COMPUTATIONAL STUDY OF NATURAL VENTILATION AIR FLOW AND HEAT TRANSFER FOR A ROOM OF DIFFERENT FLOW PATH AND WINDOW CONFIGURATIONS IN BANGLADESH

BY

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Student ID: 1014093003
Session: October 2014

MASTER OF PHILOSOPHY
IN
MATHEMATICS

DEPARTMENT OF MATHEMATICS
BANGLADESH UNIVERSITY OF ENGINEERING AND TECHNOLOGY
DHAKA-1000

The thesis entitled "**COMPUTATIONAL STUDY OF NATURAL VENTILATION AIR FLOW AND HEAT TRANSFER FOR A ROOM OF DIFFERENT FLOW PATH AND WINDOW CONFIGURATIONS IN BANGLADESH**", submitted by Md. Rakibul Hasan, Roll no: 1014093003, Registration No: 1014093003, Session: October-2014, has been accepted as satisfactory in partial fulfilment of the requirement for the degree of Master of Philosophy in Mathematics on 7th September 2019.

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It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

RHasan 6.9.19

Md. Rakibul Hasan

This work is dedicated

to

my parents

Acknowledgement

I would like to affirm the continual mercy, help and blessing showered by the Almighty, without which it would have been impossible to accomplish the arduous job I was assigned to. I owe a deep depth to my supervisor, Dr. Md. Abdul Hakim Khan, Professor, Department of Mathematics, Bangladesh University of Engineering and Technology, who restlessly supported me through the M.Phil process. I would like to thank him for his invaluable contribution. His knowledge about the M.Phil process is beyond par. His contribution to this thesis, however does not only encompass his role as an academic supervisor but include his ongoing friendship, care and support on a personal level without which this journey may have never been completed.

My special thanks to K.M. Ariful Kabir, Assistant professor, Department of Mathematics, Bangladesh University of Engineering and Technology, whose support was imperative in the beginning stages of the M.Phil process. His stimulating and enthusiastic encouragement and guidance in regards to fluid dynamics and CFD in general and my M.Phil topic in particular have challenged and greatly contributed to my thinking on dissertation. Also, I am indebted to Mr. Atiqur Rahman, Lecturer, Department of Mathematics, Comilla University, who encouraged and gave me the guidance to enrol for MPhil in BUET.

I owe my gratitude to all my ex-colleagues in Department of Computer Science and Engineering, Southeast University who have assisted me by providing valuable suggestions. Especially to Mr. Shariar Manzoor, Chairman, Department of Computer Science and Engineering, Southeast University, who helped me to take the approval from the authority to study M.Phil at BUET and gave reasonable time schedule at Southeast University to continue my study.

I am grateful to Dr. Md. Mustafizur Rahman, Professor and Head, Department of Mathematics, Bangladesh University of Engineering and Technology, for his expert guidance and valuable suggestions in the course of being successful to reach the objectives of this dissertation. I would also like to express my sincere thanks and gratitude to Dr. Mohammed Forhad Uddin, Professor, Department of Mathematics, BUET and Dr. Rehena Nasrin, Professor, Department of Mathematics, BUET for many helpful discussion and suggestions during my study support that was essential for the success of this work. Moreover, my special gratitude to all of my teachers of Department of Mathematics, BUET for their moral support and guidance.

I am thankful to the external member of the Board of Examiners, Dr. Md. Tarek Uddin, Professor, Department of Civil and Environmental Engineering, IUT for his valuable suggestions in improving the quality of the work.

My deep love and appreciation go to my family members for creating a delightful atmosphere as well as relieving me from family duties in order to complete the courses, research studies and final production of the thesis work. These past several years have not been an easy ride for me, both academically and personally.

Abstract

Natural ventilation is an effective system to reduce the consumption of energy required to condition buildings and to improve the quality of indoor air. Buildings will construct such a way that can use natural energy more proficiently can lead to save energy, while maintaining comfort for occupants'. This study has been focused to airflow and heat transfer analyses in a room through opening(s)/awning opening(s) and then compare the results obtained from both different opening. Computational fluid dynamics (CFD) whose application is gaining popularity has been used to model single-sided and cross ventilation in a single room through window where door was closed. Two and Three-dimensional model has been calculated of a cubic room assuming twelve different opening configurations. In this research, Reynolds averaged Navier–Stokes equation (RANS) approach has been applied to wind driven natural ventilation in a cubic building. Two equation based $k - \epsilon$ model is used for stationary and unsteady solution. Moreover, turbulent air flow coupling with or without heat also has been considered and showed in different results. The mathematical model has been solved numerically with CFD/commercial software. The temperature fields, flow patterns, ventilation rate, heat transfer coefficients and temperature distribution effectiveness have been presented and discussed. The numerical results have been also compared with experimental data, showing a good agreement. The room heated up and reached its thermal comfort level, but the velocities exceeded the maximum acceptable level set by ASHRAE [15] guidelines. In the case of heat transfer and ventilation, Awning opening gives better result than opening.

Contents

Nomenclature

m	Mass of the system.
t	Time
g	Gravity
M	External force
p	Pressure
E	Total energy
k_{eff}	Effective conductivity
C_p	Constant specific heat
u, v, w	Velocity component
x, y, z	Cartesian coordinates
T	Temperature
k	Von Karman's constant
U	Streamwise velocity component
U_0	Reference velocity
T_i	Turbulence intensity
l_t	Turbulence length scale
U_{ref}	Reference velocity
U_{avg}	Average flow velocity

Greek symbol

ρ	Density of fluid
μ	Viscosity
β	Thermal expansion coefficient
$\bar{\bar{\tau}}_{eff}$	Effective stress tensor
v	Velocity scale
l	Length scale

Subscripts

avg	Average
o	Reference

Abbreviation

IEA	International Energy Agency
CFD	Computational Fluid Dynamics
SREDA	Sustainable and Renewable Energy Devolvement Authority
NV	Natural ventilation
RANS	Reynolds Averaged Navier–Stokes equation
LES	Large-eddy simulation

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Chapter 1
Preliminary

Bangladesh is a tropical country and most of the time of the year a lot of wind blows through it because of its geographic location on the world. It is a common solution for the buildings of Bangladesh to arrange for windows to receive the natural wind and enough sunlight. Maintaining natural air flow and thermal comfort in the interior spaces is the only way for good health and healthy ventilation in a cost efficient way.

1.1 Introduction

For cooling and ventilating purpose, the uses of energy are expected to grow and a rise in cost happen with the energy increase. Ventilation in buildings will increase as the economic development occur in the regions of the world. In developed countries buildings are responsible for one-third of all heat consumption [1]; atmospheric pollution and global warming are increasing due to increase of fossil-based heat consumption. Developed country is using 25 times more energy than the developing country in case of ventilation and cooling purpose [2]. With the increases in energy use and cost, it is important to design buildings to have ventilation systems that are energy efficient, cost effective and maintain occupants' comfort.

In Bangladesh, uses of energy in ventilation in buildings are increasing day by day due to high rise building increasing [3]. As a result, energy demands increase for cooling and ventilating purpose. Figure: 1.1 shows that how power and energy demand are increasing day by day in household sector. At present time, most of the people stay inside a room or building more than 90% of his time. Therefore, it is most important to fixed focus on a good and healthy indoor environment and have to do this by saving energy or using less energy. To be more independent of the coal/gas as an energy source and also to reduce the damaging outlets to the environment, an increasing use of sustainable technologies such as solar energy, better use of daylight and use of natural ventilation is more and more often discussed when new buildings are built or old ones are renovated. Unfortunately, not all sustainable technologies can be used in all climates, since the weather conditions are an important factor in these technologies.

Natural ventilation is the process of supplying air to and removing air from an indoor space without using mechanical systems. It refers to the flow of external air to an indoor space as a result of pressure differences arising from natural forces. Considering natural ventilation, it can be problematic to keep steady internal/indoor circumstances, since outsider weather conditions changed often. Also, not all types of buildings are suitable for natural ventilation, since this type

Figure 1.1: Household electricity consumption per capita in Bangladesh from 2000 to 2015 (in kilowatt hours), (Source: Statistica, Bangladesh)

of ventilation sets some requirements for e.g. internal heat load in the building, depth of the rooms, room height and surroundings.

In the field of natural ventilation there are typically two types of ventilation named after the position of the openings in the outer walls. In cross ventilation (see Figure 1.2) there are openings in more than one on different walls so that the air crosses the room. In single-sided ventilation (see Figure 1.3) there are one or more openings on the same wall. The driving forces in natural ventilation are temperature differences and wind pressure differences. For cross-ventilation, the main driving force will be the wind as long as the openings are in the same height. With a difference in height the thermal buoyancy will also influence the airflow rate. In single-sided ventilation the air-change rate is much dependent on the shape of the opening. High openings will be more affected by temperature differences than low openings. Wide openings will be more affected by the wind than small and narrow openings. In single-sided ventilation also the size of the turbulent eddies and pulsations in the flow is of great importance.

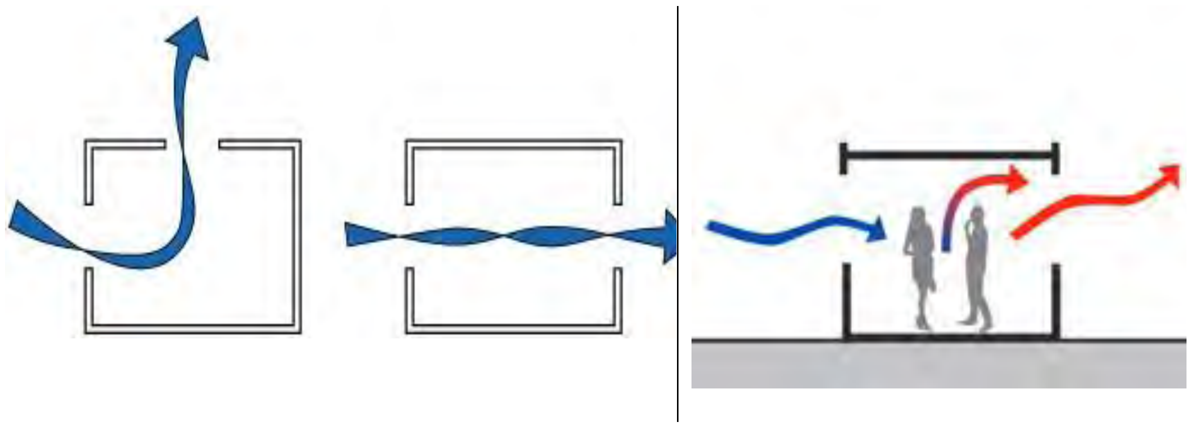


Figure 1.2: Cross ventilation, (Source: Efficient Windows and Vent)

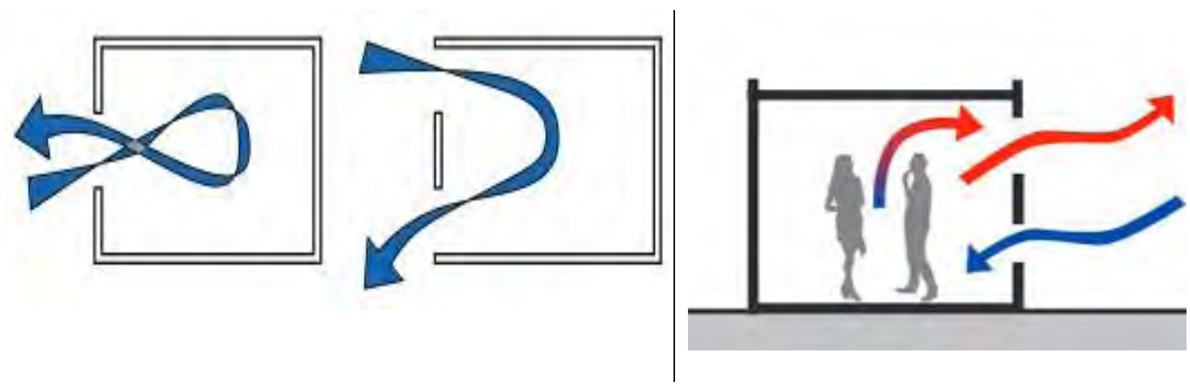


Figure 1.3: Single Sided ventilation, (Source: Efficient Windows and Vent)

1.2 Present situation of energy consumption in Bangladesh

The heat consumption requirement has increased at a rate of 2 % per year for the past 25 years and it will increase continuously at the same rate if current heat consumption patterns persist, according to the International Energy Agency (IEA). Energy is used for heating and cooling purposes in most of the office and residential buildings in urban society. Whereas in

Bangladesh, the energy consumption patterns are as follows: Domestic (50.18%), Industry (35.45%) and Commercial (9.27%) [3] which is shown in Figure 1.4 and increasing day by day. At present 80 percent people of Bangladesh have access to electricity facilities. There is enormous demand for electricity, oil, gas and natural resources in agriculture, industry and service sector as well as daily life of Bangladesh. The total installed electricity generation capacity stood at 15,755 MW of which the highest generation was 9,479 MW in FY2016-17. Besides, net electricity production was 52,193 million kilowatt-hours in FY2015-16 which increased to 57,276 million kilowatt-hours in FY2016-17. In addition, total system loss of transmission and distribution of electricity substantially declined to 9.98 percent in FY2016-17 from 21.25 % in FY2005-06. Moreover, energy saving and environment-friendly power generation systems have been introduced using renewable and modern technology. On the other hand, natural gas met almost 68 percent of the country's total

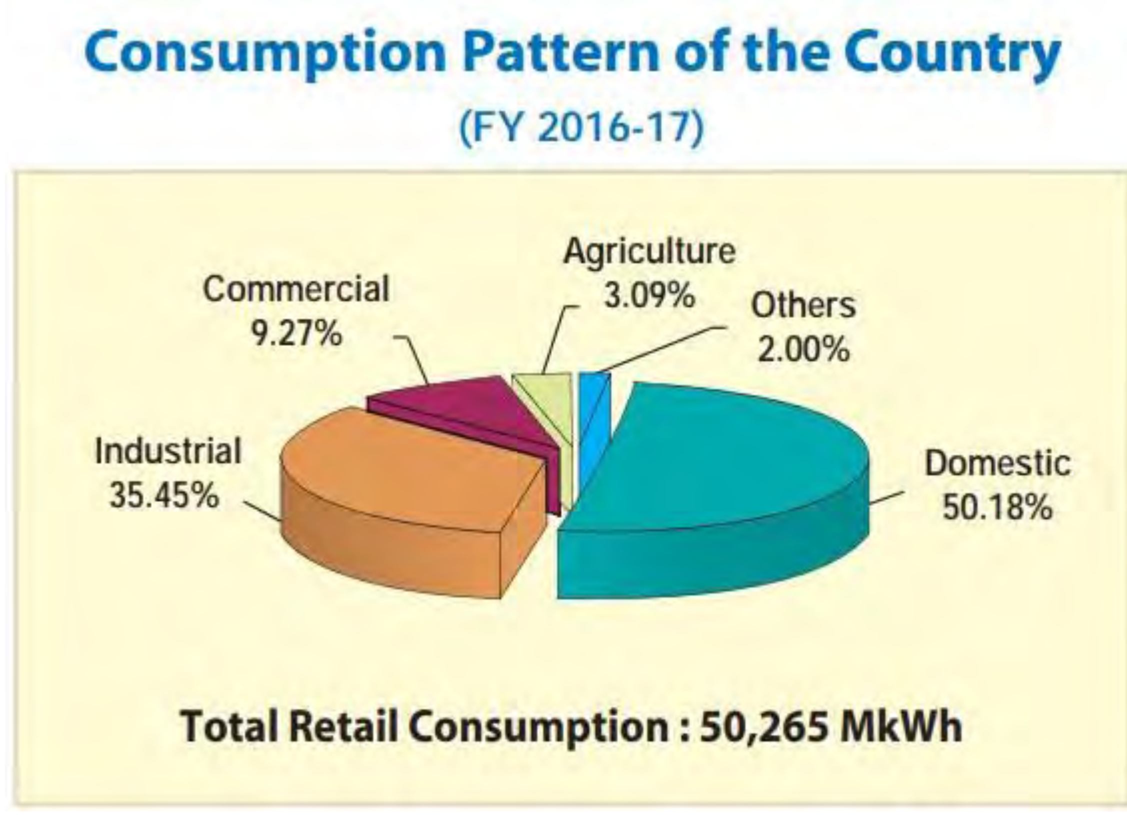


Figure 1.4: Energy consumption pattern in Bangladesh, (Source: Annual report 16-17, BPDB)

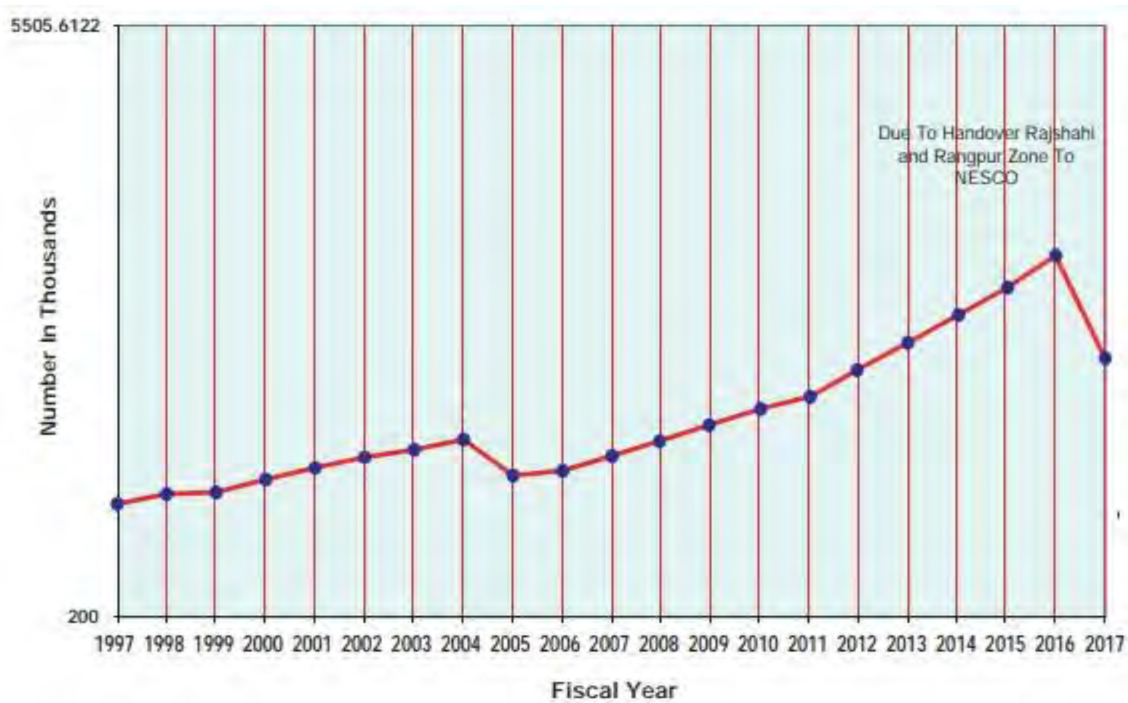


Figure 1.5: Energy consumer growth in Bangladesh, (Source: Annual report 16-17, BPDB)

commercial use of energy. A total of 26 gas fields have been discovered up to June 2017 from which about 14.73 trillion cubic feet of gas has been produced cumulatively leaving recoverable net at 12.39 trillion cubic feet. Besides, the country has a reserve of about 12.21 million metric tons fuel oil. For ensuring the energy security, a plan to set up a new unit of the Eastern Refinery has been undertaken. A policy has been formulated to encourage private sector to generate electricity under Public-Private Partnership (PPP), Rental Power Producer (RPP), and Independent Power Plant (IPP) arrangements. According to Power System Master Plan (PSMP), the Government has set a target to increase installed electricity generation capacity to 24000 MW by 2021 and 40,000 MW by 2030. Figure 1.6 shows the growth of electricity consumption per capita in Bangladesh from 2000 to 2014. Demand of electricity is increasing rapidly due to enhanced economic activities in the country with sustained GDP growth. At present, growth of demand is about 10% which is expected to be more in coming years which is warned by BPDB (Bangladesh Power Development Board) and recent energy consumption scenario is shown in Figure 1.5.

