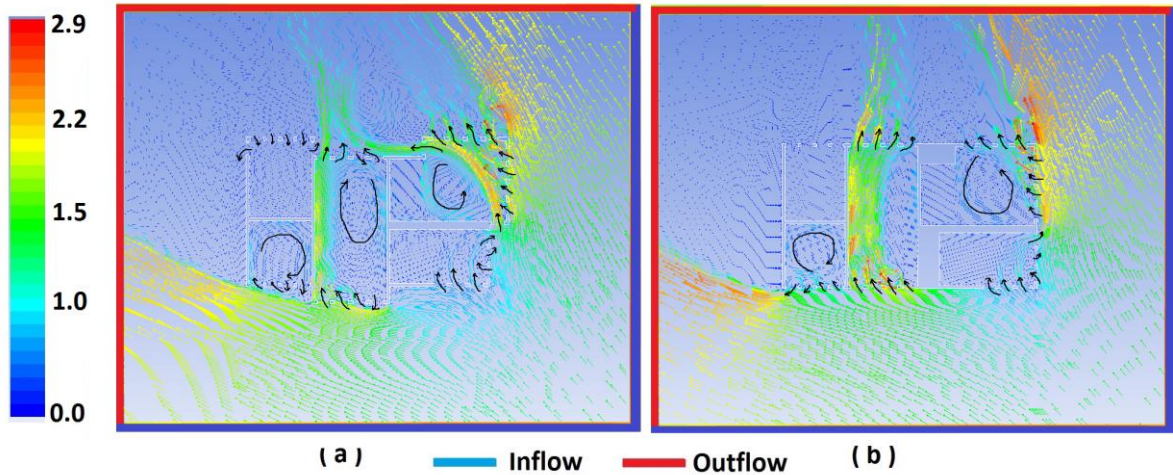
### 5.3.5 Southeast wind

There is a significant outdoor wind flow pattern difference was observed under southeast wind direction conditions (see Fig. 5.22). Benchmark building southeast room with Cumba collect more wind Compared with benchmark building without Cumba and direct the southwest wind through the low-pressure zone (see Fig. 5.23). Southeast room average indoor velocity was increased 285% with presence of Cumba (see Table 5.25). Although northwest room volumetric flow rate was not changed, northeast room volumetric flow rate increased 0.6 m<sup>3</sup>/s with Cumba (see Table 5.26).

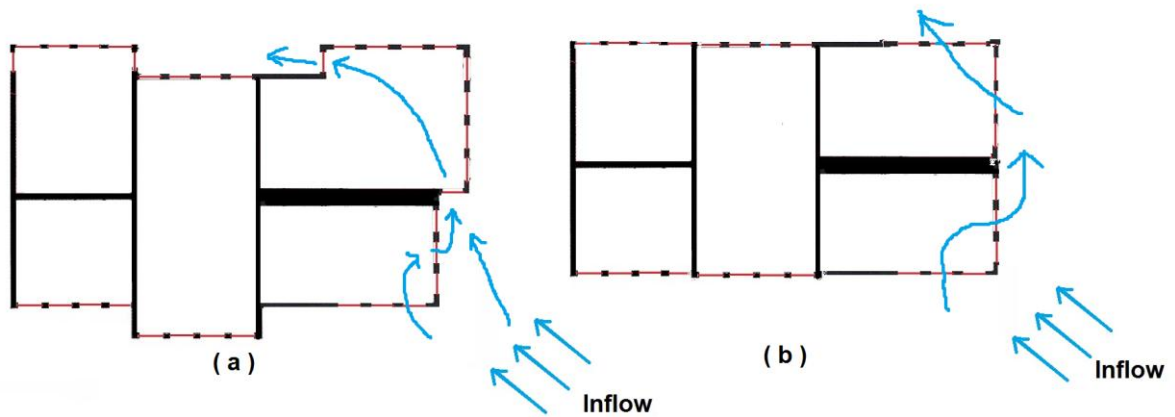


**Figure 5.22:** Southeast wind outdoor air flow characteristic (a) Benchmark with Cumba (b) Benchmark without Cumba

As seen in **Fig. 5.24** indoor air pattern significantly contributed with Cumba, because Cumba work as horizontal wind catcher (see **Fig. 5.24 a**).



**Figure 5.23:** Southeast wind indoor air flow characteristic  
**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba



**Figure 5.24:** Southeast wind indoor air flow characteristic  
**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba

**Table 5.25:** Percentage based difference between southeast wind simulation results for benchmark building with and without Cumba

Room	Focus Room	Max. Velocity Mag. Difference (%)	Min. Velocity Mag. Difference (%)	Ave. Velocity Mag. Difference (%)	Volumetric Flow Rate Difference (%)
Sofa		5.0	14.3	-31.0	
N - E	X	37.5	100.0	163.6	22.5
N - W	X	-66.7	0.0	284.0	4.2
S - E		-16.7	500.0	-31.5	
S - W		0.0	300.0	22.3	

Table 5.26: Southeast wind simulation results

Room	Focus Room	Room Area (m <sup>2</sup> )	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag. ( m/s)	Volumetric Flow Rate ( m <sup>3</sup> /s)
Sofa		45	28	2.1	0.08	0.67	
N - E	X	30	64	2.2	0.08	0.81	3.4
N - W	X	16	35	0.1	0.02	0.07	0.1
S - E		22	15	0.5	0.06	0.17	
S - W		16	16	0.6	0.08	0.30	
( a )							
Sofa		45	28	2	0.07	0.98	
N - E	X	30	64	1.6	0.04	0.31	2.8
N - W	X	16	35	0.3	0	0.02	0.1
S - E		22	15	0.6	0.01	0.25	
S - W		16	16	0.6	0.02	0.24	
( b )							

(a) Results for benchmark building with Cumba (b) Results for benchmark building without Cumba

### 5.3.6 Southwest wind

As seen in **Fig.5.25** outdoor wind flow pattern there is no big difference was observed between benchmark building with and without Cumba except air acceleration through Sofa (see **Fig. 5.26**).

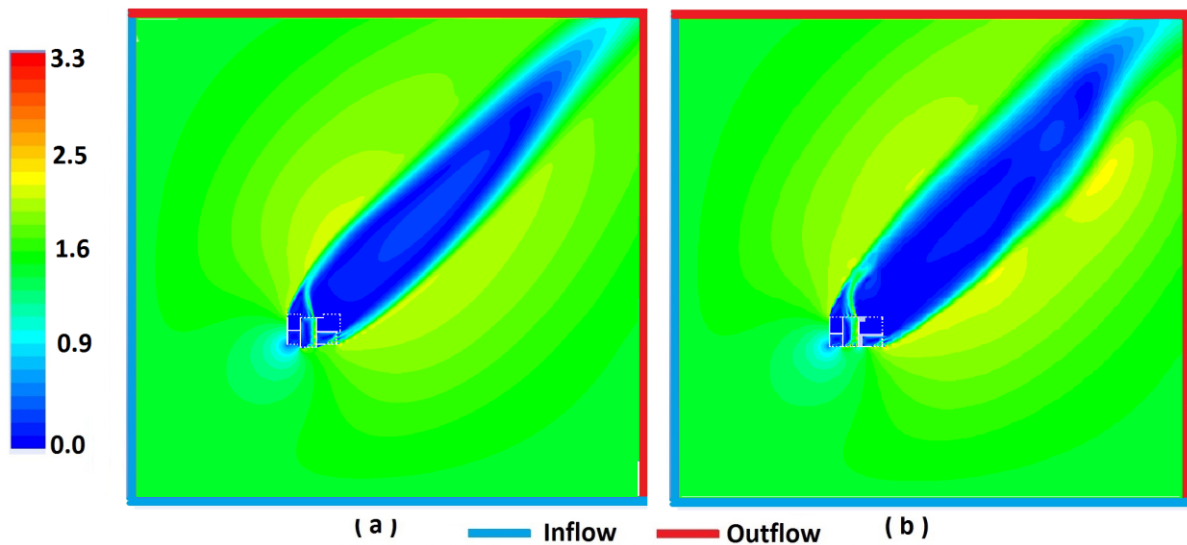


Figure 5.25: Southwest wind outdoor air flow characteristic (a) Benchmark with Cumba (b) Benchmark without Cumba

In both northwest and northeast rooms volumetric flow rates were observed significantly low Compared with previous simulations, the reason can be explained by both rooms windows blocked by the benchmark building bodies, therefore rooms windows look the low pressure zone and avoid big air circulations due to there is no air inlet (see Fig. 5.26). In contrast with previous simulations existence of Cumba cause average indoor velocity attenuation in all rooms except southeast room, particularly in northwest room, where 0.04 m/s (74.7%) (see Table. 5.27 and 5.28).

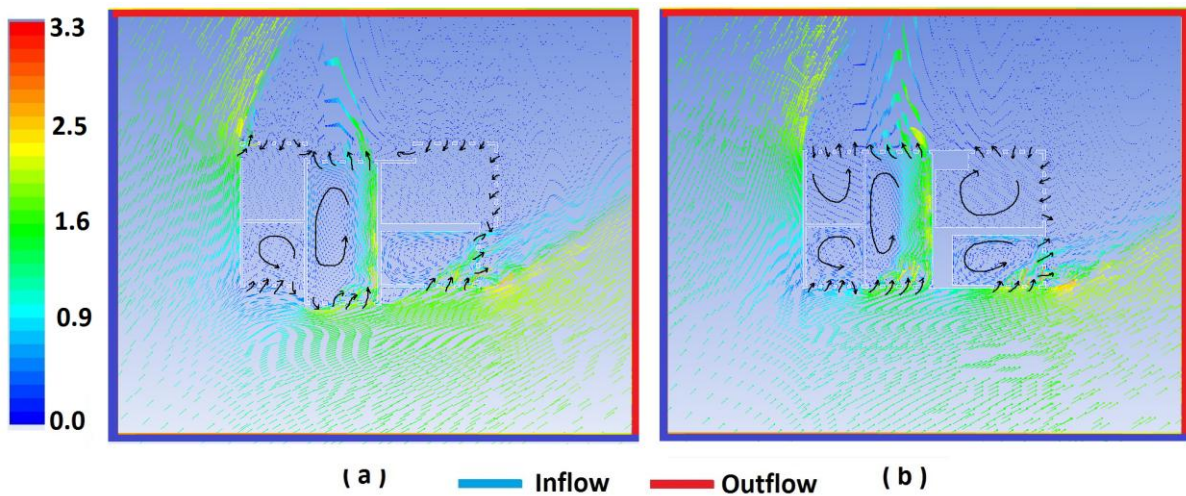


Figure 5.26: Southwest wind indoor air flow characteristic (a) Benchmark with Cumba (b) Benchmark without Cumba

Table 5.27: Southwest wind simulation results

Room	Focus Room	Room Area (m <sup>2</sup> )	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag.( m/s)	Ave. Velocity Mag.( m/s)	Volumetric Flow Rate ( m <sup>3</sup> /s)
Sofa		45	28	1.8	0.08	0.69	
N - E	X	30	64	0.05	0	0.02	0.2
N - W	X	16	35	0.06	0	0.01	0.3
S - E		22	15	0.9	0.1	0.45	
S - W		16	16	0.4	0.01	0.17	
( a )							
Sofa		45	28	2.1	0.1	0.95	
N - E	X	30	64	0.8	0	0.05	0.1
N - W	X	16	35	0.1	0.01	0.05	0.0
S - E		22	15	0.9	0.1	0.37	
S - W		16	16	0.6	0.05	0.26	
( b )							

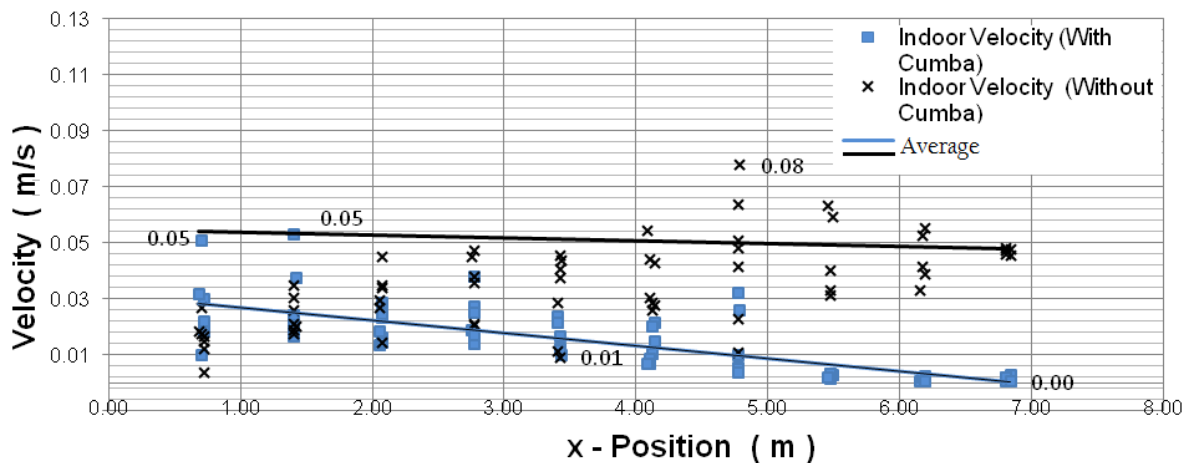
(a) Results for benchmark building with Cumba (b) Results for benchmark building without cumba

In contrast with average indoor air speed, volumetric flow rate slightly increased in focus rooms. Maximum volumetric flow rate acceleration with 0.3 m<sup>3</sup>/s (615.3%) increase was observed in northwest room with Cumba (see Table. 5.27 and 5.28).

