THE EFFECT OF THE TURBULENCE AREA ON HEATING AND COOLING ENERGY CONSUMPTION OF BUILDINGS

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ABSTRACT

THE EFFECT OF THE TURBULENCE AREA ON HEATING AND COOLING ENERGY CONSUMPTION OF BUILDINGS

Over the last decades, as a consequence of growth in global energy demand and global energy-related carbon dioxide emissions, the application of building performance simulation is a must for more efficient buildings with low energy demand. In this study, the effect of the turbulence areas on heating and cooling energy consumption of buildings is examined by the help of building performance simulation. Two 3-D models sketched in ANSYS Fluent CFD program to represent control building as a stand-alone structure and as in turbulence area. After sketching, they are meshed with multizone mesh model. Later, the realizable k-ϵ analysis used for fluid dynamics computations while steady-state thermal analysis used for heat flux computations in ANSYS Fluent. 6 different wind cases were analysed, resulting 12 cases in total. The results show that the energy need for heating and cooling energy is lower for the buildings which are in the turbulence (vortex) area. Therefore, this research has a theoretical contribution to the literature within its specific domain. It shows that researchers, practitioners and urban planners should not ignore the turbulence effect on heating and cooling energy consumption of a building for future works.

ÖZET

TÜRBÜLANS BÖLGELESİNİN BİNALARIN ISITMA VE SOĞUTMA ENERJİSİ TÜKETİMİNE ETKİSİ

Son yıllarda küresel enerji ve küresel enerji bağlantılı karbondioksit emisyonlarındaki artışın sonucu olarak, binaların enerji performanslarının simülasyon yardımıyla incelenmesi, daha efektif ve enerji tasarruflu binalar elde etmek için zorunlu bir hale gelmiştir. Bu çalışmada, türbülans bölgesinin binaların ısıtma ve soğutma enerjisi üstündeki etkisi bina performans simülasyonu ile incelenmiştir. İki adet üç boyutlu model, birinde kontrol binası kendi başına, diğerinde türbülans bölgesi içinde olmak üzere, ANSYS Fluent hesaplamalı akışkanlar dinamiği programında çizilmiştir. Çizimden sonra, modelin örgüsü (mesh) multizone örgü modeli ile yapılmıştır. Sonrasında ANSYS Fluent programında, gerçeklenebilir k-ϵ analizi akışkanlar dinamiğini çözmek için, sabit hal enerji analizi ise ısı akışlarını çözmek için kullanılmıştır. Altı farklı rüzgar durumu ve sonucunda toplam on iki durum analiz edilmiştir. Sonuçlar, türbülans bölgesindeki binaların daha az ısıtma ve soğutma enerjisine ihtiyacı olduğunu göstermiştir. Bu yüzden, bu çalışma literatüre kendi özel alanında bir katkı sunmuştur. Bu çalışma göstermiştir ki, araştırmacılar, uygulamacılar ve şehir planlamacıları gelecekteki çalışmaları için türbülans bölgesinin bir binanın ısıtma ve soğutma enerjisine etkisini göz ardı etmemelidir.

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LIST OF SYMBOLS

$C_{1\epsilon}$	Mathematical Constant
$C_{2\epsilon}$	Mathematical Constant
C_{μ}	Mathematical Constant
h_f	Fluid-side Local Heat Transfer Coefficient
k	Turbulence Kinetic Energy
P_b	Turbulence Kinetic Energy due to the Bouyancy
P_k	Turbulence Kinetic Energy due to the Velocity Gradients
q_{rad}	Radiative Heat Flux
T_f	Local Fluid Temperature
T_w	Wall Surface Temperature
Y_M	Contribution of the Fluctuating Dilatation
ϵ	Dissipation Rate
σ_{ϵ}	Mathematical Constant
σ_k	Mathematical Constant

LIST OF ACRONYMS/ABBREVIATIONS

2D	Two Dimensional
3D	Three Dimensional
BMS	Building Management System
BPS	Building Performance Simulation
CFD	Computational Fluid Dynamics
CHTC	Convective Heat Transfer Coefficients
CO_2	Carbon Dioxide
ECBCS	Energy Conservation in Buildings and Community Systems
EWS	Efficient World Scenario
GDP	Global Energy Product
IBE	Inter-building Effect
IEA	International Energy Agency
ISO	International Organization for Standardization
PBD	Performance-based Design
R&D	Research and Development
TQM	Total Quality Management

1. INTRODUCTION

1.1. Background of the Research

In 2017, global energy demand grew by 2.0% while the growth rate for the previous year was less than its half. Changes in global energy demand for the years between 2011 and 2017 are shown in Figure 1.1. In 2017, oil, natural gas and coal met %70 of this global energy demand increase while the rest was met by renewable resources. As a consequence of this trend, global energy-related carbon dioxide emissions reached all-time high of 32.5 gigatonnes with the increase rate of 1.4%, after three years of remaining flat (International Energy Agency 2018a).

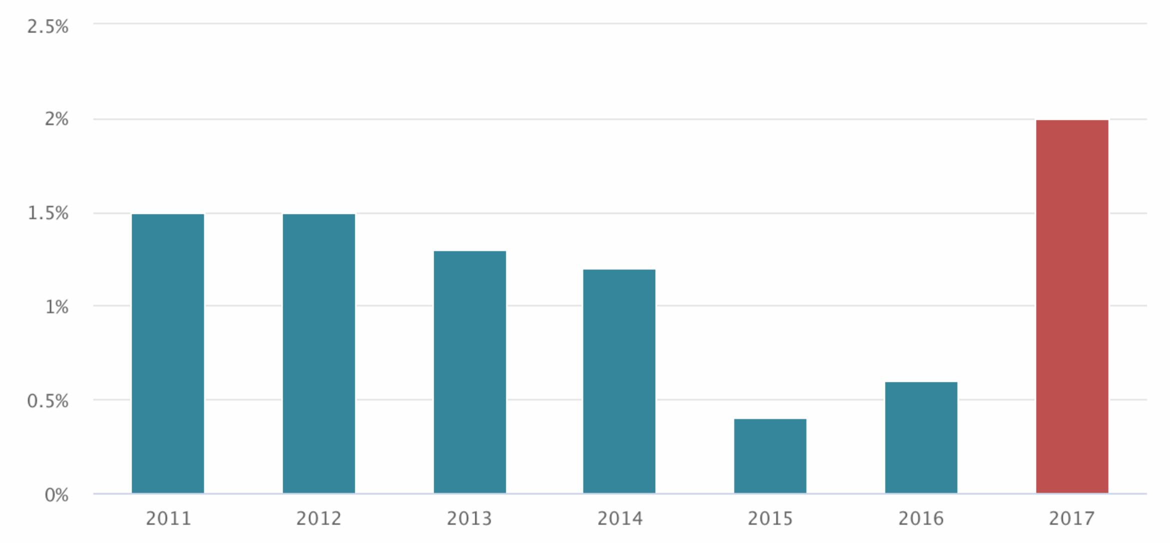


Figure 1.1. Change in Global Energy Demand, 2011-2017.

Source: International Energy Agency (2018b)

Ultimately, increase of carbon dioxide emissions resulting from global energy demand growth cause global warming. On the other hand, the emissions cuts—which are needed to reach world's climate goals— can be achieved with the right energy efficiency policies. In fact, the impact of energy efficiency policies has been important over the last few decades. Without energy efficiency policies, the global energy demand would have been 12% higher in 2017. Global energy demand with and without energy efficiency with global domestic product growth between 2000 and 2017 is shown in Figure 1.2. Energy efficiency is the major driver for uncoupling global energy demand from global domestic product —which represents the economic development— (International Energy Agency 2018c).

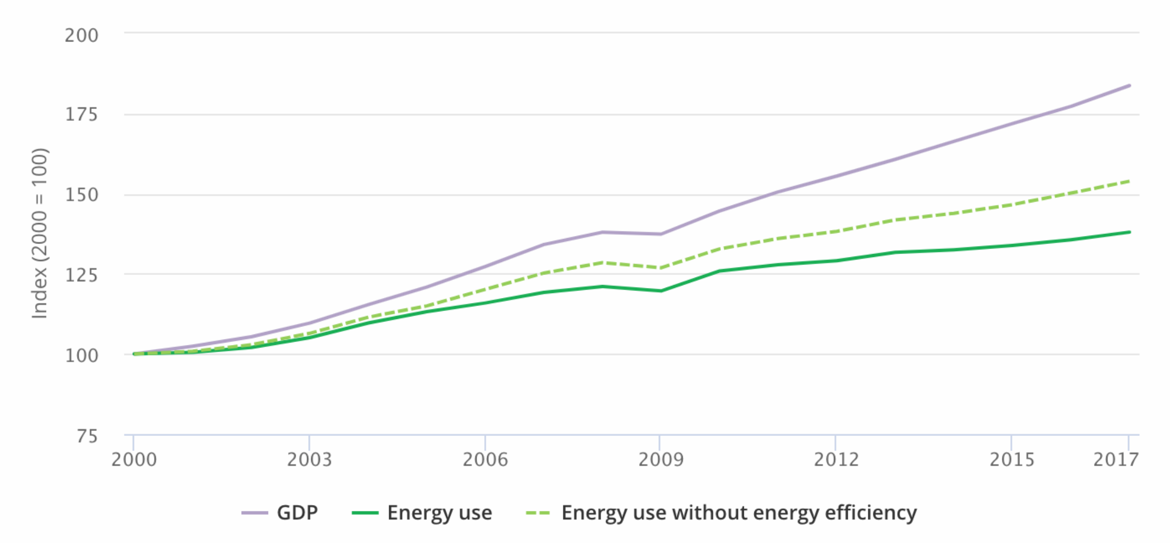


Figure 1.2. Global Energy Use with and without Energy Efficiency, 2000-2017.

Source: International Energy Agency (2018c)

However, the implementation of energy efficiency policies has not been sufficient to meet world's climate goals. The positive impact of efficiency policies has been overwhelmed by fast-growing economic activities in emerging countries that boost energy demand (International Energy Agency 2018c). Decomposition of global energy demand in world's major economies between 2000 and 2017 is shown in Figure 1.3. Energy efficiency improvement opportunities for the world are being missed and current policies are not delivering the full potential gains that are cost-effective and use today's technology. This delayed energy efficiency actions will end up locking in inefficiencies which means much strict actions need to be taken in the future (International Energy Agency 2018c).

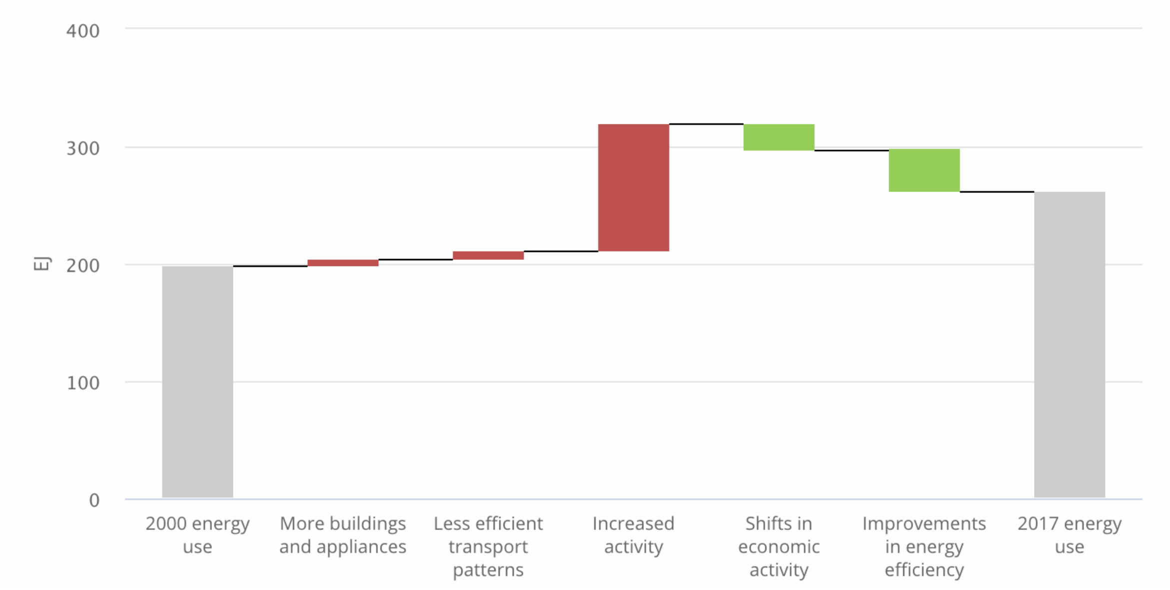


Figure 1.3. Decomposition of Global Energy Demand in World's Major Economies, 2000-2017.

Source: International Energy Agency (2018c)

On the other hand, IEA World Energy Outlook developed the Efficient World Scenario (EWS) to demonstrate the potential. The EWS shows a world with 60% more building space and 20% more people in 2040 (International Energy Agency 2018c). In this world, global domestic product will be doubled for only a very small increase in global energy demand in 2040 only if all countries will implement all the economically viable energy efficiency potential that is available. Before 2020, the EWS would result in a peak in energy-related greenhouse gas emissions, followed by a decrease by 12% in 2040 compared with today which is equal to over 40% of the abatement required to be in line with Paris Agreement targets (International Energy Agency 2018c). It would also cut key air pollutants such as nitrogen oxides, sulphur dioxide and particulate matter by one third compared to current air pollution. So, EWS shows the potential for efficiency to the all sectors that contribute to the global energy demand.

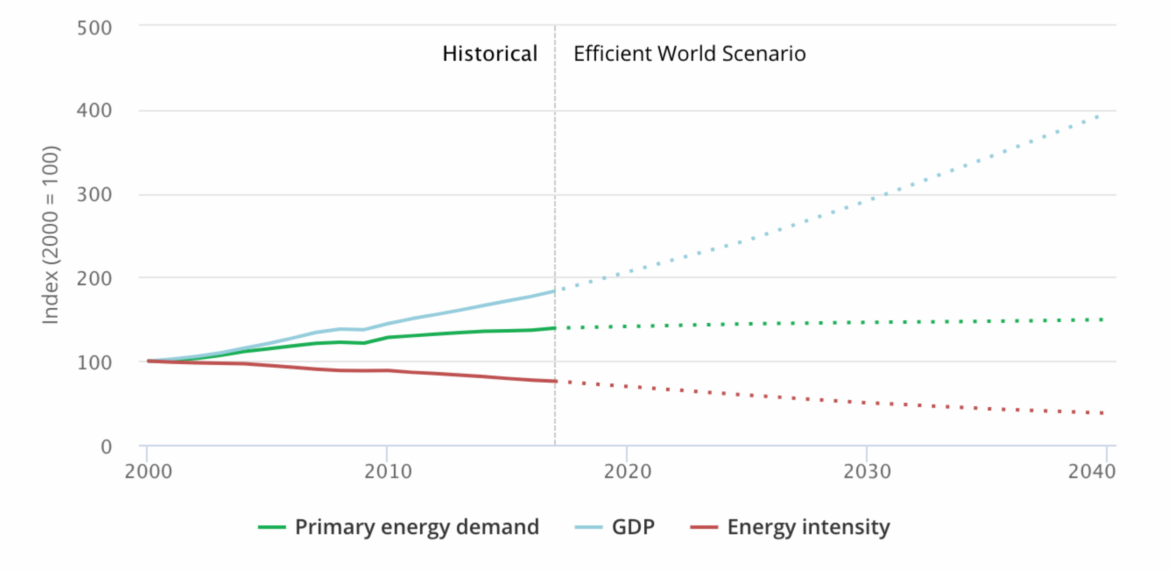


Figure 1.4. Global Energy Demand, GDP and Energy Intensity in the EWS, 2000-2040.

Source: International Energy Agency (2018c)

1.2. Problem Determination and Statement

The residential sector has the third largest share of the global energy demand with 20% (International Energy Agency 2018b). So, one of the most important reasons of the growth in global energy-related carbon dioxide emissions is the residential sector. It is expected that there will be %60 more building space in 2040. As a result of this, the energy use in residential sector is growing year by year with stronger heating and cooling energy needs in some districts. On the other hand, there is a potential to keep the global residential energy demand constant till 2040, despite of the expected 60% growth rate for the total building area.

This potential to keep the global residential energy demand constant would need comprehensive efficiency policies, targeting new and existing buildings as well as appliances. Incentives could drive consumers to adopt high efficiency appliances and undertake deep energy retrofits, with market-based instruments encouraging innovative business models. Decision making can be supported by improved quality and availability of energy performance information (International Energy Agency 2018c).

Also, since performance and efficiency are important interests in the construction environment, building performance simulation is a powerful tool to study the different aspects of building performance to reduce their energy consumption and support the challenge against climate change. There are numerous factors that can affect the building performance to study. Effect of the turbulence (vortex) area on heating and cooling energy of a building is one of them and this thesis examines this effect.

1.3. Related Studies

In recent years, interest in performance and efficiency has been increased to make construction processes better. For this trend, building performance simulation has become crucial to analyse different parameters that affect efficiency of buildings. Related to this thesis, there has been an increasing amount of literature on the effect of nearby buildings and wind for building energy demand.

Reflection and shading of nearby buildings are investigated by Han *et al.* (2015a) and they found that those parameters have a significant role in terms of energy consumption. Liu *et al.* (2015) calculated the density of nearby buildings and the wind effect on building energy consumption. Authors found that denser plan areas affects the energy consumption due to the wind sheltering effect on the exterior surfaces' convective heat transfer coefficients. They calculated 6.7% increase in the cooling energy consumption and 3.5% decrease in the heating energy consumption. Also, the effects of urban texture on building energy demand are investigated by a number of researchers (Santamouris *et al.* 2001; Ratti *et al.* 2005). Those studies considered various parameters that affect building energy consumption, leaving a gap for the turbulence (vortex) parameter that may affect the heating and cooling energy consumption of a building.

1.4. Aim and Objective of the Thesis

The aim of this thesis is to investigate the effect of the turbulence (vortex) area on heating and cooling energy consumption of a building and decide that if it is a significant parameter or not.

Therefore, the objectives of this thesis in order to fulfill the aim are as follows:

- To calculate solutions for 6 different wind cases, resulting total of 12 cases, by the help of building performance simulation,
- To compare results to find out if the effect of the turbulence area on heating and cooling energy consumption of a building is significant or not.

1.5. Scope of the Thesis

The scope of this research is mainly limited to the literature review, developing 3-D models that represent the building in the turbulence area, calculating the solutions and comparing them to decide if the parameter is significant or not.

After a detailed literature survey, 3-D models for the control building as a stand-alone structure and the control building with the tall building sketched in the computational fluid dynamics program ANSYS Fluent. 6 different wind cases calculated by the help of ANSYS Fluent. Air flow and thermal analysis had been done. Later, results are compared to evaluate the significance of the turbulence parameter on heating and cooling energy of the control building.

1.6. Organization of the Thesis

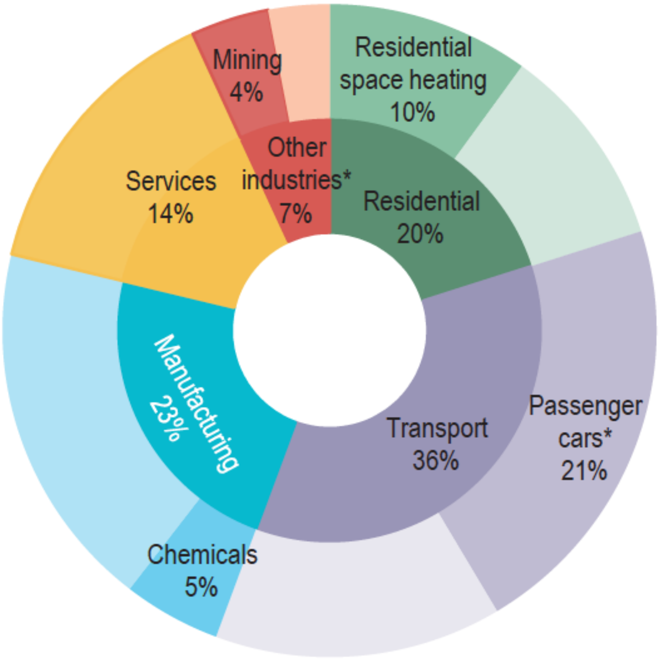
This thesis has the following chapters:

- In Chapter 2, recent research and statistics about global energy demand is presented. Also, literature review of building performance simulation with its historical background and building energy consumption factors in the literature are presented.
- In Chapter 3, the research methodology, including its theoretical background and building performance simulation steps, is presented.
- In Chapter 4, results and findings of the analysis in ANSYS Fluent is presented.
- In Chapter 5, the discussion of this thesis with its limitations and recommendations for future studies are stated.

2. LITERATURE REVIEW

2.1. Global Energy Demand

Global energy demand grew by 2.0% in 2017. It is relatively high compared to an increase of 0.9% in 2016 and an average increase of 0.9% over the last five years. As a consequence of growth rates in recent years, global energy demand reached an estimated 14 million tonnes of oil equivalent in 2017. Considering the global energy demand of 10 Mtoe in 2000, 40% growth since that time is remarkable. (International Energy Agency 2018a).



* Other industries includes agriculture, mining and construction; passenger cars includes cars, sport utility vehicles and personal trucks.

Figure 2.1. Energy Uses by Sector in IEA Countries in 2016.

Source: International Energy Agency (2018b)

The latest data on the sector's energy use is shown in Figure 2.1. The transportation sector has the largest share of the global energy demand with 36%, followed by manufacturing industry with 23%, residential sector with 20% and services sector with 14% (International Energy Agency 2018b).

The residential sector has the third largest share of the global energy demand with 20%. More than half of this significant share is due to the heating and cooling energy consumption as seen in Figure 2.2. As a result, these two energy consumption components of residential sector represent a critical share of the global energy demand with 10% (International Energy Agency 2018b).

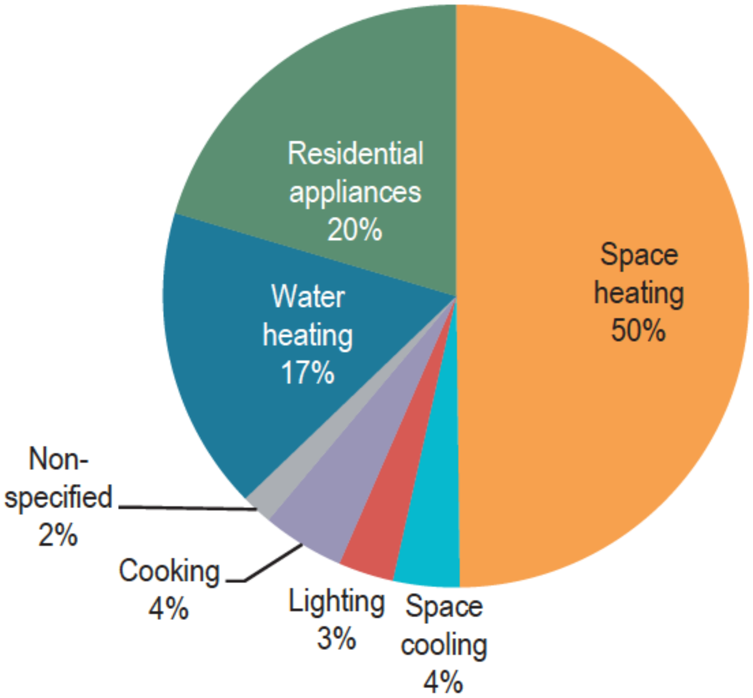


Figure 2.2. Shares of Residential Sector Energy Use in IEA Countries, 2016.

Source: International Energy Agency (2018b)

On the other hand, energy use in the residential sector continues to grow year by year. It grew by 21% between 2000 and 2017. Without the improvement of energy efficient building designs and investment trends, it would have been 12% higher in 2017. This amount of saving is considerably sufficient at the given level of economic welfare expansion, population and residential building growth for those years. At the same time, International Energy Agency highlights the potential of keeping the global residential energy demand constant till 2040, despite of the expected 60% growth rate for the total building area (International Energy Agency 2018c). For this aim, buildings should be 40% more energy efficient. Considering the energy efficiency developments in last decades, it is achievable.