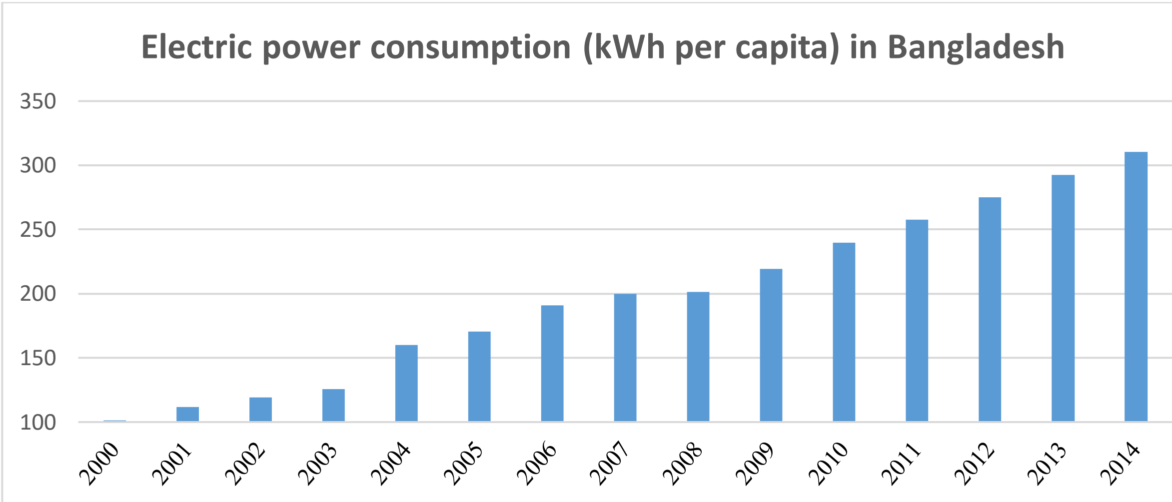


Figure 1.6: Electric power consumption (kWh per capita), (Source: Annual report 16-17, BPDB)

1.3 Outdoor weather condition in Bangladesh

The outdoor conditions are play the vital role for natural ventilation and in natural ventilation, wind and temperature are the core elements. However for a naturally ventilated building, fluctuating ambient temperature, humidity, wind speed, and wind direction must be considered [4-5].

In Bangladesh, there are "THE BUILDING CONSTRUCTION ACT, 1952" for constructing building but there is no weather based act. However Bangladesh has lots of scope to construct buildings using outdoor weather condition to reduce the depending on the mechanical system for ventilation.

The criterion for the weather data is that, it should represent the general weather characteristic from different months. The average temperature found from the "World weather online .com" for Bangladesh from 1991-2015 is shown in Table 1.1 and average Monthly Temperature graph is shown in Figure1.7. In Bangladesh, the fastest growing city is the capital city Dhaka where it is more essential to use the natural ventilation for buildings. The maximum and minimum temperature for the year 2018 for Dhaka city is shown in Figure 1.8 (from the same source). On the other hand, the average wind speed in m/s for different city is shown in Figure 1.9. It will be beneficial if it is possible to show wind flow rate with respect to temperature and hour. In general wind flow rate is high during daytime which is quite practical whereas mean temperature is higher during daytime and during daytime people are currently using mechanical system in most of the case (at home or office).

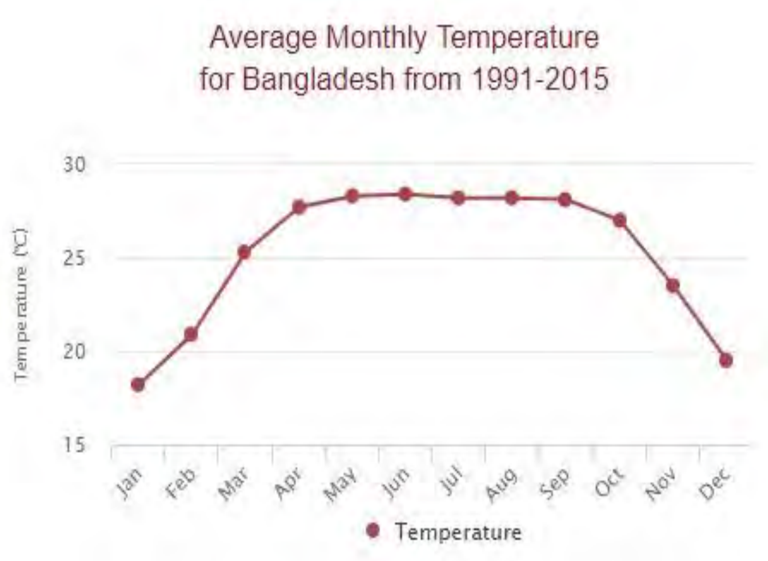


Figure 1.7: Average monthly temperature, (World weather online .com)

Table 1.1: Weather data (taken from meteorological department's website)

Months	Average Temperature
January	18.2 °C
February	20.9 °C
March	25.3 °C
April	27.7 °C
May	28.3 °C
June	28.4 °C
July	28.2 °C
August	28.2 °C
September	28.1 °C
October	27 °C
November	23.5 °C
December	19.5 °C

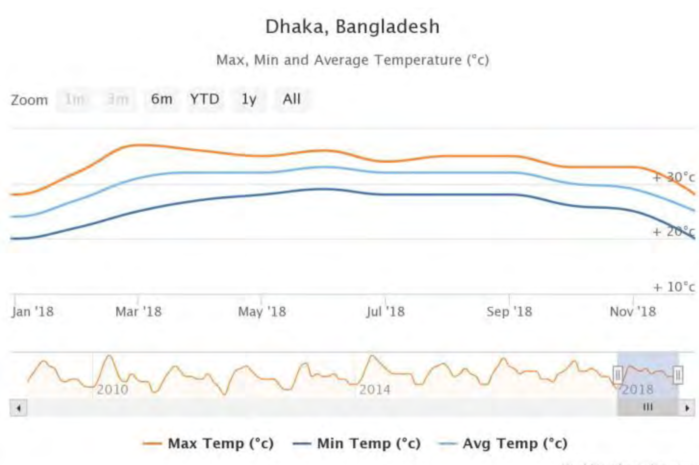


Figure 1.8: Monthly temperature of Dhaka for 2018, (World weather online .com)

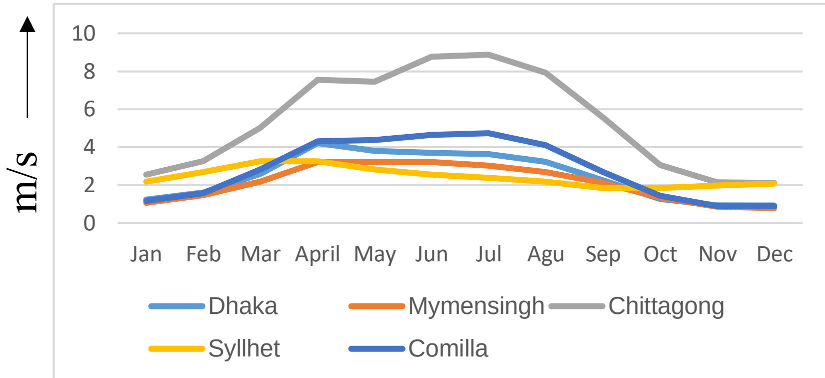


Figure 1.9: Average wind speed in m/s for different city, (World weather online .com)

Moreover, comfort living needs the highest air change during daytime and there by the highest pressures changes during this period. It will be more beneficial to analyze the outcome with respect to wind direction over the year but unfortunately there is no data available related to this. Ahmed [6] and Hossain *et al*. [7] took average air velocity and temperature are 1.12 m/s and 25°C respectively for their findings in Dhaka.

1.4 Different types of openings

There are different types of openings are available for ventilation which are using all over the world. Among them I am going to talk about normal openings (casement, sliding) and awning opening. Awning and casement or sliding openings are usually mentioned to as crank openings, since they are opened using a cranking mechanism. These types of window easily glide open or shut by turning an easy-to-reach fold-down handle. Both are very similar in style, but have distinct differences.

A sliding opening is a type of opening which opens horizontally by sliding, usually parallel to a wall, Casement openings are hinged at the side and open outward, to the left or to the right. They are available in different number of configurations. Casement openings are made for openings in which the height is greater than the width. On the other hand, awning openings are hinged at the top. Awning openings are made for openings in which the width is greater than the height. All the openings type are shown in Figure 1.10.

a. Sliding openings

b. Casement openings

c. Awning openings

Figure 1.10: Diferent types of openings, (source :Stanek Windows)

1.5 Motivation of this research

Chen [36] and Chen *et al*. [37] predicted ventilation performance in buildings using a number of tools, such as analytical models, empirical models, small scale experimental models, full-scale experimental models, multizone network models, zonal models, and CFD models. Much attention is given to CFD models, and this is the modeling approach used in this study.

I brought up in small town of Bangladesh and when I was younger, I observed that electricity is the biggest crisis of Bangladesh and load-shading was the daily life problem and sometimes several times in a day. Now I live in capital city and Bangladesh is now more developed then previous times. Now-a-days, life style in Bangladesh is very standard and using a lots of things for comfortable life which consumes energy. However, still there are so many places in Bangladesh where peoples are facing the electricity and energy problem. Not only have these but also for more growth of industrial and commercial development required more energy and electricity. That is why, government of Bangladesh introduced a new department named Sustainable and Renewable Energy Devolvement Authority (SREDA) in 2014. The mission of govt. is to save energy for future development. Already mentioned and showed that Bangladesh has meaningful resources to save energy.

Usage of energy for cooling and heating (in winter) in buildings in Bangladesh has been increasing over time. As a result there is an additional cost increases. The consumption of energy for cooling space is projected to rise in the USA during the next three decades because of an increased migration to the warmer southern climates [8]. To reduce the amount of energy required to cool and heat spaces can be optimized by using Natural Ventilation (NV). Naturally ventilated buildings can save upto 40% energy than a mechanically ventilated buildings [9]. NV can be effective when the thermal comfort level and outdoor temperature are almost same. Moreover, it is beneficial to use NV because its installation and maintenance cost are very low while maintaining acceptable indoor air quality [10] and also a great saving in designing building because buildings which are designed for NV have a little mechanical difficulty and easy electrical design. Zhao *et al*. [11] and Vladimir Gerlich [12] showed that natural ventilation has significant role to decrease operating costs to condition buildings while maintaining acceptable indoor air quality. NV is driven by wind around a building, which causes pressure differences, temperature differences between the indoor and outdoor environments, and a combination of both. Allocca *et al*. [9] simulated flow in a single-sided ventilated room and a building with heat sources, and they found that the effects of buoyancy were higher at lower wind speeds around the building and the effect decreased with higher wind speeds. The computational model used a large domain, and Allocca *et al*. [9] found that convergence was difficult when buoyancy effects were great.

Natural ventilation is effective in improving air quality, thermal comfort, and reducing energy consumption when utilized properly. It is most effective in climates where there is low noise, low pollution, and where the outdoor temperature is within comfort levels. Appropriate air velocities and thermal comfort levels can be found in ASHRAE standard 55-2004 [13]. Air flow into buildings can be driven by wind velocities, buoyancy, mixing, and temperature differences. When implementing a natural ventilation system, the indoor air quality must be considered. The average person in the U.S. spends more than 90 % of their time in buildings [14]. Thus, it is important to maintain comfortable indoor conditions. Two principles that are important when designing buildings for natural ventilation are thermal comfort and air quality. Recommendations for thermal comfort and maximum air velocities are prescribed in the ASHRAE standard 55 [15]. Thermal comfort is determined from conditions where 80% of the occupants find the environment acceptable. Moving air leads to an increase in the acceptable temperature. The thermal conditions and corresponding temperatures increase with air speed, and are summarized in Table 1.2 and Table 1.3 [15]. The upper limit of air speed for light activity is approximately 0.9 m/s.

Table 1.2. Thermal comfort conditions, (source: ASHRAE Standard 55)

Outdoor Ambient Temperature	10℃		33.5℃	
	Lower Limit	Upper limit	Lower Limit	Upper limit
90% acceptable	17.5℃	23.5℃	23℃	30.5℃
80% acceptable	18.5℃	24.5℃	26℃	31℃

Table 1.3. Increase in acceptable temperature due to moving air, (source: ASHRAE Standard 55)

Air Speed (m/s)	Temperature Increase (°C)
0.6	1.2
0.9	1.8
1.2	2.2

Studies have been performed to understand the physics of natural ventilation systems. Mahajan [16] experimentally measured the heat and mass transfer through an opening, placed between two different thermally-conditioned rooms. The velocity and temperature measurements at the doorway (opening) were compared with values predicted by an algorithm based on the application of Bernoulli's equation. However, the analyses showed that the values from an algorithm did not agree well with the experimental results. Schaelin *et al*. [17] utilized Computational Fluid Dynamics (CFD) and validated a model to predict a free plume and single-sided ventilation, modeling the work of Mahajan. Several studies have been pursued using CFD for natural ventilation through buildings, in addition to David Park [18], solve the heat transfer and air flow in a room numerically and got results close to Mahajan [16]. Computational fluid dynamics (CFD), based on the numerical solution of the set of governing equations which describe the flow field. CFD-based programs are widespread and provide a detailed description of the air flow. In recent years, their application has become more and more popular thanks to the increase of computational power and to the improvements in turbulence modelling. Among the available models, Reynolds averaged Navier–Stokes equation (RANS) and large-eddy simulation (LES) are the most common. RANS is widely used by most of the commercial CFD software. It is based on the time-averaging of the flow field governing equations; this means that all of the unsteadiness is considered as part of the turbulence and is averaged out. On the other hand, LES is based on the space filtering of the turbulent structures. The fluid flow is separated into large eddies and small eddies; the first ones are solved by the governing equations, while the last ones are approximated and described by suitable subgrid-scale models. Jiang *et al*. [19] applied LES to wind driven ventilation; they determined pressure and velocity distribution inside and around a scale cubic building model, showing a good agreement between numerical and experimental results. LES models have also been successfully applied to cross natural ventilation in a group of apartments [20].

Despite their reliability, LES models are time-consuming and for this reason they are seldom used, unless an extreme precision is required. On the contrary, RANS models require less computing time, but sometimes they lack the due precision. As an example, Jiang and Chen [21] compared LES and RANS performance in wind driven natural ventilation, concluding that RANS might not be appropriate for the determination of the ventilation rate. A comparison between the results provided by RANS and LES models in natural ventilation problems is also available in [22]. Due to the large use of RANS models, an extensive research is needed to further test their reliability and improve their application to natural ventilation problems. Previous studies concerning RANS modelling of wind driven natural ventilation in a building immersed in an atmospheric boundary layer can be found in literature [23], but they were based on a two dimensional approach and little attention was paid to the determination of the ventilation rate.

Evola *et al*. [24], determined ventilation rate for single-sided and cross ventilation using k-ε turbulence model and Renormalization group (RNG) theory and compared the result. Cho and Awbi [25] studied the effect of heater locations in a ventilated room and predicted the mean velocity for different locations of the heater. Stoakes *et al*. [26, 27] modeled natural ventilation flows in large, multistory buildings using the commercial software Fluent 6.0. They performed passive cooling and heating cases in whole buildings, and showed the potential of CFD to model natural ventilation in buildings.

The challenge of CFD is modeling realistic flows, particularly in the area of turbulence modeling and buoyancy driven flow. The most common turbulence model is the $k-\varepsilon$ model in which the turbulent kinetic energy, k, and turbulent dissipation rate, ε, are modeled. There are three types of $k-\varepsilon$ turbulence models: standard $k-\varepsilon$, renormalization group theory (RNG), and realizable $k-\varepsilon$. The standard $k-\varepsilon$ model is considered as the simplest two-equation turbulence model that solves two transport equations. The RNG model includes an additional term to improve the accuracy in the ε transport equation for rapidly strained flows and for swirling flows. The transport equation for ε is also modified for the realizable $k-\varepsilon$ model to satisfy certain mathematical constraints on the Reynolds stresses.

Several studies have focused on turbulence models appropriate for natural ventilation. Chow and Li [28] tested four turbulence models to study fire-induced thermal plumes: the standard k-ε, low-Reynolds number (LRN) k-ε, Chen-Kim modified k-ε (CK model) and RNG model. The authors found good agreement with experiments using the standard k-ε model while the other models did not give better agreements. Stavrakakis *et al*. [29] experimentally and numerically investigated natural cross-ventilation in buildings. Three different turbulence models (standard, RNG, and realizable k-ε models) were tested. All turbulence models showed acceptable agreement with the experimental measurements, but overall differences were smallest for the standard k-ε model. Awbi [30] mentioned that the standard k-ε model is the most used and developed turbulence model, and predicts airflow in buildings fairly well.

1.6 Objectives of this research

The aims of this study are to simulate the ventilation of a building and to give recommendations to architects and engineers based on the results.
The objectives of the research are as follows:

- To construct the mathematical model of the problem and then solve it using Finite Element Method (FEM).
- To analyze the indoor and outdoor flow pattern for different situations as well as for different window positions and different types of window.
- To obtain standard thermal comfort inside the room for local weather condition and compare with ASHRAE Standard.
- To compare the obtained result with experimental and analytical results of other researchers.
- To recommend a suitable opening for maximum comfort of residents of the residential building in Bangladesh.

1.7 Methodology and scope of this research

A commercial software will be engaged to model and simulate air flow patterns and heat transfer in structures that employ cross-ventilation and single-sided ventilation (forward and leeward). Ventilation in simple structures will be modeled using building-like room (250 mm ×250 mm ×250 mm.) and different type (normal and awning) window openings and locations.