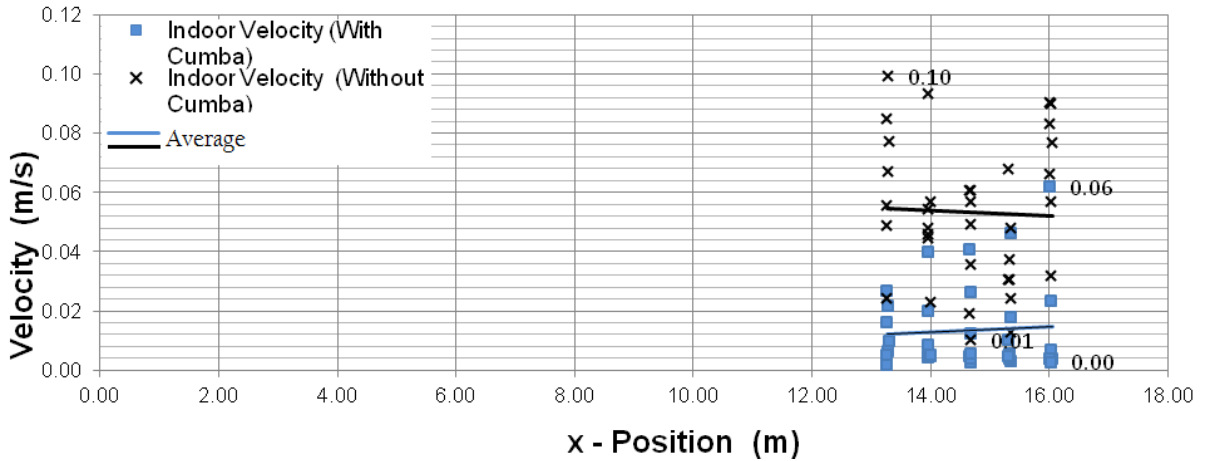
Incorrect with previous simulations in average indoor velocity it was observed that average indoor velocities in northeast and west rooms sample with Cumba have lower average indoor air velocity Compared with benchmark without Cumba (see Graph 5.19 and 5.20).

**Table 5.28:** Percentage based difference between southeast wind simulation results for benchmark building with and without Cumba

Room	Focus Room	Max. Velocity Mag. Difference (%)	Min. Velocity Mag. Difference (%)	Ave. Velocity Mag. Difference (%)	Volumetric Flow Rate Difference (%)
Sofa		-14.3	-20.0	-27.1	
N - E	X	-93.8	0	-70.1	197.7
N - W	X	-40.0	-100.0	-74.7	615.4
S - E		0.0	0.0	23.4	
S - W		-33.3	-80.0	-34.4	



**Graph 5.18:** Northeast room with and without Cumba indoor velocity



Graph 5.19: Northwest room with and without Cumba indoor velocity

5.3.7 South wind

Similar to west majority of previous simulations the existence of Cumba particularly influence the air flow through Sofa, which also influence the outdoor air flow pattern. In addition to this there is more movement observed in northeast room with Cumba (see Fig. 5.27 and 5.28).

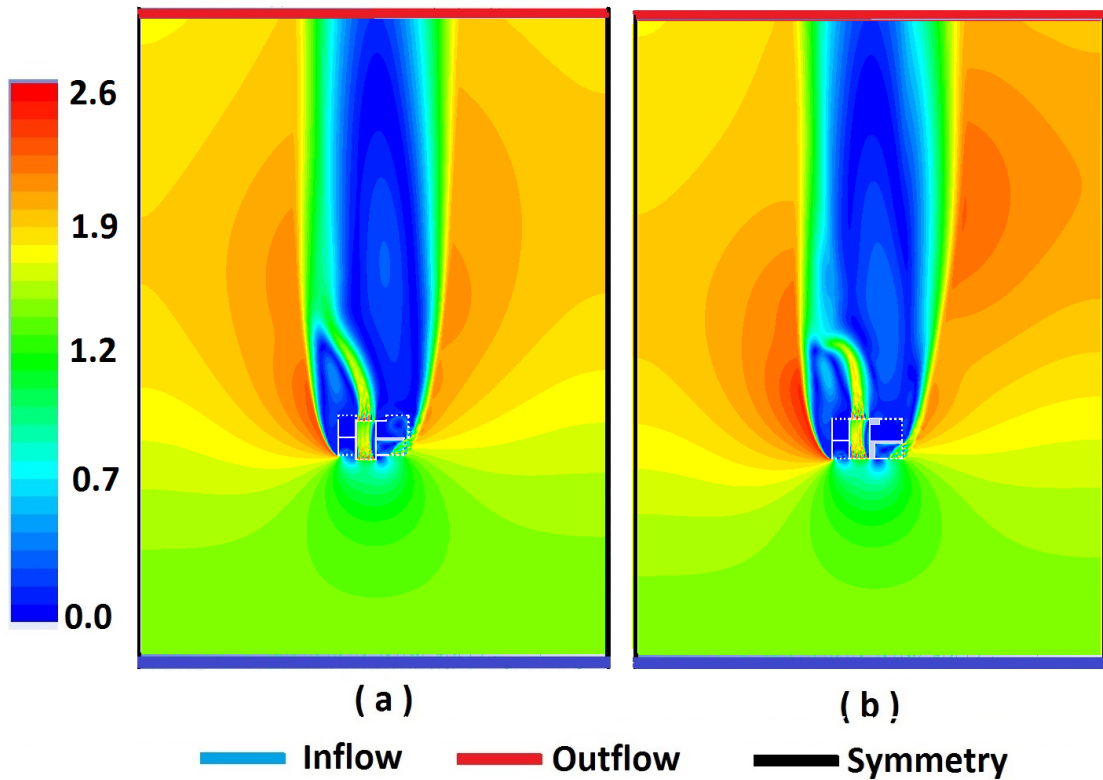
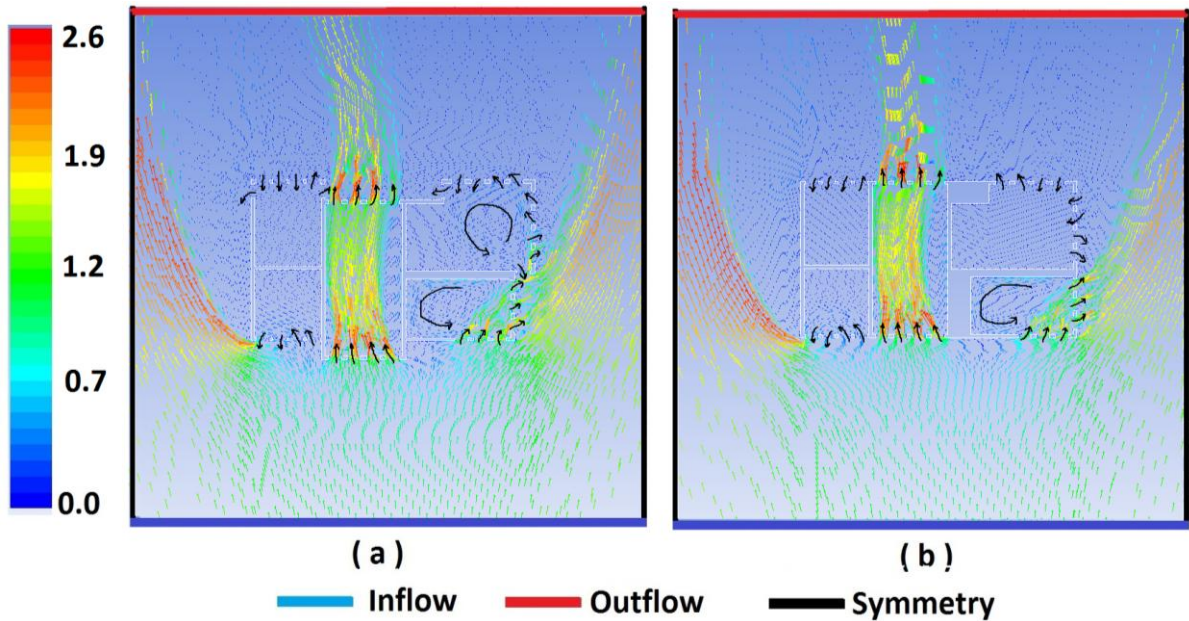


Figure 5.27: South wind outdoor air flow characteristic  
 (a) Benchmark with Cumba (b) Benchmark without Cumba

There is an indoor vortex air flow pattern (**Fig 5.28a**) and 20m<sup>3</sup>/s volumetric flow rate increase was observed in benchmark with Cumba (**Table 5.29**). Although 125.9% volumetric flow rate increase was observed with Cumba the average indoor velocity is decreased 18.5% for northeast room and 21.6% for northwest room (see **Table 5.30**).



**Figure 5.28:** South wind indoor air flow characteristic  
 (a) Benchmark with Cumba (b) Benchmark without Cumba

**Table 5.29:** South wind simulation results

Room	Focus Room	Room Area (m2)	Number of Sensors	Max. Velocity Mag. ( m/s)	Min. Velocity Mag. ( m/s)	Ave. Velocity Mag. ( m/s)	Volumetric Flow Rate ( m <sup>3</sup> /s)
Sofa		45	28	2.2	0.1	1.17	
N - E	X	30	64	0.3	0.01	0.16	0.36
N - W	X	16	35	0.07	0.01	0.02	0.10
S - E		22	15	0.7	0.02	0.53	
S - W		16	16	0.3	0.02	0.13	
( a )							
Sofa		45	28	2	0.02	1.07	
N - E	X	30	64	1.6	0.01	0.20	0.16
N - W	X	16	35	0.2	0.01	0.03	0.07
S - E		22	15	0.6	0.2	0.39	
S - W		16	16	0.7	0.02	0.13	
( b )							

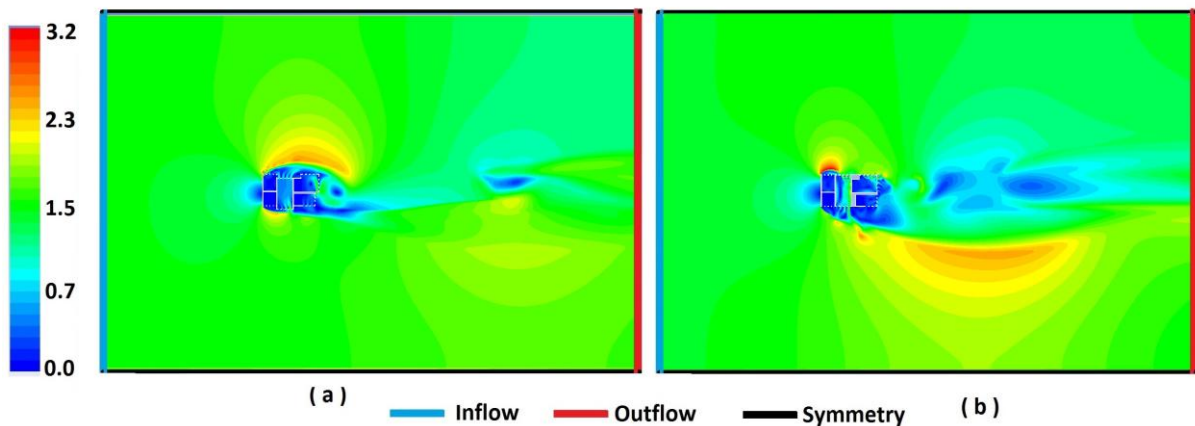
(a) Results for benchark building with Cumba (b) Results for benchmark building without Cumba

**Table 5.30:** Percentage based difference between south wind simulation results for benchmark building with and without Cumba