For keeping the global residential energy demand constant, traditional engineering design tools are inconvenient because of the following reasons: they are typically solution-oriented, mono-disciplinary and very restricted in scope. On the other hand, computational building performance simulations are problem oriented, multi-disciplinary and wider in scope (Hensen and Lamberts 2011, p.1-14). They have assisted to lower the growth rate of the global residential energy demand since 1960s.

2.2. Building Performance Simulation

In recent years, there has been increasing interest in performance and efficiency to make machines, human activities and production processes better. Relevant stakeholders strongly focussed on job performance, high performance computing and economic performance. This also applies to the construction environment, where building performance has grown to be a significant concern across the sector (de Wilde 2018, p. 1–14). For this concern, building performance simulation (BPS) is a powerful tool to study the different aspects of building performance during its life-cycle using a computer-based, mathematical model generated on a basis of fundamental physical and engineering principles (Maile *et al.* 2007). BPS can help achieve some targets, such as, improving indoor air, thermal, visual and acoustic comfort, reducing energy consumption and environmental impacts, thus it is opening a new era to all stakeholders in construction sector (Nguyen *et al.* 2014). Contrary to what is believed, BPS is not only useful for pre-construction, but also in construction and post-construction processes. It provides the quantification of aspects of building performance at relatively low effort and cost. Those performance aspects could be relevant to building's design, construction and operation & post-construction control (de Wilde 2018, p. 325–422).

2.2.1. Aspects of Building Performance Simulation

Design is the first key part for BPS. It specifies the look and the functioning of structures by detailed drawings. It includes both architecture and engineering. Also, decisions made in design process are crucial because of their effects on later processes; construction, operation and control (de Wilde 2018, p. 328-343). Therefore, building performance simulation starts with the design of the building. It is named performance-based design (PBD) in the literature and it has been reviewed for numerous aspects in many studies. Becker (2008) suggested a conceptual framework and systematic approach with some formulated fundamental principles of PBD. Energy efficient and environmental friendly building designs with PBD support were reviewed for several perspectives such as; thermal, visual and acoustic comfort, air quality, water and energy efficiency, lightning and daylight efficiency (Ward 2004; Roaf *et al.* 2001; Day 2016). The passivhaus concept which is relatively new, rigorous, performance-based and voluntary standart for ultra-low energy buildings to reduce the building's ecological footprint was reviewed (Krainer 2008; Hopfe and Mcleod 2015).

Construction is the second key part for BPS. It is the process of actually building the structure according to the drawings that result from the design process. Even if the design is perfect and efficient, performance of a building relates to the execution of that design. As Ahire and Dreyfus (2000) pointed out, design and construction management has equal importance for the ultimate quality of buildings. Buildings, as a human-made, have many stake-holders and activities in the construction process. The general field that aims to conduct this complex process is construction management (de Wilde 2018, p. 374–377). Within this domain, total quality management (TQM) is a crucial concept to direct the construction process. Howarth and Greenwood (2017) reviewed TQM in aspects of key theories on quality management models, quality, learning in organizations, project and corporate performance and health and safety aspects. Also, ISO 9000 is defined as the international standard that specifies the fundamentals of TQM such as leadership, customer focus, process management, involvement of people, synergy, continuous improvement, systems view, and effective decision making (International Organization for Standardization 2015).

The third and the last key part for BPS is operation and control. Ultimately, even if a building designed and constructed well, its performance under actual use conditions still depends on the interactions between building, residents and a wide variety of external factors (de Wilde 2018, p. 387-390). Those interactions need a simulation practice for tracking, analyzing, diagnosing and resolving its issues. Building management system (BMS) has been fulfilling this need for the last decades. It consists of a cycle. Stage one of the cycle is about collecting the actual performance data and analyzing it in terms of how it changes over time. Stage two involves the analysis of performance data to detect abnormalities in the system. Stage three consists of identifying the issues that cause abnormalities and finding solutions to them. For last, stage four applies these solutions and tracks the results for future abnormalities (California Commissioning Collaborative 2001).

2.2.2. History of Building Performance Simulation

A short historical overview of BPS is written by Spitler (2006) in his editorial: “Building performance simulation: the now and the not yet”. He states that:

> “Simulation of building thermal performance using digital computers has been an active area of investigation since the 1960s, with much of the early work (see e.g. Kusuda 1999) focusing on load calculations and energy analysis. Over time, the simulation domain has grown richer and more integrated, with available tools integrating simulation of heat and mass transfer in the building fabric, airflow in and through the building, daylighting, and a vast array of system types and components. At the same time, graphical user interfaces that facilitate use of these complex tools have become more and more powerful and more and more widely used.”

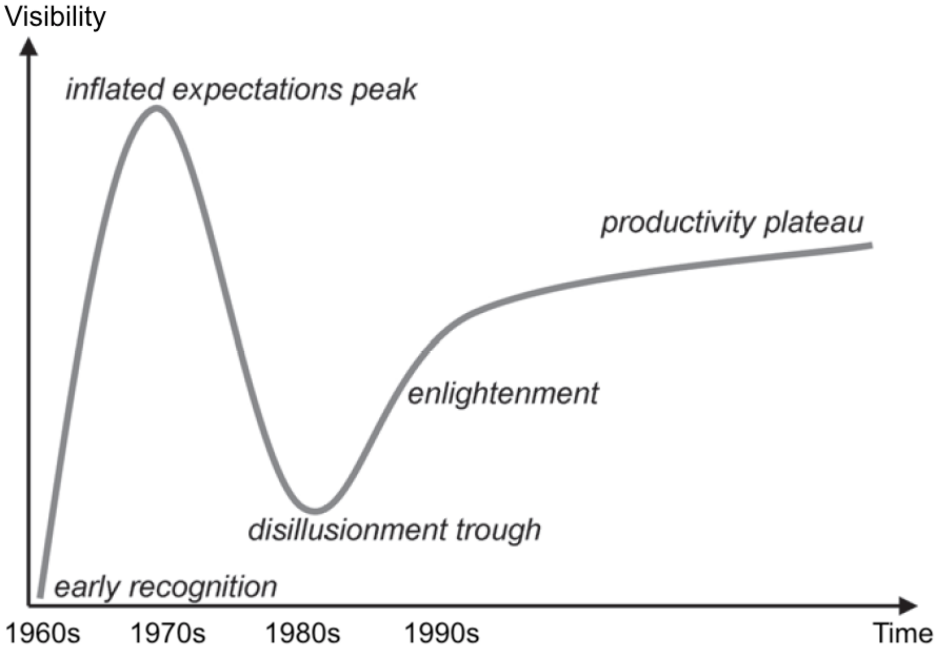


Figure 2.3. Hype Cycle for Building Performance Simulation.

As many other technological innovations, building performance simulation also experienced hype cycle (Fenn and Raskino 2008), as shown in Figure 2.3. The very early developments of BPS started in 1960s, with the rise of the personal computers, in the United States and Sweden. Later, it became one of the most significant topics of the 1970s within the energy research community. During these two decades, several methods had been introduced for analyzing single component systems (e.g. heating loads) and most of the research activities were devoted to the fundamentals of load and energy assumptions for buildings (Hong *et al.* 2000). BRIS, which is the very first building performance simulation program, was developed in 1963 by the Royal Institute of Technology in Stockholm (Brown 1990). Later that, DOE-2, BLAST, ESP-r, TRNSYS and HVACSIM+ were introduced in early 1970s (Kusuda 1999). With these developments, expectation of BPS was peaked in early 1970s. However, despite of the availability of BPS tools, they rarely used in the construction industry because of the high cost and difficulty involved in their implementation (Hong *et al.* 2000). As a result, this peak of inflated expectations followed by the trough of disillusionment in early 1980s. Later, the situation has changed since 1990s when personal computer software and hardware were both more affordable for BPS in both research and industry (Wand and Zhai 2014). Also, harmful fluorocarbon-based materials and the wasteful consumption of fossil fuels were blamed for global warming. So, creating effective structures with reduced negative impact on the environment and less energy consumption has become a challenge for the industry. This demand for green and more effective buildings has made the application of BPS a must (Hong *et al.* 2000). As a result, early 1990s can be seen as a start point for building performance simulation's productivity plateau.

On the other hand, with the realization of the importance of energy use in buildings, the International Energy Agency (IEA) has funded numerous R&D activities in the building sector. These R&D activities have been progressing simultaneously with the BPS sector, starting with its first annex in 1977. The IEA Energy Conservation in Buildings and Community Systems (ECBCS) now has 80 annexes shown in Table 2.1, Table 2.2, Table 2.3 and Table 2.4. Seventeen of these annexes are ongoing projects. Tasks are directed at energy calculations and efficiency technologies. Results are being used to improve energy standards and guidelines (Hong *et al.* 2000). Considering the annexes funded and developed by IEA ECBCS, it can be seen that building performance simulation is one of the key technologies for the construction of modern-era buildings which are more environmentally-friendly, health responsive and energy efficient.

Table 2.1. IEA-ECBCS Annexes from Code 1 to Code 6.

Code	Annex Title	Period
1	Load energy determination of buildings completed	1977-1980
2	Ekistics and advanced community energy systems	1976-1978
3	Energy conservation in residential buildings	1979-1982
4	Glasgow commercial building monitoring	1979-1982
5	Air infiltration and ventilation centre	1977-
6	Energy systems and design communities	1979-1981

Table 2.2. IEA-ECBCS Annexes from Code 7 to Code 35.

Code	Annex Title	Period
7	Local government energy planning	1981-1983
8	Inhabitant behaviour with regard to ventilation	1984-1987
9	Minimum ventilation rates	1982-1986
10	Building HEVAC system simulation	1982-1987
11	Energy auditing	1982-1987
12	Windows and fenestration	1982-1986
13	Energy management in hospitals	1985-1989
14	Condensation and energy	1987-1990
15	Energy efficiency in schools	1988-1990
16	Building energy management systems: part 1	1987-1991
17	Building energy management systems: part 2	1988-1992
18	Demand controlled ventilation systems	1987-1992
19	Low slope roof systems	1987-1993
20	Air flow patterns within buildings	1988-1991
21	Environmental performance	1988-1993
22	Energy efficient communities	1991-1993
23	Multizone air flow modelling	1990-1996
24	Heat, air and moisture transport	1991-1995
25	Real time HEVAC simulation	1991-1995
26	Energy efficient ventilation of large enclosures	1993-1996
27	Evaluation and demonstration of domestic ventilation systems	1993-1997
28	Low energy cooling systems	1993-1997
29	Daylight in buildings	1995-1999
30	Bringing simulation to application	1995-1998
31	Energy related environmental impact of buildings	1996-1999
32	Integral building envelope performance	1996-1999
33	Advanced local energy planning	1996-1998
34	Computer-aided evaluation of HVAC system performance	1997-2001
35	Hybrid ventilation in office buildings (HybVent)	1998-2002

Table 2.3. IEA-ECBCS Annexes from Code 36 to Code 64.

Code	Annex Title	Period
36	Retrofitting in educational buildings	1999-2003
37	Low exergy systems for heating and cooling	1999-2003
38	Solar sustainable housing	1999-2003
39	High performance thermal insulation systems (HiPTI)	2001-2005
40	HVAC systems for improving energy performance	2001-2004
41	Whole building heat, air and moisture response (MOIST-EN)	2003-2007
42	The simulation of building-integrated fuel cell COGEN-SIM)	2003-2007
43	Testing and validation of building energy simulation tools	2003-2007
44	Integrating environmentally responsive elements in buildings	2004-2011
45	Energy-efficient future electric lighting for buildings	2004-2010
46	Assessment tool-kit for government buildings (EnERGo)	2005-2010
47	Cost effectiveness of existing and low energy buildings	2005-2010
48	Heat pumping and reversible air conditioning	2006-2011
49	Low exergy systems for high performance buildings	2005-2010
50	Prefabricated systems for low energy renovation	2006-2011
51	Energy efficient communities	2007-2013
52	Towards net zero energy solar buildings	2008-2014
53	Total energy use in buildings: analysis & evaluation methods	2008-2013
54	Analysis of micro-generation in buildings	2009-2014
55	Reliability of energy efficient building retrofitting	2010-2015
56	Cost-effective energy & CO_2 emissions in building renovation	2010-2017
57	Evaluation of embodied energy and for building construction	2011-2016
58	Reliable building energy performance characterisation	2011-2016
59	High-temp cooling and low-temp heating in buildings	2012-2016
60	New generation computational tools for buildings	2012-2017
61	Business and technical concepts for retrofit of public buildings	2012-2017
62	Ventilative cooling	2012-2018
63	Implementation of energy strategies in communities	2013-2018
64	LowEx communities	2013-2018

Table 2.4. IEA-ECBCS Annexes from Code 65 to Code 80.

Code	Annex Title	Period
65	Long term performance of super-insulating materials	2013-
66	Definition and simulation of occupant behavior in buildings	2014-
67	Energy flexible buildings	2014-
68	Design and op. strategies for high IAQ in low energy buildings	2014-
69	Practice of adaptive thermal comfort in low energy buildings	2014-
70	Building energy analysis of real building energy use at scale	2016-
71	Building energy performance based on in-situ measurements	2016-
72	Assessing environmental impacts caused by buildings	2016-
73	Towards net zero energy public resilient communities	2017-
74	Competition and living lab platform	2018-
75	Renovation with combining energy efficiency & renewables	2017-
76	Renovation of historic buildings	2017-
77	Integrated solutions for daylight and electric lighting	2018-
78	Supplementing ventilation with gas-phase air cleaning	2018-
79	Occupant-centric building design and operation	2018-
80	Resilient cooling	2018-

2.3. Building Energy Consumption Factors

The world is continually stepping towards a critical energy crisis due to an increasing global energy demand compared to supply. This constant increase in global energy demand causes numerous environmental problems with the scarceness of fossil fuels and growing concern of CO_2 and other greenhouse gas emissions (Escrivá-Escrivá 2011). Considering the share of residential sector in global energy demand, which is 20%, analysis and conservation of building energy consumption is crucial for improving the global energy efficiency (Yuan *et al.* 2016). Therefore, an important amount of studies have been published on factors influencing building energy consumption. These factors can be categorized into groups of building related characteristics, occupant related characteristics and nature and nearby environment.

2.3.1. Factors of Building Related Characteristics

Some of the most important factors that affect the building energy performance is obviously related to the building characteristics. They formed the central focus of a study by Yu *et al.* (2011) in which authors found even a slight difference in some building related parameters would result in significant decrease in the building energy consumption. As the European Union's energy performance of buildings directive addressed that decreasing the energy consumption of buildings is affected by not just how they are designed, but also how they are built (Janda 2011).

Papadopoulos *et al.* (2002), Tso and Yau (2003), Saidur (2009), Chan (2011), Escrivá-Escrivá (2011), Mourshed (2011), Yu *et al.* (2011) and Yun and Steemers (2011) identified some factors such as type, orientation, age, envelope, floor area & size, shape, thermal insulation, materials and construction quality as building characteristics related parameters which affect building energy consumption. Papadopoulos *et al.* (2002) investigated the energy renovation of existing buildings and found that design parameters such as surface to heated volume ratio, size of the building, and also some structural parameters such as thermal insulation of windows, roofs and walls affect the building energy consumption. Chan (2011) reported that energy consumption and the indoor climate of a building can be affected by some building envelope characteristics such as wall color, glazing material, window-to-wall ratio, building shape, thermal insulation, shading devices and green roof system. Tso and Yau (2003) give descriptive information on domestic energy usage patterns and study the effects of housing type, age and size on building energy consumption.

Factors of building related characteristics that influence building energy consumption are shown in Table 2.5.

Table 2.5. Factors of Building Related Characteristics in Literature.

Factors of Building Related Characteristics	Reference
Type	Tso and Yau (2003)
	Yun and Steemers (2011)
Age	Saidur (2009)
	Tso and Yau (2003)
	Yun and Steemers (2011)
Size	Papadopoulos *et al.* (2002)
	Saidur (2009)
	Tso and Yau (2003)
	Yun and Steemers (2011)
Thermal insulation	Papadopoulos *et al.* (2002)
Design/Structural parameters	Escrivá-Escrivá (2011)
	Papadopoulos *et al.* (2002)
Orientation	Escrivá-Escrivá (2011)
	Papadopoulos *et al.* (2002)
Envelope	Saidur (2009)
	Chan (2011)
Construction quality	Escrivá-Escrivá (2011)
Indoor Thermal Quality	Yu *et al.* (2011)

2.3.2. Factors of Occupant Related Characteristics

As Janda (2011) stated, buildings do not use energy, but people do. Schipper *et al.* (1989) found that approximately half of the building energy consumption is related to the occupants and their behaviour. In this sense, a large and growing body of literature has investigated occupant effects on building energy performance for more than a century (Rosa *et al.* 1988). These previous researches has indicated the energy use in buildings as a social problem rather than a technological one (Stern and Aronson 1984). From this aspect, it can be said that reducing energy consumption of buildings not only requires changes in the building's characteristics, but also requires changes in the entire fabric of society (Rosa *et al.* 1988).

Occupants have a critical share in building energy consumption but it is poorly understood and often overlooked in the building sector (Janda 2011). Effects of occupants on building energy consumption may be divided into two main categories in the light of previous studies. Some of the researchers have focused on the effects of occupant presence, while others have focused on the effects of occupant behaviour (Yu *et al.* 2011). Emery and Kippenhan (2006) conducted a survey on the effects of occupant presence in four nearly identical houses and found that it increases the total energy consumption. Tso and Yau (2003) identified the number of household members as a significant factor that influence building energy consumption. On the other hand, Ouyang and Hokao (2009) researched the potential of energy saving by improving occupant behaviour in 124 households in China and found that more than 10% of building energy consumption can be reduced with energy-conscious behaviour. The connection of occupant thermal comfort and building energy consumption has investigated (Yu *et al.* 2011; Schipper *et al.* 2011) and researchers found that modifying occupant behaviour for a balance between the thermal comfort and energy efficiency is significant (Yu *et al.* 2011; Bohdanowicz 2006). However, changing the behaviour of occupants who do not have energy-saving habits may be difficult (Kempton *et al.* 1992), most particularly when the change contains personal inconvenience for them (Nair *et al.* 2010).

Factors of occupant related characteristics that influence building energy consumption are shown in Table 2.6.

Table 2.6. Factors of Occupant Related Characteristics in Literature.

Factors of Occupant Related Characteristics	Reference
Occupancy rate	Emery and Kippenhan (2006) Tso and Yau (2003)
Occupancy behaviour	Janda (2011) Kempton *et al.* (1992) Nair *et al.* (2010) Ouyang and Hokao (2009) Rosa *et al.* (1988) Schipper *et al.* (2011) Yu *et al.* (2011)
Preference relevant to indoor comfort	Bohdanowicz (2006)
Awareness of energy consumption	Bohdanowicz (2006)

2.3.3. Factors of Nature and Nearby Environment

Climate can be identified as the long-term trends in the weather system (Drake and Foster 1995) and it can not be determined or modified by human. It is one of the most important factors that affecting the building energy consumption and a short overview of the interaction between climate and buildings can be found in a journal article by Lam *et al.* (2005): "Weather data analysis and design implications for different climatic zones in China". Authors state that:

> "Building acts as a climatic modifier, separating the indoor built environment from the external climate described by the prevailing long-term weather conditions. The climate of a particular location tends to influence the shapes and forms of the local buildings and dictates the types of environmental control required. There is often a distinct correspondence between special architectural features and different climatic zones. Proper selection of climatic variables and their analysis can affect the building load calculations, performance of the corresponding heating, ventilation and air-conditioning (HVAC) equipment and the accuracy of the heating energy consumption estimation. The climate-specific properties of the

> building designs and building energy consumption can be obtained by evaluating the long-term measured hourly/daily weather data. Understanding climatic influences is an essential part of the building design process."

Also, a number of researchers identified climate as a huge influential factor on building energy consumption (Lam *et al.* 2005; Hviid *et al.* 2008; Oxizidis *et al.* 2008; Wan *et al.* 2011; Yu *et al.* 2011; Jim and Peng 2012; Kalamees *et al.* 2012; Tagliabue *et al.* 2012). Lam *et al.* (2005) qualified long-term hourly and daily weather data for five cities in China which were selected to represent the five main architectural climates; hot summer and warm winter, mild, hot summer and cold winter, cold and severe cold. Temperature, solar radiation and wind conditions were investigated in the study. Wan *et al.* (2011) researched the interaction between the local climates and future building energy consumption for heating and cooling. They found that overall energy use for space heating and cooling would be affected by the prevailing local climates and the actual climate change in future years. They listed moisture content of air, wind speed/direction, temperature and solar radiation as essential weather parameters. Yu *et al.* (2011) investigated the effects of climate on occupant behaviour, thereby on building energy performance. Kalamees *et al.* (2012) found that the cold in the winter season is the most important factor on the heating energy demand, while the hot in the summer season has the similar impact on cooling energy demand. Hviid *et al.* (2008) presented a simple building energy simulation tool for integrated daylight and thermal analysis. Tagliabue *et al.* (2012) researched the effect of the amount of natural light using on building energy demands for heating, cooling and lightning.

On the other side, buildings are affected by not just their own characteristics, occupant behaviour or climate, but also the nearby buildings and local environment which could exert a mutual influence on building energy consumption dynamics. A considerable amount of literature has been published on these impacts. Han *et al.* (2015a) developed a systematic approach to disaggregate and quantify the influence of mutual reflection and mutual shading within a network of buildings. Also, they introduced the concept of the Inter-Building Effect (IBE) to understand the complicated mutual influence within spatially proximal buildings. Urban Heat Island (UHI) effect is investigated by Han *et al.* (2015b). Heidarinejad *et al.* (2016) conduct a parametric analysis to support the improvement of coupled simulations of solar radiation at building surfaces and outdoor airflow in different plan area densities. Liu *et al.* (2015) investigated the exterior surfaces' convective heat transfer coefficients (CHTCs) at the leeward, external windward and roof surfaces of a building which is located in an urban environment with different plan area densities. They found that exterior surface CHTC correlations have a direct impact on the urban micro-climate, thereby building energy consumption. The effects of urban texture on building energy consumption are investigated by a number of researchers (Santamouris *et al.* 2001; Ratti *et al.* 2005). Also, there is a large volume of published studies examining the role of nearby trees on building energy consumption. The first serious discussions and analyses of trees emerged during the 1980s with the recognition of their impact on building energy use by Heisler (1986). Akbari (2002) researched the urban shade trees' benefits in improving urban air quality and reducing building air-conditioning demand by lowering smog. Hes *et al.* (2011) investigated the results and problems encountered when trying to model trees effectively for understanding the impact of them on building energy consumption.

Factors of nature and nearby environment which affect building energy consumption can be found in Table 2.7.

Table 2.7. Factors of Nature and Nearby Environment in Literature.

Factors of Nature and Nearby Environment	Reference
Climate	Lam *et al.* (2005)
	Hviid *et al.* (2008)
	Oxizidis *et al.* (2008)
	Wan *et al.* (2011)
	Yu *et al.* (2011)
	Jim and Peng (2012)
	Kalamees *et al.* (2012)
	Tagliabue *et al.* (2012)
Urban micro-climate	Wan *et al.* (2011)
	Santamouris *et al.* (2001)
	Ratti *et al.* (2005)
Amount of daylight usage	Hviid *et al.* (2008)
	Tagliabue *et al.* (2012)
Mutual shading in network of buildings	Han *et al.* (2015a)
Mutual reflection in network of buildings	Han *et al.* (2015a)
Urban Heat Island (UHI)	Han *et al.* (2015b)
Outdoor airflow	Heidarinejad *et al.* (2016)
Solar radiation	Heidarinejad *et al.* (2016)
Nearby trees	Heisler (1986)
	Akbari (2002)
	Hes *et al.* (2011)

3. METHODOLOGY

The aim of this thesis is to investigate and quantify the effect of the rotor turbulence area on heating and cooling energy consumption of buildings and find out if it is significant or not. ANSYS Computational Fluid Dynamics (CFD) program Fluent is used to simulate air flow and energy calculations. In order to achieve this, the following steps will be taken:

- Sketching two 3-D models in DesignModeler,
  - The control building as a stand-alone structure,
  - The control building & the tall building which creates the turbulence area,
- Meshing both 3-D models,
- Calculating the solutions for 6 different wind cases for both of the 3-D models (6 x 2 = 12 cases),
- Comparing the results to find out if the effect of the turbulence area on heating and cooling energy consumption of buildings is significant or not.