There are two simple structures that will be investigated in this study: a room with two openings representing windows on each side for cross-ventilation and one opening on one side for single sided ventilation and with awning openings for every cases. As a consequence, in the present study six different cases are considered:

_ Case 1: single-sided ventilation with an opening on the windward wall;
_ Case 2: single-sided ventilation with an opening on the leeward wall;
_ Case 3: cross ventilation with openings on both windward and leeward walls;
_ Case 4: single-sided ventilation with an awning opening on the windward wall;
_ Case 5: single-sided ventilation with an awning opening on the leeward wall;
_ Case 6: cross ventilation with awning openings on both windward and leeward walls.

Here, two types of opening is used. First opening is normal opening (casement or sliding) and the other one is awning opening. One of the objective of this study is that, observing the air flow pattern for both case carefully. However, using awning gives more protection from dust. Awning openings can protect home against moisture, even when they are open during a rainstorm, because of the awning openings constructed. They allow for nearly 1000% of viable ventilation without the threat of water seeping into the home.

The effects of boundary conditions will be explored to find the differing flow patterns and heat transfer in the rooms. The investigation will be done to find potential regions of stagnant or stale air, examine the overall air quality, and to make recommendations in the design of rooms that utilize cross-ventilation.

For every cases, the room dimension and window dimension are same. For awning cases, the size of the awnings is (250/6 mm). The air flow patterns and overall air quality will be explored to make recommendations in the overall design utilizing single-sided and cross ventilation. The structure used in this thesis is a local one room building in Dhaka.

The overall climate and conditions of the region where the apartment is located, combined with the layout of the room, match a situation where natural ventilation is expected to be effective. Conditions late on a hot summer day, late at night after the exterior temperature has dropped, is simulated to examine the efficacy of natural ventilation in a real building and in a situation that challenges the effectiveness of natural ventilation. Finally the comparison between awning and normal opening based on results.

1.8 Organization of thesis

In Chapter 1, a brief introduction is presented with significance and objective of the study. This chapter consists of physical phenomena of natural ventilation, weather condition of Bangladesh and present energy state. A literature review of the past studies on the above physical facts is included.

In Chapter 2, geometrical description 2D/3D along with meshing are discussed.

In Chapter 3, the basic governing equation for the flow fields and energy equation are shown. Numerical procedures and discretization of the governing equation are discussed.

Air flow through the surrounding and the room are studied in Chapter 4. The influence of the position and category of openings, ventilation rate, velocity profiles and stream-lines are shown.

Temperature distribution and thermal comfort around the room are discussed in Chapter 5.

A summary of major conclusions, recommendation and some schemes of further work are expressed in conclusion chapter.

Chapter 2
Geometrical model of the problem

Good ventilation has positive effects on occupants' comfort and indoor-air quality. So in this chapter all geometrical model used in this research for residents' comfort inside the room are described. This includes a description of the room with different openings and the total domain which are considered in the work. Meshing for different cases are also shown here.

2.1 Introduction

The configurations of building/room and especially the location of openings on the wall in relation to dominant wind direction at the site, have major effects on the ventilation rates in room. Locating openings near high-pressure surfaces of a room and exit openings at low-pressure ones produces higher flow rates through openings. Accordingly, a considerate of air flow around the room is required to design well-ventilated residences. External flows around room is very complicated involving severe pressure gradients, streamline curvature, spin, separation and reattachment together with the resulting effects of enhancing and suppression of turbulence.

2.2 Geometry and mesh of the problem

There are two types of ventilation principles: cross and single-sided ventilation. Cross ventilation involves with the existence of two or more openings on opposite sides of the building, and it provides lager ventilation rates than ventilation rates obtained by single-sided ventilation usually and Cross ventilation used for cooling purposes, which relies on wind to transport the cool air into an inlet (window, door, etc.) and to transport the warm interior air through an outlet. Single-sided ventilation involves a room with one opening are located on a single side. The temperature difference between the indoor and the outdoor atmosphere makes a pressure difference, and the air is ventilated through an opening. In this research, six different cases are considered:

_ Case 1: single-sided ventilation with an opening on the windward wall;

_ Case 2: single-sided ventilation with an opening on the leeward wall;

_ Case 3: cross ventilation with openings on both windward and leeward walls;

_ Case 4: single-sided ventilation with an awning opening on the windward wall;

_ Case 5: single-sided ventilation with an awning opening on the leeward wall;

_ Case 6: cross ventilation with awning openings on both windward and leeward walls.

Also depending on the position of the openings, two positions are considered.

i. Lower position and
ii. Middle position.

In total 12 cases are discussed. For comparison with previously published results which are available in literature, the analysis are studied on a building-like model similar to the one used in [10], dimensions of the room are 250 mm ×250 mm×250 mm. For cross ventilation, there are two awning openings of the same dimension on both windward and leeward wall. Height of the opening(s) and awning opening(s) are 125mm shown in Figure 2.1 and Figure 2.2 and it is used to analyze wind flow and heat transfer for all the 12 cases. The thickness of the wall is 6 mm in this model shown in Figure 2.2. Figure 2.3(b) shows the dimension of the computational domain and the room with awning opening on the windward

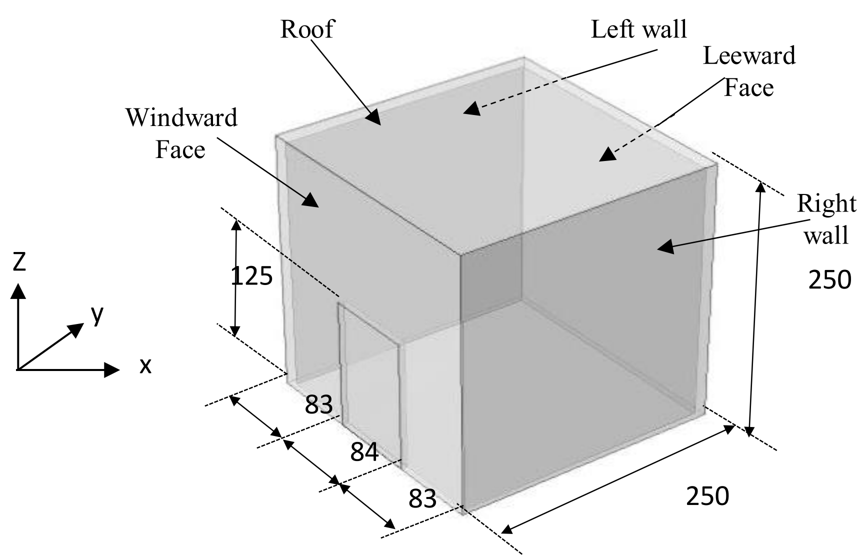


Figure 2.1: Description of the building model in single sided ventilation with an opening in the windward wall (case 1(i))

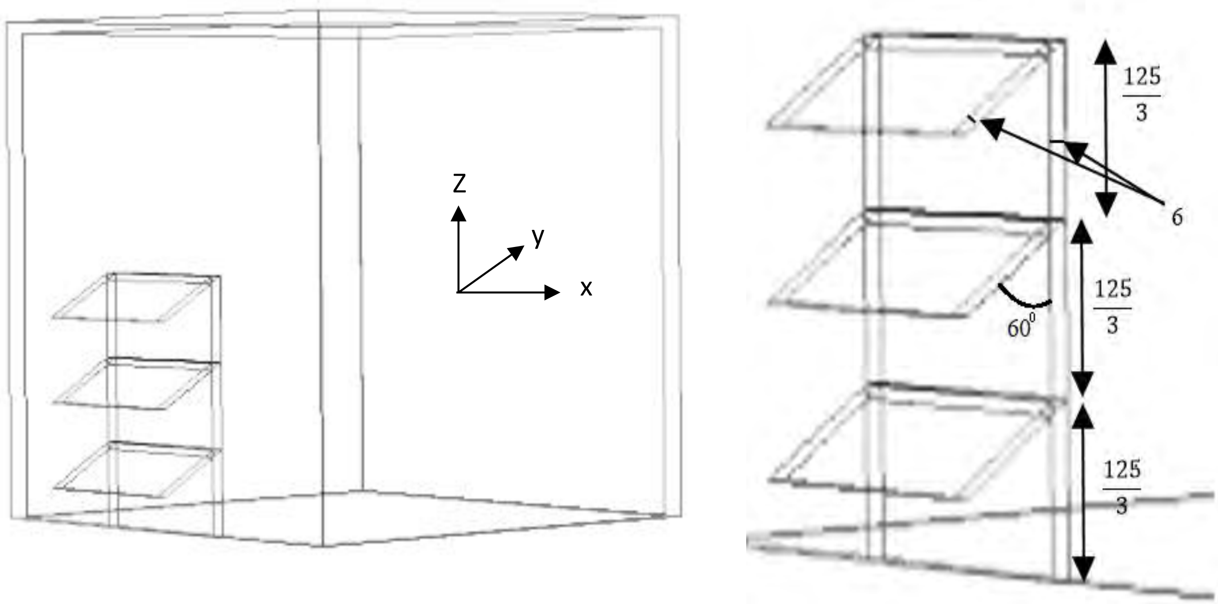
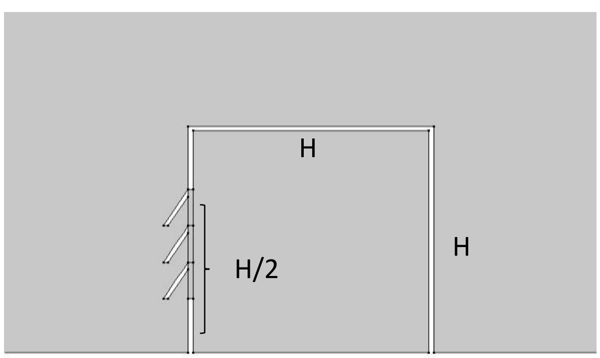
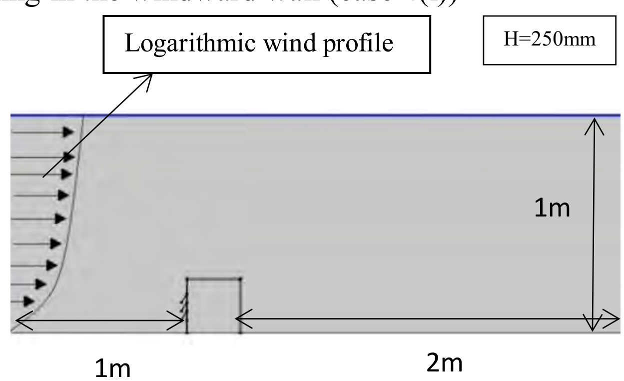


Figure 2.2: Description of the building model (measurement are same as Figure 2.1) in single sided ventilation with an awning opening in the windward wall (case 4(i))



(a)



(b)

Figure 2.3(a): Dimensions of the room: Awning opening position in the middle (case 4(ii))

Figure 2.3(b): logarithmic wind profile.

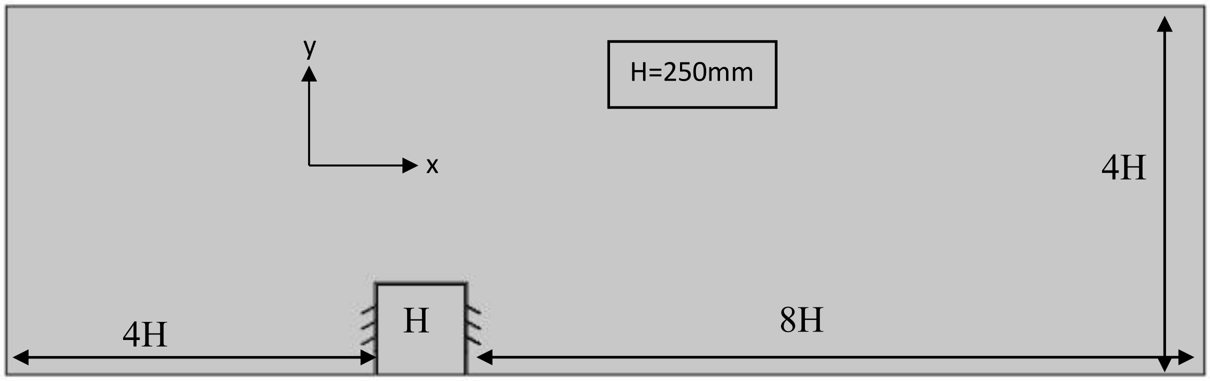


Figure 2.4: Dimensions of the computational domain (2D view): Awning opening position in the middle (case 6(ii))

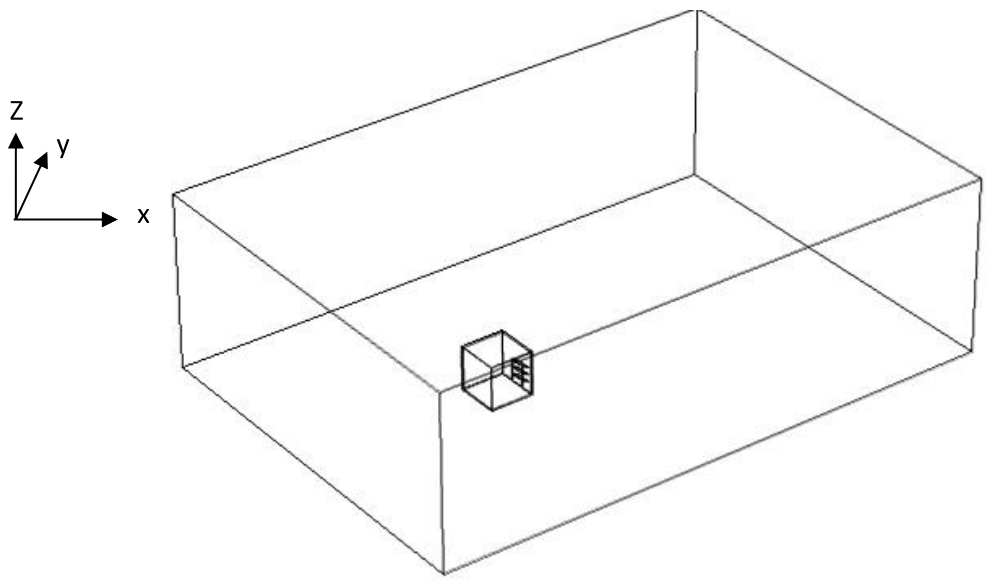


Figure 2.5: Dimensions of the computational domain (3D view) (case 5(i))

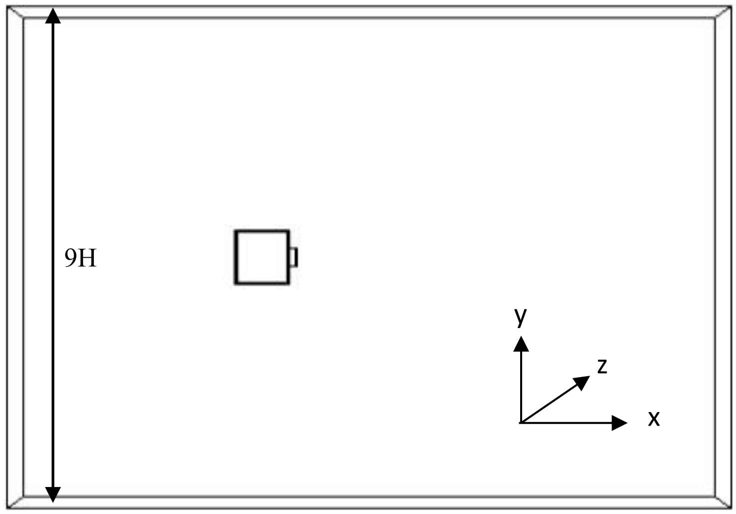
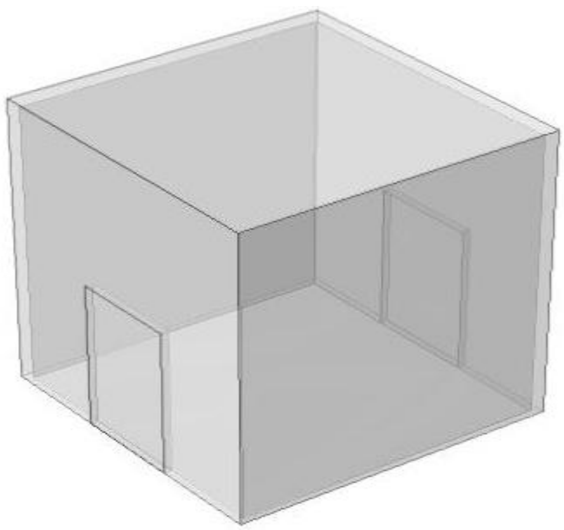


Figure 2.6: Computational domain (3D XY plane view)

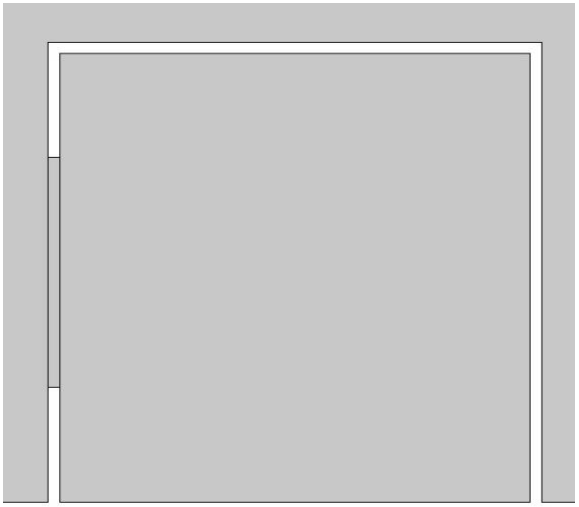


(a)

Figure 2.7 (a): Geometry of cross ventilation (case 3(i)) (3D view)

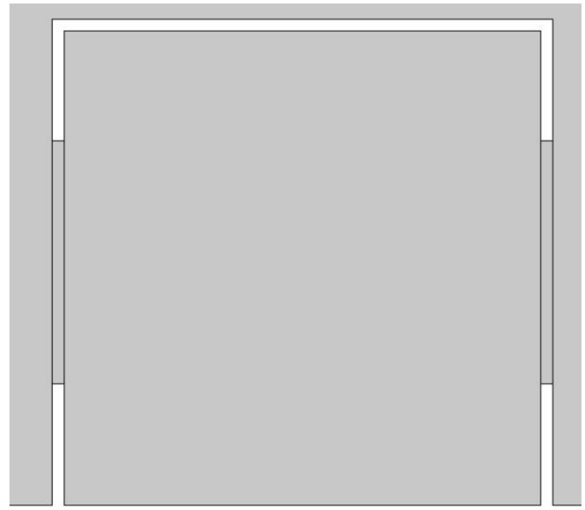
(b)

Figure 2.7 (b): Geometry of cross ventilation (case 3(i)) (2D view)