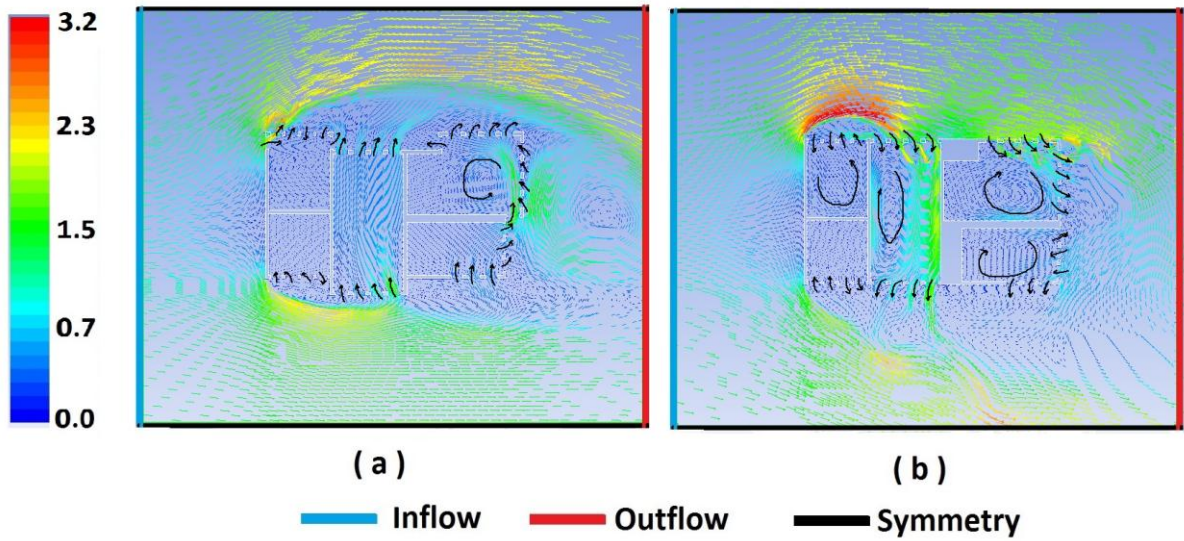
Room	Focus Room	Max. Velocity Mag. Difference ( % )	Min. Velocity Mag. Difference ( % )	Ave. Velocity Mag. Difference ( % )	Volumetric Flow Rate Difference ( % )
Sofa		10.0	400.0	9.9	
N - E	X	-81.3	0.0	-18.5	125.9
N - W	X	-65.0	0.0	-21.6	44.1
S - E		16.7	-90.0	36.0	
S - W		-57.1	0.0	0.6	

### 5.3.8 West wind

As seen in **Fig. 5.29** outdoor air flow pattern considerably changed with existence of Cumba. Northwest room Cumba cause blockage to west wind (**Fig. 5.30**) and this decrease 1071.% northeast and 90% northwest room volumetric flow rate. Although northeast room average indoor air speed 5.1% increased, northwest room average indoor air speed 45.7% decreased (**see. Table 5.31 and 5.32**)



**Figure 5.29:** West wind outdoor air flow characteristic  
**(a)** Benchmark with Cumba **(b)** Benchmark without Cumba



**Figure 5.30:** West wind indoor air flow characteristic  
 (a) Benchmark with Cumba (b) Benchmark without Cumba

**Table 5.31 :** West wind simulation results

Room	Focus Room	Room Area (m <sup>2</sup> )	Number of Sensors	Max. Velocity Mag.(m/s)	Min. Velocity Mag.(m/s)	Ave. Velocity Mag.(m/s)	Volumetric Flow Rate ( m <sup>3</sup> /s)
Sofa		45	28	0.7	0.2	0.50	
N - E	X	30	64	1.4	0.04	0.40	0.32
N - W	X	16	35	0.3	0.03	0.11	0.08
S - E		22	15	0.6	0.03	0.21	
S - W		16	16	0.09	0	0.03	
<b>( a )</b>							
Sofa		45	28	1.9	0.2	1.03	
N - E	X	30	64	1.5	0.07	0.38	3.71
N - W	X	16	35	0.4	0.05	0.20	0.16
S - E		22	15	0.5	0.06	0.22	
S - W		16	16	0.1	0.03	0.07	
<b>( b )</b>							

(a) Results for benchmark building with Cumba (b) Results for benchmark building without Cumba

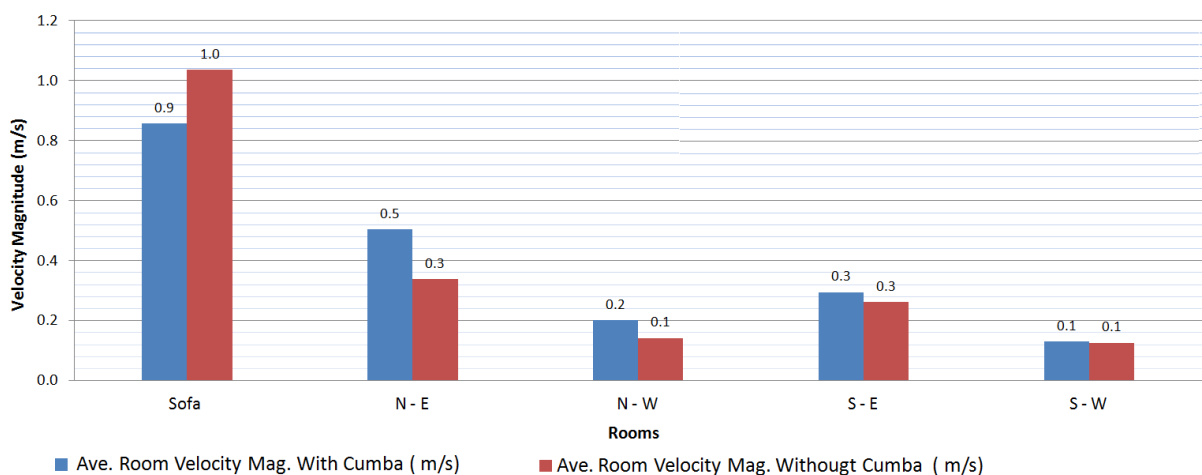
**Table 5.32:** Percentage based difference between west wind simulation results for benchmark building with and without Cumba

Room	Focus Room	Max. Velocity Mag. Difference (%)	Min. Velocity Mag. Difference (%)	Ave. Velocity Mag. Difference (%)	Volumetric Flow Rate Difference (%)
Sofa		-63.2	0.0	-51.7	
N - E	X	-6.7	-42.9	5.1	1071.1
N - W	X	-25.0	-40.0	-45.7	90.3
S - E		20.0	-50.0	-4.0	
S - W		-10.0	-100.0	-50.4	

5.3.9 Wind direction simulation outcomes summary

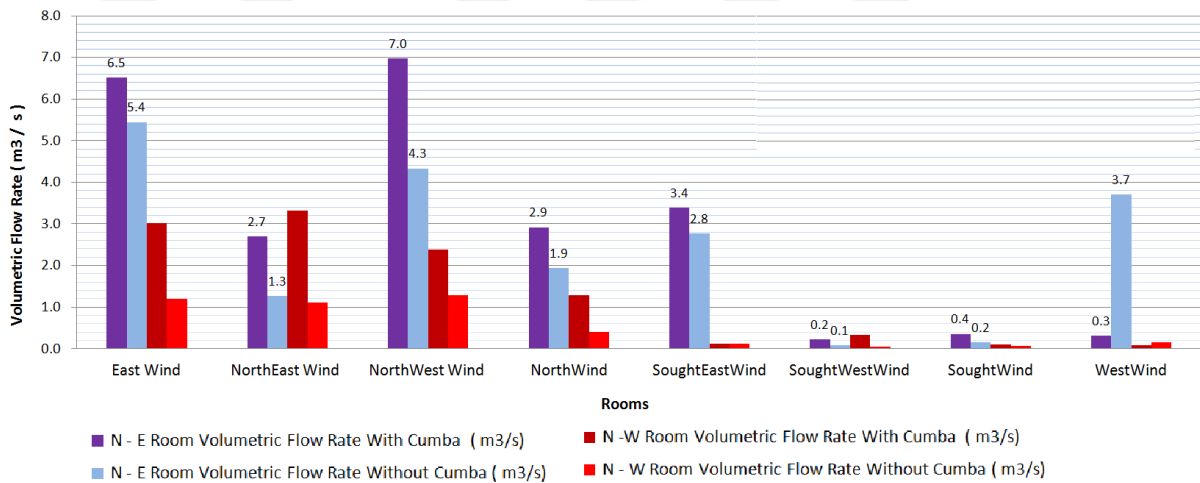
To examine the influence of wind direction on Cumba natural ventilation effect, all wind directions simulation results summarised and compared. As depicted in **Graph 5.20**, the influence of wind directions on overall average indoor air velocity was summarised to make outcomes more clear. In all 8 different wind directions all rooms average indoor velocity is contributed by presence of Cumba except Sofa. It was observed that existence of Cumba case 0.1m/s overall speed attenuation in Sofa. The reason can explain the blockage effect of Cumba for Sofa. Cumba become an obstacle, which disturb the air flow pattern through Sofa. However particularly at focus rooms (i.e. northeast and northwest room) overall average indoor air speed is almost two times increased with existence of Cumba (**see Graph 5.20**).

For each wind directions, overall wind direction influence on Cumba natural ventilation effect is also compared for focus room’s volumetric flow rate (**see Graph 5.21 and 5.22**). With Cumba a significant volumetric flow rate contribution was observed for all wind directions except west wind direction (**see Graph 5.21**). The biggest volumetric flow rate contribution was observed on northwest room under southwest wind conditions, where 615% volumetric flow rate rise was observed (see **Graph 5.22**)

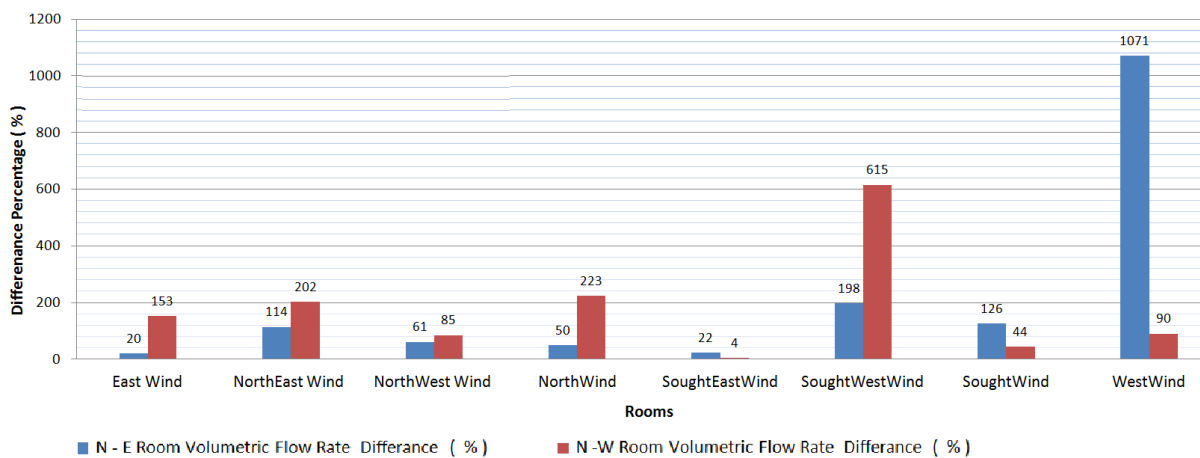


**Graph 5.20:** Overall wind direction influence on average indoor air velocity

Minimum contribution was observed as 4% in south-west room with southeast wind direction. In contrast in northeast room volumetric flow rate was 1071% decreased with Cumba under west wind conditions (see Graph 5.22). It can be concluded that wind direction has a considerable influence on natural ventilation by Cumba. In addition to this, considering the wind direction simulation outcomes study hypothesis is valid, where Cumba have considerable natural ventilation contribution. Graph 5.23 illustrates focus rooms (i.e. northeast and northwest room average volumetric flow rate, which cover volumetric flow rates averages for a total of eight wind directions. As seen in Graph 5.23 Cumba contribute the volumetric flow rate average 0.4 m<sup>3</sup>/s for northeast room and 0.8 m<sup>3</sup>/s for northwest room in all wind directions.