3.1. Methodology Background

In this section, firstly the technical information of turbulence (vortex) areas is presented. Later on, theoretical background of the meshing and solution method of Fluent simulations follows.

3.1.1. Turbulence (vortex)

Cook (1986) explains turbulence (vortex) as a general flow around a surface mounted obstacle in his book: “Designers guide to wind loading of building structures - part 1”. He states that:

> “When an atmospheric boundary layer (ABL) wind profile approaches normal to the spanwise direction of the obstacle, the wind speed increases with the height above the ground. The flow at about two-thirds of the obstacle height comes to

> rest to form the front stagnation point. From this point the flow deviates into four main streams. In one of these above the stagnation point, the flow goes up and over the top of the obstacle. Below this point the flow goes down until it reaches the ground where it has more kinetic energy than the incident wind at this level. It is therefore able to move upstream against the wind, losing energy until it comes to rest at a separation point on the ground. The flow rolls up into a horizontal standing vortex next to the ground upstream of the windward face of the obstacle. The third and fourth streams are formed by the air entering the standing vortex escaping around either side of the obstacle. When the flow next to the ground is observed, this vortex forms the shape from which it derives its name of the horseshoe vortex."

Velocity magnitude path lines and turbulence (vortex) areas forming around an obstacle can be seen in Figure 3.1 and Figure 3.2. There are four type of vortexes entitled as stagnation vortex, top vortex, side vortex and leeward vortex. This thesis especially investigates the leeward vortex effect on heating and cooling energy consumption of buildings.

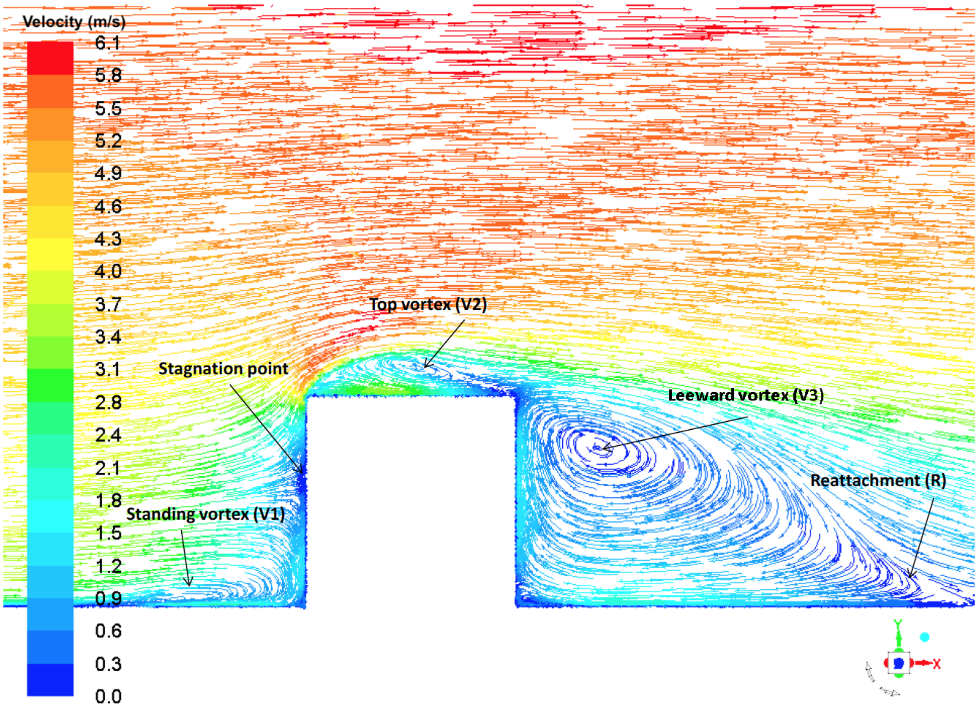


Figure 3.1. Velocity Magnitude Path Lines Passing Through the Vertical Center Plane.

Source: Pancholy *et al.* (2017 Preprint)

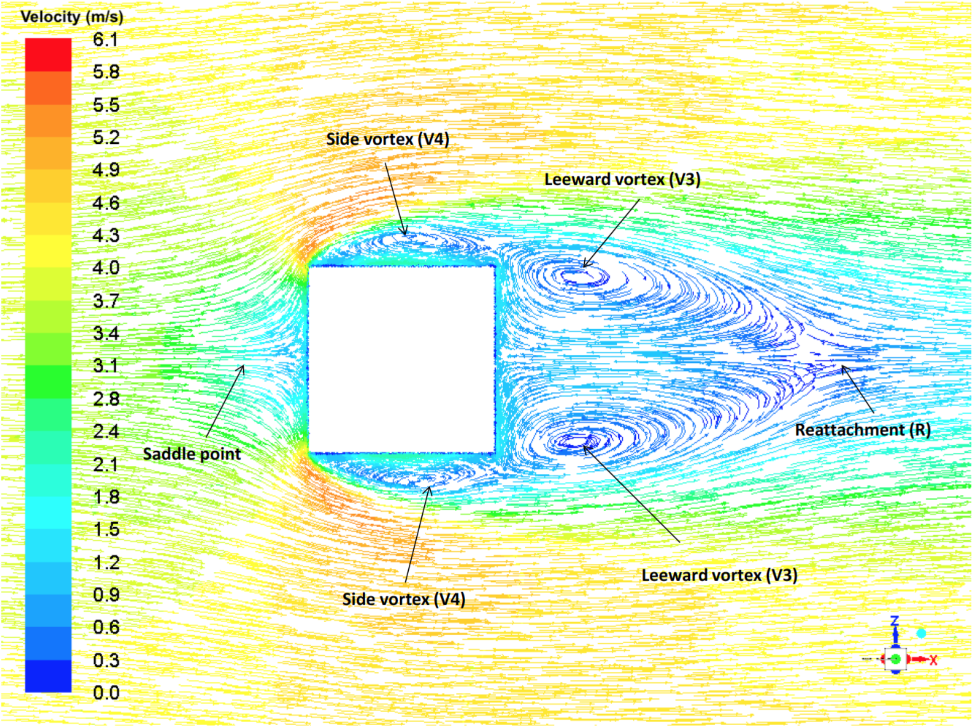


Figure 3.2. Velocity Magnitude Path lines at Ground Level.

Source: Pancholy *et al.* (2017 Preprint)

3.1.2. Meshing

Proper meshing plays a critical role in computer simulations which are the prediction of real-world behavior. High quality meshing provides more accurate results. Meshing in ANSYS Fluent has 4 main steps:

- Global mesh controls are defined (e.g., general sizing and mesh method),
- Local mesh controls are defined (e.g., contact sizing and inflation),
- Mesh is generated and previewed,
- Mesh quality parameters are checked (e.g., skewness and aspect ratio)

Some of the most commonly used meshing methods can be seen in Figure 3.3, Figure 3.4 and Figure 3.5.

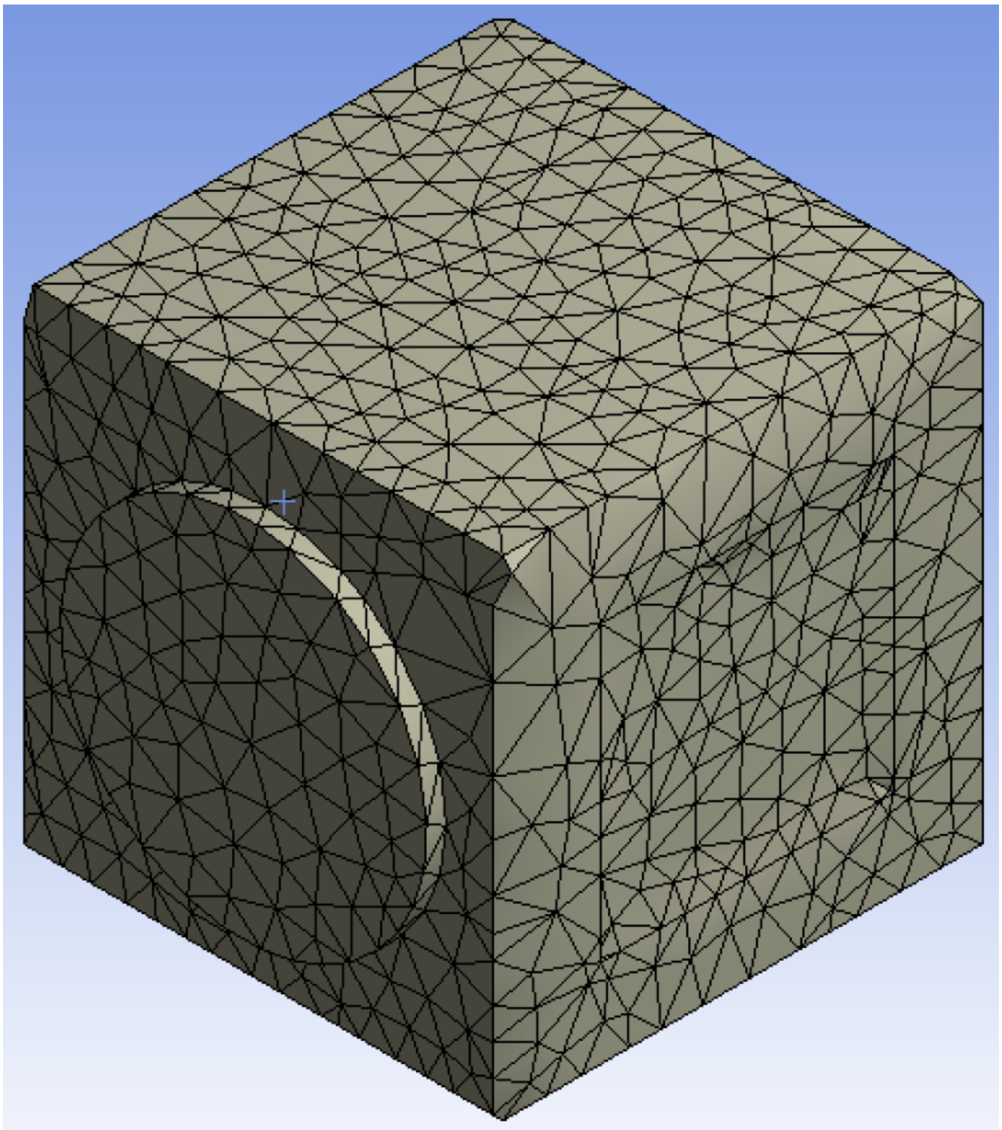


Figure 3.3. Tetrahedral Meshing Method.

Also in meshing, boundary layers are hard-to-adjust regions. Inflation is used for these boundary layers in order to increase the mesh resolution for better results. It can be seen in Figure 3.6.

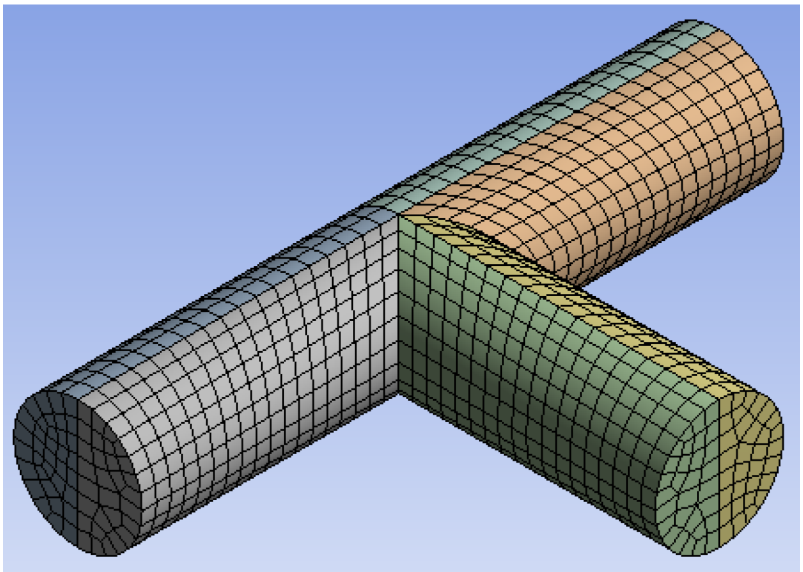


Figure 3.4. Sweep Meshing Method.

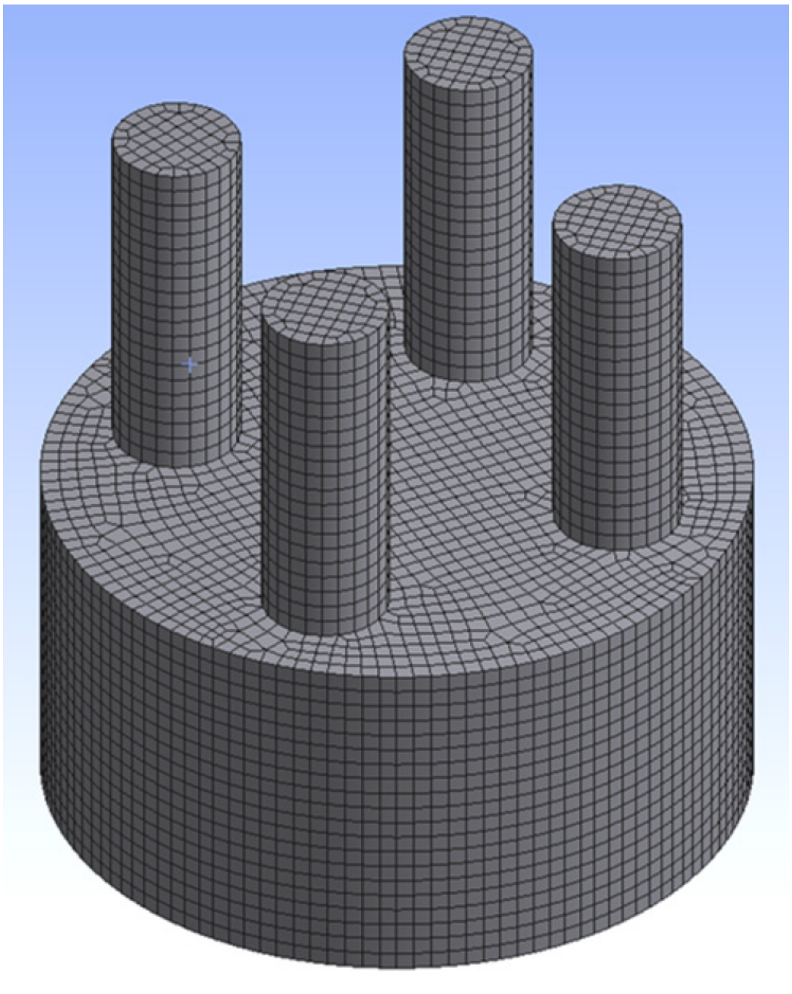


Figure 3.5. Multizone Meshing Method.

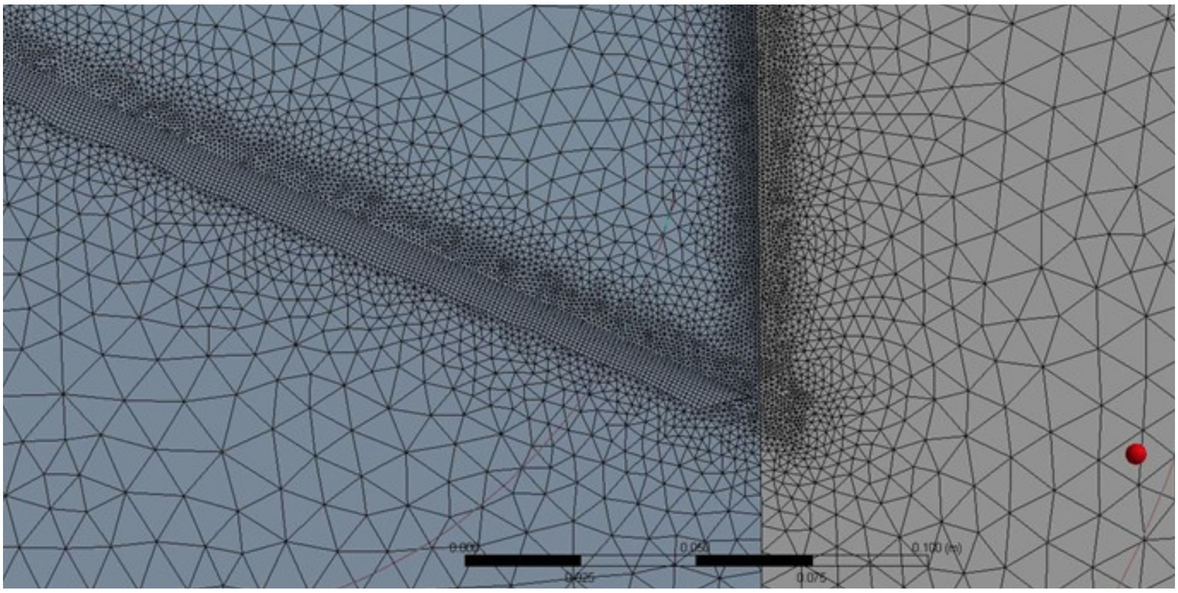


Figure 3.6. Inflation in Meshing.

After meshing completed, its quality should be checked and improved if needed. Different physics and solution methods have various requirements for mesh quality. However, skewness and aspect ratio are the most commonly used mesh quality metrics. Skewness formula is shown in Equation 3.1. Aspect ratio formula in 2-D can be seen in Equation 3.2 and in 3-D can be seen in Equation 3.3. For better quality, the recommended value is less than 0.95 for skewness and less than 100 for aspect ratio.

$$\text{skewness} = \frac{\text{optimal cell size} - \text{ cell size}}{\text{cell size}} \tag{3.1}$$

$$\text{aspect ratio} = \frac{\text{length of the mesh element}}{\text{height of the mesh element}} \tag{3.2}$$

$$\text{aspect ratio} = \frac{\text{circumscribed circle radius of the mesh element}}{\text{inscribed circle radius of the mesh element}} \tag{3.3}$$

3.1.3. Solution Methods

3.1.3.1. Realizable k-ϵ Model. In computational fluid dynamics (CFD), even simple flows are difficult to simulate. The computational complexity grows exponentially when accounting for turbulence flows which are irregular fluid motions that span a wide range of scales in space and time. For this reason, selecting the right method for turbulence modeling is critical for accurate fluid dynamics simulations. While turbulence can be fully described by the Navier-Stokes equations, direct numerical simulation is impractical due to massive resource requirements. Therefore, the simplest models of turbulence are the two-equation models in which the solution of two separate transport equations allow the turbulent velocity and length scales to be independently determined.

The realizable k-ϵ model which is one of the two-equation models is used to simulate turbulence flows in this thesis. The realizable k-ϵ model (Launder and Spalding 1972) is a semi-empirical model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ϵ). The model transport equation for k is derived from the exact equation, while the model transport equation for ϵ was obtained using physical reasoning and bears little resemblance to its mathematically exact counterpart.

The turbulence kinetic energy (k), and its rate of dissipation (ϵ), are obtained from the following transport equations:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\epsilon - Y_M + S_k \tag{3.4}$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}\left(P_k + C_{3\epsilon}P_b\right) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_\epsilon \tag{3.5}$$

where P_k represents the generation of turbulence kinetic energy due to the mean velocity gradients,

$$P_k = -\rho \overline{u_i' u_j'} \frac{\partial u_j}{\partial x_i} \tag{3.6}$$

P_b is the generation of turbulence kinetic energy due to buoyancy,

$$P_b = \beta g_i \frac{\mu_t}{\mathrm{Pr}_t} \frac{\partial T}{\partial x_i} \tag{3.7}$$

Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate,

$$Y_M = 2\rho\epsilon \mathrm{M}_t^2 \tag{3.8}$$

$$\mathrm{M}_t = \sqrt{\frac{k}{a^2}} \tag{3.9}$$

and $C_{1\epsilon}$, $C_{2\epsilon}$, C_μ, σ_k, σ_ϵ are constants.

$$C_{1\epsilon} = 1.44, \quad C_{2\epsilon} = 1.92, \quad C_\mu = \frac{1}{A_0 + A_s \frac{kU^*}{\epsilon}}, \quad \sigma_k = 1.0, \quad \sigma_\epsilon = 1.3 \tag{3.10}$$

3.1.3.2. Steady-State Thermal Analysis. Heat flux is defined as a flow of energy per unit time per unit area. In heat flux computations of control building walls, steady-state thermal analysis in ANSYS is used. The steady-state heat equation is not dependent on time. In other words, it is assumed conditions exist such that;

$$\frac{\partial u}{\partial t} = 0 \tag{3.11}$$

In this condition, ANSYS uses the following equation to calculate the heat flux to the wall from a fluid cell;

$$q = h_f(T_w - T_f) + q_{\text{rad}} \tag{3.12}$$

where h_f is fluid-side local heat transfer coefficient, T_w is wall surface temperature, T_f is local fluid temperature and q_{rad} is radiative heat flux.

3.2. ANSYS CFD Fluent Simulations

ANSYS CFD Fluent simulations part has three main steps. First step is sketching two 3-D models which are the control building as a stand-alone structure and the control building with the tall building. Second step is meshing both 3-D models with fine quality. Last step is calculating the solutions for 6 different wind cases for both 3-D models.