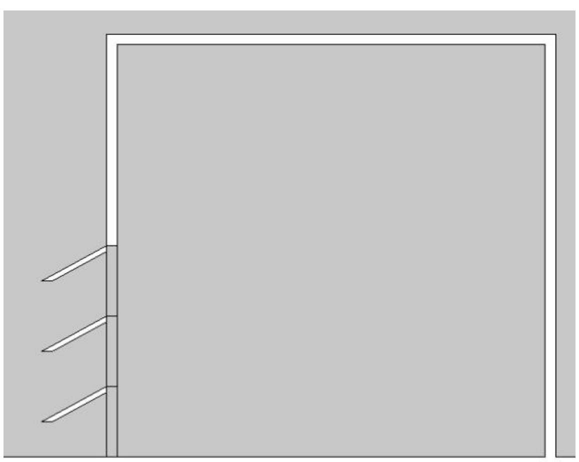
(a)

Figure 2.8 (a): Geometry of single ventilation (case 2(ii))



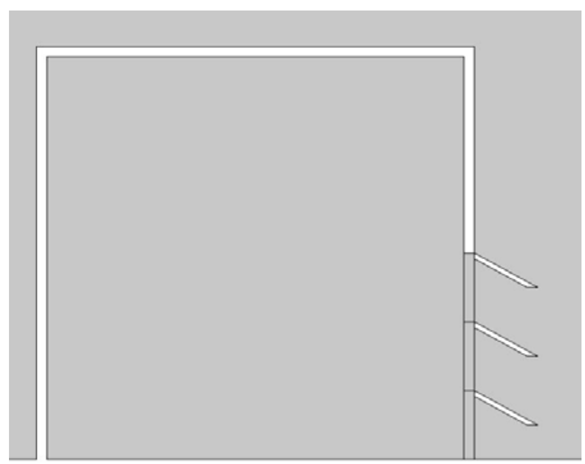
(b)

Figure 2.8 (b): Geometry of cross ventilation (case 3(ii))



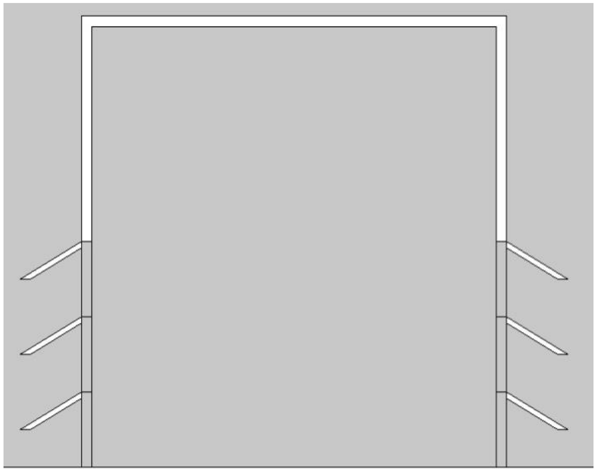
(a)

Figure 2.9 (a): Geometry of single ventilation (case 4(i))



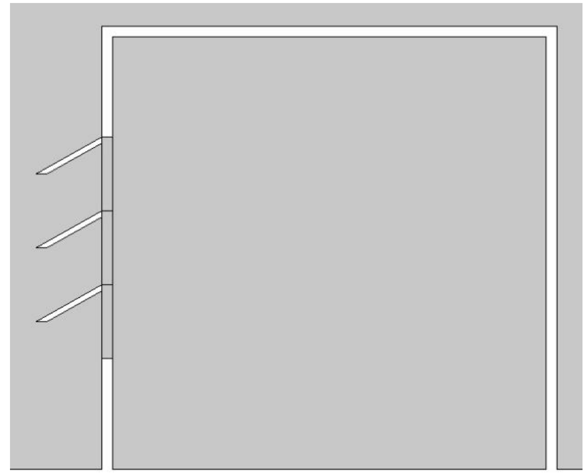
(b)

Figure 2.9 (b): Geometry of cross ventilation (case 5(i))



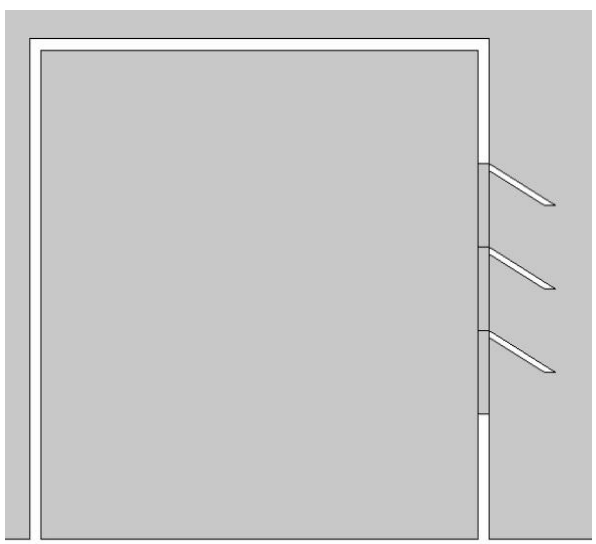
(a)

Figure 2.10 (a): Geometry of cross ventilation (case 6(i))



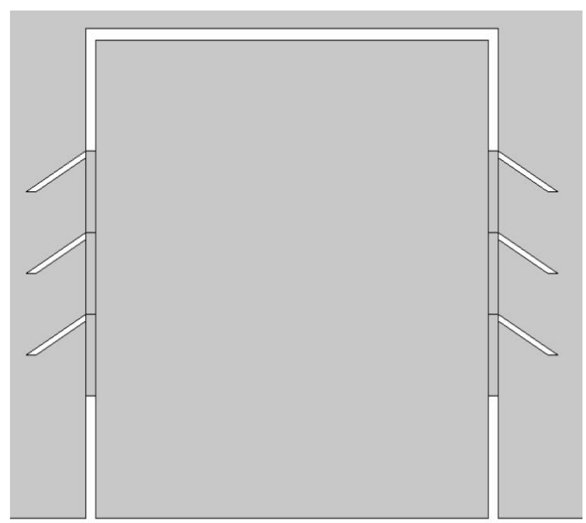
(b)

Figure 2.10(b): Geometry of single sided ventilation (case 4(ii))



(a)

Figure 2.11 (a): Geometry of single sided ventilation (case 5(ii))



(b)

Figure 2.11 (b): Geometry of cross ventilation (case 6(ii))

wall. Since wind flow around the building can be disturbed by the wind flow reflects from Computational domain walls, so it consider large enough in order not to disturb the wind flow around the building. In the present study, angle of the awning is considered 60°. Moreover, in this study, a logarithmic wind profile (shown in Figure 2.3(b)) upwind of the building is considered for comparison. Figure 2.4, Figure 2.5 and Figure 2.6 are showing the whole computational domain where H=250 mm from different view. Figure 2.7 to Figure 2.11 are showing the geometry of the building for different cases. A detailed geometry was prepared in this study, so that it calculates the flow in a detailed manner. The detailed geometry prepared for this study is shown in Figure 2.1 to Figure 2.4. As seen from the detailed geometry, the air enters the room through single/multiple air inlet(s). The mesh for the geometry was prepared using Comsol Multiphysics Meshing. Finalized geometry has 8 domains, 46 boundaries, 86 edges, and 50 vertices for case 5(i). Mesh consists of 1675025 domain elements, 69605 boundary elements, and 1919 edge elements. Figure 2.12 shows mesh prepared for case 5(i) that is single-sided ventilation with an awning opening on the leeward wall and opening position in lower. Table 2.1 shows the details meshing of this case. For 3D cases number of mash is taken within 1500000-1800000. Similarly for 2D case as for example, 23787 domain elements and 919 boundary elements are considered for case 5(i). Figures 2.13 shows mesh prepared for case 5(i) (2D) and Table 2.2 shows the details meshing for this case.

Table 2.1: Meshing for case 5(i) in 3D

Element Type	Number of Element
Tetrahedral	1417381
Pyramid	3987
Prism	253657
Triangular	67260
Quadrilateral	2345
Edge	1919
Vertex	50
Total Element	1675025

Table 2.2: Meshing for case 5(i) in 2D

Element Type	Number of Element
Triangular	20254
Quadrilateral	3533
Edge	919
Vertex	100
Total Element	23787

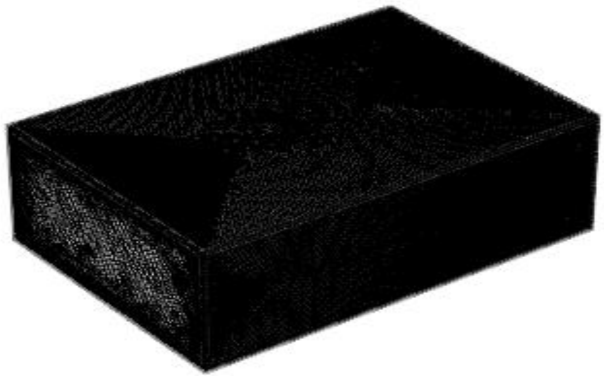


Figure 2.12(a): Meshing of case 5(i)

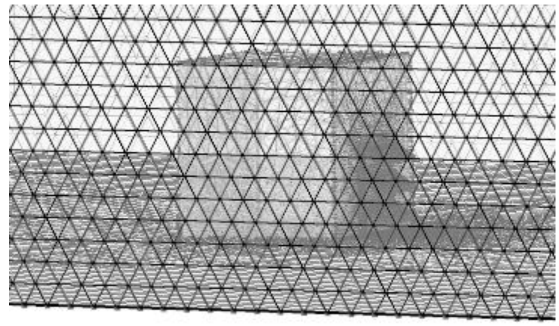


Figure 2.12(b): Meshing of case 5(i), close view.

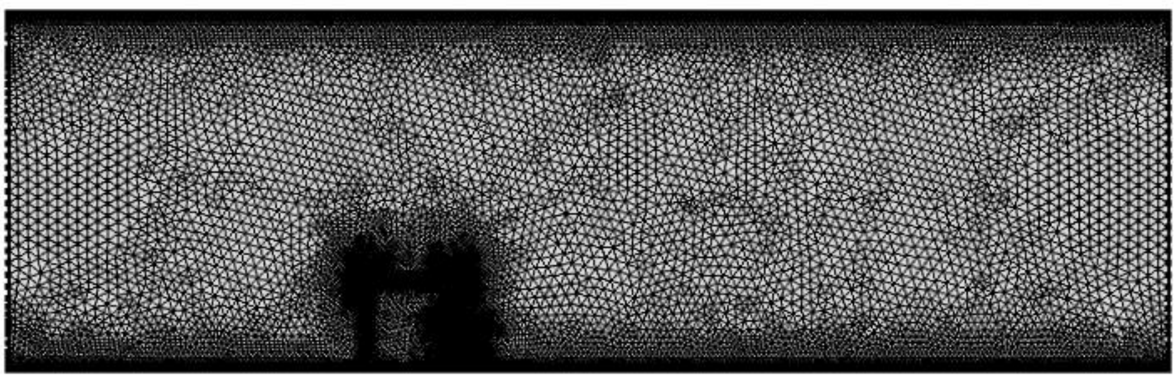


Figure 2.13 (a): Meshing of case 5(i) for 2D

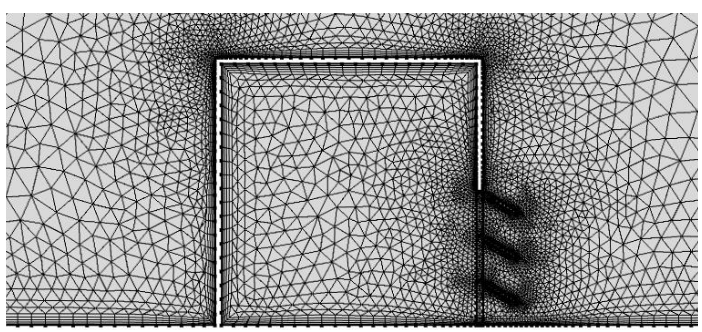


Figure 2.13 (b): Meshing of case 5(i) for 2D, close view.

Chapter 3
Governing equations of the problem

The numerical approach that the physical solution will use is explained in this section. A commercial software is used for all simulations. The basic governing equations for the flow and energy in standard vector form and the mathematical modeling of the problem for various cases with grid resolution study will be presented in this chapter.

3.1 Introduction

The foundation of computational fluid dynamics is consist of fluid dynamical governing equations; the continuity, the momentum (Navier-Stokes equation) and the energy equations. These equations illustrate the physics of various flows. Computational fluid dynamics solves partial differential equations that describe the movement of a fluid. The velocity and temperature are solved with the Two/Three-dimensional Navier-Stokes equations and the energy transport equation. The equations use a finite element of fluid and apply basic laws for mass, momentum, and energy. They are the mathematical statements of the three fundamental laws or principles upon which fluid dynamics is based:

- Mass is conserved for a system;
- Second law of Newton;
- First law of Thermodynamics; Energy is conserved.

3.2 The Governing equations in Cartesian coordinate system

The following equations are used in this work.

Mass conservation (continuity) equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \tag{1}$$

For incompressible steady fluid flow;

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{2}$$

Momentum (Navier-Stokes) equations

X- direction: $\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right)=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)+\rho g_x$

Y- direction: $\rho\left(\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\rho g_y$

Z- direction: $\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g_z$ (3)

Energy or Heat equation

$$\frac{\partial T}{\partial t}+u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (4)$$

3.3 Turbulence model

Most indoor airflow has been found to be turbulent [9] and therefore must be modeled in CFD. The standard $k-\varepsilon$ model has been found to be sufficient for natural ventilation flow fields [31]. The standard $k-\varepsilon$ model (Launder and Spalding, 1974) has two model equations, one for k and one for ε, based on one's best understanding of the relevant processes causing changes to these variables. Use of k and ε are to define velocity scale v and length scale l representative of the large-scale turbulence as follows: $v=k^{\frac{1}{2}}, l=\frac{k^{\frac{3}{2}}}{\varepsilon}$

The standard $k-\varepsilon$ model uses the following transport equations for k and ε:

$$\frac{\partial(\rho k)}{\partial t}+\underline{\nabla}.\left(\rho k\underline{q}\right)=\underline{\nabla}.\left[\frac{\mu_t}{\sigma_k}\underline{\nabla}k\right]+P_k-\rho\varepsilon$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\underline{\nabla}.\left(\rho\varepsilon\underline{q}\right)=\underline{\nabla}.\left[\frac{\mu_t}{\sigma_\varepsilon}\underline{\nabla}\varepsilon\right]+C_{1\varepsilon}\frac{\varepsilon}{k}P_k-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}$$

where $\mu_t=\rho C_\mu\frac{k^2}{\varepsilon}$

The equations contain five adjustable constants: $C_\mu, \sigma_k, \sigma_\varepsilon, C_{1\varepsilon}$ and $C_{2\varepsilon}$. The standard $k-\varepsilon$ model employs values for the constants that are arrived at by comprehensive data fitting for a wide range of turbulent flows:

Table 3.1. Constants for the Turbulence Model [24]

C_μ	.009
σ_k	1.00
σ_ε	1.30
$C_{1\varepsilon}$	1.44
$C_{2\varepsilon}$	1.92

3.4 Ventilation rate Calculation

The design calculation of the air flow rate provided by natural ventilation is usually accomplished by means of simple relationships. For single-sided wind driven natural ventilation an empirical model is available [24], according to which the ventilation rate can be calculated as:

$$Q_{ss} = .025 * A * U_h \tag{5}$$

where A (m^2) is the opening area and U_h(m/s) is the reference wind velocity, measured at the building height. The wind profile adopted in this study provides $U_h = 10.4$ (m/s).

For cross ventilation, the following semi-empirical model can be used, derived from the application of the Bernoulli equation:

$$Q_{CR} = C_d * A_{eff} * U_h * \sqrt{\Delta C_p} \tag{6}$$

where C_d is the discharge coefficient of the openings, ΔC_p the difference between the mean pressure coefficients associated to the opposite openings and A_{eff} (m^2) is the effective area; the latter is defined by:

$$\frac{1}{A_{eff}^2} = \frac{1}{A_{in}^2} + \frac{1}{A_{out}^2} \tag{7}$$

In the present study, $A_{eff} = 7.416 \times 10^{-3}\ m^2$, and reasonably assume $C_d * A_{eff} = .61$, which is the typical value of the discharge coefficient for a sharp opening [24] and $\Delta C_p = .9$ [24].