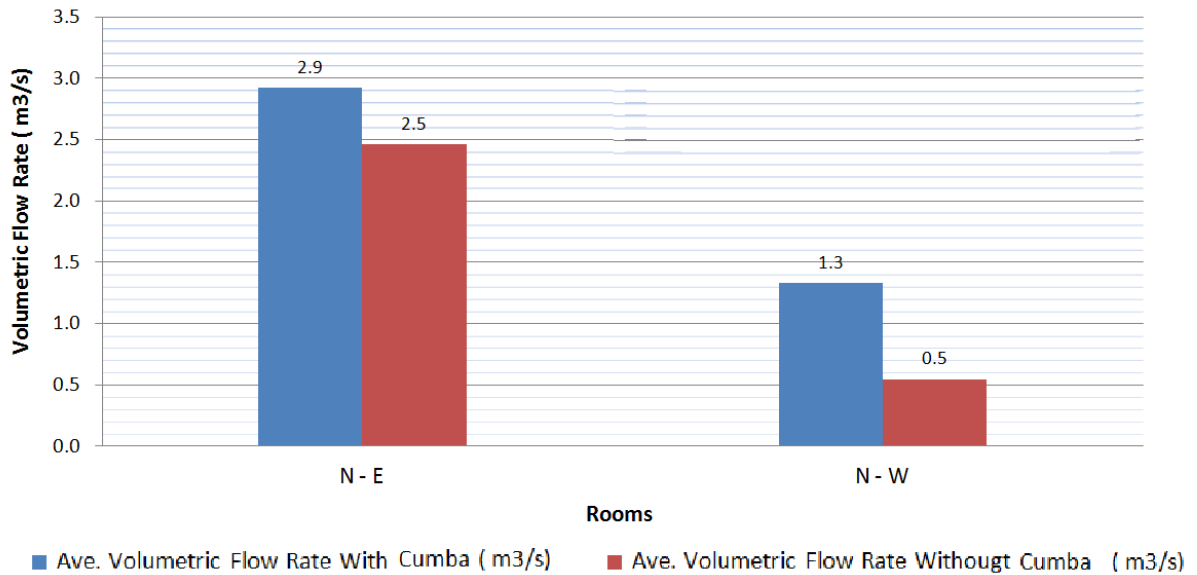


Graph 5.21: Overall wind direction influence on volumetric flow rate



Graph 5.22: Overall volumetric flow rate average difference percentages

In addition to this it can also conclude that Cumba create more natural ventilation contribution on rooms, which have opening on only one facade, because with Cumba room obtain openings on three different facades. However, Cumba considerably contributes to rooms opening on two different facades, because with Cumba such rooms effectively obtain openings on four different facades.



**Graph 5.23:** Overall volumetric flow rate average results for all wind directions averages for focus rooms

In the light of obtained CFD simulation outcomes, study extended with energy simulations to test the research hypothesis and asses the influence of Cumba on building cooling loads attenuation.

# **PART 3: SUMMARY, ENERGY DEMAND ASSESSMENT AND CONCLUSION**

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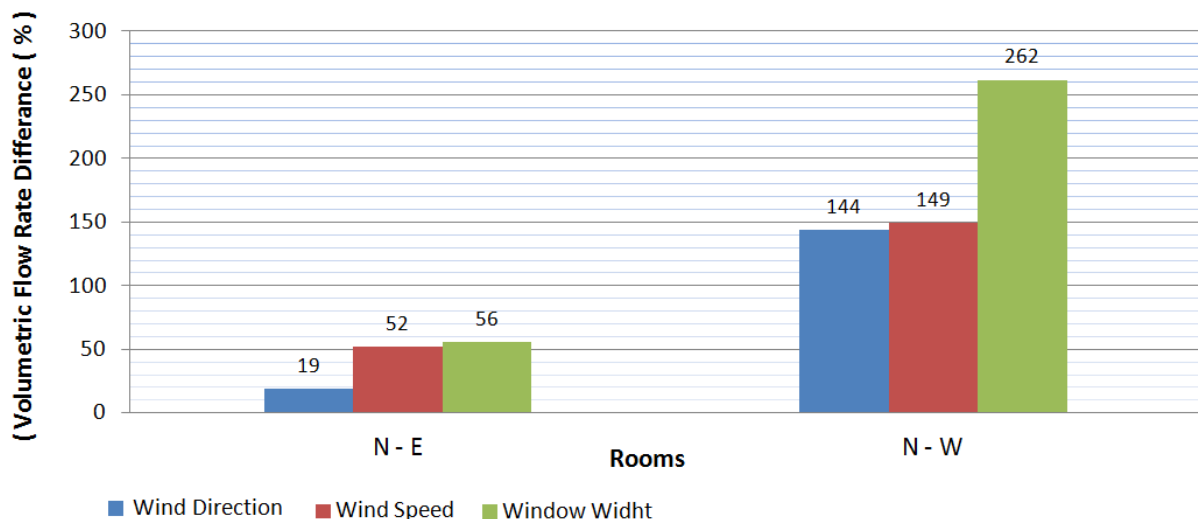
Part 3 aims to give reader overall summary and conclusion about the study. Considering the number of the simulations and length of the study it is reasonable to underline the importance of summary and comparison of all simulation results to obtaining clear and advance understanding about the study outcomes and increase comprehension of the study. Furthermore, this part contains the assessment of potential cooling load attenuation with Cumba to clearly reach the research aim (*i.e. analysis the natural ventilation effect of Cumba for testing research hypothesis and obtaining fundamental data to contribute passive cooling strategies and energy demand attenuation for dwellings.*). Benchmark building potential cooling load was tested with Echotect energy simulations to provide reader broader perspective about the study outcomes. In addition to this, there is a suggestion concept design proposed for future studies to contribute natural ventilation in modern buildings with realistic applicability.

## CHAPTER 6: OVERALL CFD COMPARISON AND COOLING LOAD ATTENUATION

This chapter contains overall CFD simulations comparisons to clearly assess the natural ventilation effect of Cumba and the influence of the mentioned parameters on the natural ventilation effect of cumba. All graphs mentioned in rest of the study are average volumetric flow rate and indoor air velocity outcomes for particular variables (*i.e. all eight wind direction conditions influencing average contribution, all six wind speed conditions influences’ average and so on*). In addition, energy simulations were performed to assess the benchmark building potential cooling load attenuation.

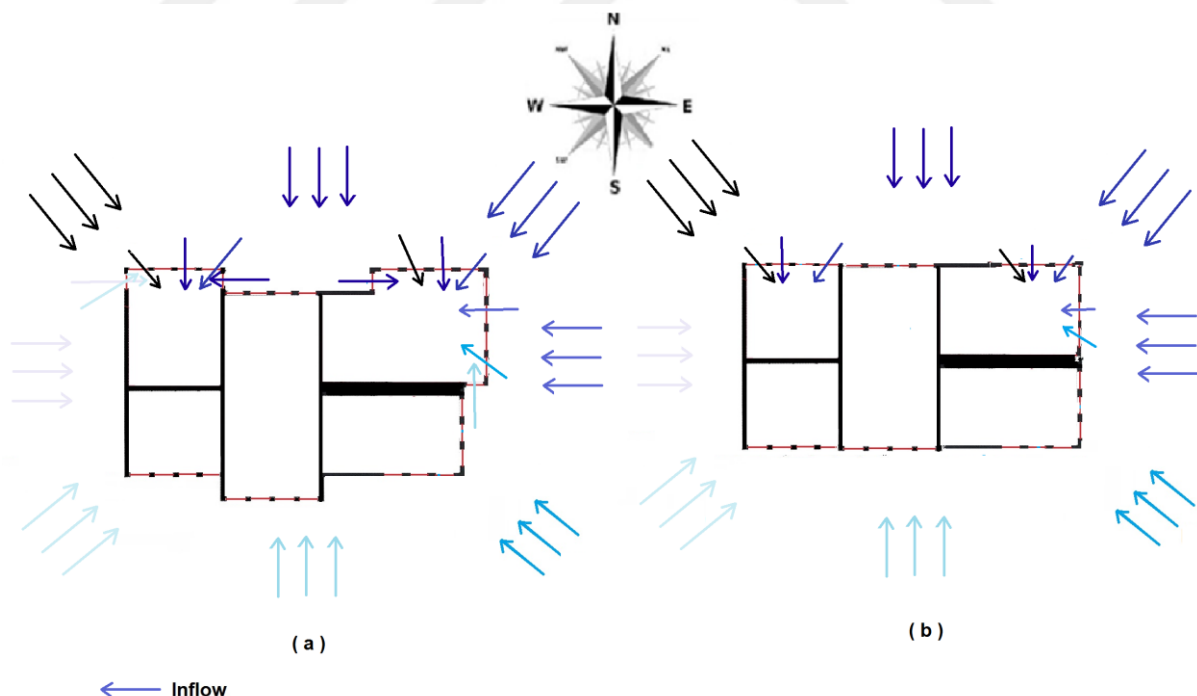
### 6.1 Overall Average Volumetric Flow Rate Contribution

The comparison of mentioned conations (*i.e. different wind directions, wind speeds and window widths*) influence on natural ventilation effect of Cumba is addressed as percentages in **Graph 6.1**. As seen in **Graph 6.1** Cumba is considerably contributed focus rooms’ volumetric flow rate in all test conditions. The highest contribution on both focus rooms was observed with window with changes, particularly in northwest room, where the existence of Cumba contributes 262% to the volumetric flow rate. The minimum Cumba volumetric flow rate contribution was observed in the northeast room with different wind direction conditions (19%) (**see Graph 6.1**).



**Graph 6.1:** Comparison of overall average influence of variables as percentage on natural ventilation effect of Cumba

The reason wind direction has a minimal influence on both rooms can be explained by the room characteristics. As seen in **Fig 6.1**, even without Cumba the northeast room has windows on two facades, and with Cumba it has windows on four different facades. As seen in **Fig 6.1**, the benchmark building without Cumba takes five different wind directions (**Fig 6.1 b**) while with Cumba it takes seven (**Fig 6.1a**). However, as seen in **Fig 6.1**, the northeast room Cumba provides only two extra windows located on the west and south faces (**Fig 6.1b**). Considering that the Cumba adds two extra windows and the benchmark building without Cumba already harvests from five different wind directions, the lowest volumetric flow rate difference (*i.e.* 19%) can be explained with the directions and numbers of widows (**Fig.6.1 and Graph 6.1**). The reason window width causes the biggest volumetric flow rate difference (*i.e.* 262%) in the northwest room can be explained by the room plan.