3.2.1. Sketching

Two 3-D models were sketched in DesignModeler for comparing the effect of the turbulence (vortex) area on heating and cooling energy consumption of a building. One of the models contains the control building as a stand-alone structure can be seen in Figure 3.7. The other model contains the control building & the tall building which provides the rotor turbulence area is shown in Figure 3.8 and Figure 3.9. Both 3-D models have bounding atmosphere box with the dimensions of 1000 meters of length, 300 meters of width and 200 meters of height. The atmosphere box has 60 million m^3 volume. In both models, side surfaces (+y & -y faces) and the top surface (+z face) of atmosphere box are defined as symmetry to obtain zero-shear slip boundaries while bottom surface (-z face) of atmosphere box is defined as ground. The side surface (-x face) is defined as velocity inlet while the other side surface (+x face) is defined as velocity outlet. All surfaces of atmosphere box with boundary conditions are shown in

Figure 3.10. Both 3-D models have empty area of 300-400 meters length on the side of velocity inlet, 600 meters length on the side of velocity outlet and 125-185 meters height above the buildings approximately. Adequate amount of atmosphere box and empty area & proper boundary conditions are needed to provide enough space for accurate CFD simulations. The wind comes from the -x direction and flows to the +x direction. The control building has 15 meters of length, 15 meters of width and 15 meters of height with 30 centimeters wall thickness for all its surfaces. The tall building has 75 meters of length, 75 meters of width and 75 meters of height. The distance between two buildings is 10 meters and the control building is in the leeward turbulence (vortex) area which is created by the tall building. Walls of the control building are numbered separately and it can be seen in Figure 3.11. They numbered one by one to obtain individual heat flux values in analysis as follows:

- Wall 1 is the -x face of the control building
- Wall 2 is the -y face of the control building
- Wall 3 is the +x face of the control building
- Wall 4 is the +y face of the control building
- Wall 5 is the +z face of the control building

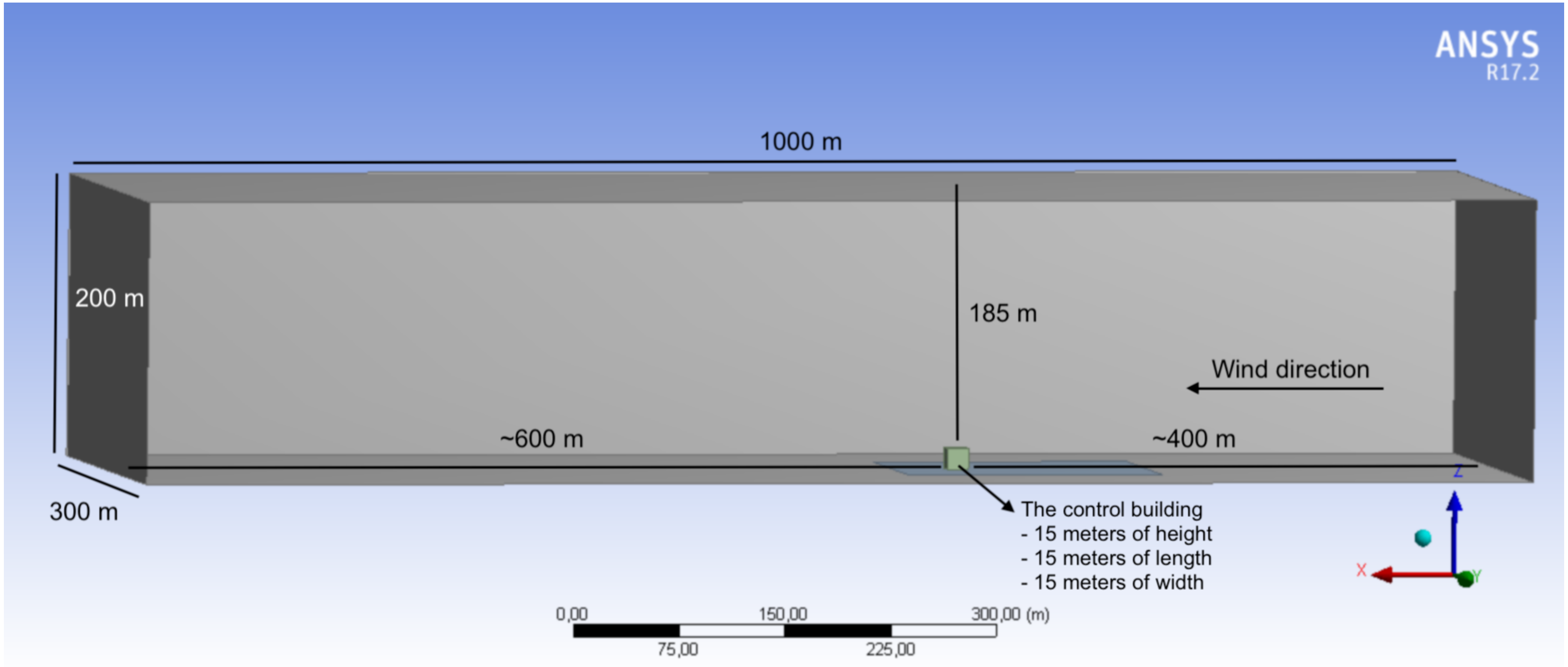


Figure 3.7. The 3-D Model of Control Building as a Stand-alone Building.

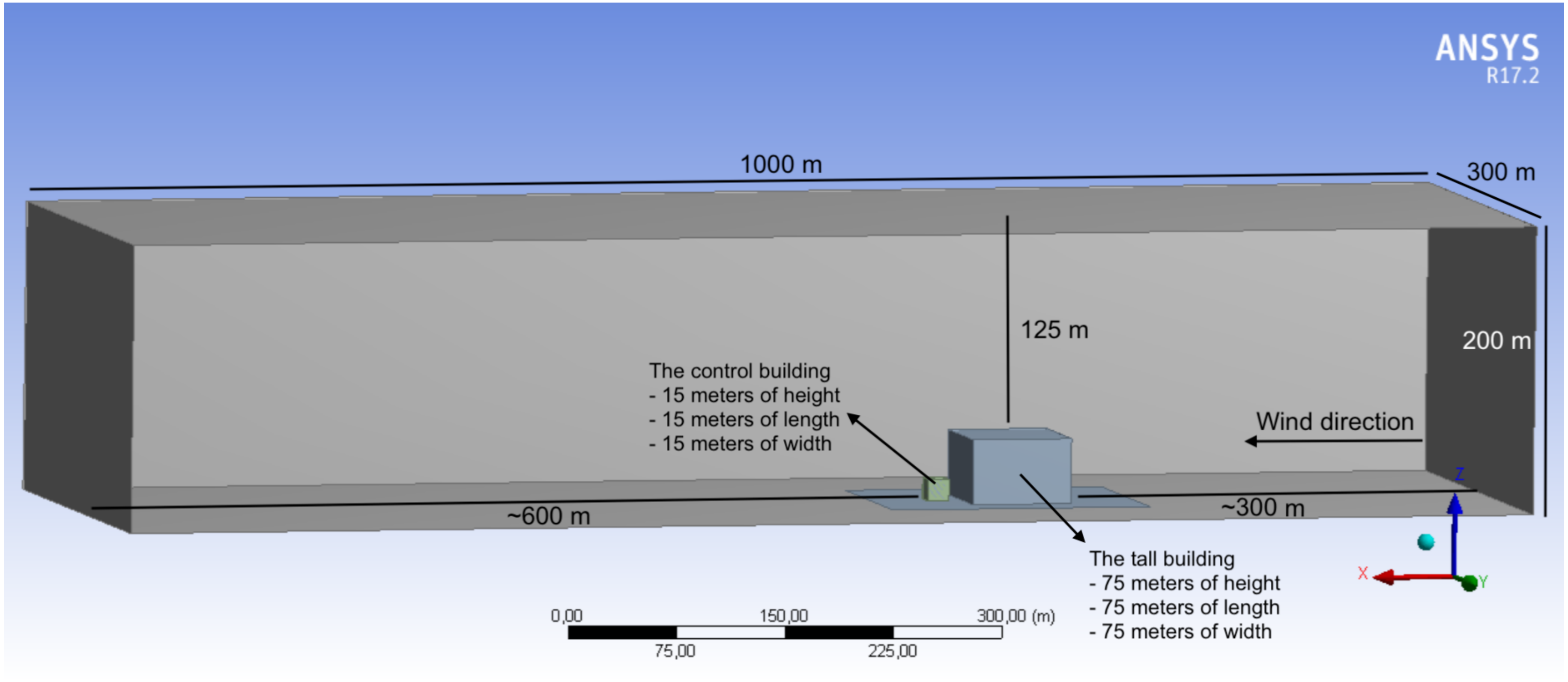


Figure 3.8. The 3-D Model of the Control Building with the Tall Building (a).

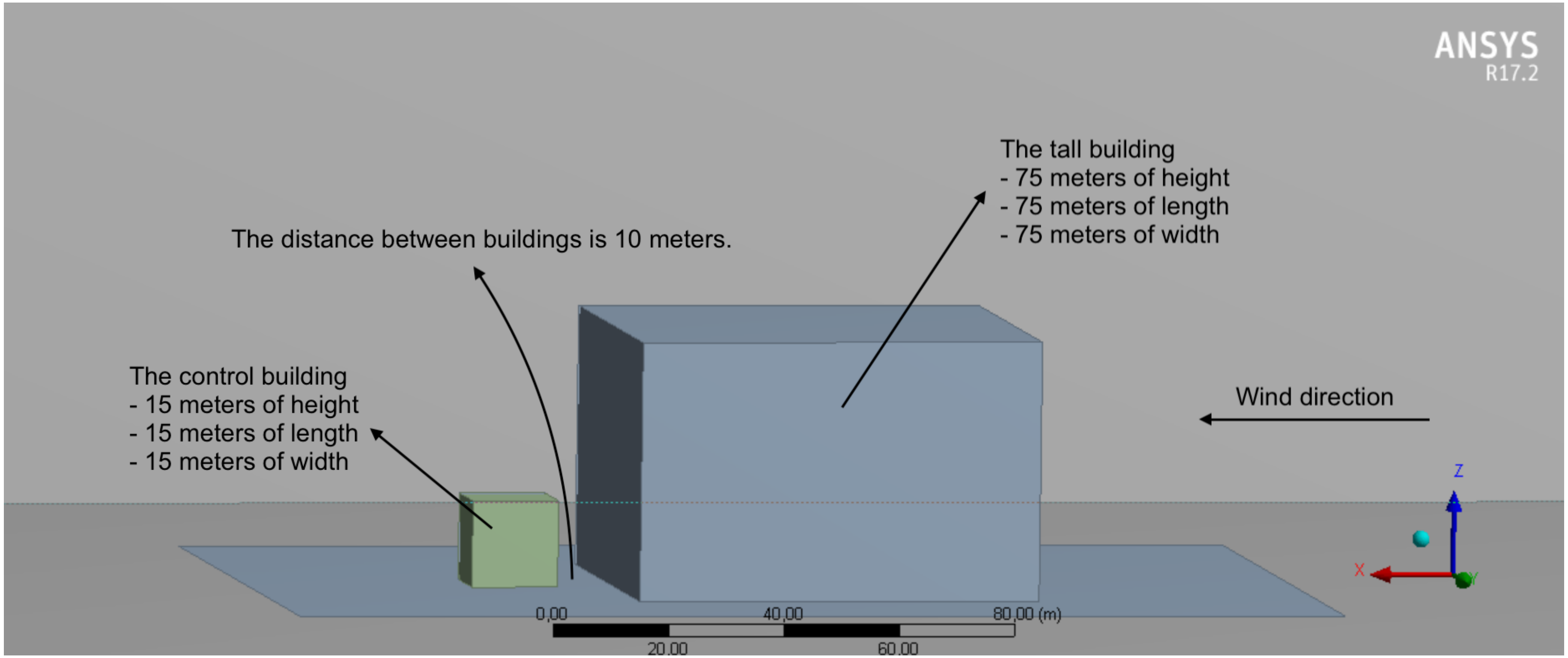


Figure 3.9. The 3-D Model of the Control Building with the Tall Building (b).

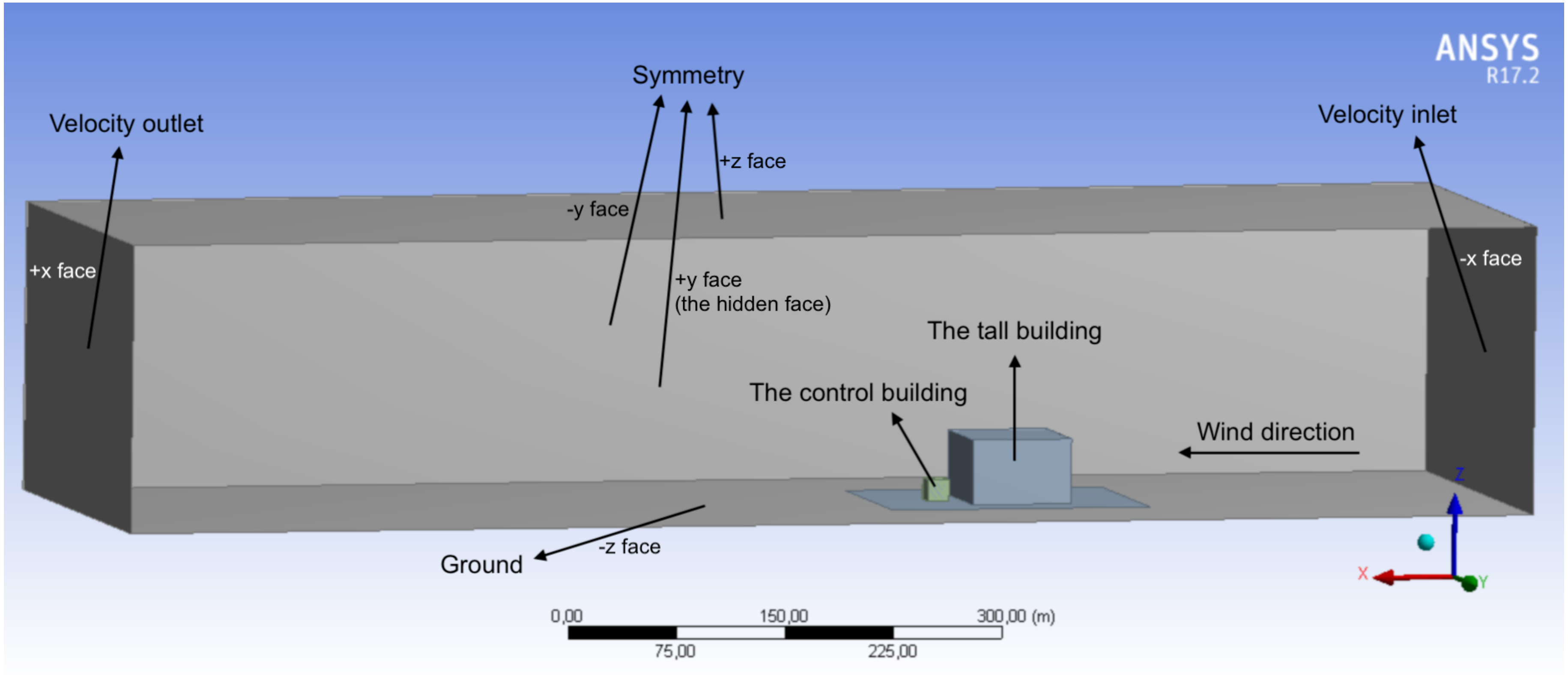


Figure 3.10. Boundary conditions of atmosphere box.

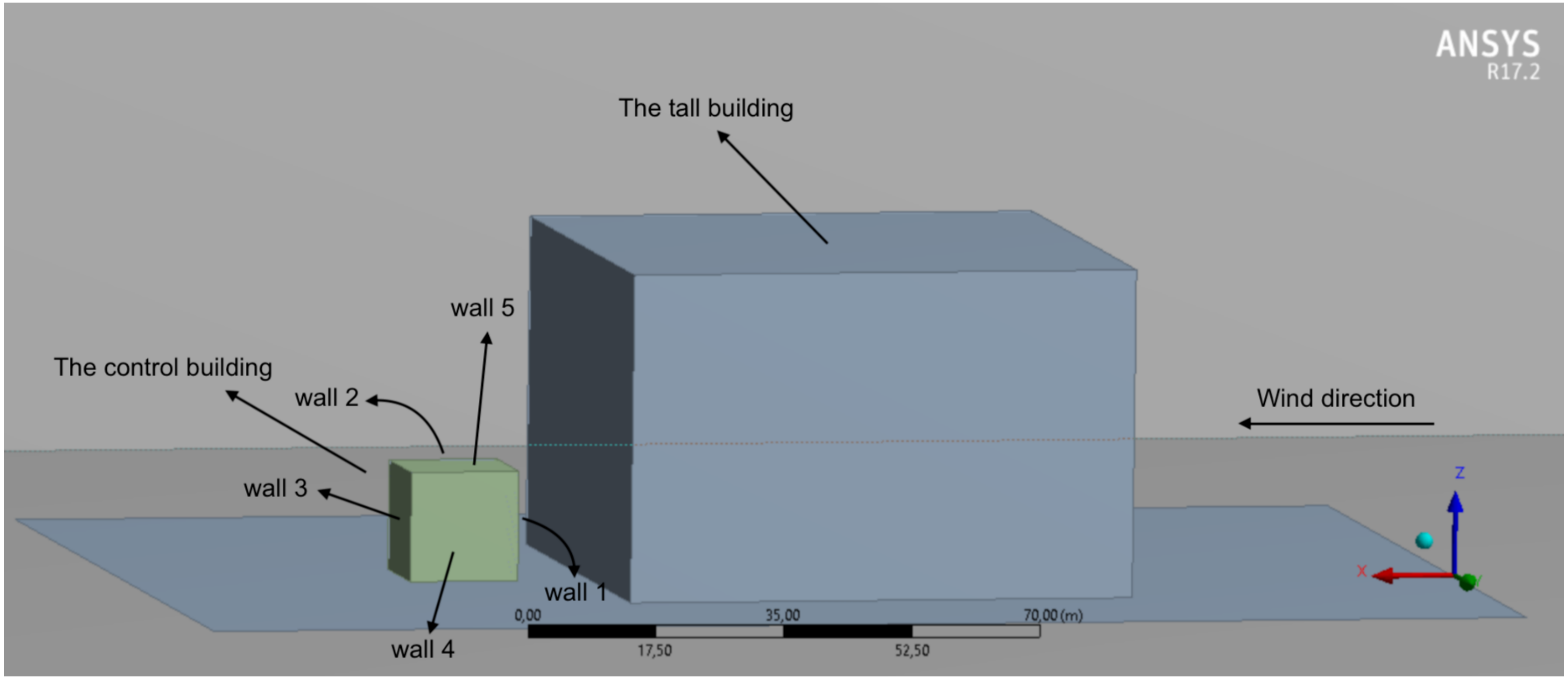


Figure 3.11. Wall numbers of the control building.

3.2.2. Meshing

Both 3-D models are meshed with multizone mesh model. It is a patch independent meshing technique which generates a pure hexahedral mesh where possible and then fills the more difficult to capture regions with unstructured mesh. Inflation layers are defined for necessary boundaries. The wall of the control building is meshed separately with extreme quality. Mesh quality of both 3-D models are checked with the aspect ratio (eq. 3.2 & eq. 3.3) and skewness (eq. 3.1) metrics.

The mesh for the 3-D model of the control building as a stand-alone structure is shown in Figure 3.12. It has 1,309,790 nodes and 1,271,670 mesh elements. Maximum aspect ratio value of the mesh is 43,84 while the average aspect ratio value is 6,67. Maximum skewness value of the mesh is 0,60 with the average skewness value of 0,09.

The mesh for the 3-D model of the control building with the tall building can be seen in Figure 3.13. It has 765,374 nodes and 733,647 mesh elements. Maximum aspect ratio value of the mesh is 50,88 while the average aspect ratio value is 4,90. Maximum skewness value of the mesh is 0,51 with the average skewness value of 0,11.

The boundary regions between atmosphere and walls of buildings have inflation layers to obtain accurate results. The section plane of the 3-D model of the control building with the tall building to demonstrate inflation layers is shown in Figure 3.14. Inflation growth rate is 1,4 and maximum layer number is 10. The first inflation layer thickness is 5 cm and it grows with smooth transition.

The walls of the control building are meshed on an individual basis for extreme quality. Mesh elements of the wall have 30 millimeters width to obtain precise thermal analysis of the wall. The section plane of the control building's wall from bottom view is shown in Figure 3.15.

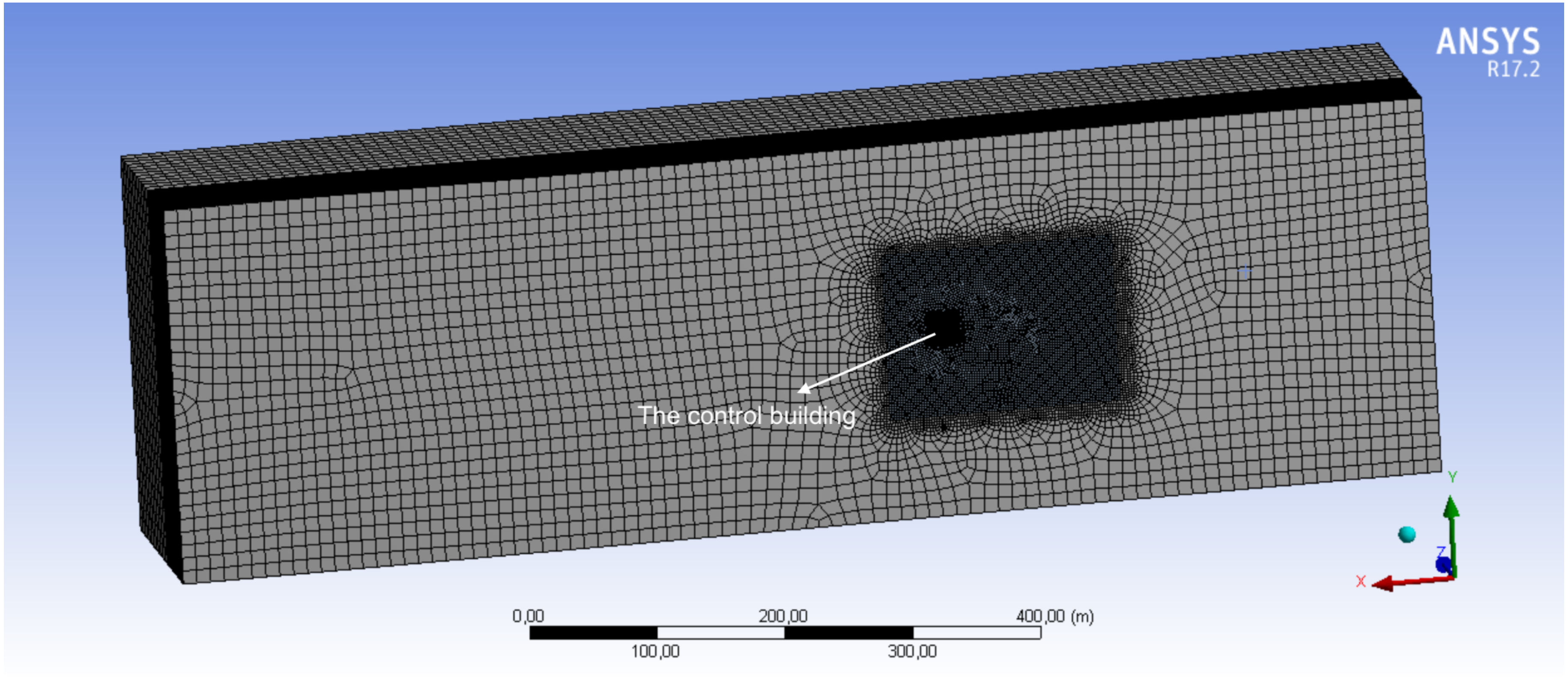


Figure 3.12. The Mesh for the 3-D Model of the Control Building from Bottom View.

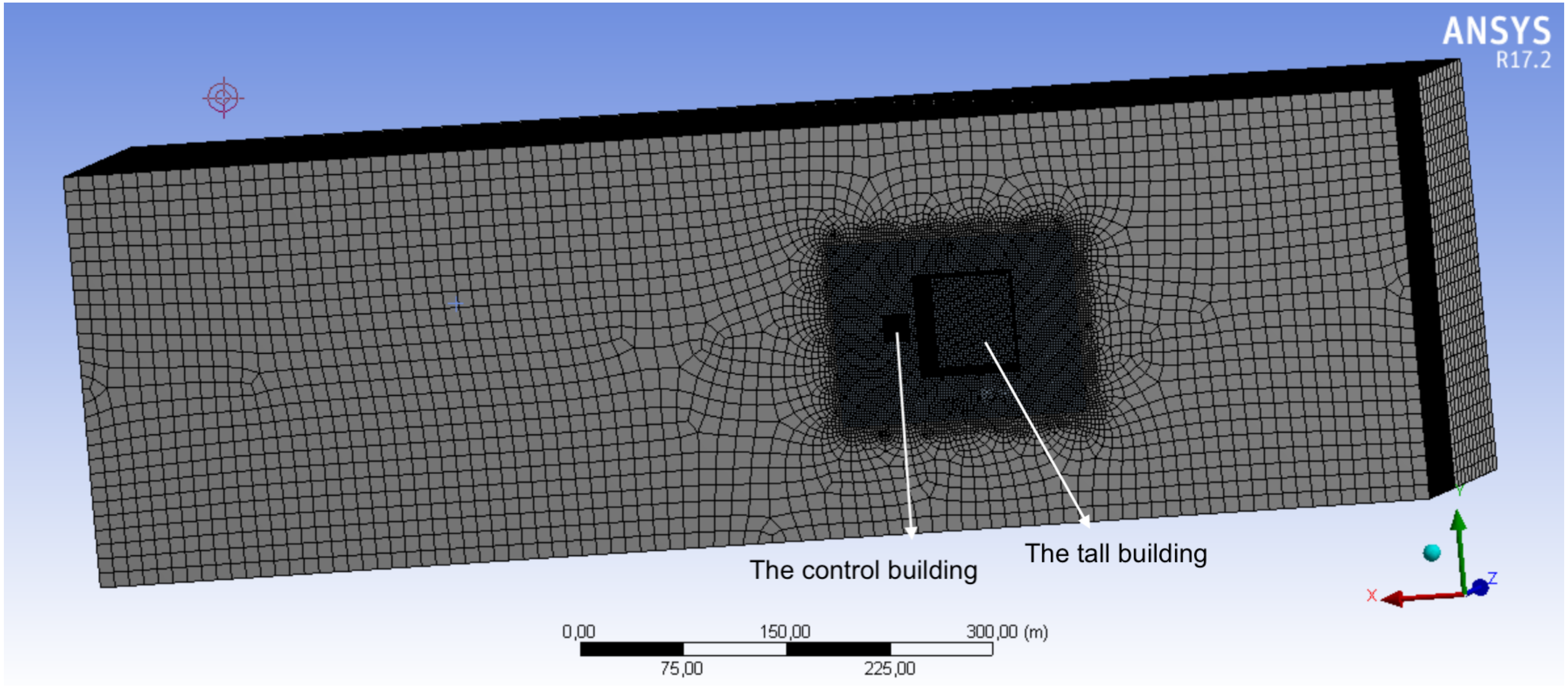


Figure 3.13. The Mesh for the 3-D Model of the Control Building with the Tall Building from Bottom View.