3.5 Discretization methods

The Finite Element method (FEM) is used to solve the governing equation by a commercial software. The finite element analysis in that commercial software is performed by following a procedural flow as viewed in Figure 3.1. The method can be divided into three elementary

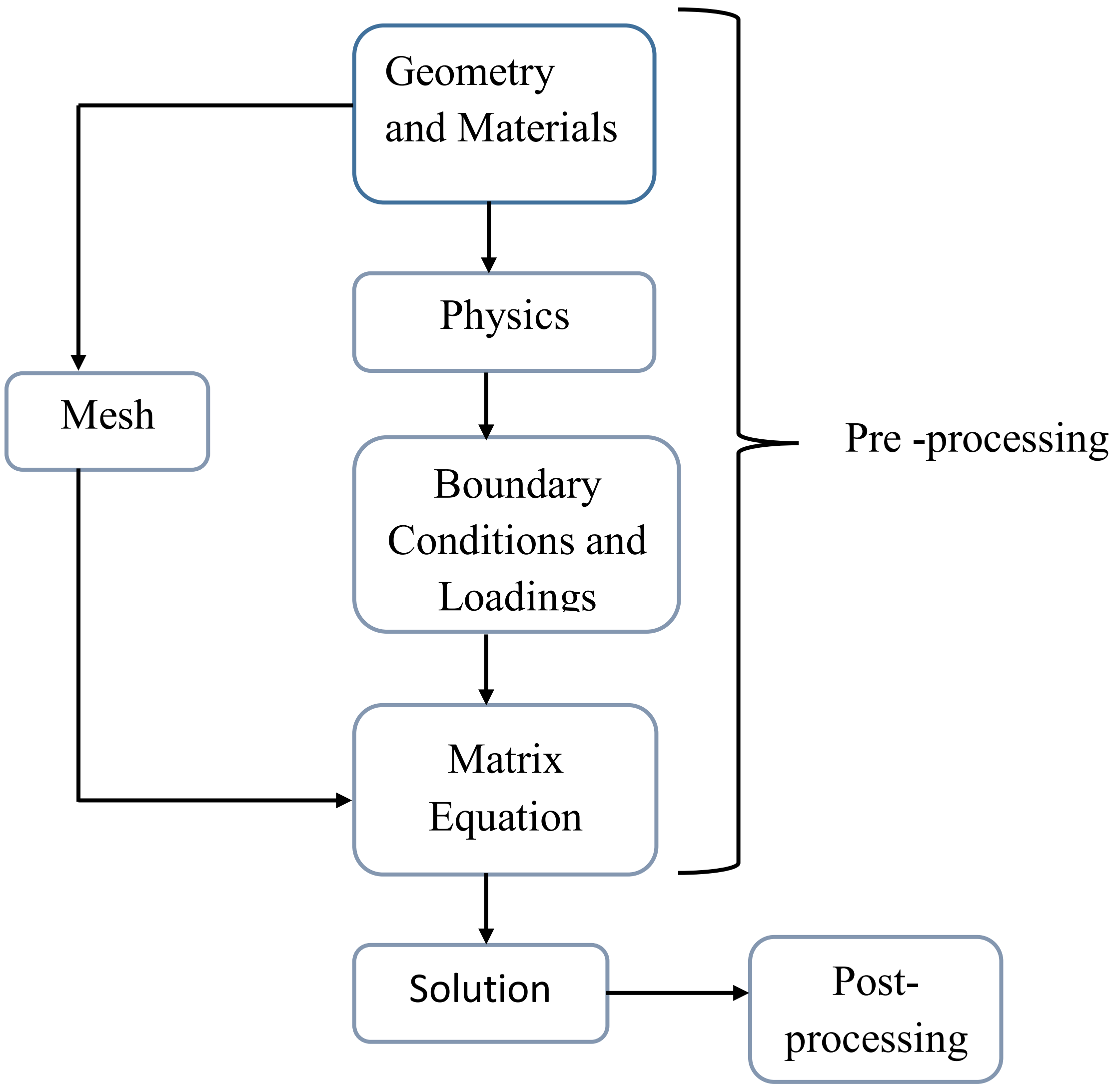


Figure 3.1: Basic steps to perform a finite element analysis in this research

steps, namely pre-processing, solver and post processing. The pre-processing steps enables the user to build the model. Since it contains all the information regarding the FEM application for interconnect study, it is convenient to divide it into smaller sub-steps. The first sub-step involves the creation of the interconnect geometry to represent the domain under study and assign the material properties to the domain. Then the physical environments of the problem under investigation are generated by assigning the underlying physics (or multi-physics), mathematical equations, and finite element formulation to the model. Naturally, the latter is unseen among the core of the commercial software. After that, the application of appropriate loadings, boundary and initial conditions to the domain under study, as well as its discretization into finite elements, determines the matrix equation governing the model. This step is followed by solving the set of algebraic equations, which provides the physics-related nodal solutions of the model. This software mainly employs two methods to obtain the model solution, namely segregated step method and fully coupled method. The segregated step method generates the set of algebraic equations for every physical model under consideration and calculates the resulting solutions for each of those models by following a sequence specified by the user. The fully coupled method generates the single set of algebraic equations for all the involved physical models and implements them in a single iteration scheme which is repeated until convergence is reached.

Once the solutions of the problems are determined, the post-processing step enables the user to evaluate the results of the finite element analysis by means of plotting and data exporting tools.

3.6 Numerical solution and boundary condition

A CFD software based on the finite element method has been used to solve the set of equations provided by $k-\epsilon$ models introduced in the previous section. Different types of element (discussed in Chapter 4) with $1.5\times10^6-1.8\times10^6$ element is used depending on the cases. As far as the boundary conditions are concerned, at the inlet of upwind boundary a logarithmic profile (Figure 2.3(b)) of the streamwise velocity component U is applied:

$$U(h)=\frac{U_0}{k}.\ln(\frac{h}{h_0}) \quad (8)$$

where h is the distance from the ground, k = 0.41 is the Von Karman's constant, $U_0 = 1.068\ m/s$ and $h_0 = 0.005\ m$ have been determined through the best fit of the available data and experimental data provided in [19,24]. The velocity components along vertical and spanwise direction are equaled to zero.

In addition, as the distribution of k and ε on the inlet boundary is not known, the following relations are used [24]:

$$k = \frac{3}{2}\left(U_{avg}.T_i\right)^2 \quad \varepsilon = C_\mu^{\frac{3}{4}} \frac{k^{\frac{3}{2}}}{l_t} \tag{9}$$

where U_{avg} is the average flow velocity, T_i the turbulence intensity and l_t is the turbulence length scale. According to the literature, $T_i = 4\%$ and $l_t = .4m$ [24] have been used. A constant pressure is assumed at the outlet of the computational domain, while the gradients of all the dependent variables are assumed to vanish. The ambient conditions at the domain boundary are represented by specifying ambient pressure of 1 atm and temperature of $20\ °C$. For all cases, 30 °C heat entered to the region through the inlet. Standard wall functions were used and the no-slip velocity boundary condition is applied for the fluid-wall interaction. The wall is modeled as adiabatic is considered. The thermal expansion coefficient of the air is based on the mean temperature of the heater and the ambient temperature.

Furthermore, a co-located variable arrangement is employed, together with time dependent study step segregated solver is used. The coupling between temperature and velocity distribution is obtained using PERDISO.

3.7 Code validation

To validate the code used in the research, first of all, run the code for Evola *et al* [24] using the same geometry used there and Figure 3.2 showing the good agreement. Here, only 2 sections of Case 1, section A and section B are shown.

Results obtained in Evola *et al*. [24] Results obtained in this research

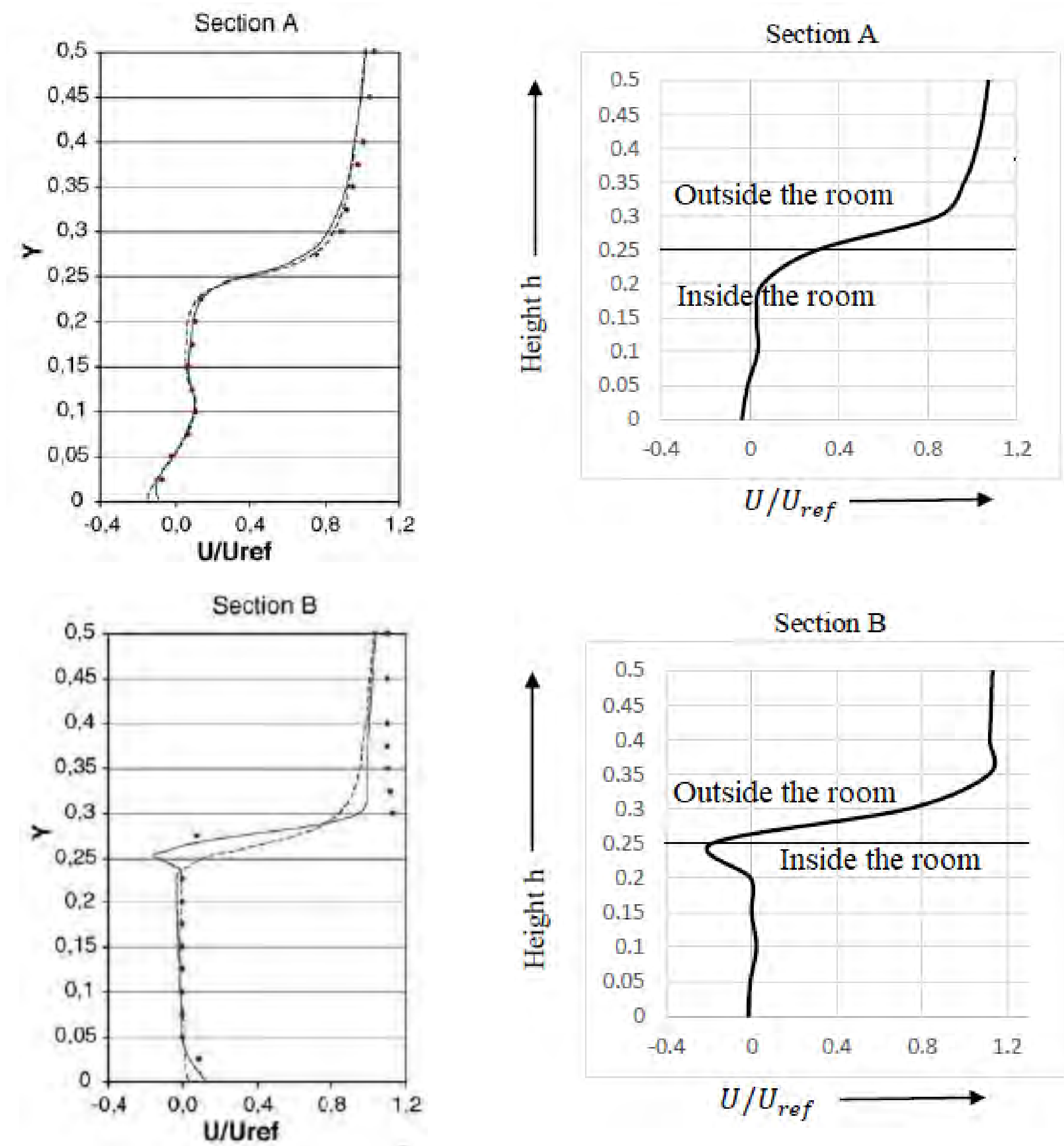


Figure 3.2: code validation (case 1)

Chapter 4
Results and discussion: Air flow

To find the different characteristics in cross-ventilation and single-sided ventilation, all the results from the research will be described in this section, the results from indoor and outdoor data(s) will be described. All cases will be discussed for air flow inside and around the building. In this section, ventilation (cross and single sided) is predicted in a simple structure with opening(s) on forward/leeward faces.

4.1 Introduction

From the journey of life, human body is exposed to air and so it is very important that the air around us should fresh enough. Since most of our time is spent indoors, it is extremely compulsory that the indoor air is free from pollutants. The term “indoor air” refers to the air that is inside confined spaces, such as homes, offices, schools, etc. Air, around us plays an important role in our lives. The term “indoor air quality” (IAQ) usually mentions to the amount and type of pollutants present in the air. There are well-defined ASHRAE standards, which give information about the tolerable number of pollutants in the air. It also essentially refers to the air quality within and around buildings, which relates to the health and comfort of building occupants. People normally tend to believe that only improving the quality of outdoor air is important since most of the major pollutant sources exist in the outdoor environment. People believe that the indoor environment is safe and the air they breathe is free from pollutants. Over the last 30 years, there have been significant developments both in the intensity with which indoor air quality (IAQ) is being challenged and in the understanding of various parameters that influence IAQ Tham [32]. The paper of Tham also further presents that the indoor environment is dynamic and affected by several parameters, such as materials (furniture and fabrics), HVAC systems, and presence of human beings. All these parameters bring impurities into the air and makes the air polluted. These parameters are parts of the indoor environment that cannot be neglected and, therefore, a more holistic approach is needed to efficiently remove the impurities from indoor air. Several studies can be found in the literatures that have shown the importance of indoor air quality on health. The health effects of household air pollution are aggravated when polluted air takes a long time to be flushed out of the cooking area, which is directly related to the indoor ventilation rate. Jones [33] presented a large number of emission sources that can lead to indoor air pollution, and these can cause significant effects on health. Sundell [34] mentioned that indoor air was believed to be a major environmental factor in the past, but then other factors, such as outdoor air quality, energy consumption, and sustainable buildings, became dominant. It is true that a major environmental concern today regards climate change due to outdoor air pollution, but indoor air quality is not something that can be ignored.

In developed countries, concern and awareness regarding indoor air quality can still be relevant. Due to cold weather conditions, airtight buildings have restricted the natural flow of air. In such circumstances, proper ventilation systems must be present for effective removal of pollutants from the air. Health problems such as allergies, airway infections and cancers are some of the consequences of poor ventilation systems Sundell [34]. In addition to indoor air quality, the thermal comfort of the occupant within the indoor environment is also important. Thermal comfort essentially means the condition of mental satisfaction with the thermal environment. In practice, it is not necessary to provide thermal comfort that satisfies each person. Instead, a level of thermal comfort that can satisfy the majority of occupants should be provided. The indoor thermal environment also influences the perception of air quality and can directly or indirectly affect occupant health. It is a known fact that there are differences in factors such as climatic conditions, lifestyles, and building design. Thus, the strategies and methods for maintaining suitable indoor environment conditions such as indoor air quality and thermal comfort are different for different countries as well.

4.2 Results and discussions

The aim of this study is to examine the wind profiles inside the buildings through awning openings rather than normal openings so that it can open all the times in all weather. In this study, considered the same geometry used in experimental and numerical research. After that, obtained and compared results to proof the solution procedure followed in the present study are fruitful. Then set up the targeted geometry and obtained results and compared to numerical and experimental results and will show that targeted geometry maintain the Ashree standard for thermal comfort inside a room. To compare with others results, 5 (five) vertical lines [24] are considered, shown in Figure 4.1, among the five lines, 3 lines are inside the buildings and agree to give complete behavior of the velocity of the flow along the lines. And the other two which are outside but close to the buildings, gives the flow profiles close to the buildings. The velocity components along the horizontal, U and vertical, V have been obtained respectively. . Here reference velocity $U_{ref} = 12\ ms^{-1}$ is taken, is the highest stream wise velocity used in the experimental experiments to plots U and V refer to scaled values.

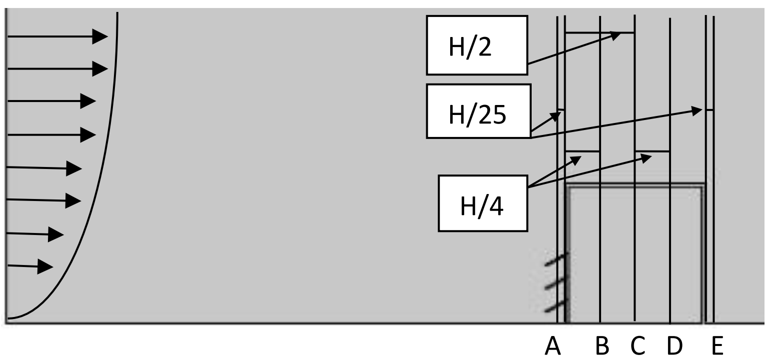


Figure 4.1: 5 vertical line location

4.2.1 Results and discussions of air velocity when the program run for only air velocity

The graphs in Figures 4.2-4.10 display the distribution vertically of numerical and experimental velocity profiles of the designed evaluated for ventilation

From the Figures: 4.2-4.4, lines shows the obtained results using the geometry used in the experimental [35] and numerical observation's geometry [24] using the program used in the research and there is a decent agreement of the stream wise velocity component U in the case of single sided ventilation among present study's result and results obtained in [24] using $k-\epsilon$ method. Above the roof ($Y > .25$) and in the velocity component V for cross sectional flow there are some disagreements in few sections. Moreover, along the velocity component V, similar conclusion can be drawn for all cases. Since the program's result shows good agreement with published results, therefore the results for opening position in the middle showed in the Figure 4.5 -4.7. Main purpose of this study is use of awning openings instead of normal openings and description of the velocity profile inside the building and near to the openings and therefore Figure 4.8-4.10 showed the obtained results for awning opening(s) compared with the results obtained by these research using geometry [24]'s $k - \epsilon$ method, may be considered sufficient. However, in the cross ventilation, velocity component V shows some disagreements can be identified for all opening position. Nevertheless, the description of the flow inside the building and close to the openings, which is the main purpose in natural ventilation design, may be considered satisfying. Figure 4.11 shows flow distribution and velocity stream lines inside and around the building for position of the opening and for all cases considered in this study. Since obtained results using experimental geometry shows good agreement in Figure 4.2-4.10, therefore Figure 4.11, showed the result for the opening position at lower and middle, which already showed a good agreement with the experimental and others published result. From the study, it is clear that in single sided ventilation wind movement inside the building enclosed space more significant than cross ventilation.

4.2.2 Results and discussions of air velocity coupling with heat transfer

Velocity profiles are registered when underneath heat loads exist and the cool and warm air flows interact. Experimental laboratory study revealed that in the case of the underneath heat gains, even no upward plume was generated and the dummy only acted as a flow obstacle, having a significant effect on the velocity profile.

For this case, initial temperature of the room was 293.15° K and 303.15° K temperature air entering into the considered domain through inlet. Due to temperature effect, results shows slight changes from the result obtain without coupling with heat transfer. Figure 4.12-4.14 shows the obtain results for all cases. Air flow distribution and stream line are almost same. That's why, figure for air flow and stream lines are put in the Appendix.

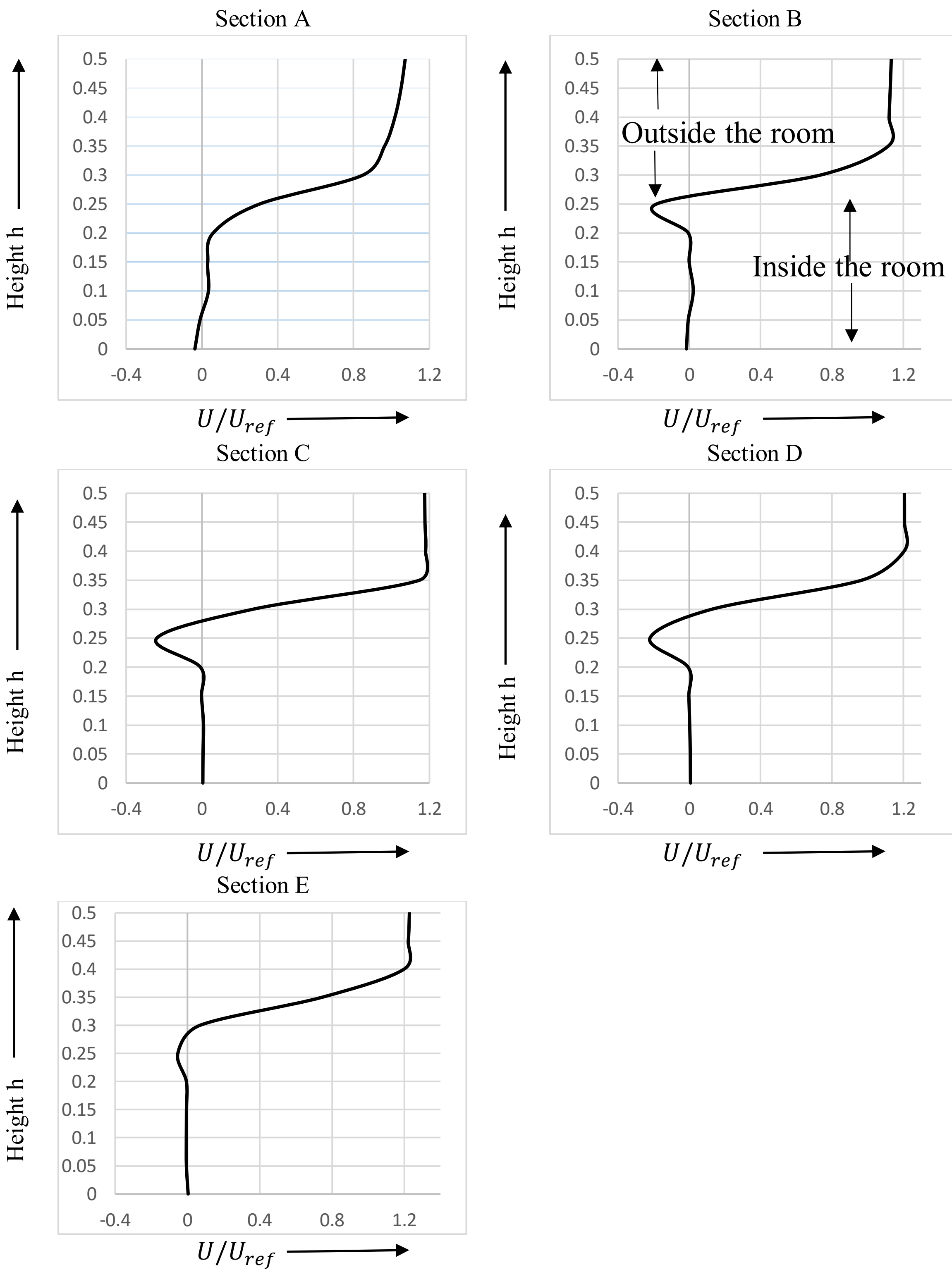


Figure 4.2 (a): Single sided velocity profiles for windward air flow (case: 1(i)) [velocity ratio U/U_{ref} (x) against height h (y)]