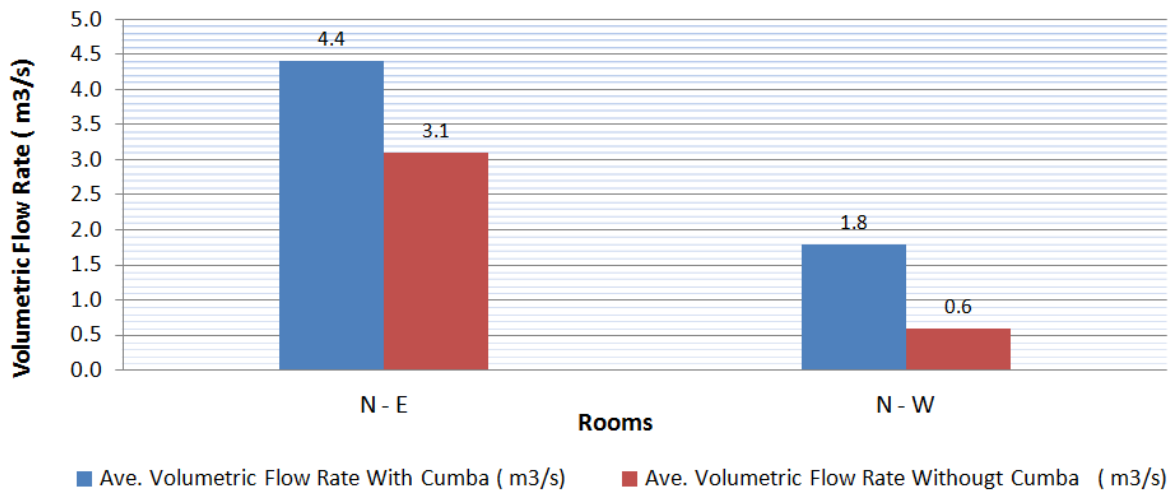


**Figure 0.1:** Air flow characteristics according to wind directions (a) with Cumba (b) without Cumba

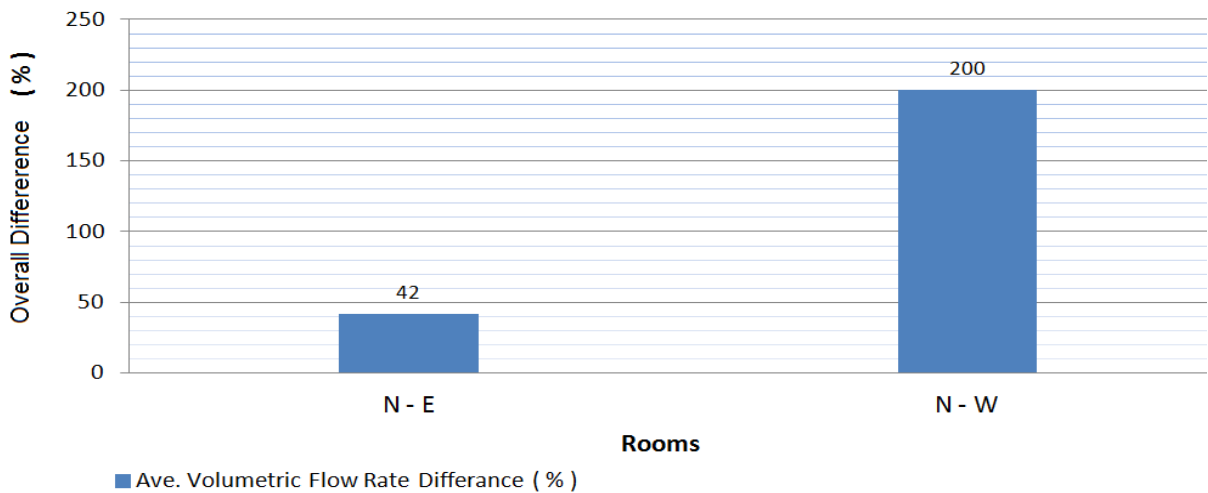
The northwest room without Cumba has four windows on only one facade, and can harvest wind from only three wind directions. In addition to this, air access and exit occurs in the same facade, which causes considerable wind flow disruption on both room inflow and outflow (**Fig 6.1b**). However, with Cumba the northwest room has six windows and harvests wind from six different directions. In addition, the room air inlet and outlet are on different facades, which contributes to air flow inside the room and increases the volumetric flow rate (**Fig 6.1 a**). It was also observed on indoor and outdoor flow pattern that the existence of Cumba on the northwest room in many cases creates Venturi effect and significantly increases both indoor air velocity and volumetric flow rate.

The reason why window width has the greatest impact on volumetric flow rate can be explained by the volumetric flow rate equation (**see eq. 6**). The area of fluid pass and volumetric flow rate have are directly proportional and fluid flow speed and volumetric flow rate have direct proportion too, thus air speed causes the second biggest contribution after window width variables. The reason for the big difference between the volumetric flow rate on northeast and northwest rooms can be explained with reference to the number of windows under with and without Cumba conditions. The existence of Cumba does not have such a big influence as northwest room on the northeast room because the southeast room already has eight windows on two different facades and the Cumba provides two additional windows and two more directions (**see Fig.6.1 and Graph 6.1**).

An overall average of all 40 simulations' volumetric flow rate comparison between focus rooms with and without Cumba conditions is illustrated in **Graph 6.2**. The percentage based contribution of Cumba presence on volumetric flow rate is shown in **Graph 6.3**. As seen in **Graph 6.2**, the average of all 40 simulations shows that Cumba contributes  $1.3 \text{ m}^3/\text{s}$  (42%) to the northeast room's average volumetric flow rate in all conditions and contributes  $1.2 \text{ m}^3/\text{s}$  (200%) northwest room's volumetric flow rate (see **Graph 6.2 and Graph 6.3**)



**Graph 0.1:** Comparison of influence of overall simulations average on natural ventilation effect of cumba



**Graph 0.2:** Comparison of influence of overall simulations average percentage on natural ventilation effect of cumba

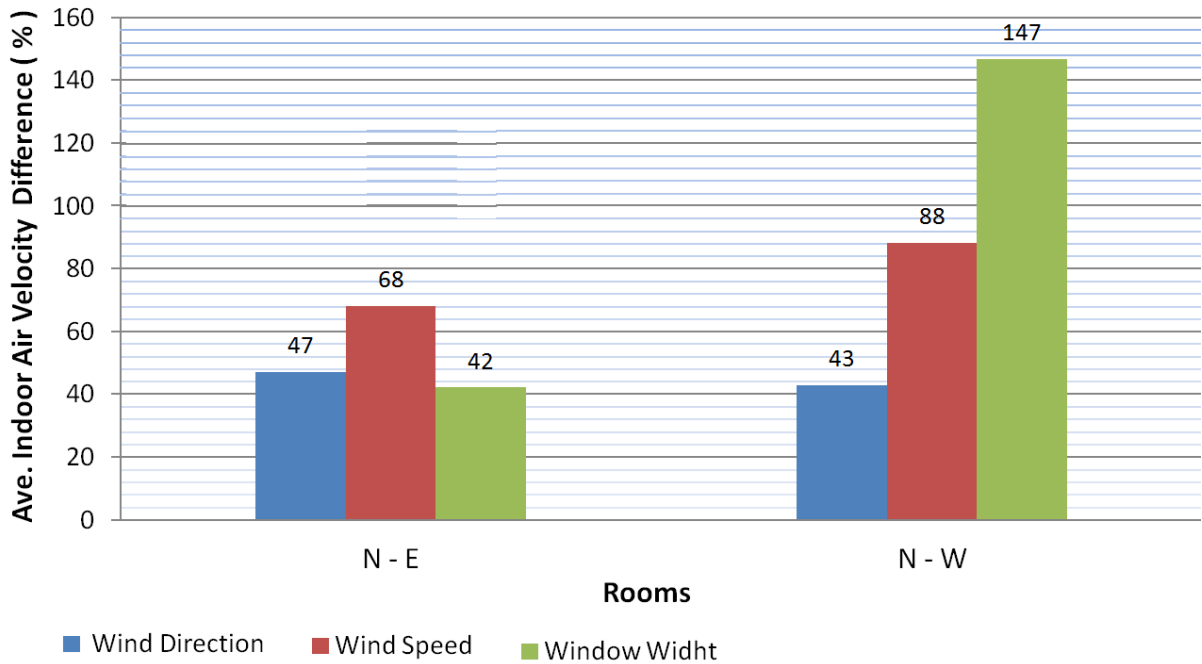
## 6.2 Overall Average Indoor Air Velocity Contribution

Overall average indoor air velocity contribution of all 40 simulations with existence of Cumba is shown in **Graph 6.4**. It was observed that Cumba considerably contributes to both northwest and northeast rooms’ indoor air velocity. Similar to volumetric flow rate, window width has the greatest influence on the northwest room. This can be explained by northwest rooms’ window number and directions influence, similar to volumetric flow rate case.

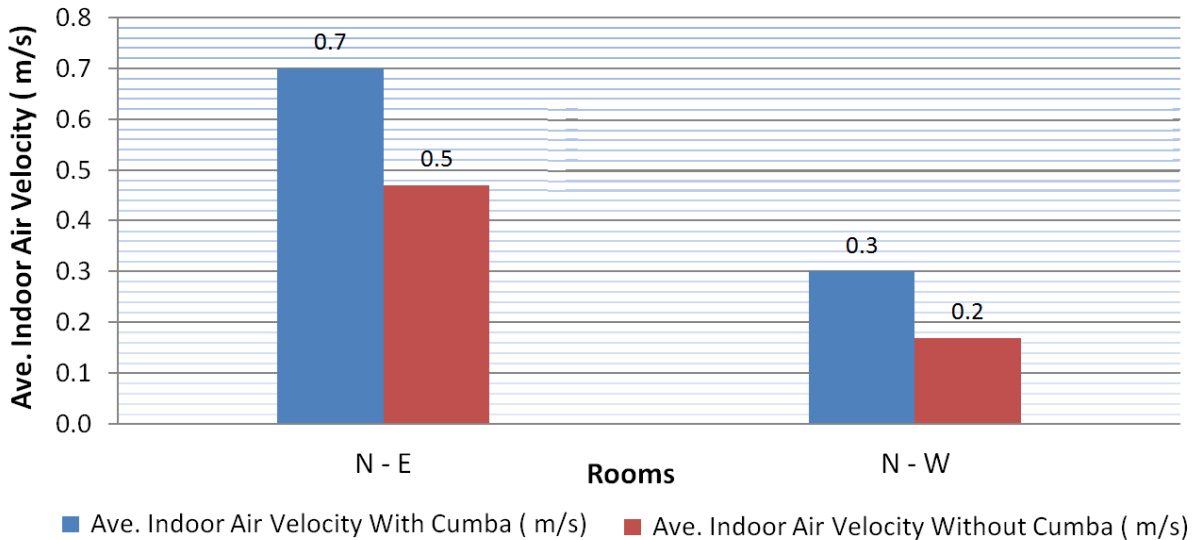
Minimum indoor air velocity contribution is observed in northeast room window width with 42% contribution and maximum contribution is observed in northwest room with different window widths with 147% differences. It is also observed that in northeast room the influence of wind direction and window width on Cumba indoor air velocity contribution is almost equal, but wind speed has more influence on indoor air velocity (see **Graph 6.4**).

In addition to this the influence of wind direction is considerably high on average indoor air velocity compared with volumetric flow rate. This can be explained by the data monitoring process. As mentioned in previous part, average indoor air speed data were extracted from 282 homogenously located point sensors, and it was observed that wind direction has a considerable influence on indoor air flow pattern. Some wind direction cases in particular led to a vortex being observed in both focus rooms, which accelerates the indoor air even in the recesses of the room. Therefore wind direction affects air flow pattern, which focuses the room's average indoor air velocity.

The influence of wind speed in northeast room can be explained by, as in volumetric flow rate case, window size not influencing the northwest room because of the number of windows and facades that include windows. However, wind speed has a considerable influence on the northeast room because the air speed access to the room is changing, which is directly proportional with indoor air flow velocity. The reason why wind speed does not have the greatest influence in the northwest room while it does in the northeast room is due to window width having the greatest influence, related to the number of windows and facades (see **Graph 6.4**). As seen in **Graph 6.5**, Cumba average contribution in all conditions in the northeast room indoor velocity is 0.2 m/s (49%) and in northwest room indoor velocity is 0.1m/s (76%).



**Graph 0.3:** Comparison of average influence of variables as percentage on natural ventilation effect of Cumba



**Graph 0.4:** Comparison of influence of overall simulations average influence on natural ventilation effect of Cumba

### 6.3 Potential Cooling Load Attenuation Assessment

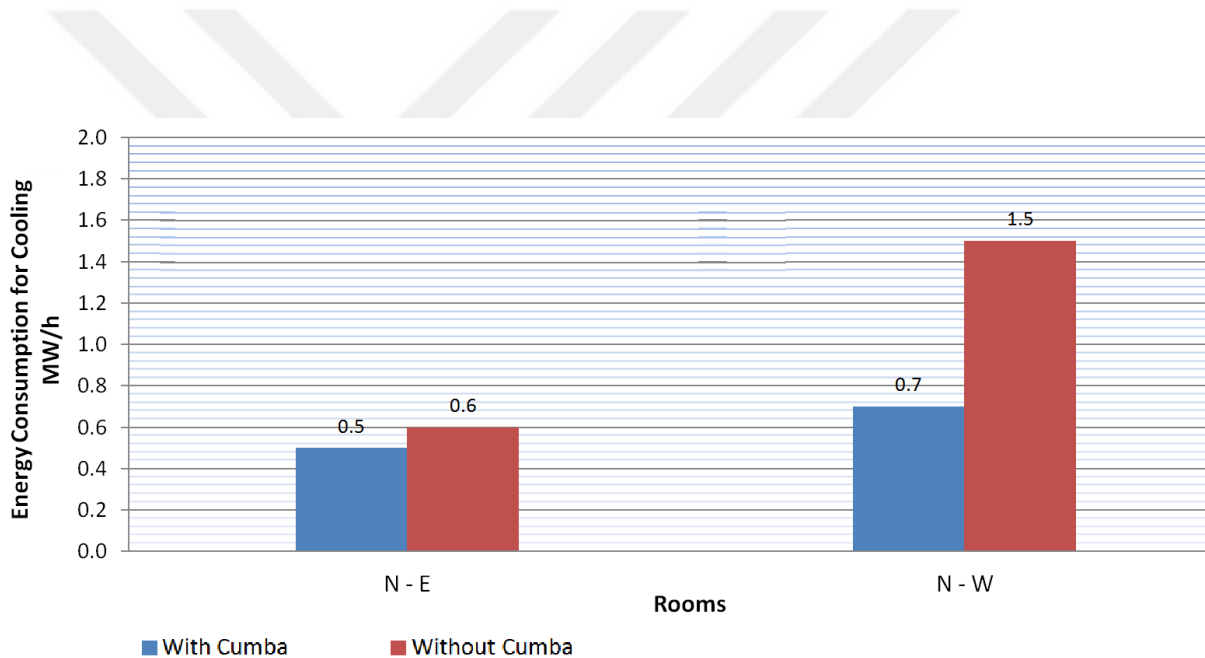
This section assesses the influence of presence of Cumba on the benchmark cooling load. Assessment of energy saving is important to clarify the outcomes of this study and reach the research aim with taking account the research problem. This study has importance, particularly for Turkey, because of several reasons:

- The historical and cultural links of architectural element Cumba with Turkish culture.
- Turkey has a fast growing economy and population, with 6% annual average economic growth between 2001 and 2011 (**T. C. MFA, 2014**) and 13.7% average population increase (**TÜİK, 2014**).
- Turkey’s growth triggers approximately 8% energy demand increase each year (**UN, 2014**).
- Energy imports comprise 22% of total imports to Turkey, causing considerable stress on the economy as well as the environment and the sustainability of the country’s growth (**T.C. ETKB, 2012**).