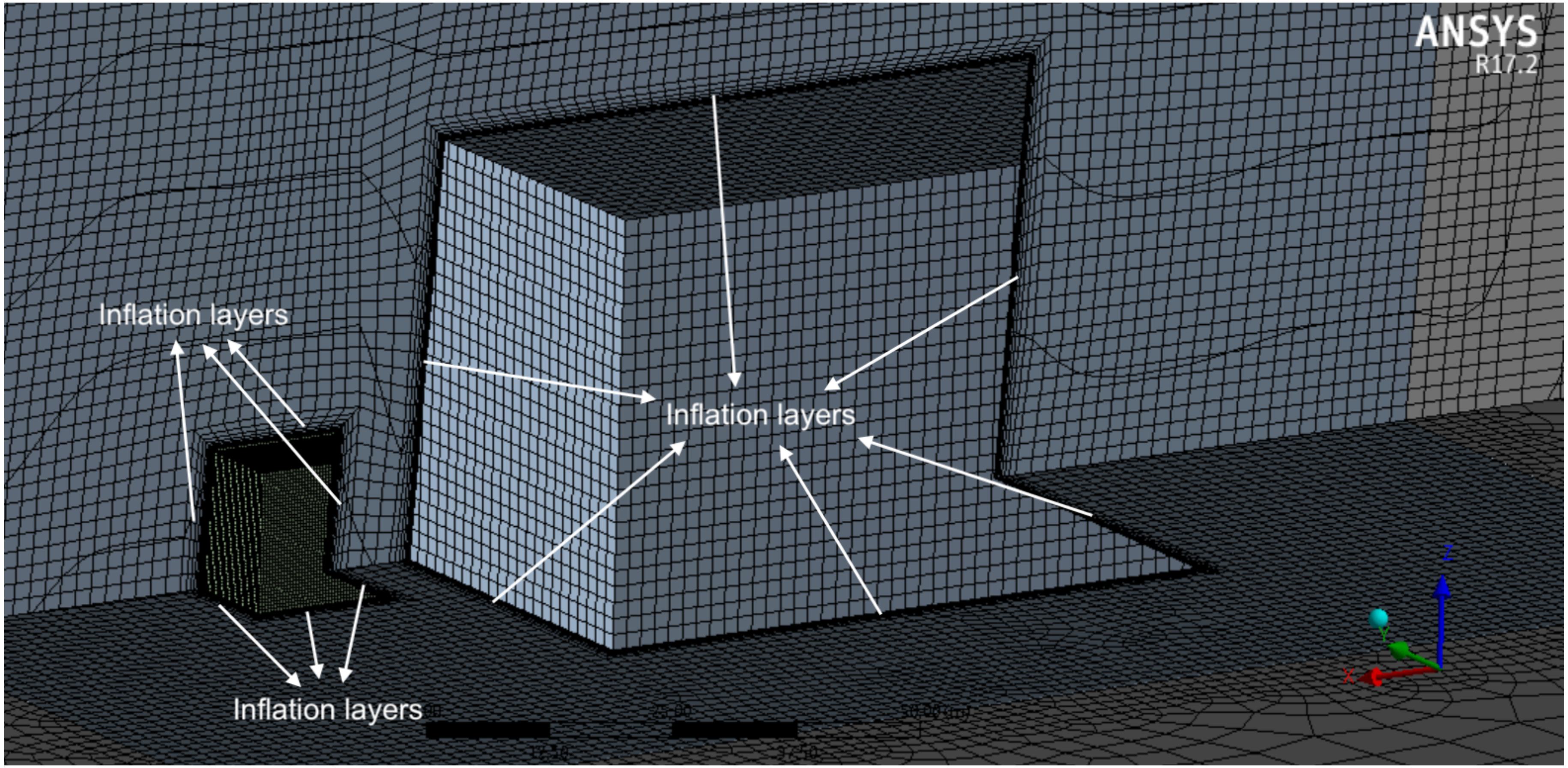


Figure 3.14. The Section Plane of the 3-D Model of the Control Building with the Tall Building.

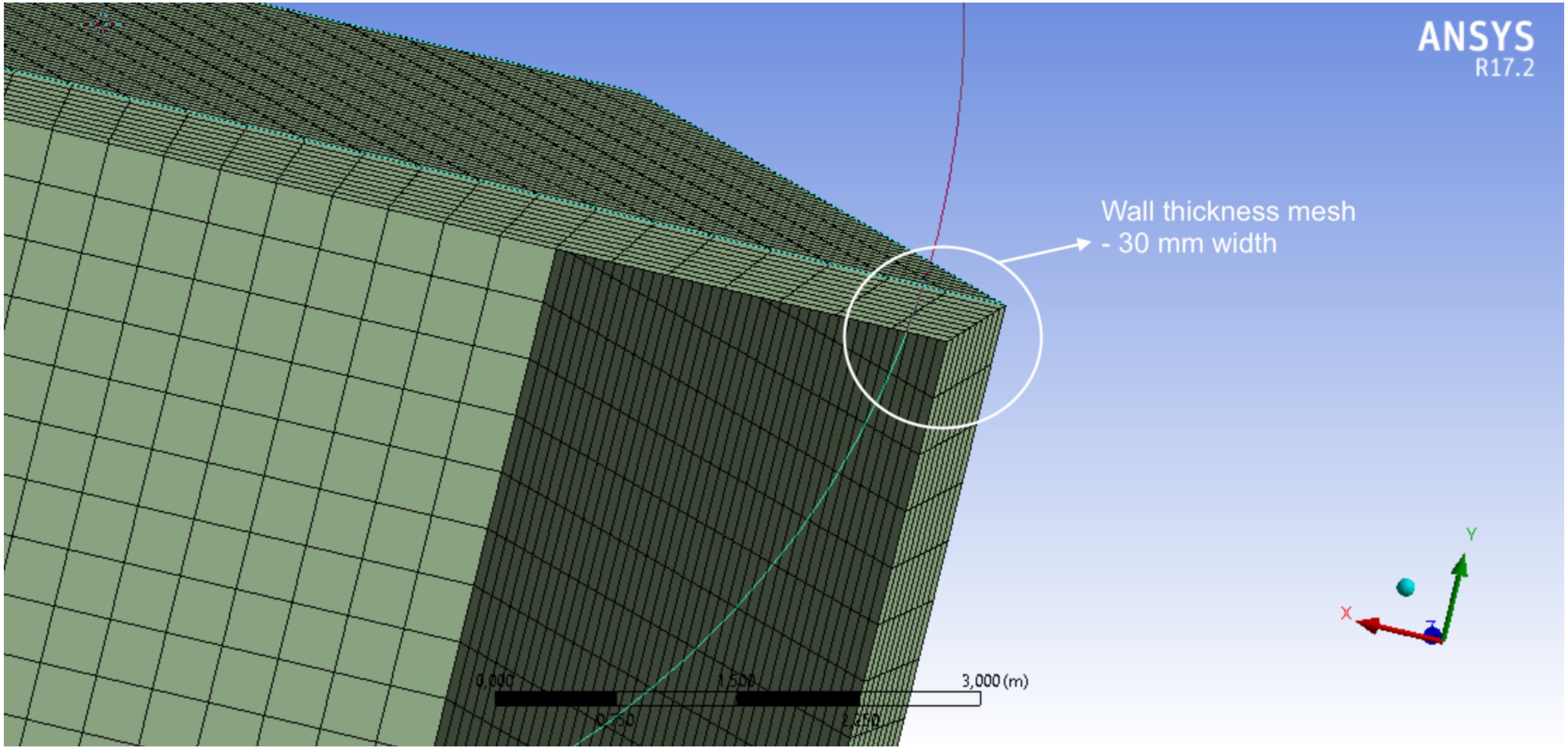


Figure 3.15. The Mesh of the Control Building's Wall from Bottom View.

3.2.3. Solution Methods and Parameters of the Analysis

After sketching 3-D models and meshing them, solution methods and parameters of the ANSYS Fluent analysis become more crucial. Solution methods are as follows;

- The realizable k-ϵ model is used for the fluid dynamics computations.
- The steady-state thermal analysis is used for the heat flux computations.
- Incompressible ideal gas condition is assumed.
- Buoyancy effect is activated.
- Non-equilibrium wall functions are used.
- Gravity is enabled in -z direction.

The realizable k-ϵ model is used for the fluid dynamics computations because it satisfies certain mathematical constraints on the Reynolds stresses, consistent with the physics of turbulent flows. Incompressible ideal gas condition is used for better air density calculations on different temperatures. Non-equilibrium wall functions are used because of their capability to partly account for the effects of pressure gradients in turbulent flows.

There are two different 3-D models for investigating the effect of the turbulence (vortex) area on heating and cooling energy consumption of a building. 6 different wind cases will be analysed for both of the 3-D models which results 12 cases in total. The wind cases are as follows;

- 10 m/s wind and 3.7 °C outdoor temperature,
- 10 m/s wind and 23.9 °C outdoor temperature,
- 15 m/s wind and 3.7 °C outdoor temperature,
- 15 m/s wind and 23.9 °C outdoor temperature,
- 20 m/s wind and 3.7 °C outdoor temperature,
- 20 m/s wind and 23.9 °C outdoor temperature,

High wind velocity values are selected such as 10 m/s, 15 m/s and 20 m/s to obtain adequate leeward turbulence (vortex) area which is created by the tall building and affects the energy consumption of control building. Outdoor temperature values are taken from Turkish Standards 825 (Turkish Standards Institution Engineering Service 2008) for İstanbul which is the most populated city in Turkey and have urban areas same as the thesis simulation models. 3.7 °C represents the average winter outdoor temperature in İstanbul while 23.9 °C represents the average summer outdoor temperature. Thermal comfort temperature is selected 21 °C for indoor conditions. 20 centimeters of brick-wall with 5 centimeters of rock wool insulation and 5 centimeters of mortar is selected for facades of the control building. Average thermal conductivity of this facade system is 0.1461 W/m K.

4. RESULTS AND FINDINGS

6 wind cases are analysed for both of the 3-D models in ANSYS Fluent CFD program, resulting total of 12 cases. Averaged 1150 iterations are performed for every wind case which results a total of 13800 iterations. Example of residuals versus iterations graph for a case of this thesis is shown in Figure 4.1. Iterations were made till the residuals converge adequately for accurate results as below;

- Continuity, k and ϵ residuals decrease at least to 1e-3,
- X-velocity, y-velocity and z-velocity residuals decrease at least to 1e-6,
- Energy residual decreases at least to 1e-10.

For all 12 cases, after an adequate decrease in residuals, heat fluxes of walls of the control building are obtained. Wall numbers of the control building are shown in Figure 3.11 in previous chapter.

Heat fluxes for walls of the control building as a stand-alone structure are shown in Table 4.1 while heat fluxes for walls of the control building in the turbulence (vortex) area of the tall building can be seen in Table 4.2. Heat fluxes for facades of the control building are shown in tables separately. Also, the total sum of heat fluxes is presented. Negative heat flux values mean that the heat flow moves from the wall to the atmosphere. On the other side, positive heat flux values mean that the heat flow moves from the atmosphere to the wall.

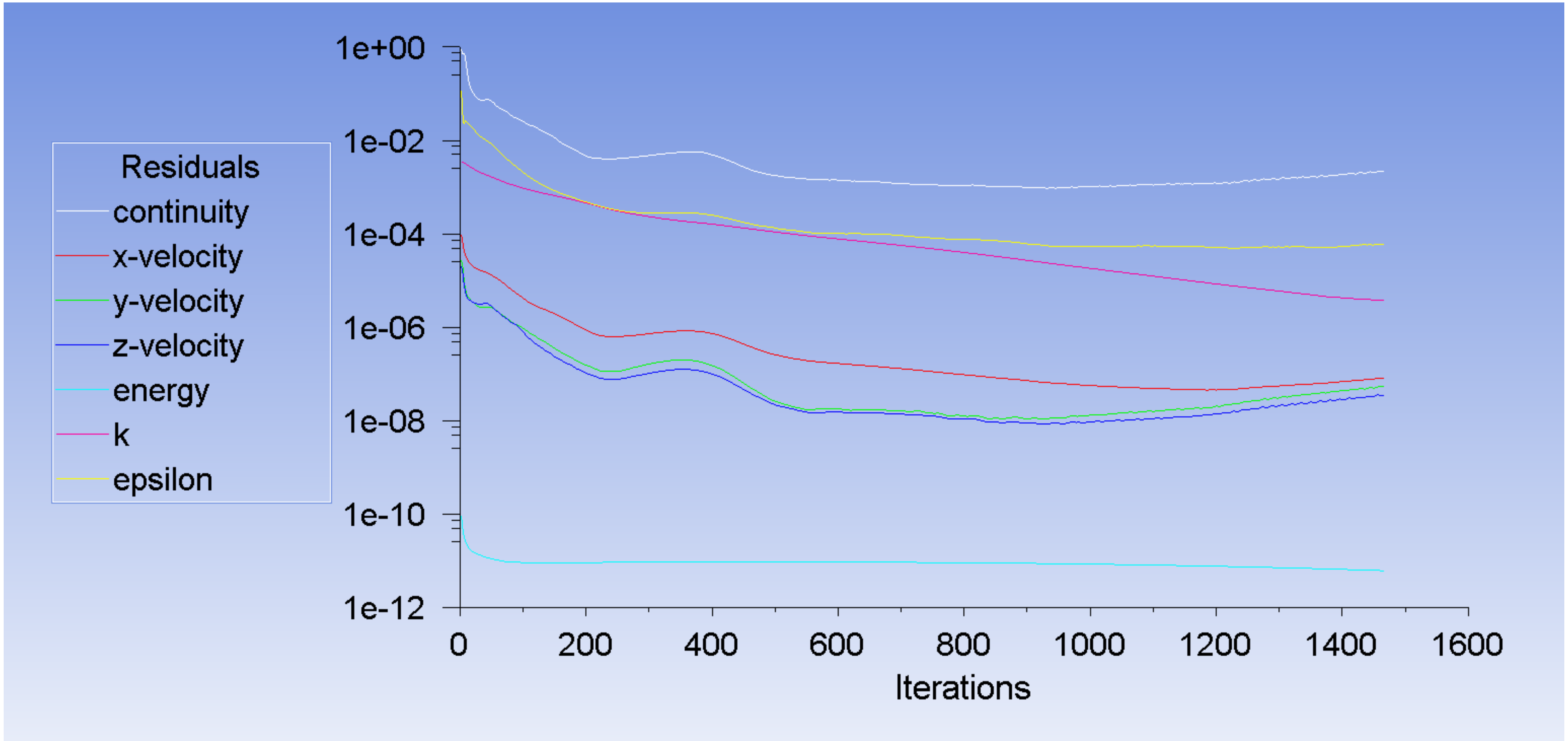


Figure 4.1. Residuals versus Iterations Graph.

Table 4.1. Heat Fluxes of Walls of the Control Building as a Stand-alone Structure.

Outdoor Temperature (°C)	Wind Velocity (m/s)	Heat Flux of Wall 1 (W/h)	Heat Flux of Wall 2 (W/h)	Heat Flux of Wall 3 (W/h)	Heat Flux of Wall 4 (W/h)	Heat Flux of Wall 5 (W/h)	Heat Flux of the Control Building (W/h)
3.7	10	-1786.21	-1779.22	-1768.39	-1778.88	-1741.38	-8854.08
3.7	15	-1791.37	-1783.66	-1779.82	-1783.80	-1745.18	-8883.83
3.7	20	-1794.16	-1785.58	-1784.86	-1786.11	-1746.90	-8897.61
23.9	10	299.38	298.16	296.36	298.11	291.87	1483.88
23.9	15	300.29	299.00	298.39	299.04	292.55	1489.27
23.9	20	300.75	299.31	299.19	299.40	292.85	1491.50

Table 4.2. Heat Fluxes of Walls of the Control Building in the Turbulence (vortex) area of the Tall Building.

Outdoor Temperature (°C)	Wind Velocity (m/s)	Heat Flux of Wall 1 (W/h)	Heat Flux of Wall 2 (W/h)	Heat Flux of Wall 3 (W/h)	Heat Flux of Wall 4 (W/h)	Heat Flux of Wall 5 (W/h)	Heat Flux of the Control Building (W/h)
3.7	10	-1734.81	-1739.28	-1755.15	-1718.78	-1700.49	-8648.51
3.7	15	-1746.95	-1749.31	-1761.37	-1738.16	-1713.36	-8709.15
3.7	20	-1769.41	-1775.40	-1779.83	-1769.58	-1729.45	-8823.67
23.9	10	291.24	292.03	295.05	288.11	286.28	1452.71
23.9	15	292.55	293.61	295.88	291.33	286.79	1460.16
23.9	20	295.90	296.72	298.27	295.68	289.58	1476.15

Thermal contours for both models in 3.7 °C outdoor temperature setting are presented in Figure 4.2 and Figure 4.3. Thermal contours for both models in 23.9 °C outdoor temperature setting are shown in Figure 4.4 and Figure 4.5. Figures are obtained from the middle plane section of buildings. Indoor temperature is selected as 21 °C for both models. Also, thermal contours for the wall 1 of the control building can be seen in figures.

Wind vectors for both models in 10 m/s wind velocity setting are shown in Figure 4.6 and Figure 4.8. Wind contours for both models in 10 m/s wind velocity setting are presented in Figure 4.7 and Figure 4.9. Wind vectors for both models in 15 m/s wind velocity setting are shown in Figure 4.10 and Figure 4.12. Wind contours for both models in 15 m/s wind velocity setting are presented in Figure 4.11 and Figure 4.13. Wind vectors for both models in 20 m/s wind velocity setting are shown in Figure 4.14 and Figure 4.16. Wind contours for both models in 20 m/s wind velocity setting are presented in Figure 4.15 and Figure 4.17. Velocity vector and contour figures are obtained from the middle plane section of buildings. Turbulence (vortex) areas created by buildings can be easily seen in wind vector figures.

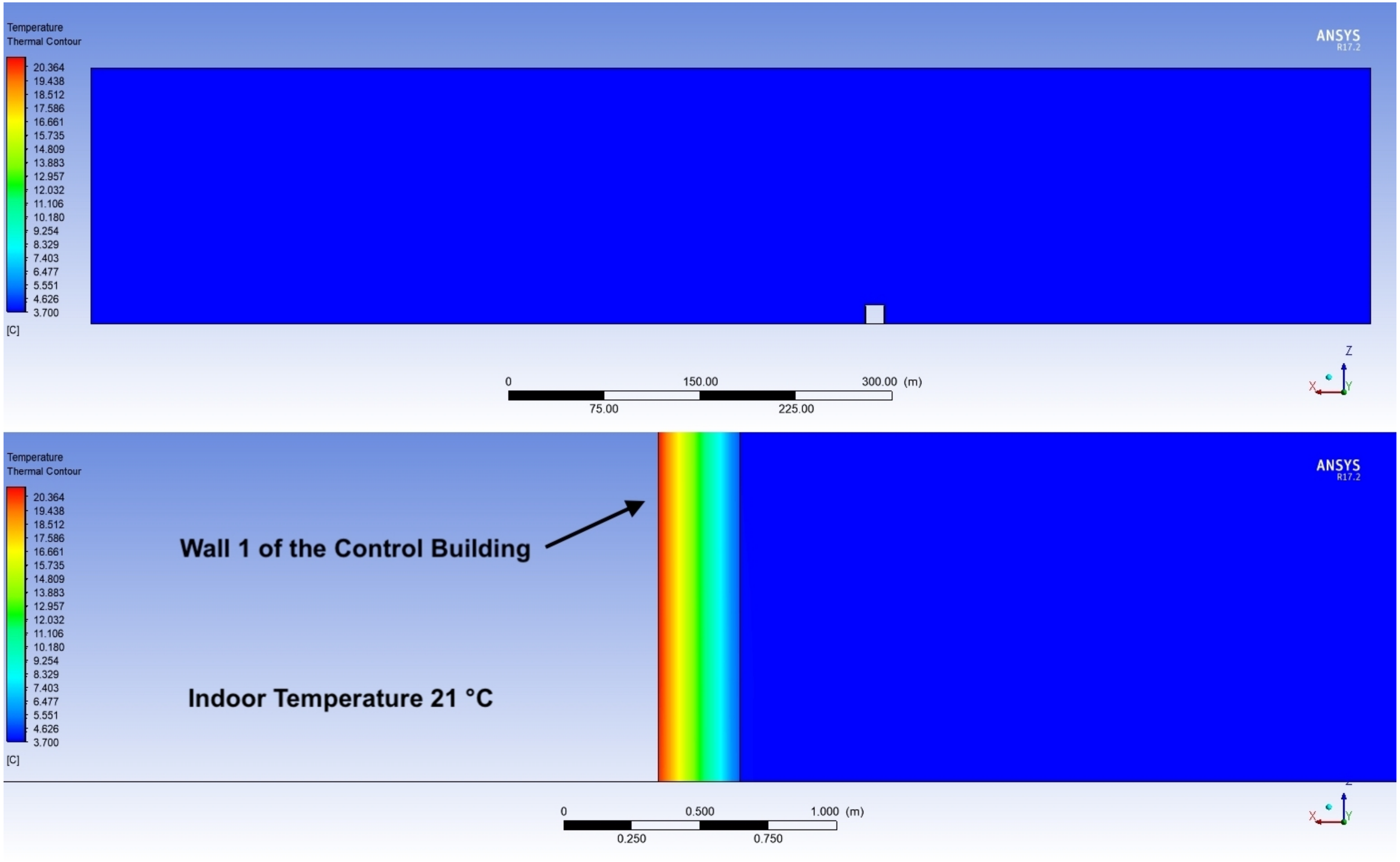


Figure 4.2. Thermal Contour for the Model of the Control Building as a Stand-alone Structure (3.7 °C Outdoor Temperature Setting).