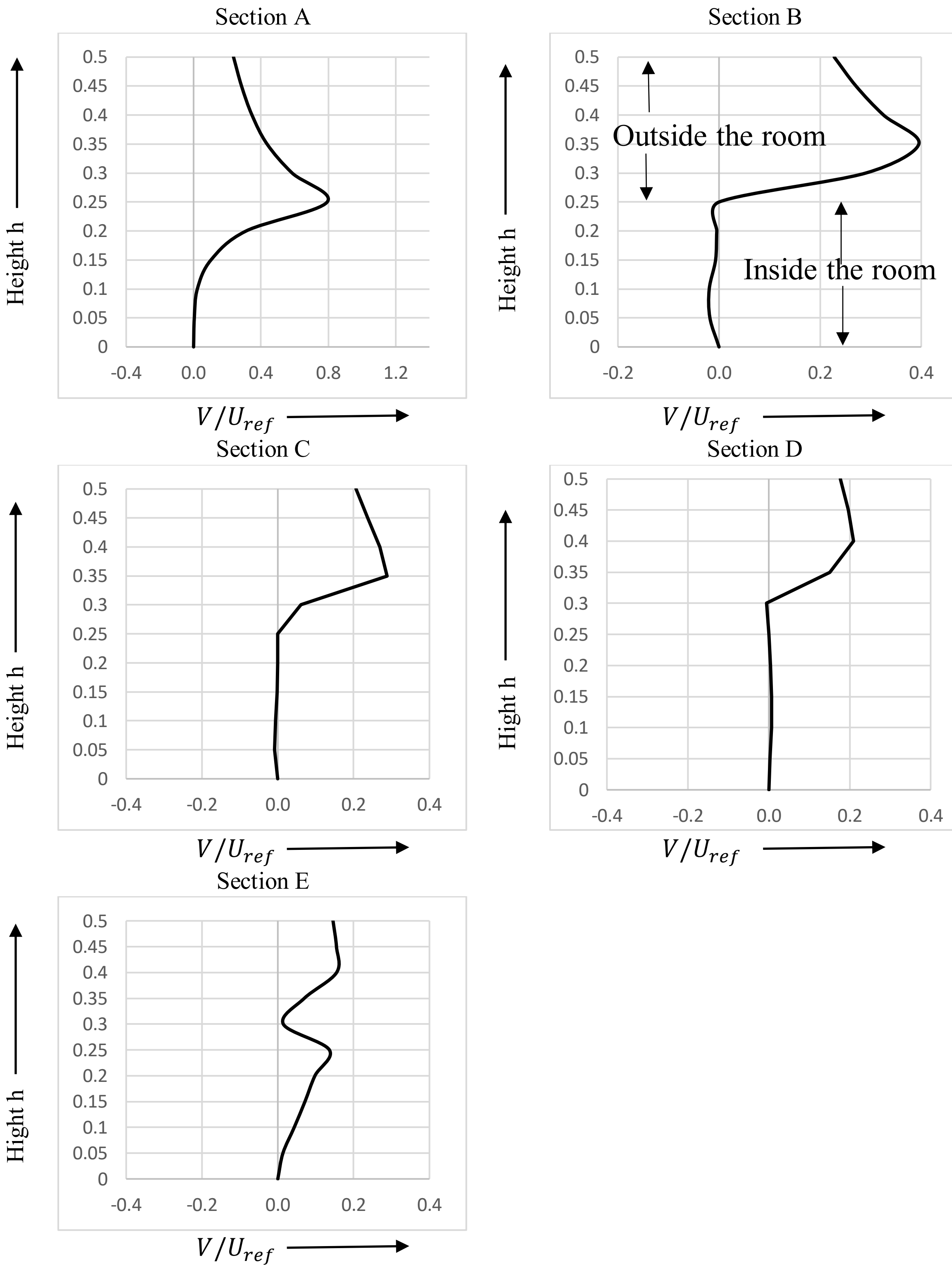


Figure 4.2 (b): Single sided velocity profiles for windward air flow (case: 1(i)) [velocity ratio V/U_{ref} (x) against height h (y)]

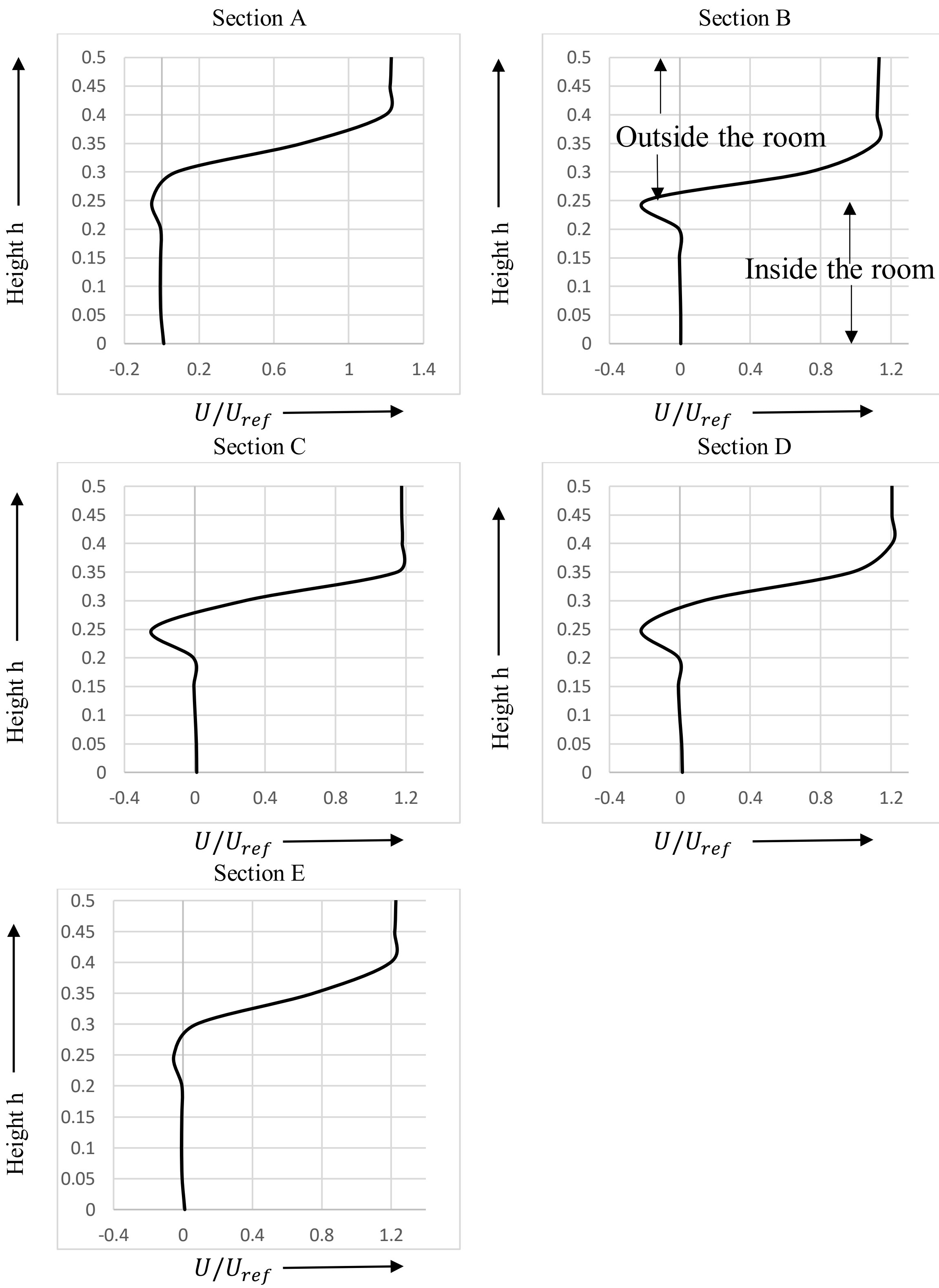


Figure 4.3 (a): Single sided velocity profiles for leeward air flow (case: 2(i)) [velocity ratio U/U_{ref} (x) against height h (y)]

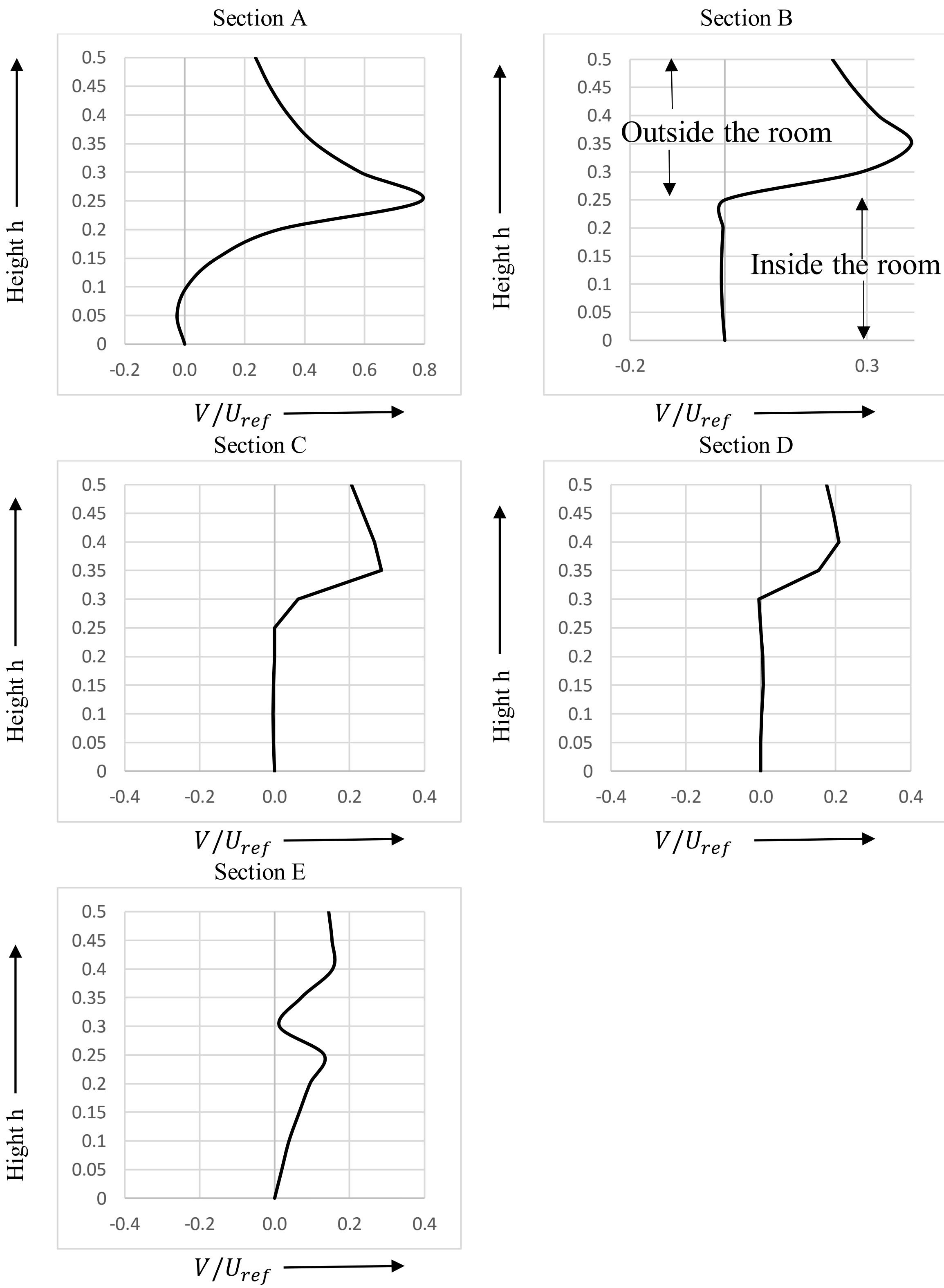


Figure 4.3 (b): Single sided velocity profiles for leeward air flow (case: 2(i)) [velocity ratio V/U_{ref} (x) against height h (y)]

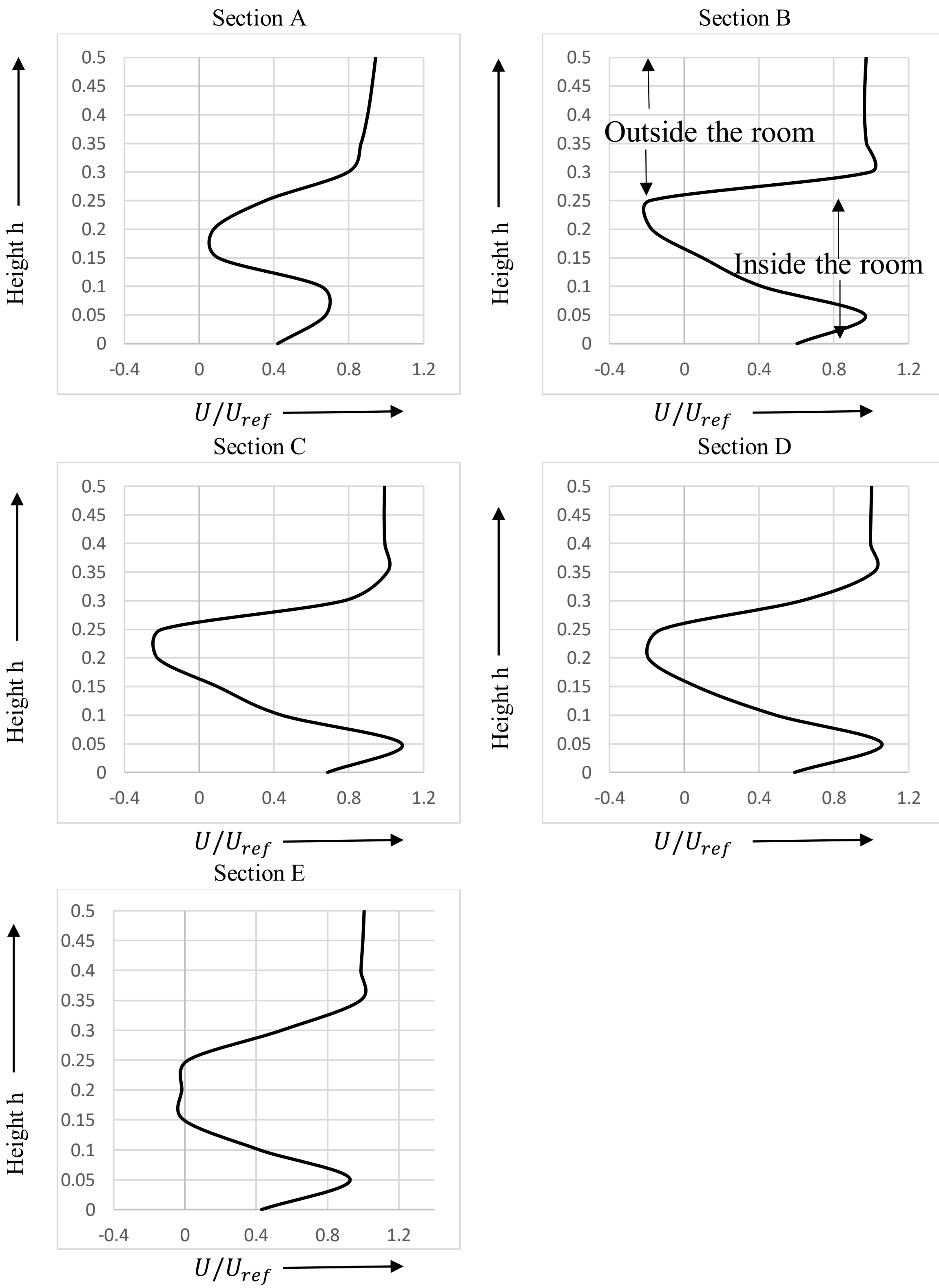


Figure 4.4 (a): Single sided velocity profiles for cross air flow of (case: 3(i)) [velocity ratio U/U_{ref} (x) against height h (y)]