Obtained volumetric flow rate from 40 simulations was used on cooling load assessments of focus rooms with Echotect energy simulation program. All simulations were performed under Istanbul environmental conditions and just the volumetric flow rates were changed in Echotect simulations according to focus rooms with and without Cumba conditions.

The contribution of Cumba presence on focus rooms cooling load attenuation is addressed in **Graph 6.7**. Existence of Cumba decreases cooling loads 0.1 MW/h (20%) in northwest room and 0.8 MW/h (114%) in northwest room (see **Graph 6.7 and 6.8**). It can clearly be seen that the cumba has a considerable influence on energy saving. An approximate assumption the potential energy saving with Cumba can underlined. Considering Istanbul’s approximate population is 14 million and the core family number is approximately four people, it can be estimated that there are approximately 3.5 million dwellings in Istanbul. Considering the outcomes illustrated in **Graph 6.7**, with the presence of Cumba 0.9 MW/h energy saved annually in the benchmark building. Thus, if all dwellings in Istanbul had Cumba approximately 3.150 GW/h energy would be saved annually in the city. Considering 1kW/h electricity is 0.4 TL in Istanbul (**TÜİK-Electricity, 2014**), the presence of Cumba could thus annually save 1,260,000 TL, which is equal to 360,000 GBP.

If all dwellings in Turkey had Cumbas, Turkey could save approximately 6,930,000 TL, which equals to 1,980,000 GBP pa. However, it should be considered that significant variations in climatic conditions in different locations of Turkey and other factors (*i.e. occupant behaviour, electricity cost etc.*) mean that such estimations are approximate, and serve mainly to underline the approximate potential of energy saving and the importance and potential of the Cumba in terms of energy consumption. **Graph.6.8** Comparison of presence of Cumba on focus rooms cooling loads attenuation average percentage.



**Graph 0.5:** Comparison of presence of Cumba on focus rooms cooling loads attenuation

## CHAPTER 7: CONCLUSION AND FUTURE WORK

It can be concluded that increasing energy demand is the great challenge for all countries. Energy demand is significantly increasing with increasing population. Approximately 82% of global energy demand is met by non-renewable energy sources which cause CO<sub>2</sub> emissions, and thus global warming and climate change. Climate change triggers the number and intensity of climate change related natural disasters, which have almost tripled since the 1980s, and cause global scale economic, environmental, political and health issues. According to predictions, world energy demand will increase by approximately 15% to 2035 and global ambient temperature will rise 3.6°C, which will make some currently inhabited areas uninhabitable. To minimize the consequences of global warming, it is important to decrease energy consumption. Studies show that 34% of global energy is consumed by dwellings, particularly due to heating and cooling loads. The majority of studies have shown that traditional buildings have better thermal performance compared to modern buildings due to passive strategies. Studies also show that natural ventilation has a considerable influence on decreasing cooling loads.

In the light of literature related to the research problem (*i.e. increasing energy demand in dwellings*), the experience of the researcher, experiential evidence and scientific investigation, the research question (*i.e. does Cumba contribute to natural ventilation?*) was devised. No previous research was identified about the natural ventilation impact of the Cumba and no secondary data exists. Therefore, the research hypothesis (*i.e. Cumba contributes to natural ventilation and decreases low-rise dwellings' cooling load.*) was formulated to define the research aim (*i.e. analysis the natural ventilation effect of Cumba for obtaining fundamental data to contribute passive cooling strategies and energy demand attenuation for low-rise dwellings*).

Primary data were obtained from CFD simulations. To maximize study reliability, extensive research was conducted concerning CFD simulation settings and mesh quality. Using CFD and quantitative methods the study adopted the positivist paradigm, with objectivist ontology and empirical epistemology to assess the natural ventilation effect of Cumba with 40 different CFD simulations under three different main headings (*i.e. the influence of wind direction, wind speed and window width on natural ventilation effect of Cumba*).

A case study was conducted with a sample of 111 traditional Turkish house plans to obtain the most common Turkish house plan typology and parameters to boost the study's reliability and contribute to the existing literature. According to the case study findings, the vast majority of traditional Turkish houses are located in Istanbul, with the internal Sofa plan typology. It was also observed that Cumba are observed in all directions (*i.e. north, east, west and south*) almost equally. The data about the Cumba orientations was important due to potential of providing clues for the natural ventilation characteristics of Cumba.

In addition, it was observed that Cumba is a widespread architectural element, and the average traditional house has two Cumbas. Thus, based on the findings of the case study, the benchmark building was defined as having two rooms with a focus room to monitor sensor points for assessing average indoor air velocity and volumetric flow rates. CFD simulation was used to monitor 282 point sensors in the benchmark building and 200 point rake sensors for each window to obtain volumetric flow rate. CFD simulations were performed under RANS method, K- $\epsilon$  turbulent scheme model, second order discretization schemes, enhanced wall treatment,  $1 \leq y^+ \leq 2$  and  $76 \leq y^+ \leq 81$  dimensionless wall distance ( $y^+$ ) and  $y^+$  adaptation respectively, 1 minimum orthogonal quality and average 6.4 maximum aspect ratio with average 374764 cell number conditions to achieve the most reliable simulation outcomes in the limits of 500,000 cells, which limited assays as a student licence was used. With the mentioned simulation conditions all monitored CFD outcomes were analysed according to outdoor and indoor air flow patterns, average indoor air speeds and volumetric flow rate variations.

According to CFD simulation outcomes it was observed that in all conditions (*i.e. different wind directions wind speeds and window widths*) Cumba make a considerable contribution to both volumetric flow rate and average indoor air velocity. It was observed that the contribution of volumetric flow rate with Cumba is influenced minimally by different wind direction conditions and maximally by window width.

It should also be emphasised that the results of the case study showed that the sample buildings had almost equal orientations in different directions and CFD simulation results validate this. Thus it can be inferred that the constructors of traditional houses were sophisticated in their utilisation of the Cumba for ventilation, with orientation toward multiple directions to maximize natural ventilation in different seasonal and daily variations.

It was also observed that Cumba contribute to northwest room significantly more than northeast room, which can be explained by the number of windows and facades containing windows in these rooms. Northwest room without Cumba has windows in only one facade, which significantly disturbs the inflow and outflow. In addition, this room can harvest winds from only three directions, however with Cumba northwest room can harvest winds from six directions and air inflow and outflow to the room is not antagonistic. In contrast, the northeast room already has eight windows on two different facades, therefore the influence of Cumba is not as marked as in the northwest room. In general, according to all 40 CFD simulations' average results, it was observed that existence of Cumba contributes to the volumetric flow rate 42% at northeast room and 200% to northwest room. Similar to volumetric flow rate, it was observed that Cumba contributes the average indoor air velocity. The minimum average indoor air velocity contribution is detected as 42% and maximum as 147%. According to overall 40 CFD simulations results existence of Cumba contributes an average of 49% northeast room and 76% northwest room.

Considering the research aim and hypothesis, CFD simulations were extended and Echotect energy simulations were used to assess the potential cooling load attenuation with Cumba. The benchmark building was simulated under Istanbul environmental conditions with the volumetric flow rates with and without Cumba. According to energy simulations results, the existence of Cumba decreases the cooling loads by 0.1 MW/h (20%) in northwest room and 0.8 MW/h (114%) in the northwest room.

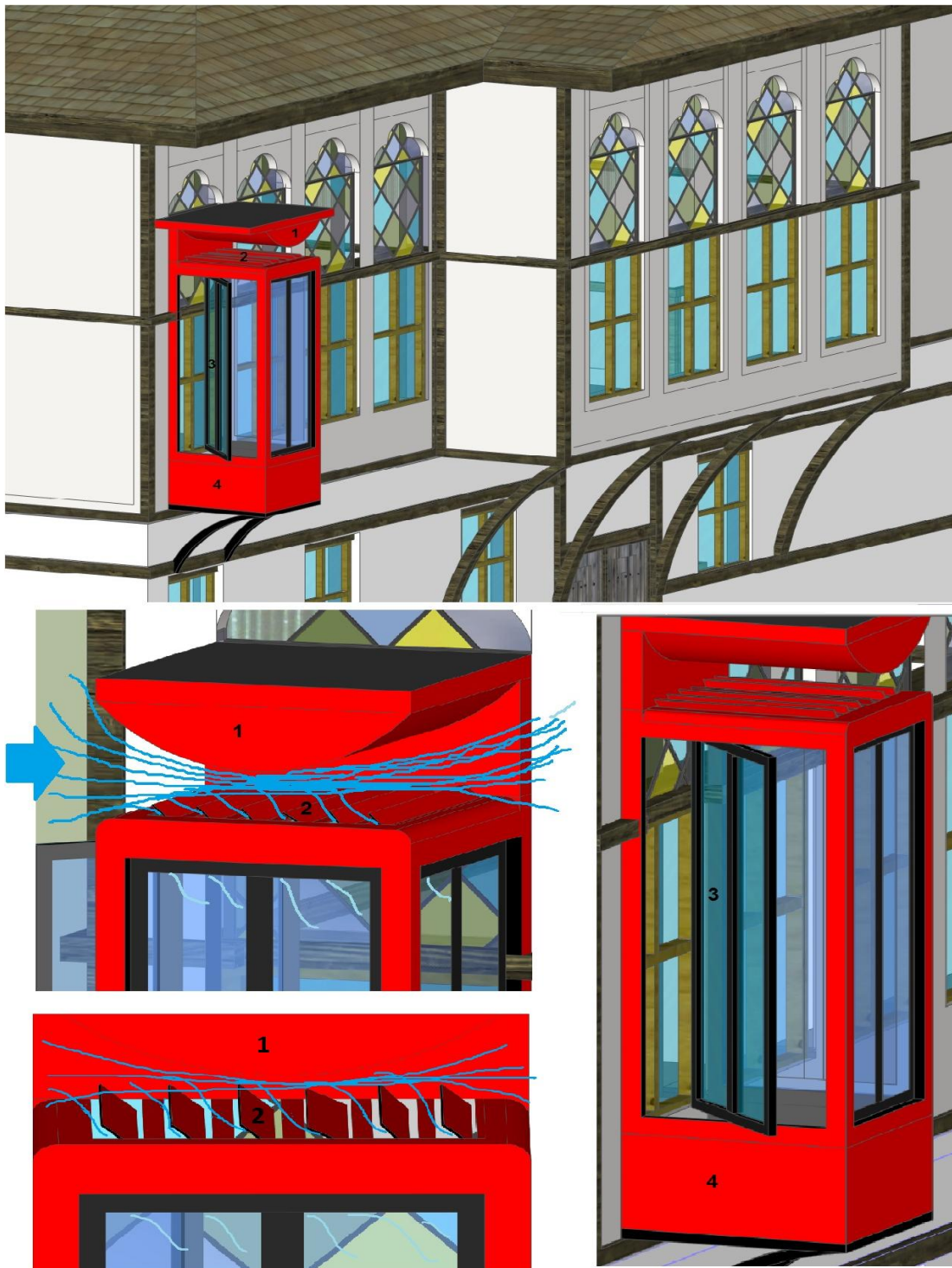
Turkey's energy demand is increasing by approximately 8% each year and energy comprises 22% of total imports. Considering this economic milieu, it was estimated that the existence of Cumba in all buildings in Istanbul would save Turkey 1,260,000 TL annually, and 6,930,000 TL could be saved yearly if Cumba existed in all dwellings across the whole country.