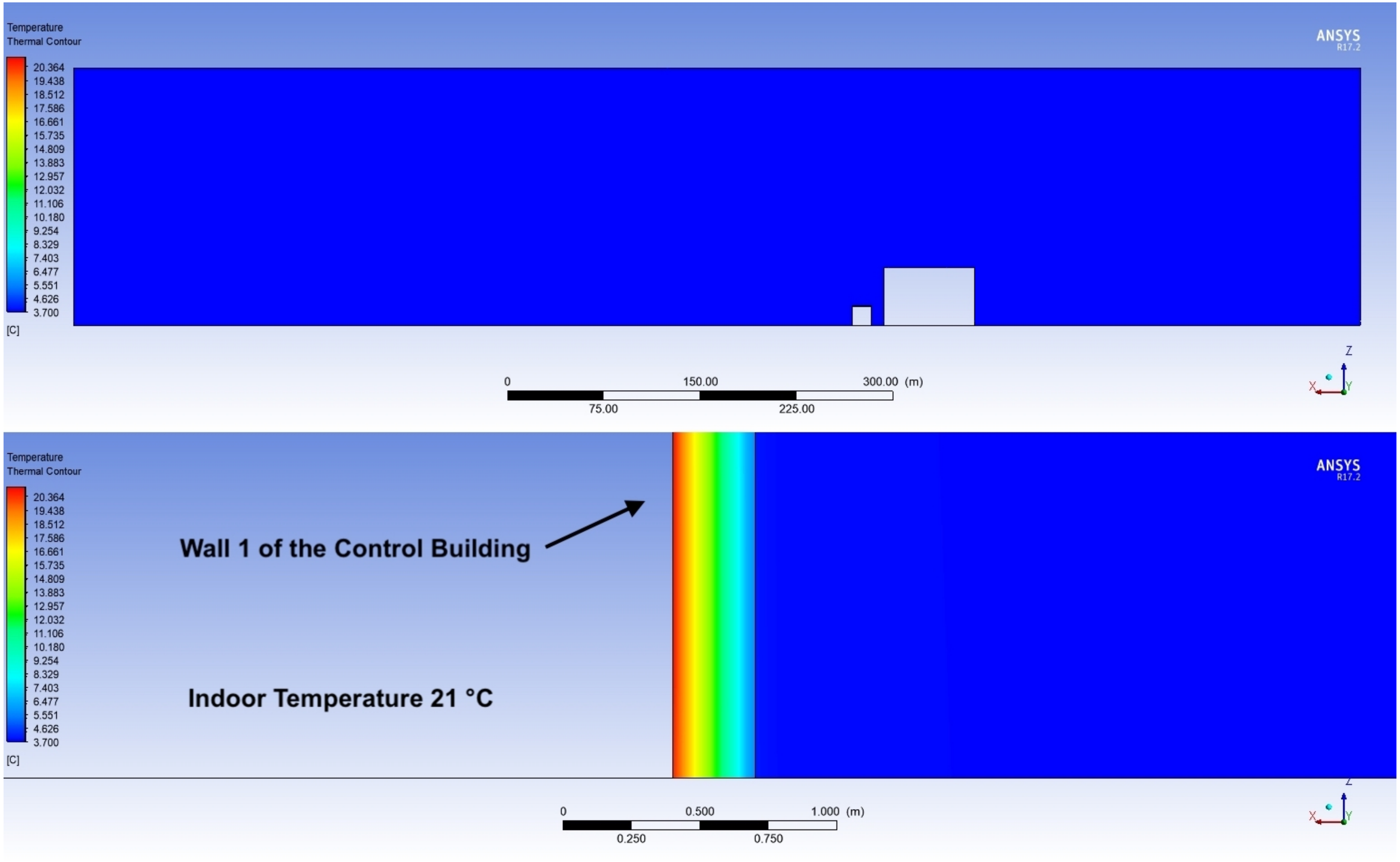


Figure 4.3. Thermal Contour for the Model of the Control Building with the Tall Building (3.7 °C Outdoor Temperature Setting).

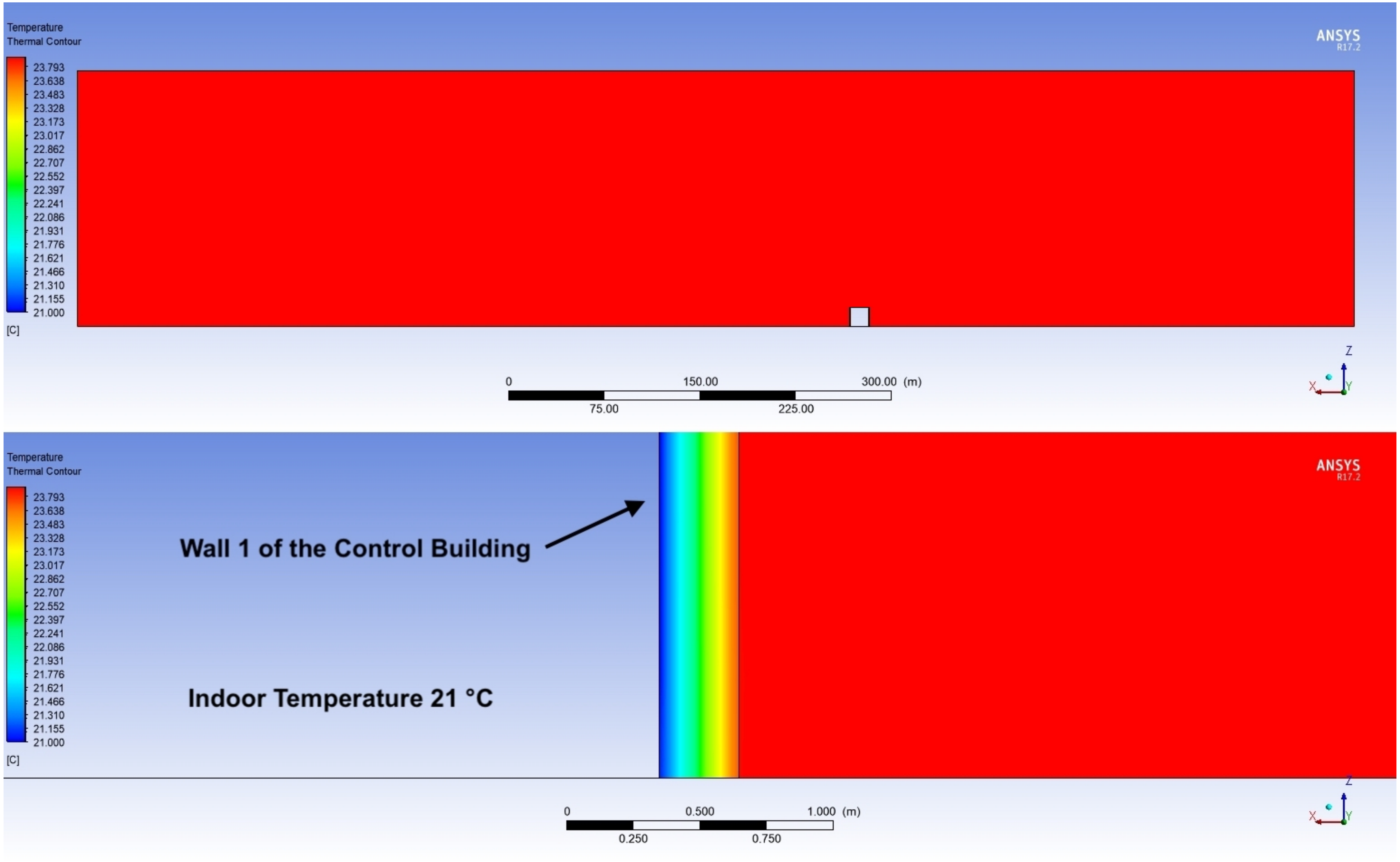


Figure 4.4. Thermal Contour for the Model of the Control Building as a Stand-alone Structure (23.9 °C Outdoor Temperature Setting).

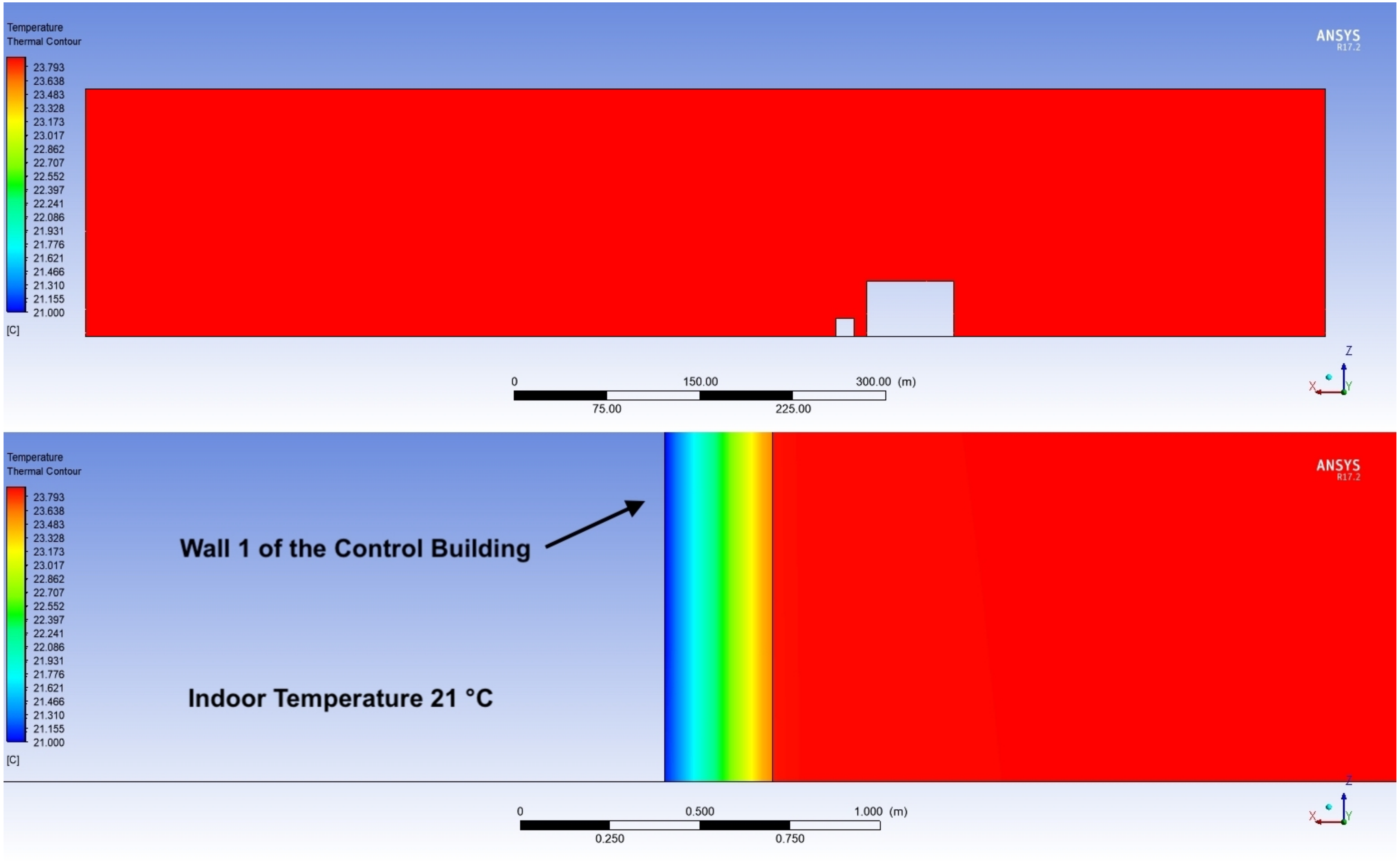


Figure 4.5. Thermal Contour for the Model of the Control Building with the Tall Building (23.9 °C Outdoor Temperature Setting).

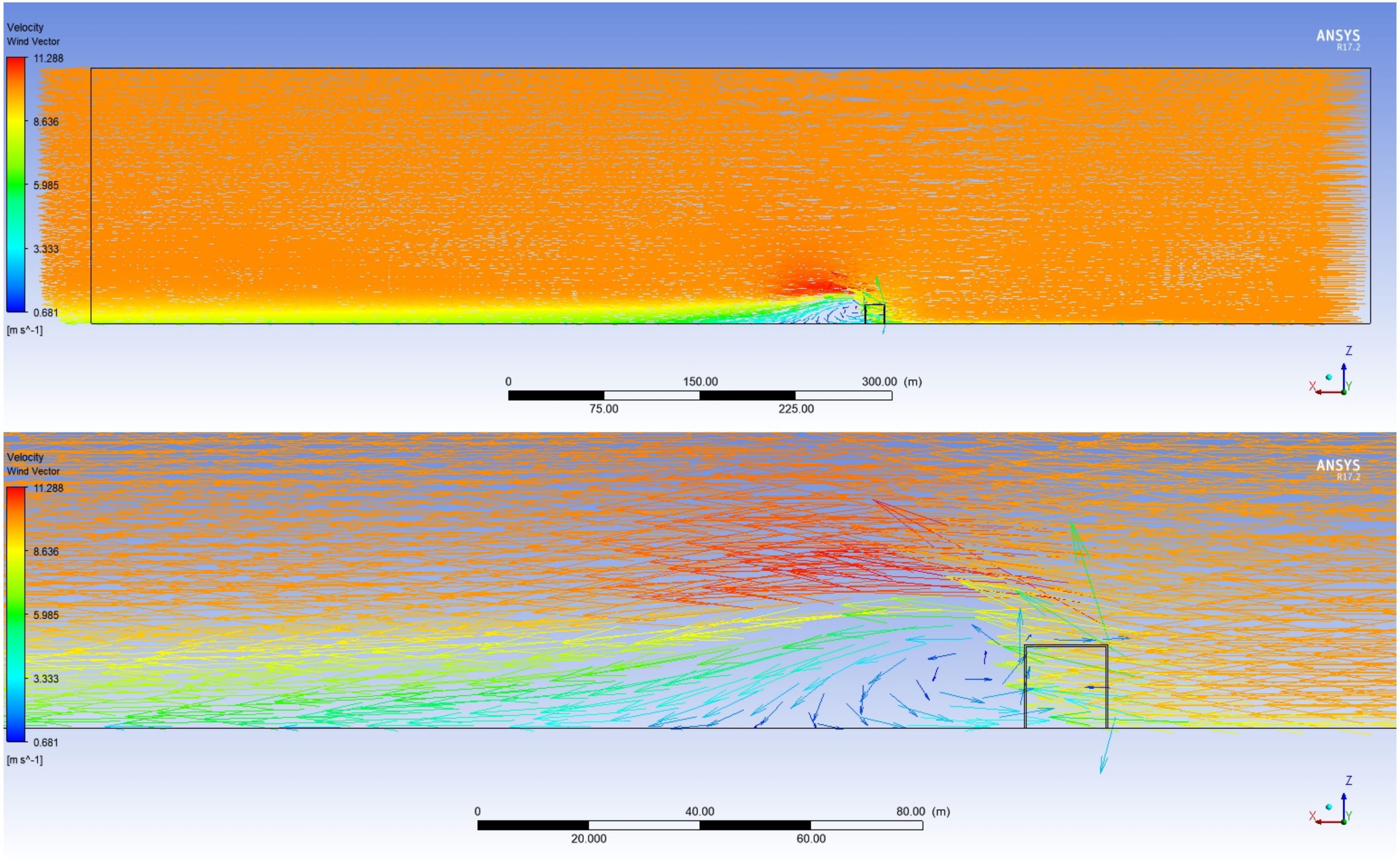


Figure 4.6. Wind Vector for the Model of the Control Building as a Stand-alone Structure (10 m/s Wind Velocity Setting).

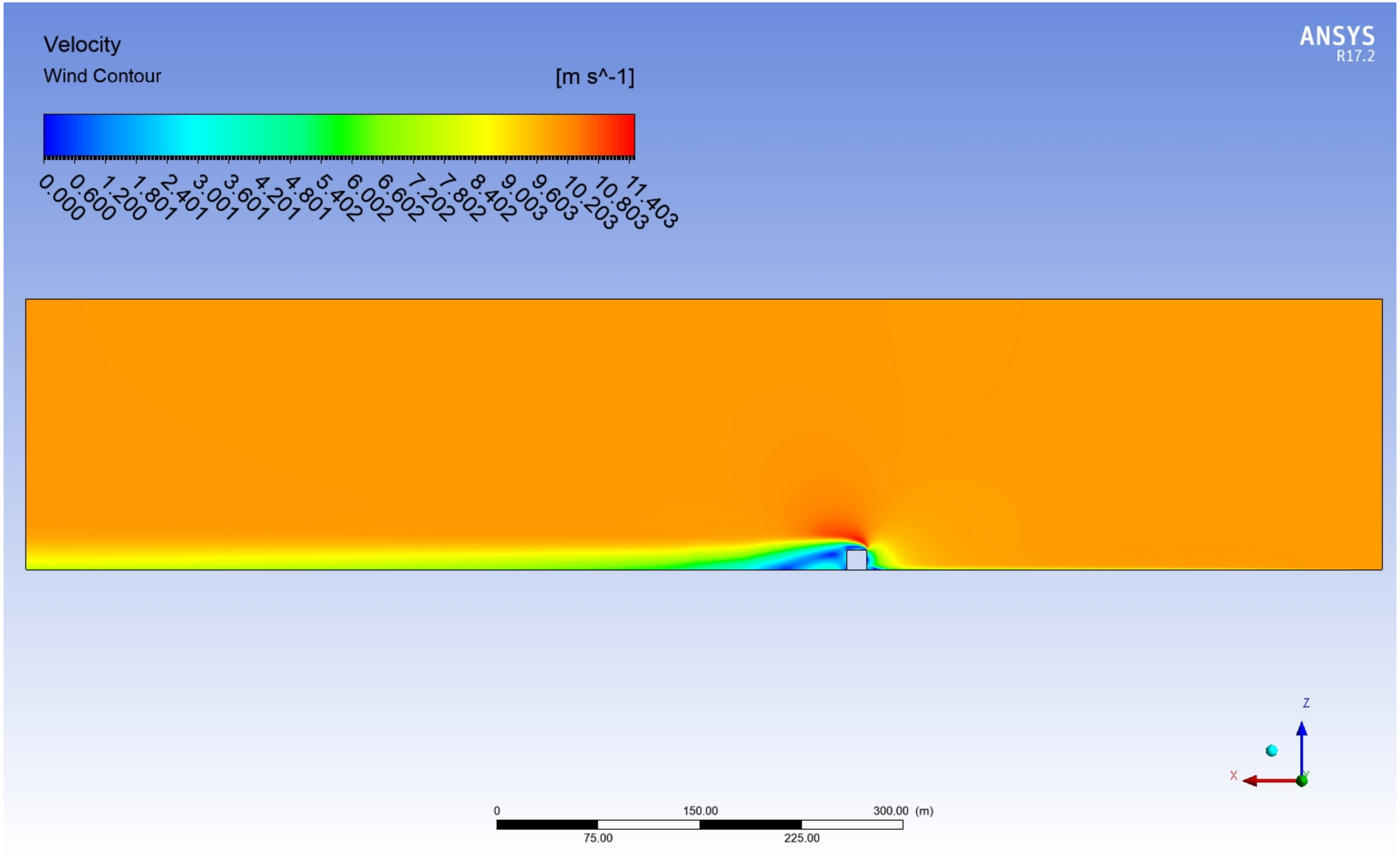


Figure 4.7. Wind Contour for the Model of the Control Building as a Stand-alone Structure (10 m/s Wind Velocity Setting).

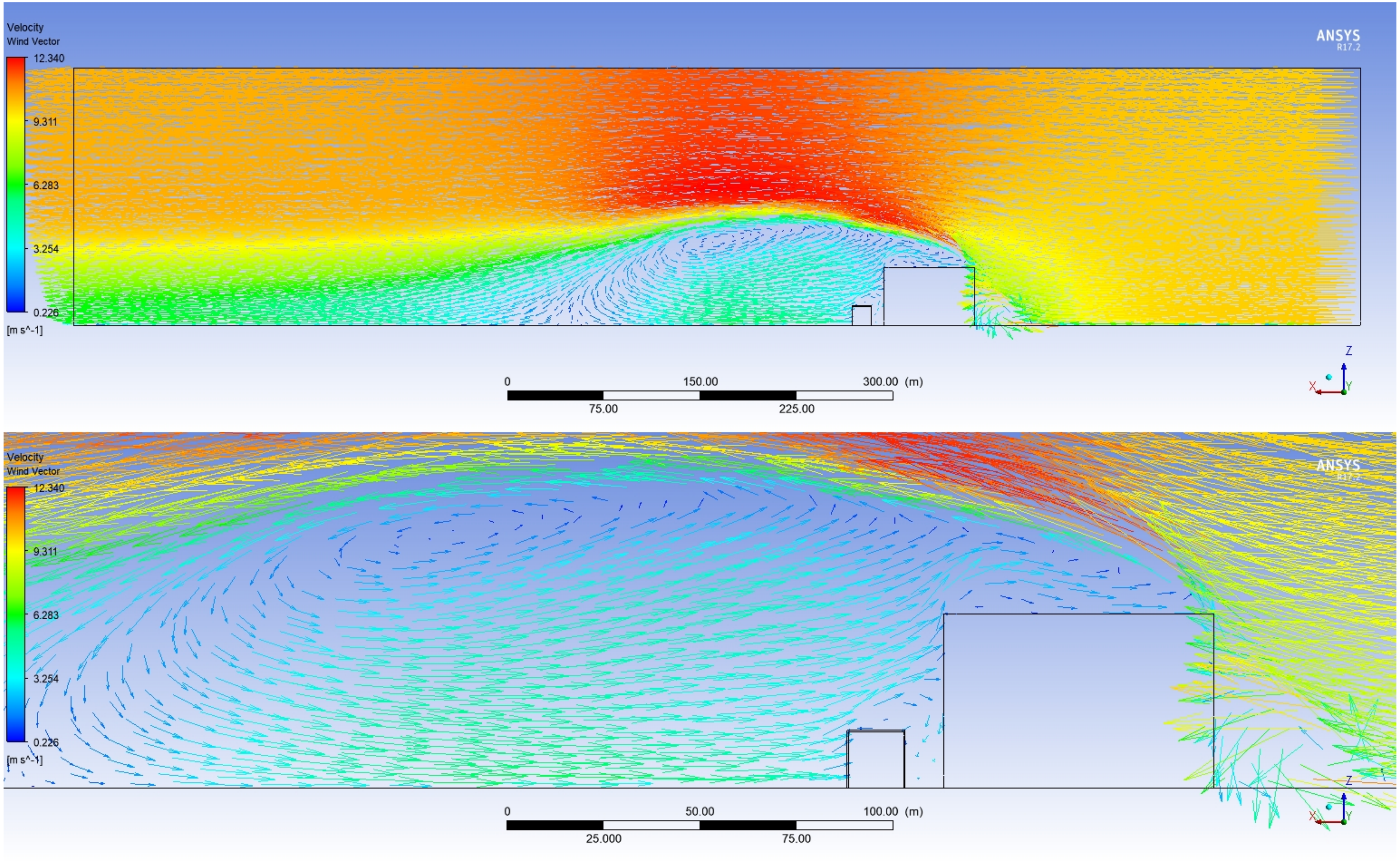


Figure 4.8. Wind Vector for the Model of the Control Building with the Tall Building (10 m/s Wind Velocity Setting).