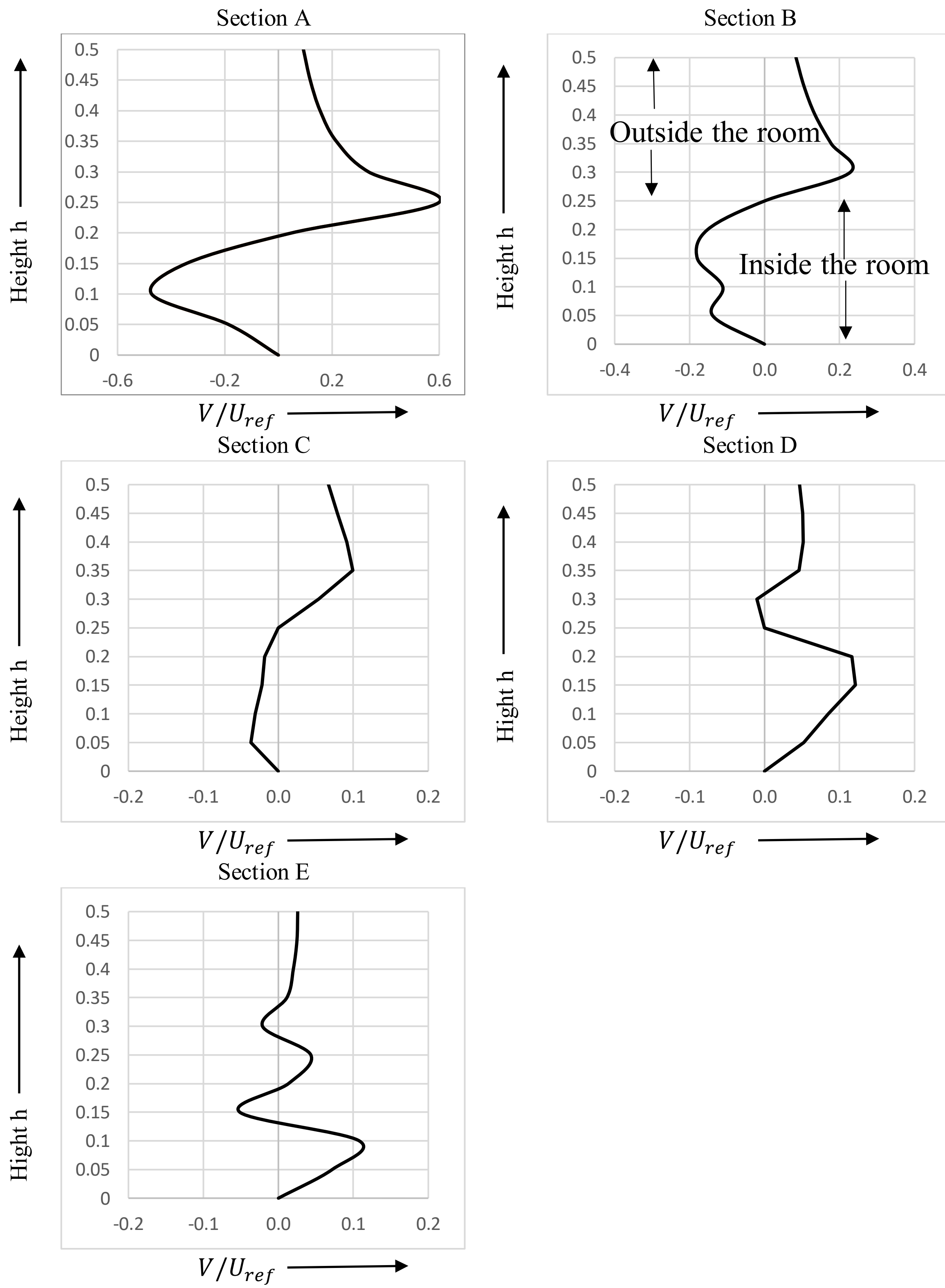


Figure 4.4 (b): Single sided velocity profiles for cross air flow of (case: 3(i)) [velocity ratio V/U_{ref} (x) against height h (y)]

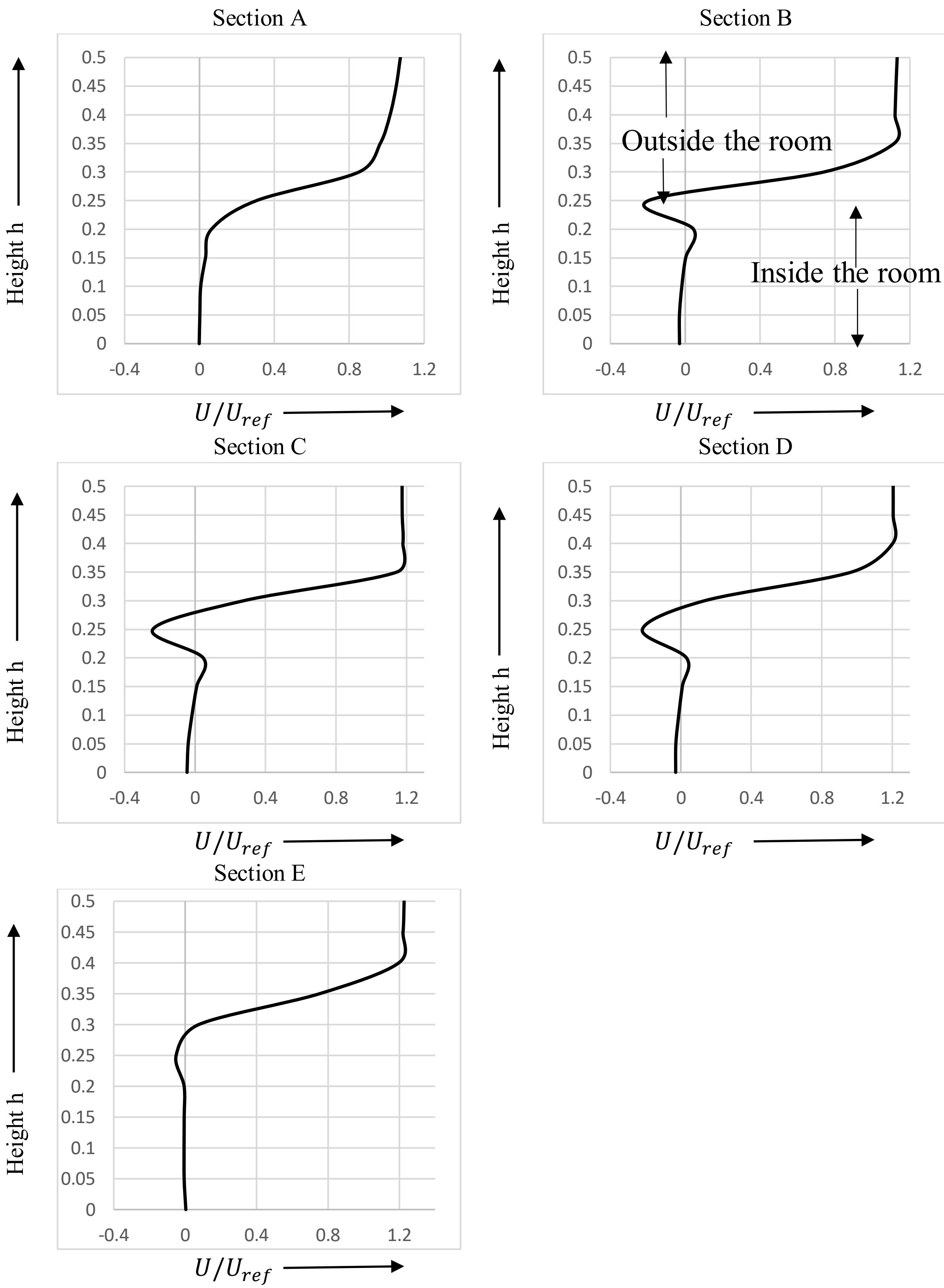


Figure 4.5 (a): Single sided velocity profiles for windward air flow of (case: 1(ii)) [velocity ratio U/U_{ref} (x) against height h (y)]

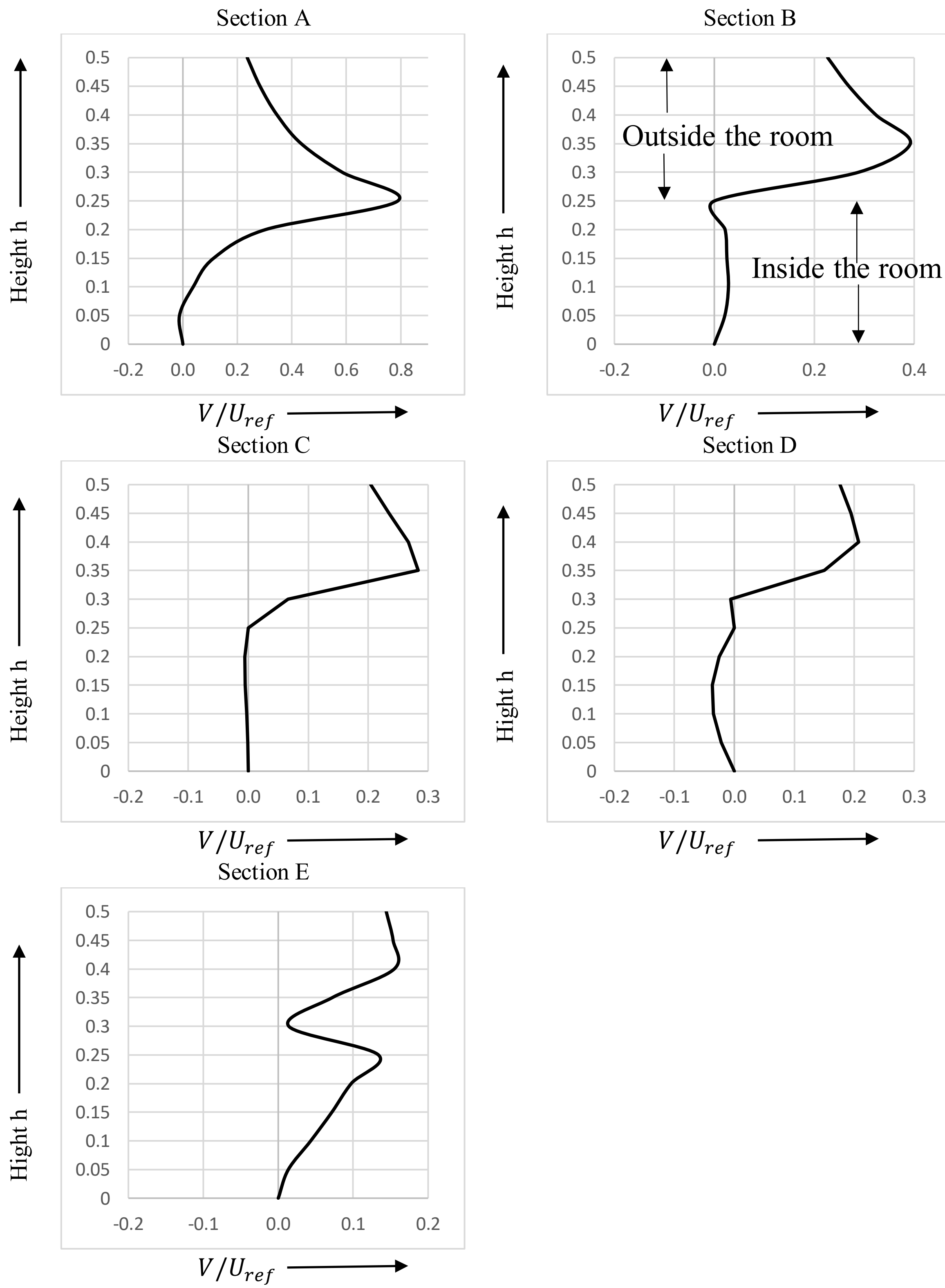


Figure 4.5 (b): Single sided velocity profiles for windward air flow of (case: 1(ii)) [velocity ratio V/U_{ref} (x) against height h (y)]

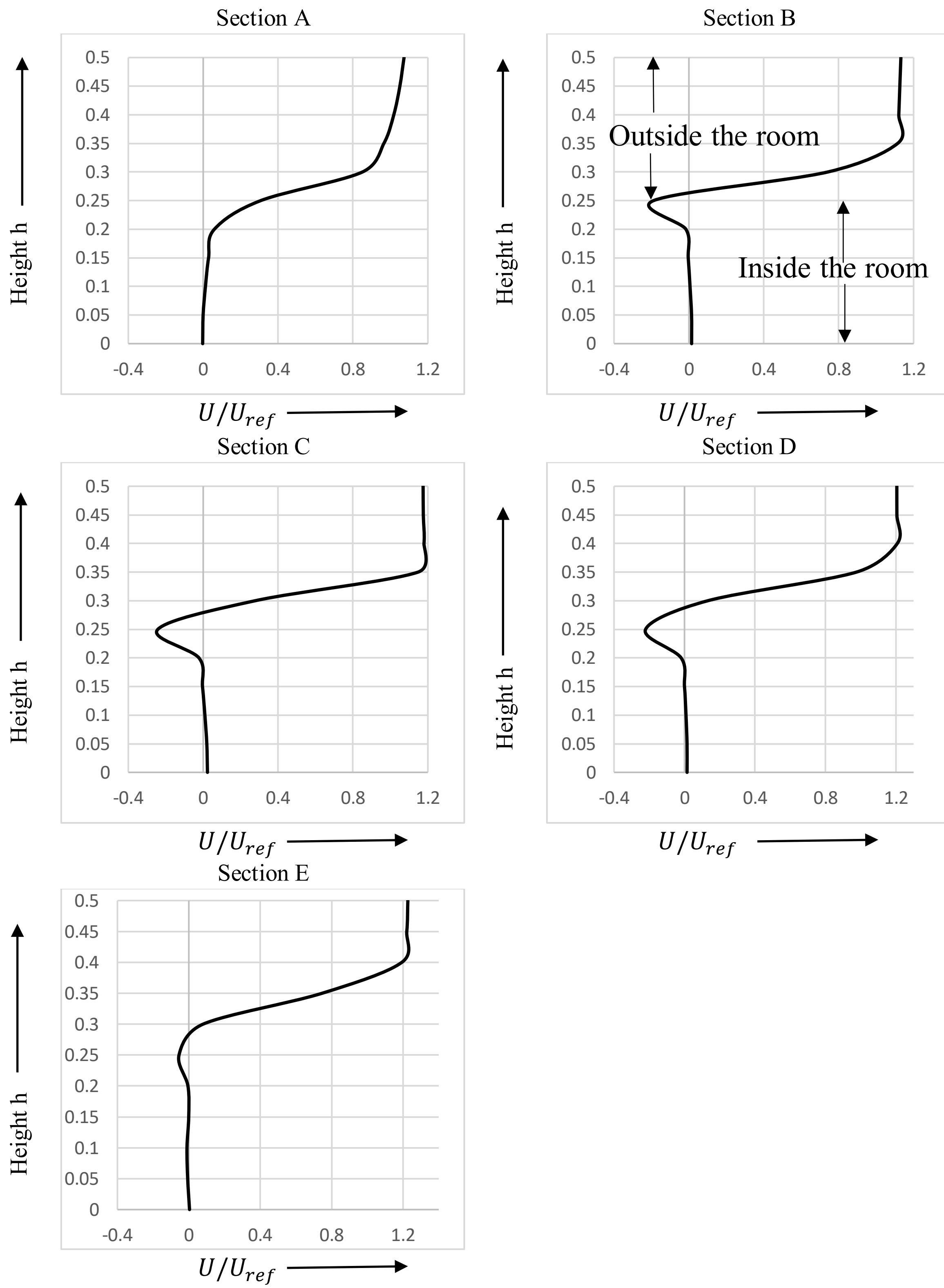


Figure 4.6 (a): Single sided velocity profiles for leeward air flow of (case: 2(ii)) [velocity ratio U/U_{ref} (x) against height h (y)]

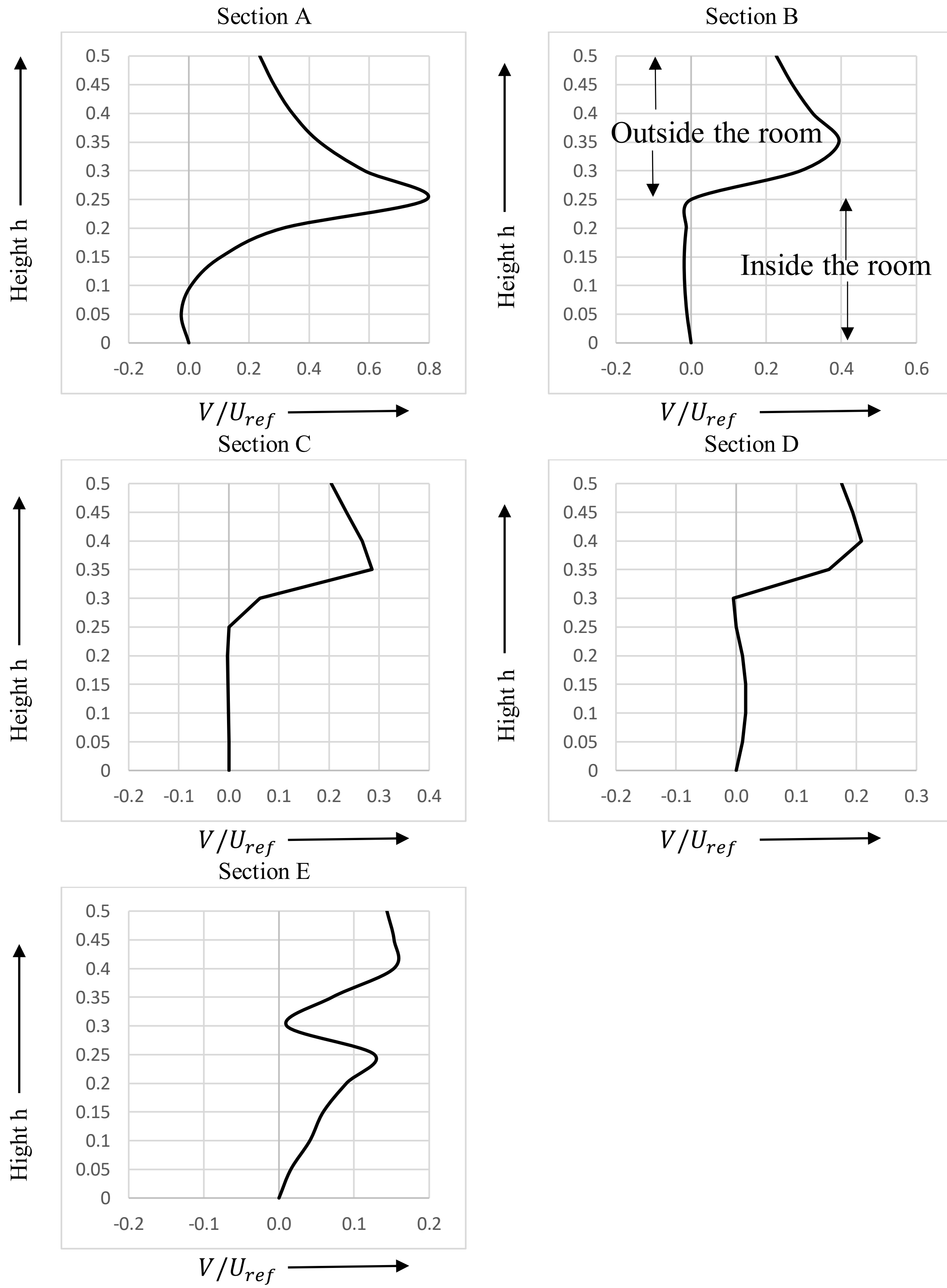


Figure 4.6 (b): Single sided velocity profiles for leeward air flow of (case: 2(ii)) [velocity ratio V/U_{ref} (x) against height h (y)]