To sum up, according to extensive research and quantitative empirical study with 42 simulations in total, the research hypothesis (*i.e. Cumba contributes to natural ventilation and decreases low-rise dwellings' cooling load*) is supported. It was observed that Cumba make a significant contribution to both average indoor air velocity and volumetric flow rate, which provide considerable cooling loads attenuation. In addition to this, it was observed that Cumba have more contributions to rooms with windows on only one facade. Also, it was observed that Cumba not only contribute to their host rooms; they also affect other rooms in the house by directing and channelling winds from different directions. It is reasonable to claim that this study is enough to obtain reliable proof for natural ventilation effect of Cumba. However it should be considered that simulations were performed in 2D, which is not as reliable as 3D simulations, and due to time limitations empirical validation of the model was not possible. Therefore, the reliability of percentages and ratios reliabilities may be controversial. Thus this study requires further validation to meet publication standards, which will be the next phase of this larger research project.

This study also shows the potential economic influence of Cumba on the national economy of Turkey (and, by inference, similar Mediterranean /West Asian countries. However, it should be considered that there are several problems (*i.e. expensive instalment, integration problems with modern buildings, potential weakness in earthquakes, hard instability in multi-storey buildings and so on*) that may emerge with applications of Cumba in modern building. Therefore, practical designs inspired by the conceptual function of the Cumba (**Figure 7.1**) are recommended for future studies.

Conceptual natural ventilation contributor apparatus is basically described as a shrunken Cumba which can easily be integrated in modern buildings' strategic windows. The predicted advantages of conceptual natural ventilation contributor apparatus are:

- Low cost
- Easy instalment and adaptability of modern buildings even in high-rise buildings.
- With location on strategic windows, it creates adequate high and low pressure areas to contribute to indoor air velocity and volumetric flow rate.
- It does not influence the wind flow pattern for other buildings or rooms as Cumba, considering the small scale.
- Possibility to use with Venturi effect or as a horizontal wind catcher for directing wind flow through the rooms.
- With some modifications, ventilation cooling effect can contribute easily with phase changed materials (PCM) or evaporative cooling using water.
- Potential integration with intelligent systems may significantly contribute to the natural cooling effect with night flush passive strategies.

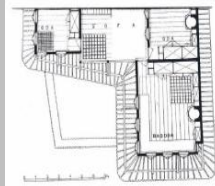
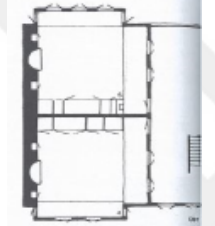
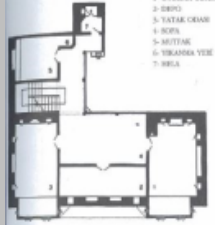
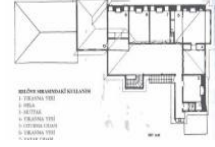

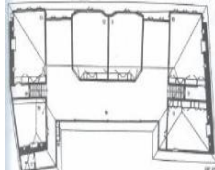



- 1- Venturi effect air accelerator apparatus
- 2- Rotatable panels for air evacuation
- 3- Rotatable Windows for directing and capturing winds
- 4- Water or PCM reservoir for contribute cooling with evaporative cooling or thermal mass.

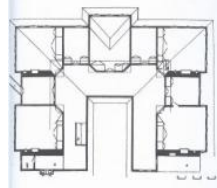
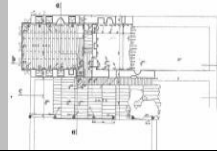
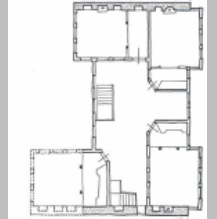
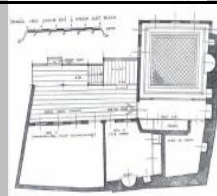


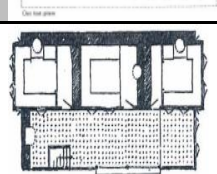
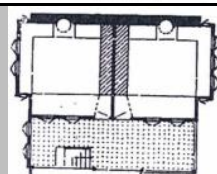
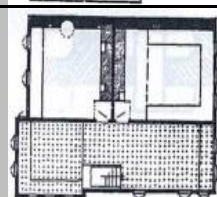
**Figure 7.1:** Conceptual natural ventilation contributor apparatus suggestion

APPENDIX

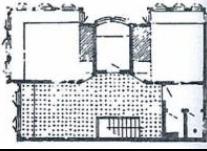
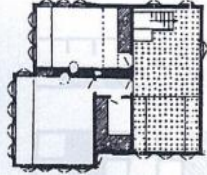
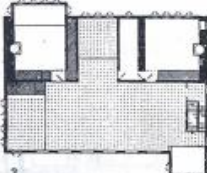


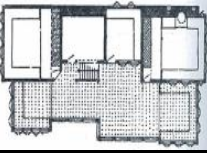
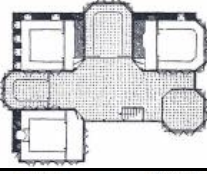
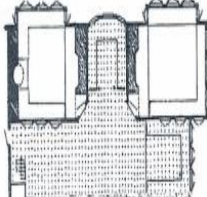

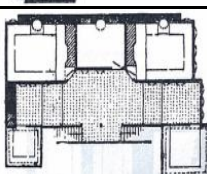
**APPENDIX A1 : External Sofa With Cumba**

General Data			Dwelling Details					Cumba Orientation/Num.				
No	Plans	Source	Location	Small Room (m <sup>2</sup> )	Main Room (m <sup>2</sup> )	Room Num.	Window Width (m)	N	S	E	W	Tot
1		Talya, 2007 P:575	Bursa	14	38.5	3	0.9	x				1
2		Bektas 2007 P:98	Antalya	35		2	0.9	x	x			2
3		Bektas 2007 P:101	Antalya	32	36	4	0.8	x				1
4		Bektas 2007 P:102	Antalya	20	44	7	0.9		x	x		2
5		Bektas 2007 P:103	Antalya	20	42	5	0.8	x	x			2
6		Bektas 2007 P:105	Antalya	27.5	35.5	6	0.7		x			1
7		Bektas 2007 P:106	Antalya	20	30	7	0.7	x			x	2


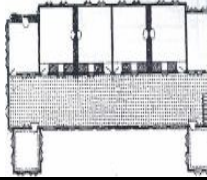

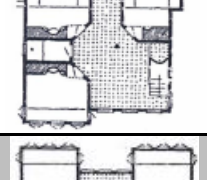
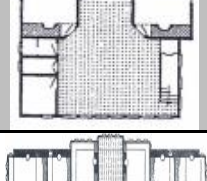
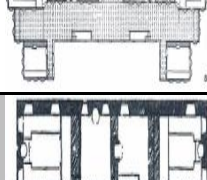
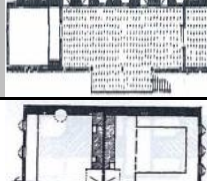
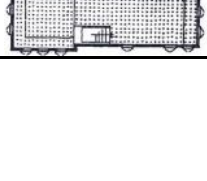
NATURAL VENTILLATION EFFECT OF "CUMBA" IN LOW RISE DWELLINGS

8		Bektas 2007 P:107	Antalya	12	30	7	0.7	x	x	x	3
9		Talya, 2007 P:390	Burdur	16	26	2	0.7			x	1
10		Talya, 2007 P:412	Edremit	16	24	4	0.8		x	x	2
11		Talya, 2007 P:775	Kütahya	14	35	4	0.8	x			1
12		Gunay 1998 P:46	Safranb olu	45	27	2	0.7	x			1
13		Gunay 1998 P:209	Safranb olu	20	30	3	0.7	x	x		2
14		Eldem 1984 P:32	Antalya	12	15	3	0.8		x	x	2
15		Eldem 1984 P:32	Antalya		30	2	0.8		x	x	2
16		Eldem 1984 P:32	Gebze	25	38.5	2	0.8	x		x	2

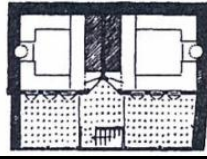
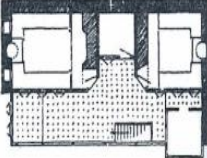
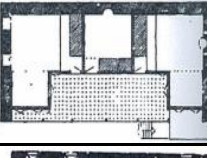
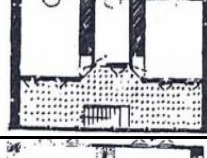
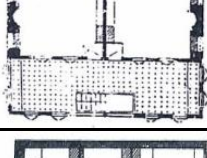
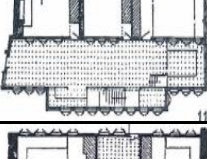
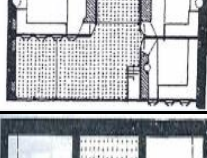
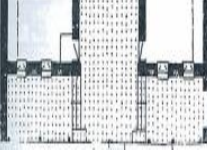
NATURAL VENTILLATION EFFECT OF "CUMBA" IN LOW RISE DWELLINGS

17		Eldem 1984 P:32	İstanbul	12	16	3	0.7	x			x	2
18		Eldem 1984 P:32	İzmit	20		27.5	0.7		x		x	2
19		Eldem 1984 P:32	Kayseri	27.5	31.5	2	0.8	x				1
20		Eldem 1984 P:32	Kayseri	27.5	32.5	2	0.8	x				1
21		Eldem 1984 P:32	Tekirdağ	27.5	54	3	0.9		x			1
22		Eldem 1984 P:32	Tekirdağ	10.5	22	4	0.7			x	x	2
23		Eldem 1984 P:32	Tselya	22.5	24	3	0.7	x	x	x	x	4
24		Eldem 1984 P:32	Edirne	16	20	2	0.8	x		x		2
25		Eldem 1984 P:32	Eskişehir	12.5	15	3	0.7	x		x	x	3
26		Eldem 1984 P:33	Kula	12	20	5	0.7	x		x	x	3

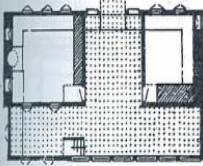
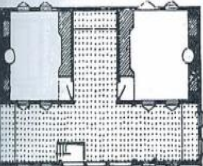

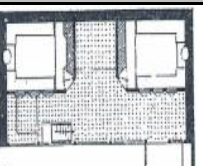
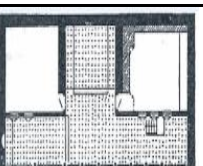

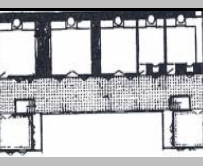

NATURAL VENTILLATION EFFECT OF "CUMBA" IN LOW RISE DWELLINGS

27		Eldem 1984 P:33	Kula	6.5	22	3	0.8		x		x	2
28		Eldem 1984 P:32	Tekirdağ	9	16	8	0.8	x	x			2
29		Eldem 1984 P:34	Kula	20.5	25	6	0.6		x	x	x	3
30		Eldem 1984 P:35	İstanbul	14	17.5	3	0.7	x	x	x		3
31		Eldem 1984 P:35	İstanbul		17.5	2	0.9	x				1
32		Eldem 1984 P:35	Kula	20.5	40	8	1	x	x	x	x	4
33		Eldem 1984 P:32	Akşehir	14	24.5	6	0.6			x		1
34		Eldem 1984 P:32	İstanbul	25	38.5	2	0.9		x		x	2

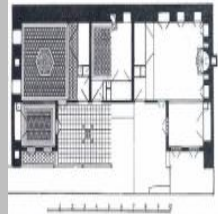
**APPENDX A2 : External Sofa Without Cumba**

General Data			Dwelling Details					Cumba Orientation/Num.				
No	Plans	Source	Location	Small Room (m <sup>2</sup> )	Main Room (m <sup>2</sup> )	Room Num.	Window Width (m)	N	S	E	W	Tot
1		Eldem 1984 P:32	Bergama		25	2	0.8					0
2		Eldem 1984 P:32	Bergama	25	31.5	2	0.7					0
3		Eldem 1984 P:32	Kütahya	25	35	3	0.8					0
4		Eldem 1984 P:32	Manisa	10	25	3	0.8					0
5		Eldem 1984 P:32	Mudanya		27.5	2	0.9					0
6		Eldem 1984 P:32	Rodos	20	30	3	0.7					0
7		Eldem 1984 P:32	Yenişehir	20	26	3	0.7					0
8		Eldem 1984 P:33	Adana	20	22	2	0.9					0


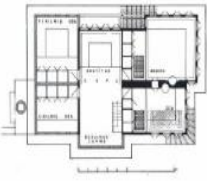


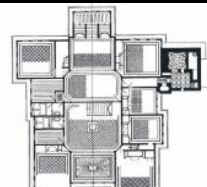
NATURAL VENTILLATION EFFECT OF "CUMBA" IN LOW RISE DWELLINGS