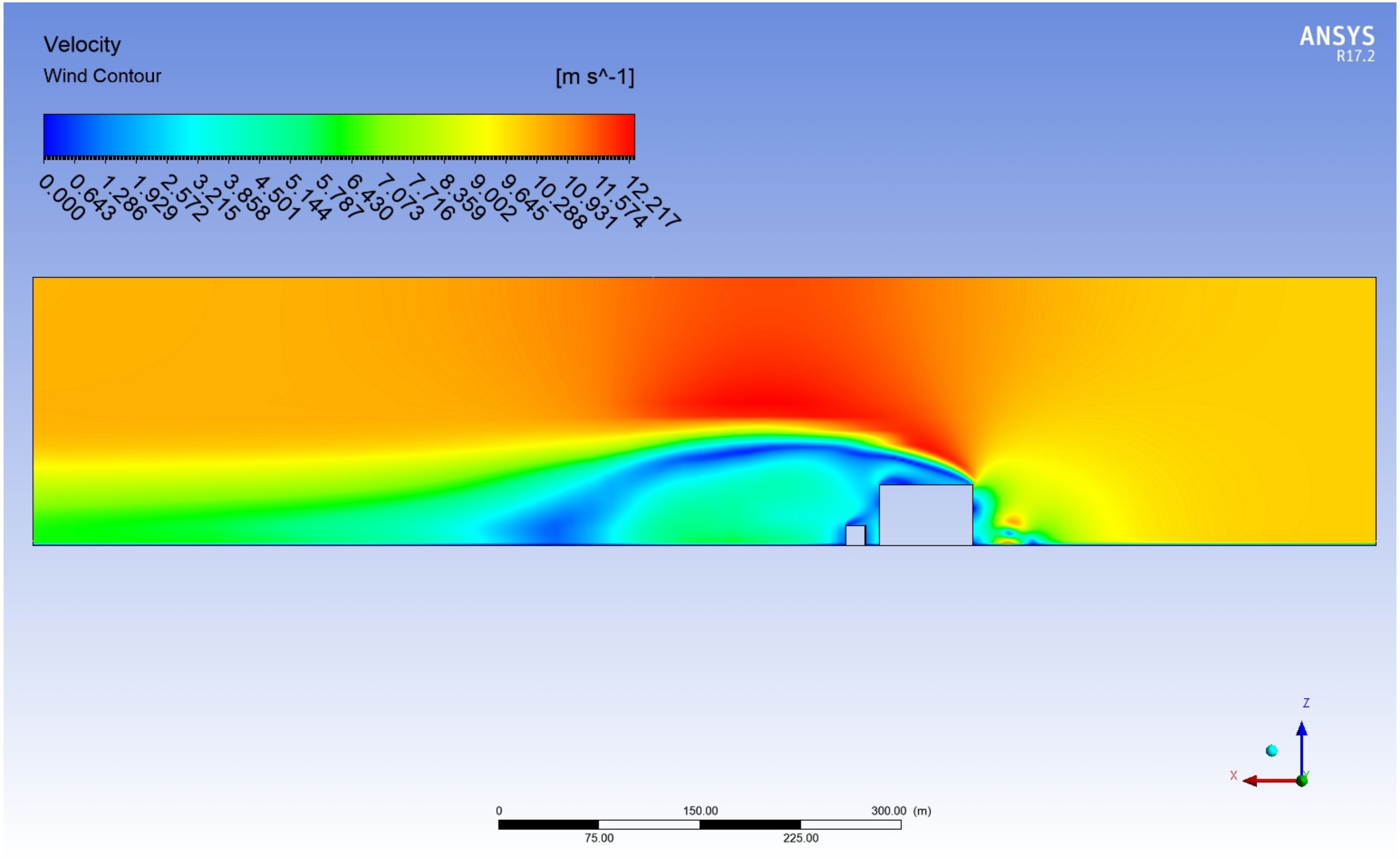


Figure 4.9. Wind Contour for the Model of the Control Building with the Tall Building (10 m/s Wind Velocity Setting).

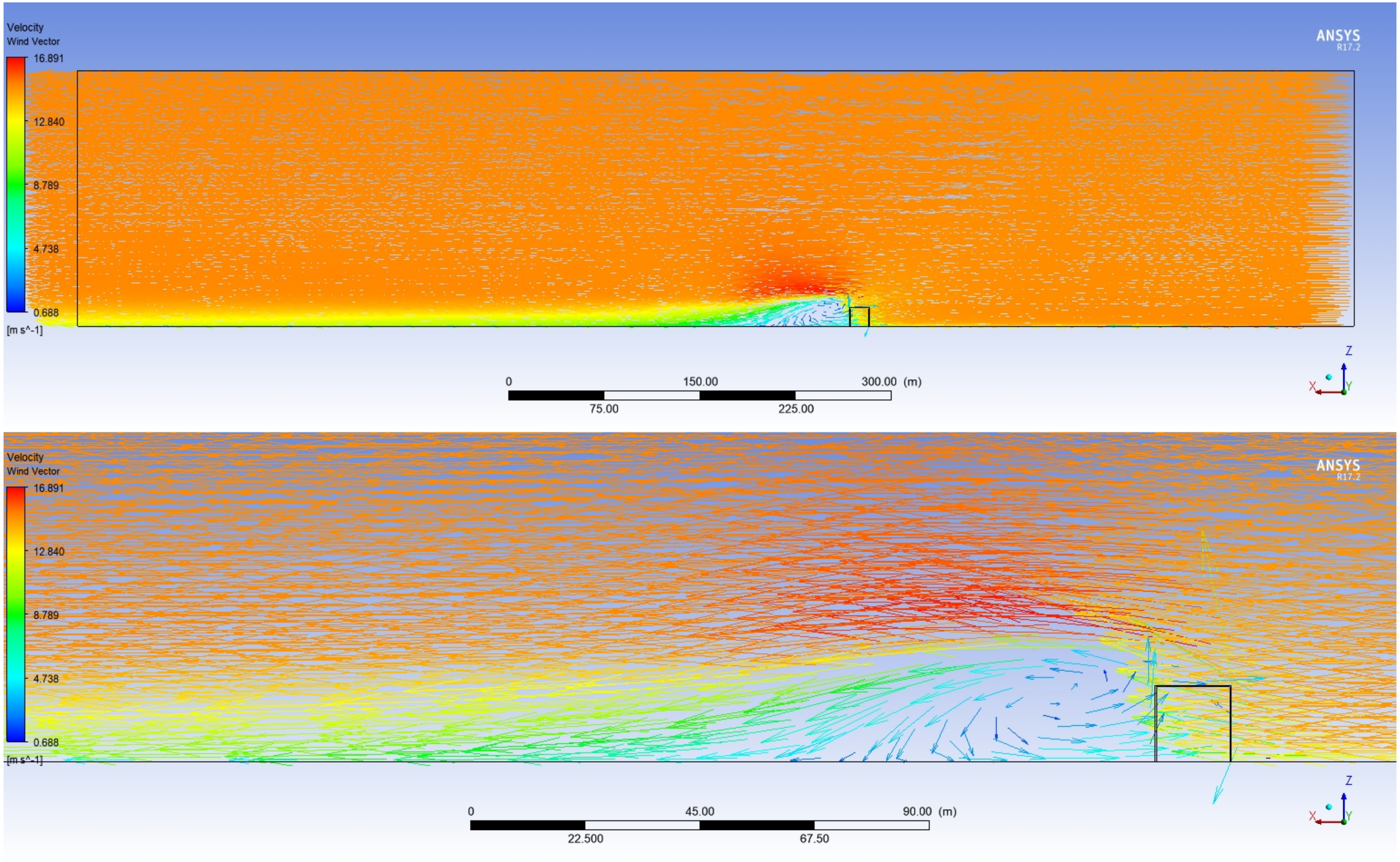


Figure 4.10. Wind Vector for the Model of the Control Building as a Stand-alone Structure (15 m/s Wind Velocity Setting).

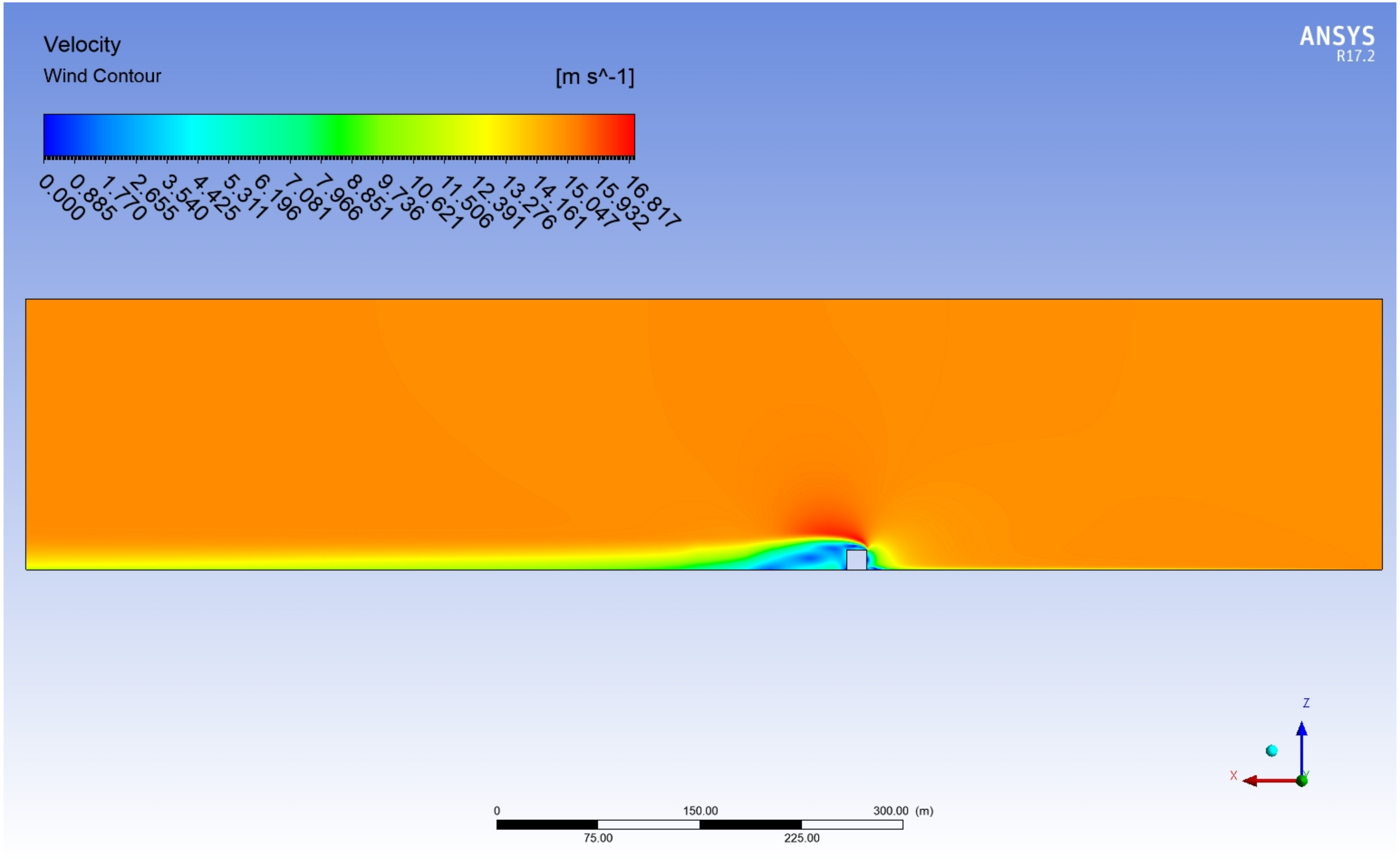


Figure 4.11. Wind Contour for the Model of the Control Building as a Stand-alone Structure (15 m/s Wind Velocity Setting).

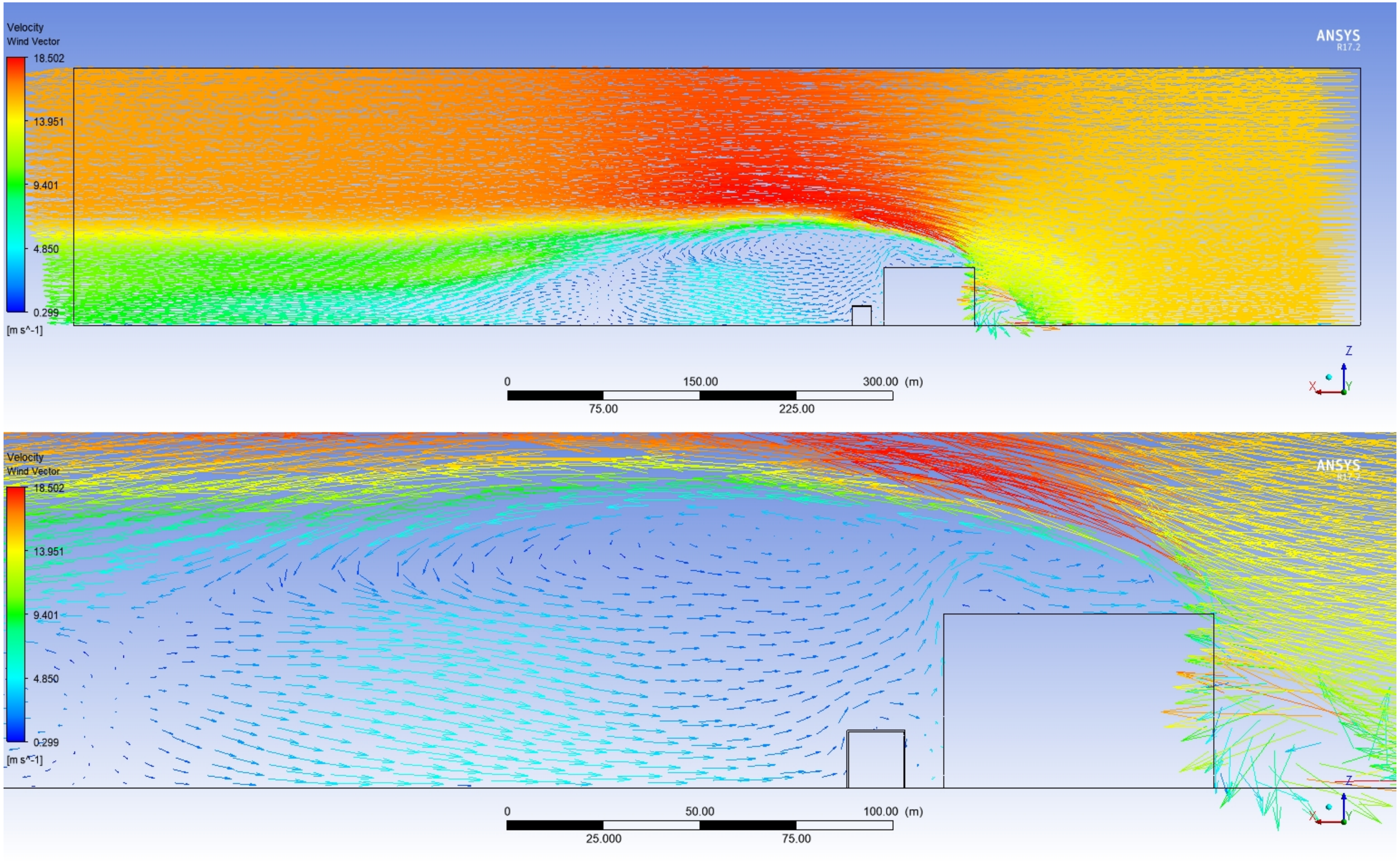


Figure 4.12. Wind Vector for the Model of the Control Building with the Tall Building (15 m/s Wind Velocity Setting).

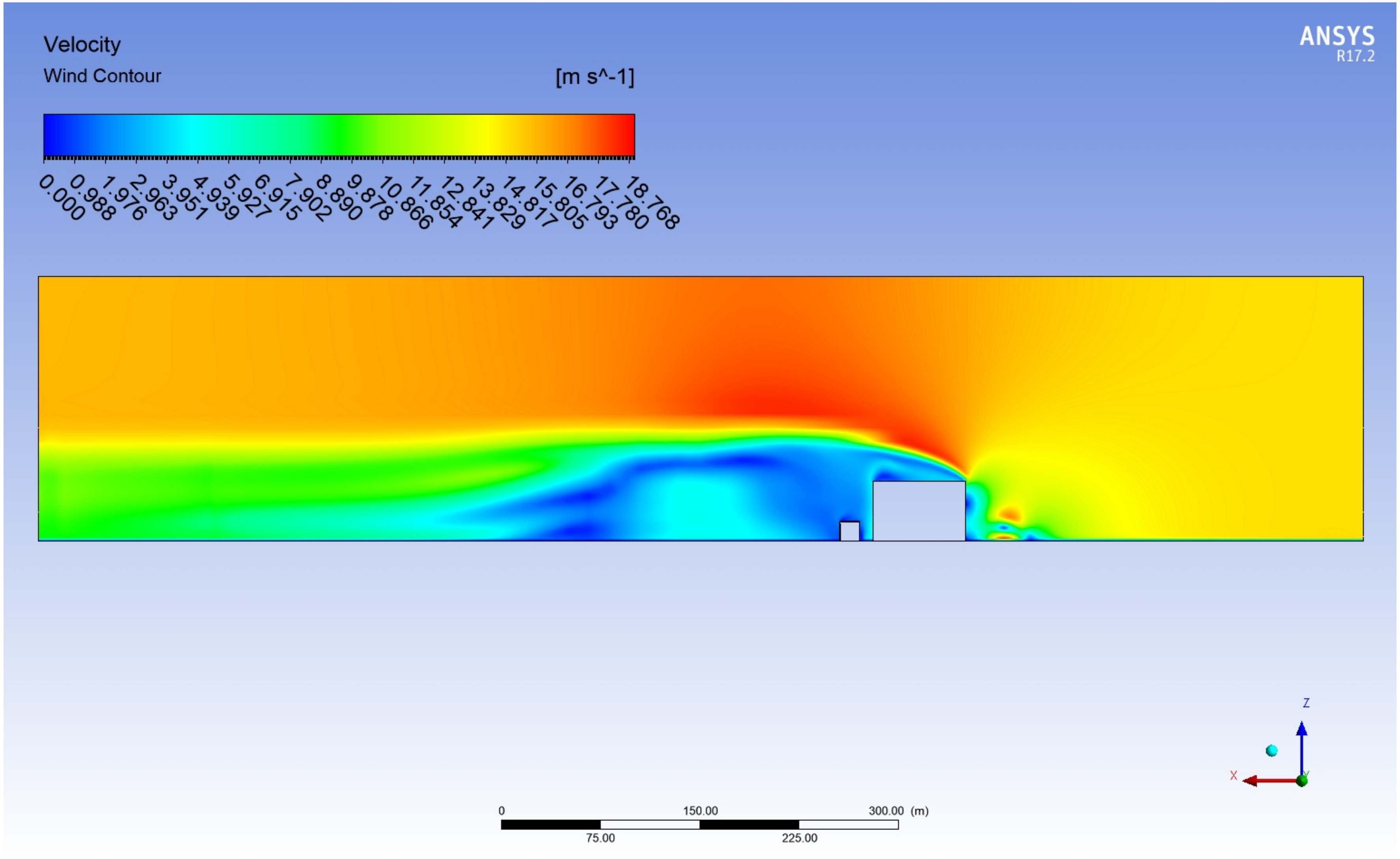


Figure 4.13. Wind Contour for the Model of the Control Building with the Tall Building (15 m/s Wind Velocity Setting).

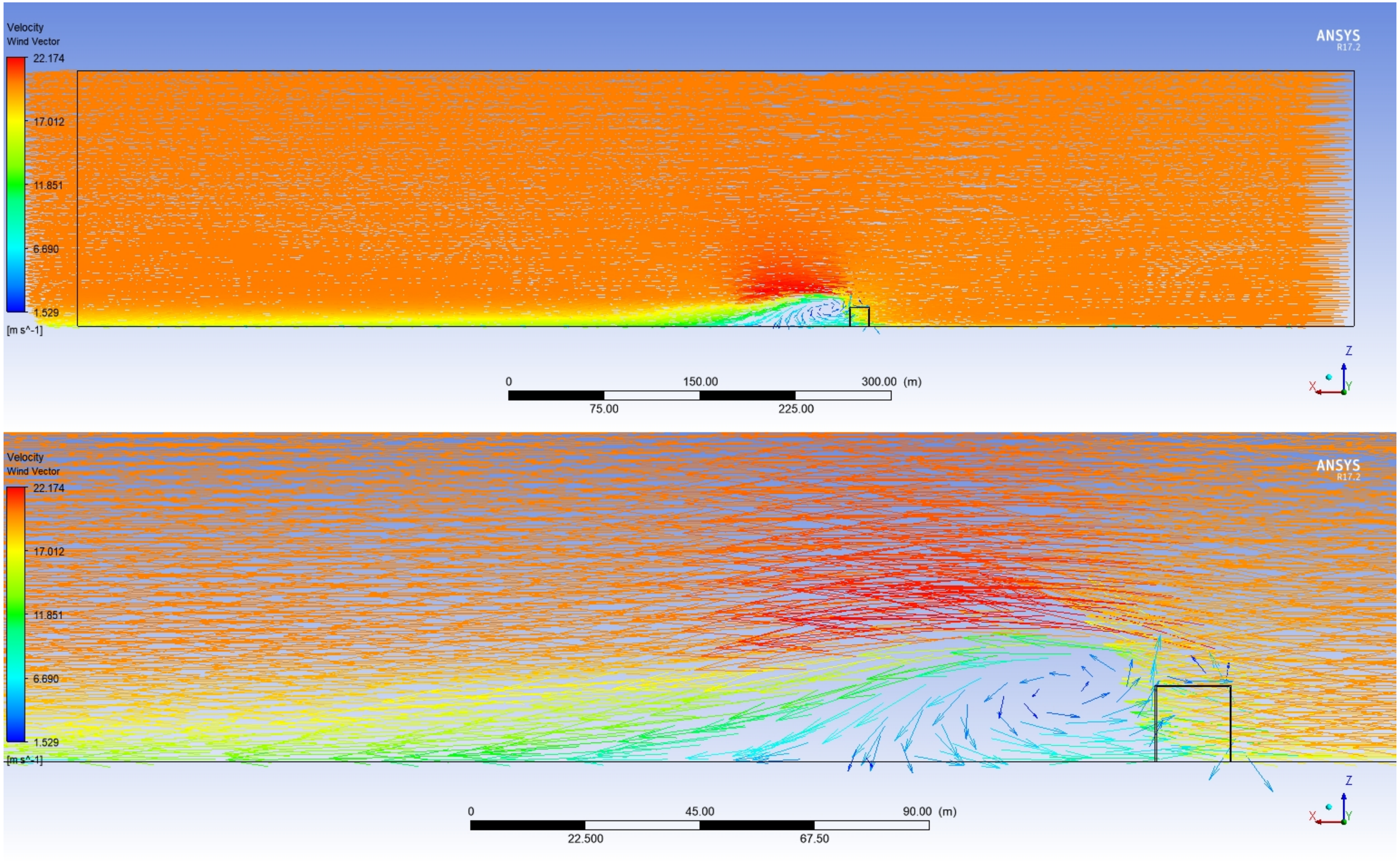


Figure 4.14. Wind Vector for the Model of the Control Building as a Stand-alone Structure (20 m/s Wind Velocity Setting).

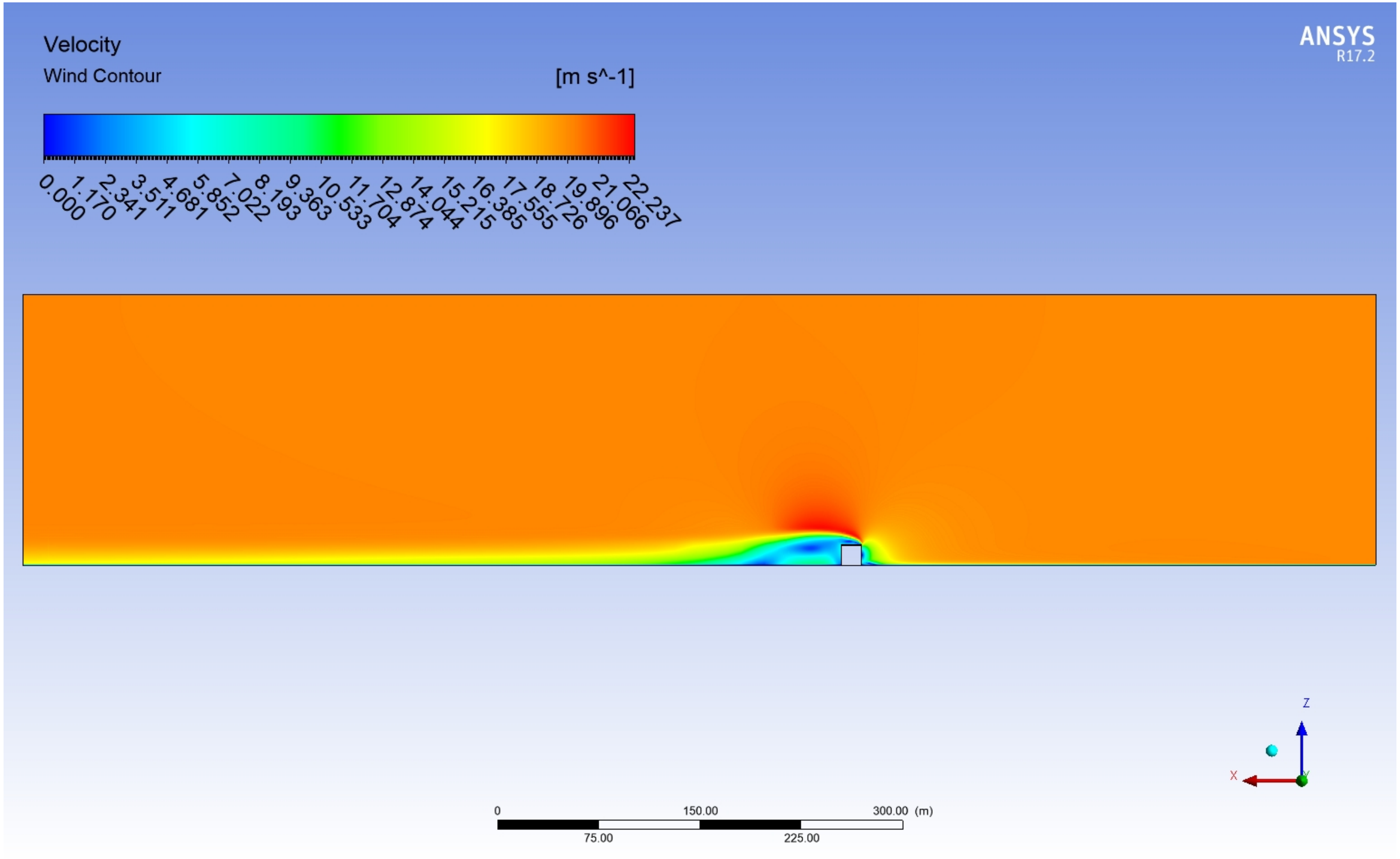


Figure 4.15. Wind Contour for the Model of the Control Building as a Stand-alone Structure (20 m/s Wind Velocity Setting).

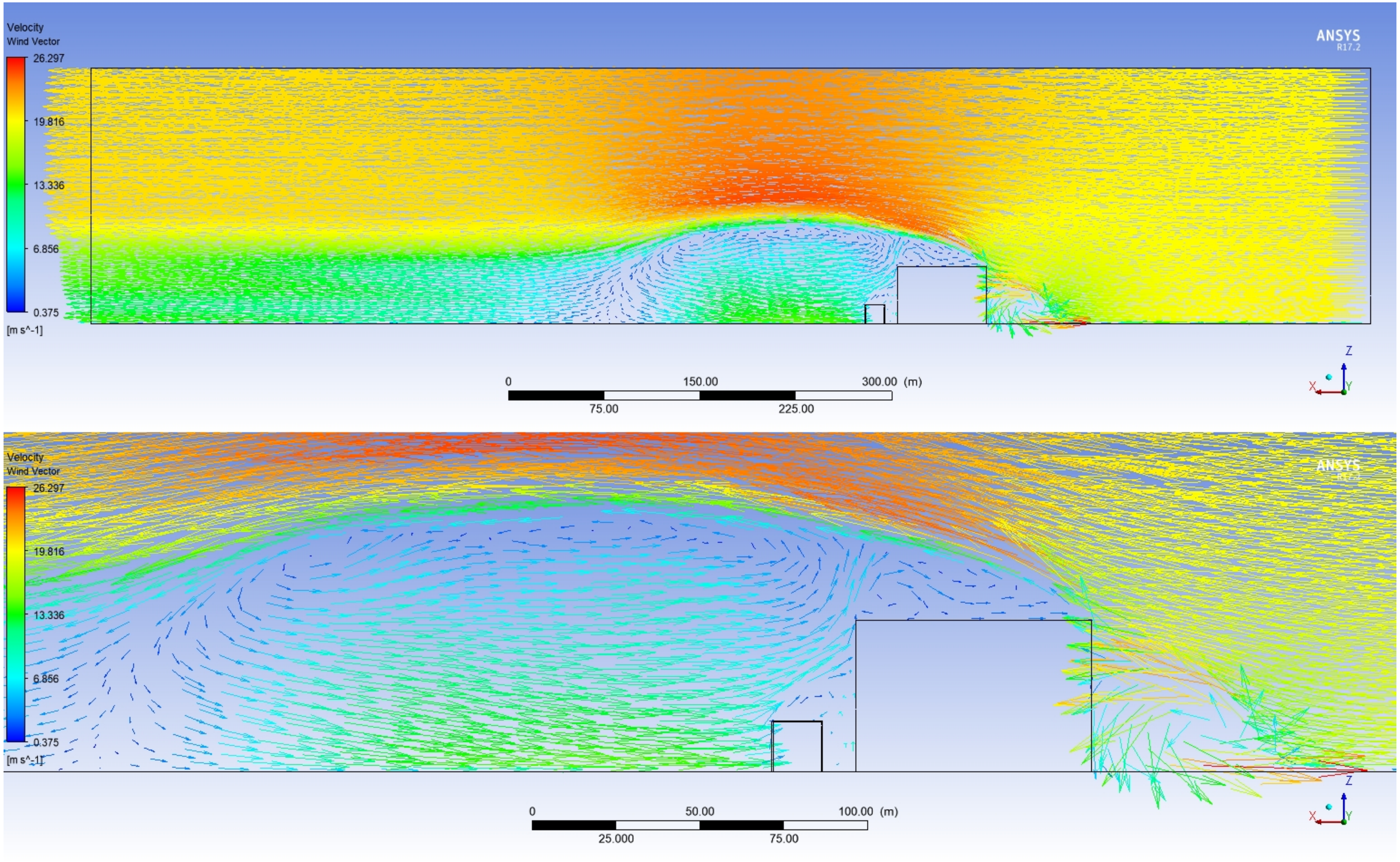


Figure 4.16. Wind Vector for the Model of the Control Building with the Tall Building (20 m/s Wind Velocity Setting).

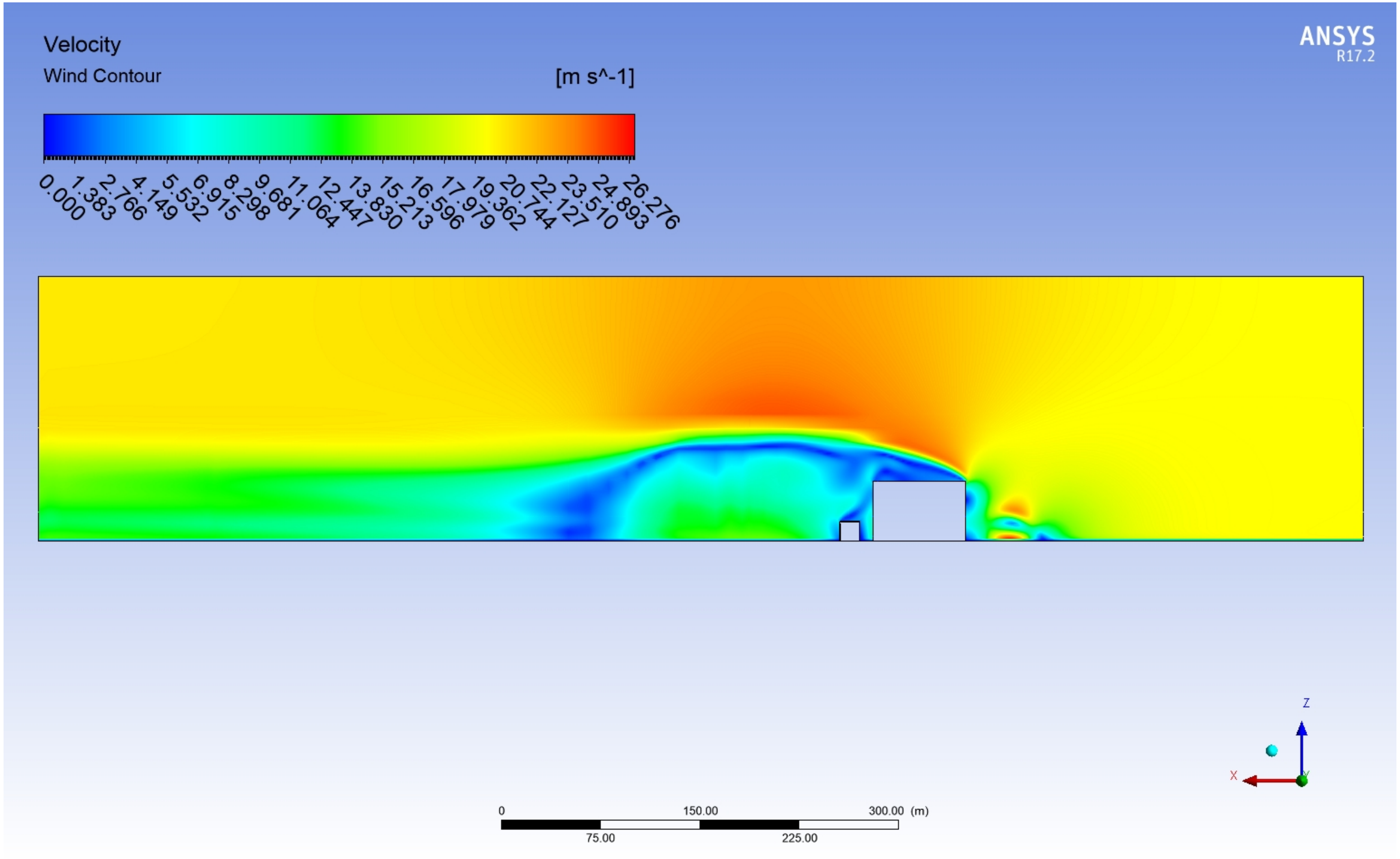


Figure 4.17. Wind Contour for the Model of the Control Building with the Tall Building (20 m/s Wind Velocity Setting).

5. DISCUSSION AND CONCLUSION

5.1. Discussion

Global demand for energy grew by 2.0% in 2017 with the fastest pace in this decade. As a consequence of this trend, global energy-related carbon dioxide emissions grew by 1.4% in 2017 and reached to 32.5 gigatons of a record high (International Energy Agency 2018a). The graph of global energy-related carbon dioxide emissions by years is shown in Figure 5.1. The IEA's executive director said that "The significant growth in global energy-related carbon dioxide emissions in 2017 tells us that current efforts to combat climate change are far from sufficient."(International Energy Agency 2018d). One of the reasons of this exceptional increase of global energy demand and carbon dioxide emissions is higher heating and cooling energy needed in some districts. Considering the significant share of residential sector on global energy demand and eventually its effect on climate change, IEA highlights the potential of keeping the global residential energy demand constant till 2040, despite of the expected 60% growth rate for the total building area (International Energy Agency 2018c). For supporting this aim and the challenge against climate change, this study focuses on a specific aspect of heating and cooling energy of buildings in order to achieve more efficient buildings with low energy demand.

To begin with, this research aims to investigate the effect of the turbulence (vortex) area on heating and cooling energy consumption of buildings with the help of the building performance simulation. Through a detailed literature review, it can be seen that researchers have been using building performance simulation since 1960s to study the different aspects of building performance during its life-cycle. Those performance aspects could be relevant to building's design, construction and operation & post-construction control (de Wilde 2018, p. 325–422). Contrary to popular belief, those performance aspects of buildings are affected by not just building's own characteristics (e.g. Papadopoulos *et al.* 2002; Tso and Yau 2003; Saidur 2009; Chan 2011; Escrivá-Escrivá 2011; Yu *et al.* 2011) or occupant behaviour (e.g. Rosa *et*

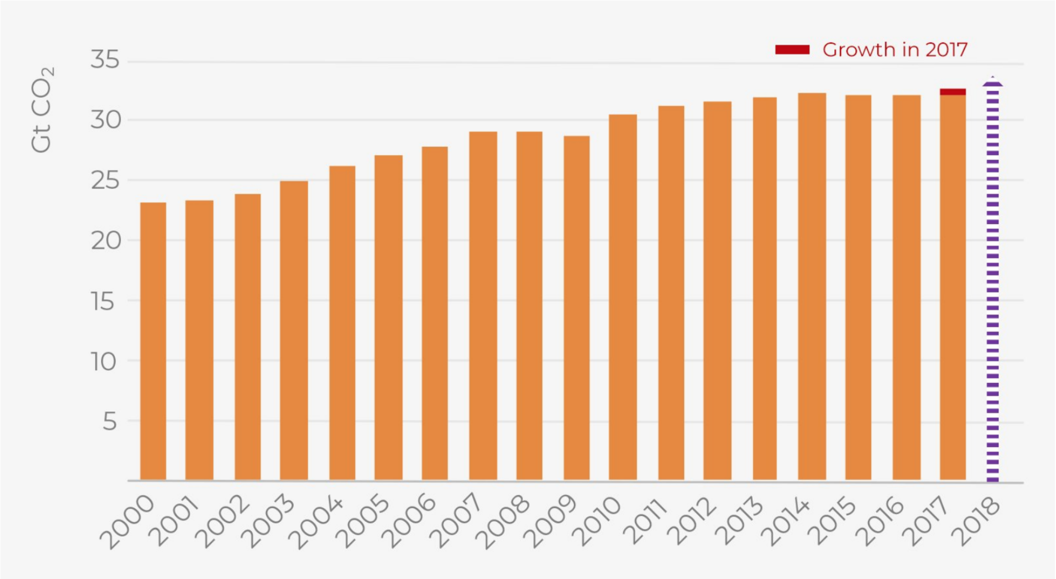


Figure 5.1. Global Energy-related Carbon Dioxide Emissions.

Source: International Energy Agency (2018b)

al. 1988; Kempton *et al.* 1992; Tso and Yau 2003; Bohdanowicz 2006; Ouyang and Hokao 2009; Nair *et al.* 2010; Yu *et al.* 2011; Schipper *et al.* 2011), but also the nearby buildings and local environment. The effects of nearby buildings and urban texture on building energy consumption are investigated by a number of researchers (Arens and Williams 1977; Han *et al.* 2015a; Liu *et al.* 2015; Nikkho *et al.* 2017). Numerous studies have attempted to explain the shading and reflection effects of nearby buildings on building energy performance in the literature (Han *et al.* 2015a; Liu *et al.* 2015). A considerable amount of literature has been published on the effects of the wind on building energy performance (Arens and Williams 1977; Nikkho *et al.* 2017). Similar to those studies, this thesis investigates an effect of a nearby building and local environment. On the other hand, it investigates a new parameter in the literature and ultimately aims to make a contribution to effective building design. Specifically, the effect of the turbulence area—which is created by relatively large nearby building and wind—on heating and cooling energy consumption of a building is examined with the help of a building performance simulation.

ANSYS Fluent CFD program is used to simulate the outdoor wind flow for the control building itself as a stand-alone structure and the results for 10, 15 and 20 m/s wind settings can be seen in Figure 4.6, Figure 4.10 and Figure 4.14, respectively. Wind velocity values are selected quite strong as 10, 15 and 20 m/s for creating adequate turbulence areas. When the wind is 20 m/s, it is difficult to walk against the wind. The small turbulence areas that created by the control building can be seen in those figures. Contrary to the other 3-D model, this control building as a stand-alone structure faces the wind directly and is not affected by the tall building's turbulence area.

Also, Fluent is used for simulating the outdoor wind flow and turbulence (vortex) area that created by the tall building. The turbulence areas for 10, 15 and 20 m/s wind settings are shown in Figure 4.8, Figure 4.12 and Figure 4.16, respectively. After examining those figures, it can be easily seen that the control building is located in the tall building's turbulence area. This turbulence area creates irregular flow motions which spans a wide range of scales in space and time.

After wind flow simulations, energy analysis for the control building as a stand-alone structure and as in the turbulence area of the tall building is done by Fluent for two different outdoor temperatures. Average seasonal temperature values of Istanbul selected because of its similar urban texture to the 3-D model of this thesis —which contains high-rise structures and regular low-side residential buildings too close to each other. This urban texture is often encountered in the development and urban transformation areas in Istanbul. An example for this urban texture from Istanbul is shown in Figure 5.2. There are a lot of low-rise residential buildings that are located in the leeward side of the high-rise buildings. 3.7 °C represents the average winter outdoor temperature in Istanbul while 23.9 °C represents the average summer outdoor temperature (Turkish Standards Institution Engineering Service 2008). Thermal comfort temperature is selected 21 °C for indoor conditions. Heat fluxes of facades of the control building calculated separately.

Heat fluxes for control building as a stand-alone structure and the control building in the turbulence area of the tall building for 6 different cases are shown in Table 4.1 and in Table 4.2, respectively. In both 3-D models, for the same outdoor temperature,

Figure 5.2. Levent District of Istanbul.

heating and cooling energy demand of the control building is increased with the increasing wind velocity. This energy demand increase is in connection with turbulence areas which are bigger with higher wind velocities.

Finally, heat fluxes of the control building as a stand-alone structure and as in the turbulence area of the tall building are compared to decide if the turbulence area has significant impact on cooling and heating energy consumption of a building. The percentaged heat flux differences between two models are shown in Table 5.1.

Heating energy demand for two models have difference of 2.3% for 3.7 °C outdoor temperature and 10 m/s wind velocity, 2.0% for 3.7 °C outdoor temperature and 15 m/s wind velocity and 0.8% for 3.7 °C outdoor temperature and 20 m/s wind velocity. Cooling energy demand for two models have difference of 2.1% for 23.9 °C outdoor temperature and 10 m/s wind velocity, 2.0% for 23.9 °C outdoor temperature and 15 m/s wind velocity and 1.0% for 23.9 °C outdoor temperature and 20 m/s wind velocity.

Table 5.1. Percentaged Heat Flux Differences between Two 3-D Models.

Outdoor Temperature (°C)	Wind Velocity (m/s)	Heat Flux of the Control Building as a Stand-alone Structure (W/h)	Heat Flux of the Control Building with the Tall Building (W/h)	Percentaged Heat Flux Difference
3.7	10	-8854.08	-8648.51	2.3%
3.7	15	-8883.83	-8709.15	2.0%
3.7	20	-8897.61	-8823.67	0.8%
23.9	10	1483.88	1452.71	2.1%
23.9	15	1489.27	1460.16	2.0%
23.9	20	1491.50	1476.15	1.0%

It can be easily seen that the heating and cooling energy demand is lower when the building is in the turbulence area. The differences between heat fluxes of two 3-D models are not very large, but it is not unexpected. Also, the difference between energy demand of two models is decreasing with the increasing wind velocity.

In the literature, a number of researchers tried to minimize the mutual influences between buildings that lead to increase in energy consumption in urban environments. Han *et al.* (2015a) developed a systematic approach to disaggregate and quantify the influence of mutual reflection and mutual shading within a network of buildings. They found the reflection and shading effect play an important role in terms of impact on energy consumption. Liu *et al.* (2015) examined the urban micro-climate environment. In common to this thesis, they tried to calculate an aspect of nearby buildings and the wind effect on building energy consumption with the help of EnergyPlus program. They found that denser plan areas affects the energy consumption due to the wind sheltering effect on the exterior surfaces' convective heat transfer coefficients, with a 6.7% increase in the cooling energy consumption and a 3.5% decrease in the heating energy consumption. It is important to notice that Liu *et al.* (2015) use the built-in feature of EnergyPlus and it does not consider the effect of the infiltration rate in their analysis. Also similar to the study by Liu *et al.* (2015), in this thesis, the control building is modeled as a closed box and has not got openings. Its openings are assumed to be perfectly isolated and are not sketched in 3-D models.

Like those previous studies, this thesis tried to determine a significant effect on building energy consumption to minimize residential sector share in continuous growth of global energy demand in recent decades. Results show that, the effect of the turbulence area is not very significant on perfectly isolated control building theoretically. The most important parameter that derives this conclusion is the model of the control building —which is a perfectly isolated closed box—. However, in the real world, openings are not perfectly isolated. Sherman (1980) showed that the energy loss due to infiltration varied between 6% and 9% of the total energy in the United States. Another study conducted by Emmerich and Persily (1998) confirmed that infiltration is responsible for 13% and 3% of the heating and cooling loads, respectively for the United States office buildings. The other important parameter that derives this conclusion is the facade system of the control building. The thermal conductivity of the facade system is selected as 0.1461 W/m K (Turkish Standards Institution Engineering Service 2008). It consists of the 20 centimeters brick wall covered with 5 centimeters plaster and 5 centimeters rock-wool board. This isolation system is commonly used in the Turkish Construction Industry even without making proper calculations because of its low-cost and critical impact on building's heating and cooling energy consumption. This isolation system for the altering outdoor temperature and radiation, satisfied some part of the insulate need for the turbulence area effect on building's heating and cooling energy consumption. Consequently, the effect of the turbulence area on heating and cooling energy of a building remained limited because of the perfectly isolated openings and facade system of the control building.

As a result, the energy need for heating and cooling energy is lower for the buildings which are in the turbulence (vortex) area, but the largest difference between two models is 2.3%. This difference is not very significant but it is expected for the perfectly isolated control building. Therefore, with a more ideal modeling with openings —which are not perfectly isolated in the real world— and real-case isolation system, the effect of the turbulence area would be more significant for sure. Ultimately, this research has a theoretical contribution to the literature within its specific domain. It presents the turbulence (vortex) area as an important effect on heating and cooling energy demand of a building. This effect should not be ignored for the design of the new buildings and the retrofit of the existing buildings for future works.

Also, this study has some limitations as well. One of these limitations are related to the design of the control building for building performance simulations. It is designed as closed box for easier and faster analysis. This design feature limited the simulations from being more realistic. In the future research, it can be designed with openings to simulate exfiltration and infiltration better. Also, another limitation in this thesis is related to the number of cases. Further case studies with various different 3-D models can be conducted to validate the proposed results. Moreover, the number of iterations are sufficient in this thesis, but much more iterations can be done with super computers for increasing results' accuracy. Additionally, in future works, 3-D models can be sketched more realistic and similar to the actual cities. The turbulence area effect on building's heating and cooling energy consumption can be calculated in the urban areas more adequately, but again it needs more powerful computers. For last, further studies are required to consider detailed variation of urban neighborhood configurations, building shapes and wind profiles & directions.

5.2. Conclusion

With constantly growing global energy demand and energy-related carbon dioxide emissions, effectiveness has become a challenge for all industries including residential sector. This demand for effectiveness in the residential sector has made the application of building performance simulation a must. For those demands, this thesis investigates the effect of the turbulence area on heating and cooling energy of a building with the help of BPS.

Firstly, literature about global energy demand and building performance simulation is reviewed. The history of BPS between 1977 and present is examined. Building energy consumption factors are researched in the literature and categorized into groups of building related characteristics, occupant related characteristics and nature and nearby environment. Later, the turbulence area on heating and cooling energy consumption of buildings investigated to find out if it is significant or not. For this investigation, following steps are completed with the help of BPS (ANSYS Fluent CFD program);

- Two 3-D models are sketched,
  - The control building as a stand-alone structure,
  - The control building & the tall building which creates the turbulence area,
- Two 3-D models are meshed,
- 6 different wind cases for both of the 3-D models are simulated,
- Heat fluxes are calculated for the control building,
- Results are compared to find out if the effect of the turbulence area on heating

and cooling energy demand of buildings is significant or not.

As a result of this research, it is found that the energy demand for heating and cooling energy is lower for the buildings which are in the turbulence (vortex) area. Therefore, this research has a theoretical contribution to the literature within its specific domain and shows that researchers, practitioners and urban planners should not ignore the turbulence effect on heating and cooling energy consumption of a building for future works.

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