9		Eldem 1984 P:33	Bursa	20	27.5	2	0.8					0
10		Eldem 1984 P:33	Mudanya	22.5	27.5	2	0.7					0
11		Eldem 1984 P:33	Tarsus	24	32	2	0.9					0
12		Eldem 1984 P:33	Tire	10.5	20	3	0.8					0
13		Eldem 1984 P:33	Tire	25	30	2	0.8					0
14		Eldem 1984 P:33	Urfa	12		5	0.7					0
15		Eldem 1984 P:33	Uşak	12	25	7	0.9					0
16		Eldem 1984 P:33	Bursa	9	24	3	0.7					0

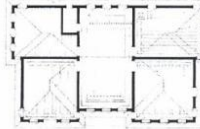
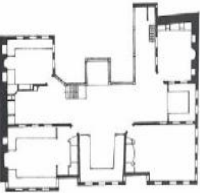
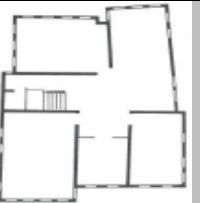

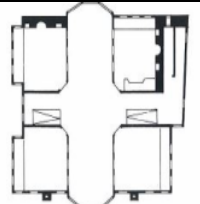
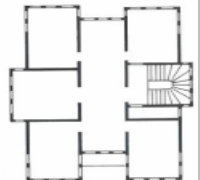
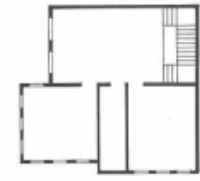
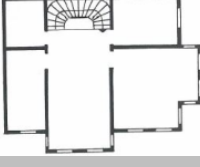
NATURAL VENTILLATION EFFECT OF "CUMBA" IN LOW RISE DWELLINGS

17		Eldem 1984 P:33	Kütahya	9	15	5	0.7						0
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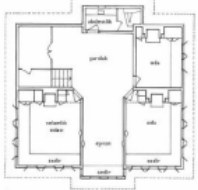

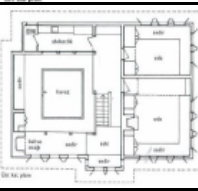
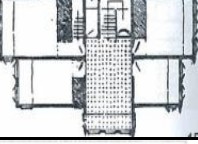

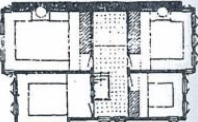
**APPENDX A3 : Internal Sofa With Cumba**

General Data			Dwelling Details					Cumba Orientation/Num.				
No	Plans	Source	Location	Small Room (m <sup>2</sup> )	Main Room (m <sup>2</sup> )	Room Num.	Window Width (m)	N	S	E	W	Tot
1		Talya, 2007 P:754	Bursa	4	16	3	0.5	x			x	2
2		Talya, 2007 P:771	İzmit	16	25	4	0.8	x	x	x		3
3		Talya, 2007 P:773	İzmit	28	54	4	0.8			x	x	2
4		Talya, 2007 P:828	İstanbul	20	45	3	1				x	1
5		Talya, 2007 P:842	İstanbul	12	20	8	0.7	x	x	x	x	4


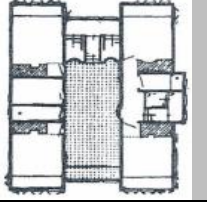


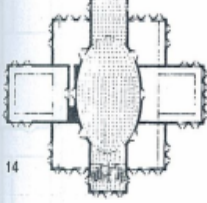
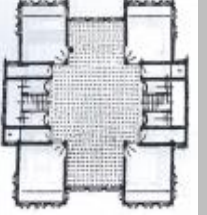
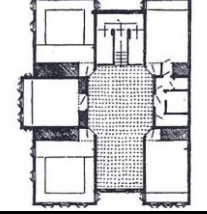
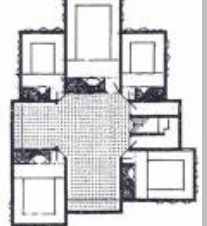
NATURAL VENTILLATION EFFECT OF "CUMBA" IN LOW RISE DWELLINGS

6		Talya, 2007 P:844	İstanbul	20	24	4	0.6		x	x	x	3
7		Ulueng in 1987 P:96	Birgi	12	35	4	0.7		x	x		2
8		Ulueng in 1987 P:99	İzmit	20	35	3	0.8		x	x	x	3
9		Ulueng in 1987 P:121	Yugosla vya	16		3	0.7		x	x	x	3
10		Ulueng in 1987 P:122	Kula	12	16	4	0.6		x	x	x	3
11		Ulueng in 1987 P:124	İstanbul	15	20	5	0.8		x	x	x	4
12		Ulueng in 1987 P:136	İstanbul	24	25	2	0.7			x		2
13		Ulueng in 1987 P:148	İstanbul	15	35	2	1			x	x	2

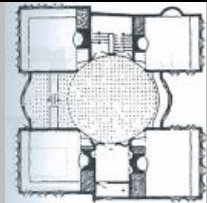
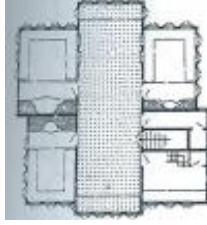
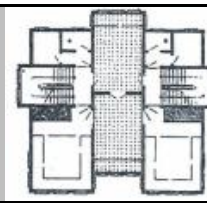


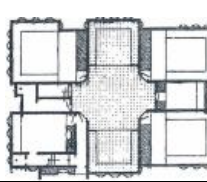
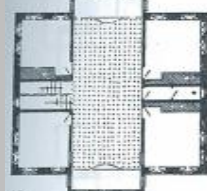

NATURAL VENTILLATION EFFECT OF "CUMBA" IN LOW RISE DWELLINGS

14		Gunay 1998 P:62	Safranb olu	17.5	35	7	0.9	x	x	x	x	4
15		Gunay 1998 P:64	İstanbul	24	25	3	0.7	x	x	x	x	4
16		Gunay 1998 P:64	İstanbul	24	25	5	0.8	x	x	x	x	4
17		Gunay 1998 P:212	Safranb olu	12	20	3	0.6	x				1
18		Gunay 1998 P:213	Safranb olu	18	30	4	0.6	x			x	2
19		Gunay 1998 P:232	Safranb olu	15	25	2	0.8	x				1
20		Eldem 1984 P:35	İstanbul	12	26	4	1	x	x	x	x	4
21		Gunay 1998 P:214	Safranb olu		30	5	0.7	x	x		x	3
22		Eldem 1984 P:35	Gebze	9	24	4	0.8			x	x	2

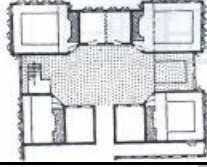
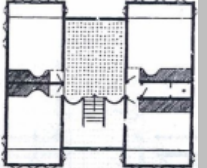
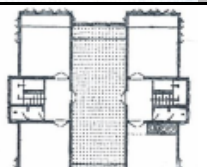
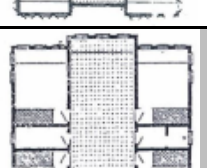
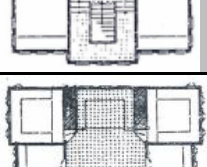
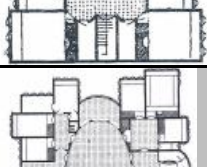
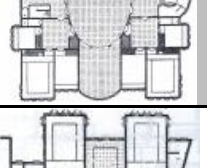
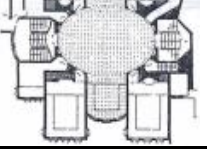
NATURAL VENTILLATION EFFECT OF "CUMBA" IN LOW RISE DWELLINGS

23		Eldem 1984 P:35	İstanbul	15	25	5	0.8	x		x	x	3
26		Eldem 1984 P:36	İstanbul	8	22	4	0.9	x		x	x	3
27		Eldem 1984 P:36	Ankara	22.5	36	4	1	x	x			2
28		Eldem 1984 P:36	Ankara	10	24	5	0.8	x	x			2
29		Eldem 1984 P:36	İstanbul	25	56	6	1	x	x	x	x	4
30		Eldem 1984 P:36	İstanbul	25		4	0.9	x	x			2
31		Eldem 1984 P:36	İstanbul	15	35	5	0.8	x	x		x	3
32		Eldem 1984 P:36	İstanbul	20	35	5	0.8	x	x	x		3

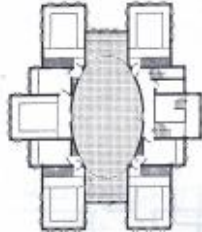
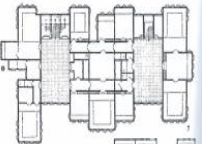
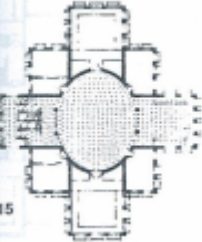


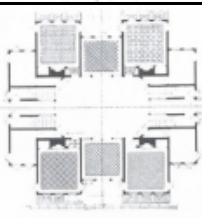
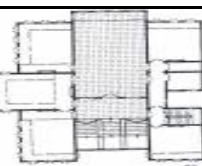
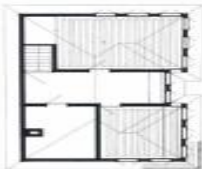
NATURAL VENTILLATION EFFECT OF "CUMBA" IN LOW RISE DWELLINGS

33		Eldem 1984 P:36	İstanbul	15	35	5	0.8			x	x	2
34		Eldem 1984 P:36	İstanbul		22	4	0.8	x	x	x	x	4
35		Eldem 1984 P:36	İstanbul	8	24	4	0.9	x	x			2
36		Eldem 1984 P:36	İstanbul	14	35	4	0.9	x		x		1
37		Eldem 1984 P:36	İzmit	16	24	6	0.7	x	x		x	3
38		Eldem 1984 P:36	İstanbul	24	42	5	0.8	x	x	x	x	4
39		Eldem 1984 P:36	Konya	20		4	1	x	x			2
41		Eldem 1984 P:36	İstanbul	13.5	27	5	0.9	x	x			2

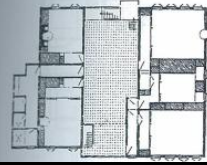
NATURAL VENTILLATION EFFECT OF "CUMBA" IN LOW RISE DWELLINGS

42		Eldem 1984 P:36	Sırbistan	22.5	42	7	0.8	x	x	x		3
43		Eldem 1984 P:36	İstanbul	24	25	4	0.6	x	x			2
44		Eldem 1984 P:36	İstanbul	20		4	0.6	x	x			2
45		Eldem 1984 P:36	İstanbul	20		4	0.7	x	x			2
46		Eldem 1984 P:36	İstanbul	12	30	6	0.6			x	x	3
47		Eldem 1984 P:37	İstanbul	16.5	48	13	1	x	x	x	x	4
48		Eldem 1984 P:37	İstanbul	12		4	0.8	x	x			2
49		Eldem 1984 P:37	İstanbul		25	4	0.9			x	x	2

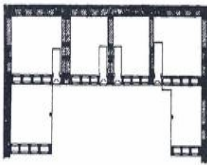
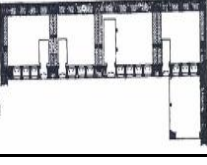
NATURAL VENTILLATION EFFECT OF "CUMBA" IN LOW RISE DWELLINGS

50		Eldem 1984 P:37	İstanbul	15	35	8	1	x	x	x	x	4
51		Eldem 1984 P:37	İstanbul	12	54	14	1	x	x	x	x	4
52		Eldem 1984 P:37	İstanbul	20	45	4	1	x	x	x	x	4
53		Eldem 1984 P:38	İstanbul	28	40	9	0.8	x	x	x		3
54		Bektas 2007 P:146	Antalya	15	30	4	0.8	x	x		x	3
55		Bektas 2007 P:146	İstanbul	7.5	20	4	0.7	x	x			2
56		Eldem 1984 P:36	İzmit	16	24	6	0.7	x	x	x	x	4
57		Talya 2007 P:828	İstanbul	20	45	3	1			x		1

**APPENDX A5 : Internal Sofa Without Cumba**

No	Plans	Source	Location	Small Room (m <sup>2</sup> )	Main Room (m <sup>2</sup> )	Room Num.	Window Width (m)	N	S	E	W	Tot
1		Eldem 1984 P:36	İstanbul	24	56	5	1					

**APPENDX A6 : Internal Sofa Without Cumba (Without Cumba)**

No	Plans	Source	Location	Small Room (m <sup>2</sup> )	Main Room (m <sup>2</sup> )	Room Num.	Window Width (m)	N	S	E	W	Tot
1		Eldem 1984 P:32	İzmit	10.5	17.5	6	0.7					
2		Talya 2007 P:32	İstanbul	12	15	5	0.9					

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