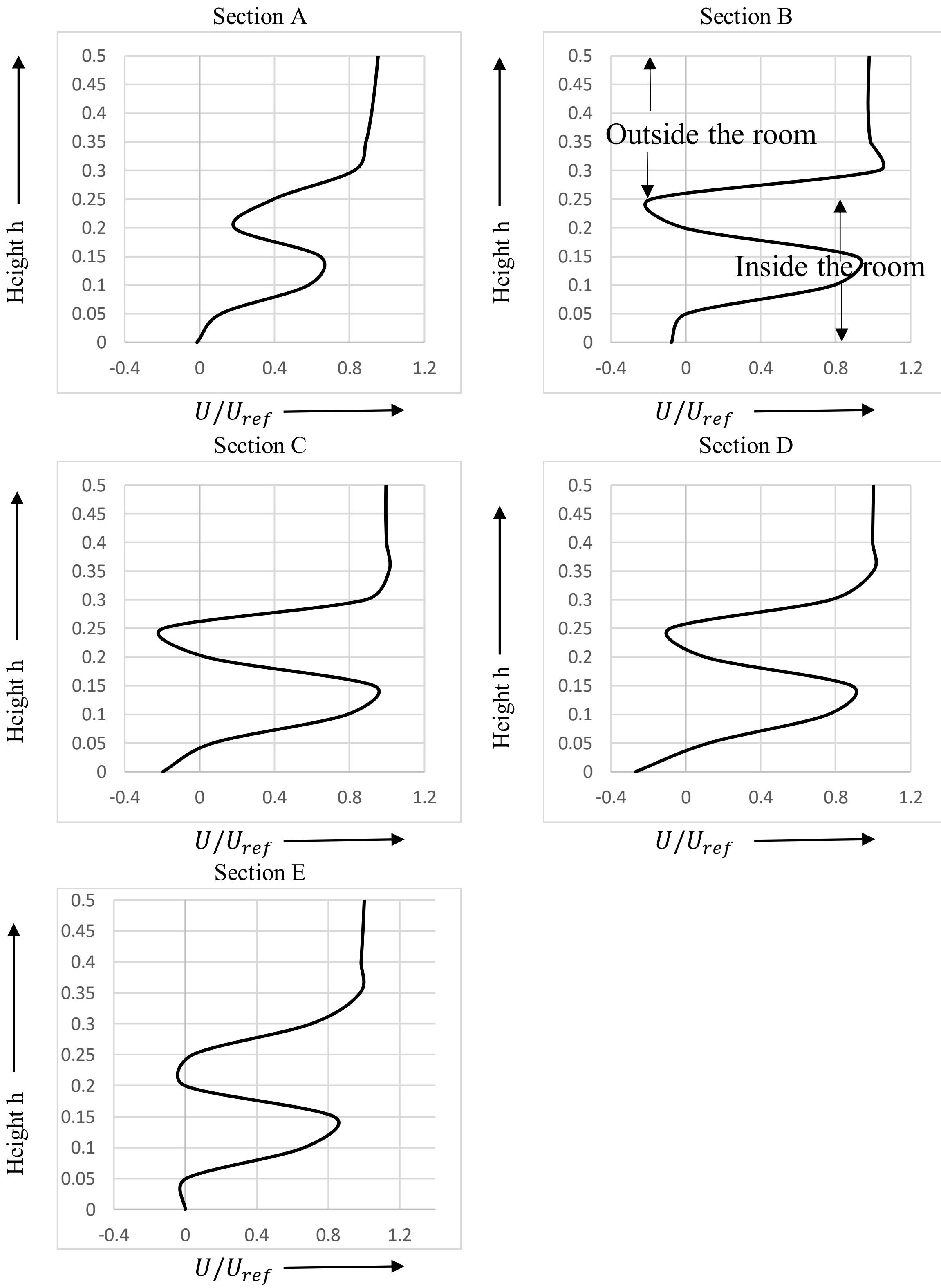


Figure 4.7 (a): Single sided velocity profiles for cross air flow of (case: 3(ii)) [velocity ratio U/U_{ref} (x) against height h (y)]

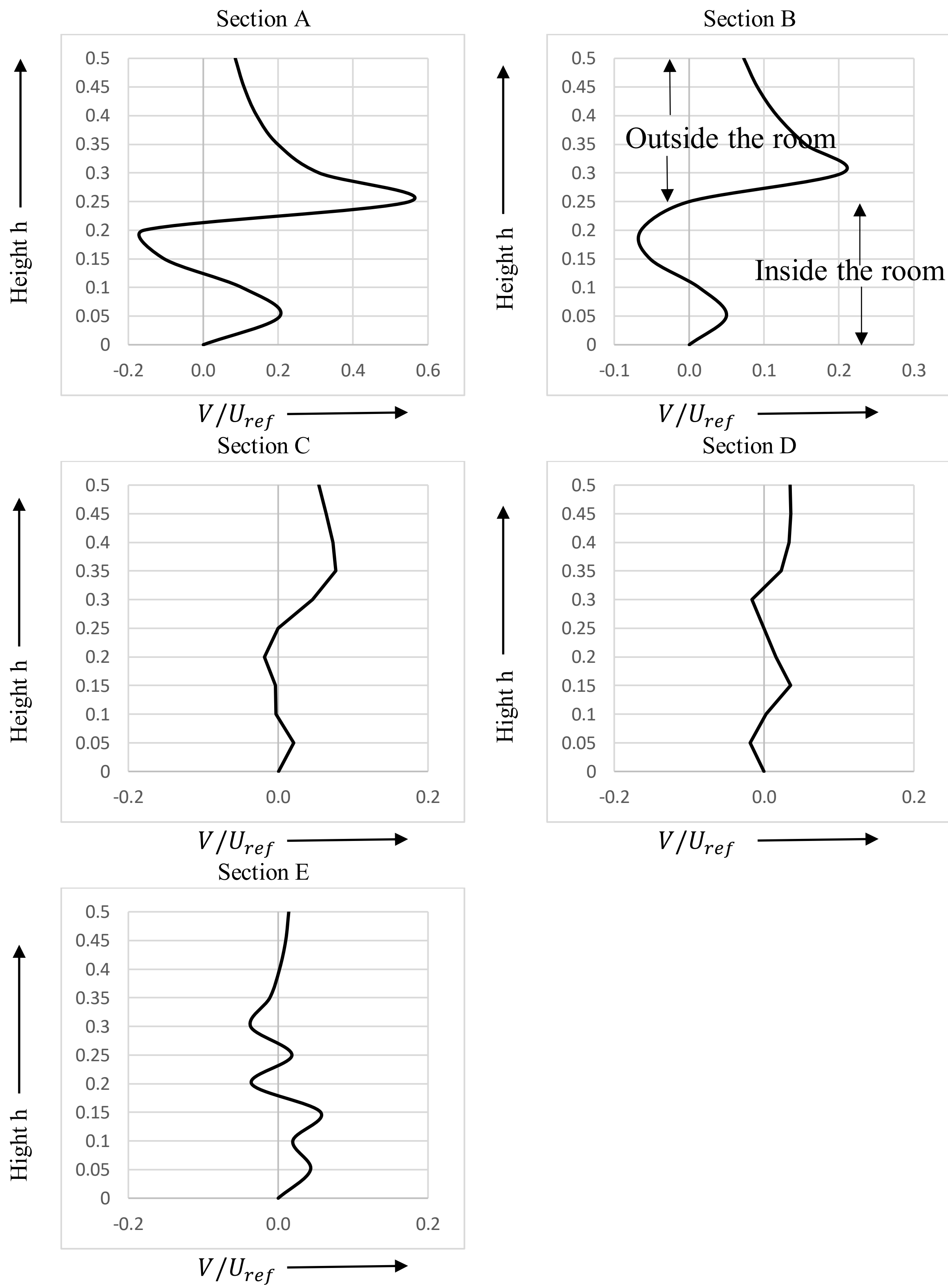


Figure 4.7 (b): Single sided velocity profiles for cross air flow of (case: 3(ii)) [velocity ratio V/U_{ref} (x) against height h (y)]

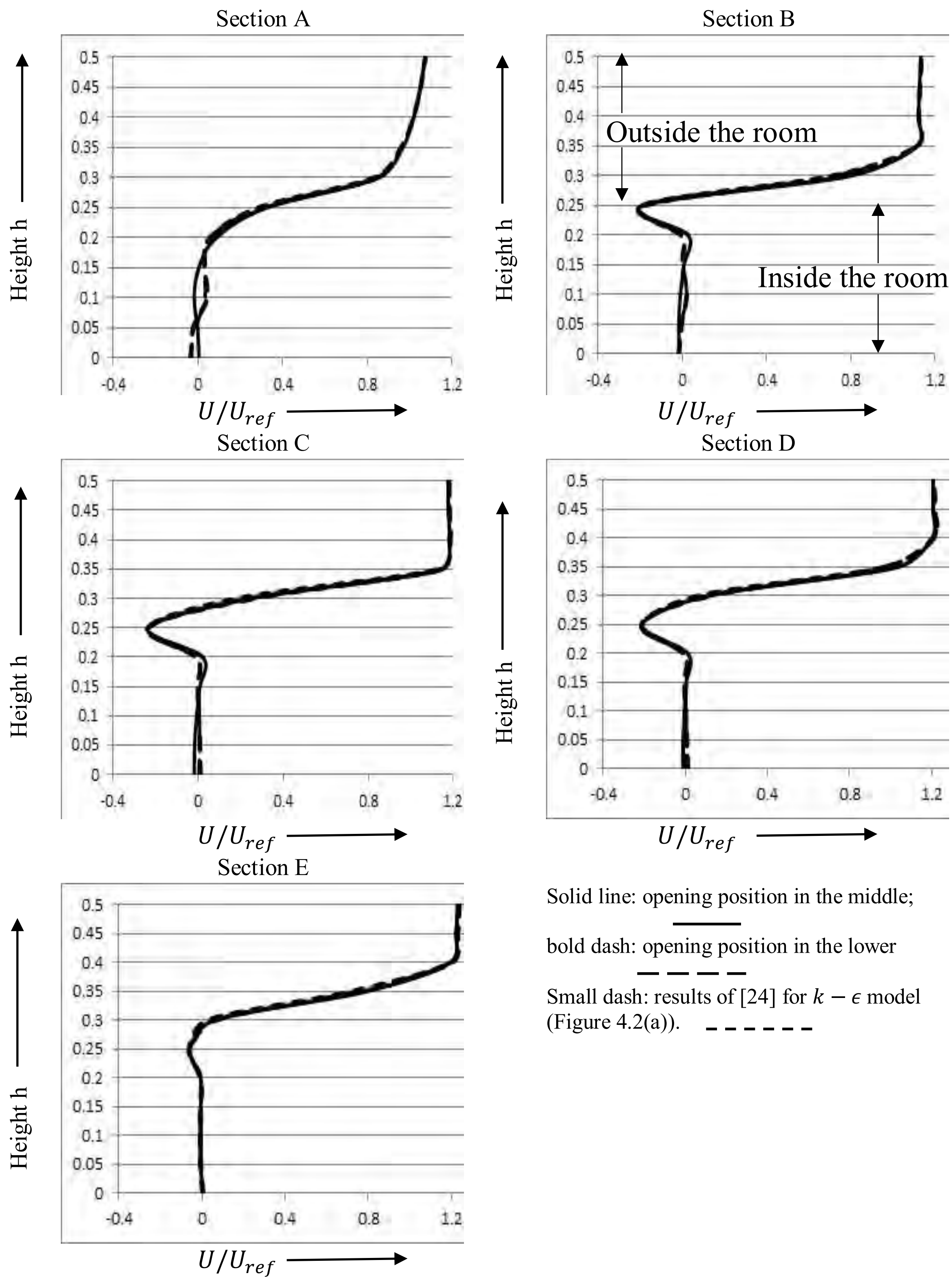


Figure 4.8 (a): Single sided velocity profiles for windward air flow for awning opening (case: 4) [velocity ratio U/U_{ref} (x) against height h (y)]

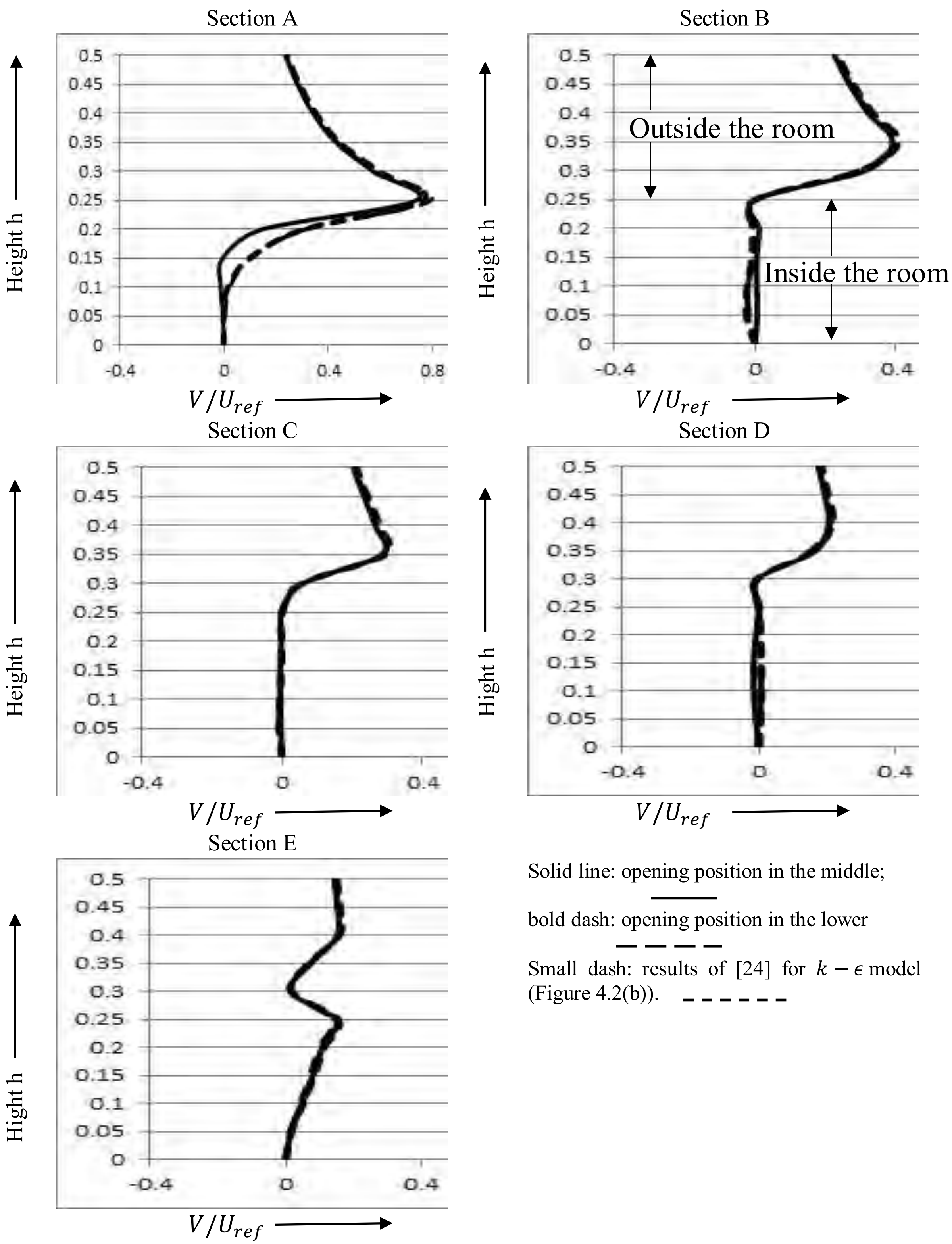


Figure 4.8 (b): Single sided velocity profiles for windward air flow for awning opening (case: 4) [velocity ratio V/U_{ref} (x) against height h (y)]

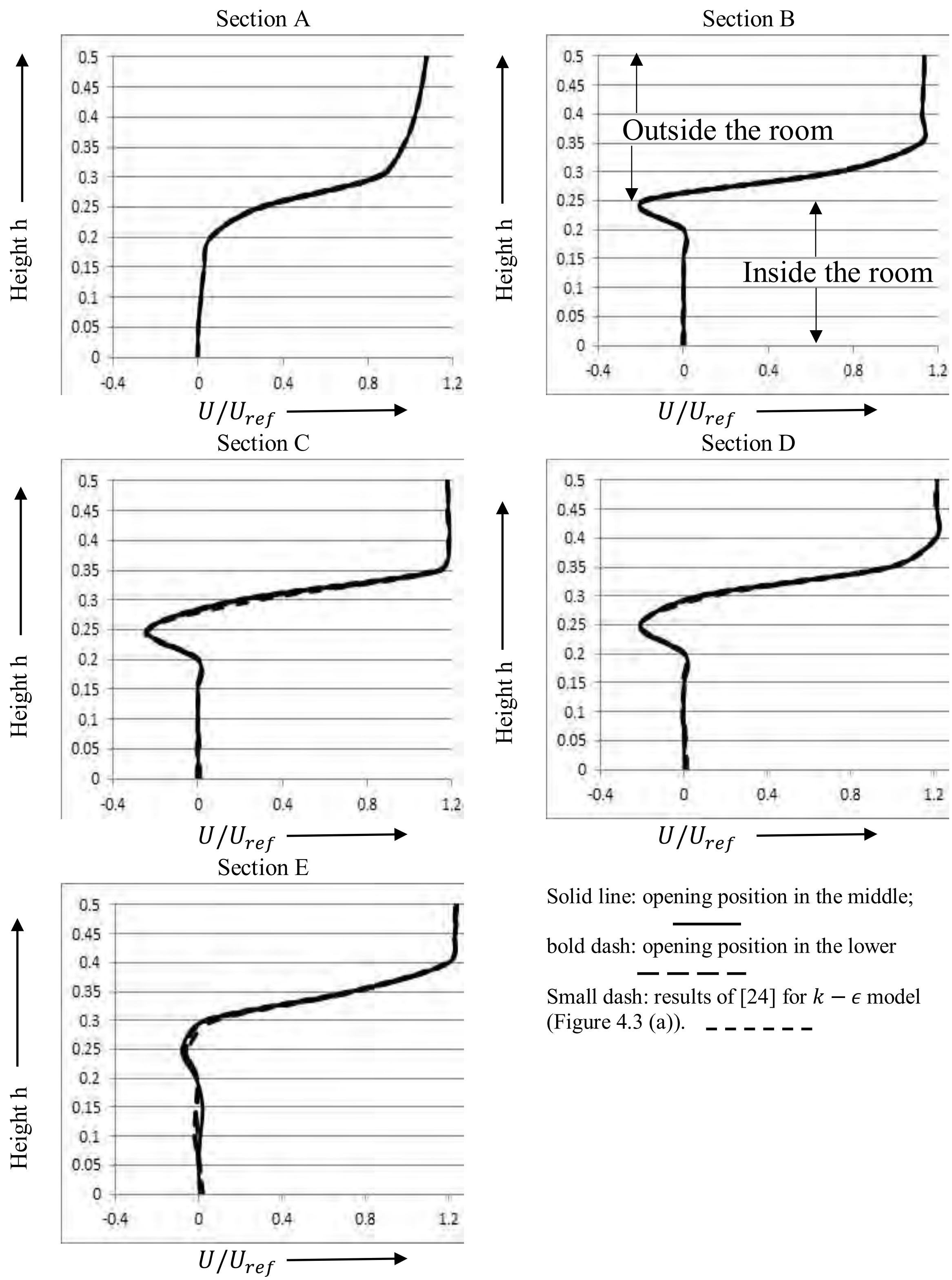


Figure 4.9 (a): Single sided velocity profiles for leeward air flow for awning opening (case: 5) [velocity ratio U/U_{ref} (x) against height h (y)]

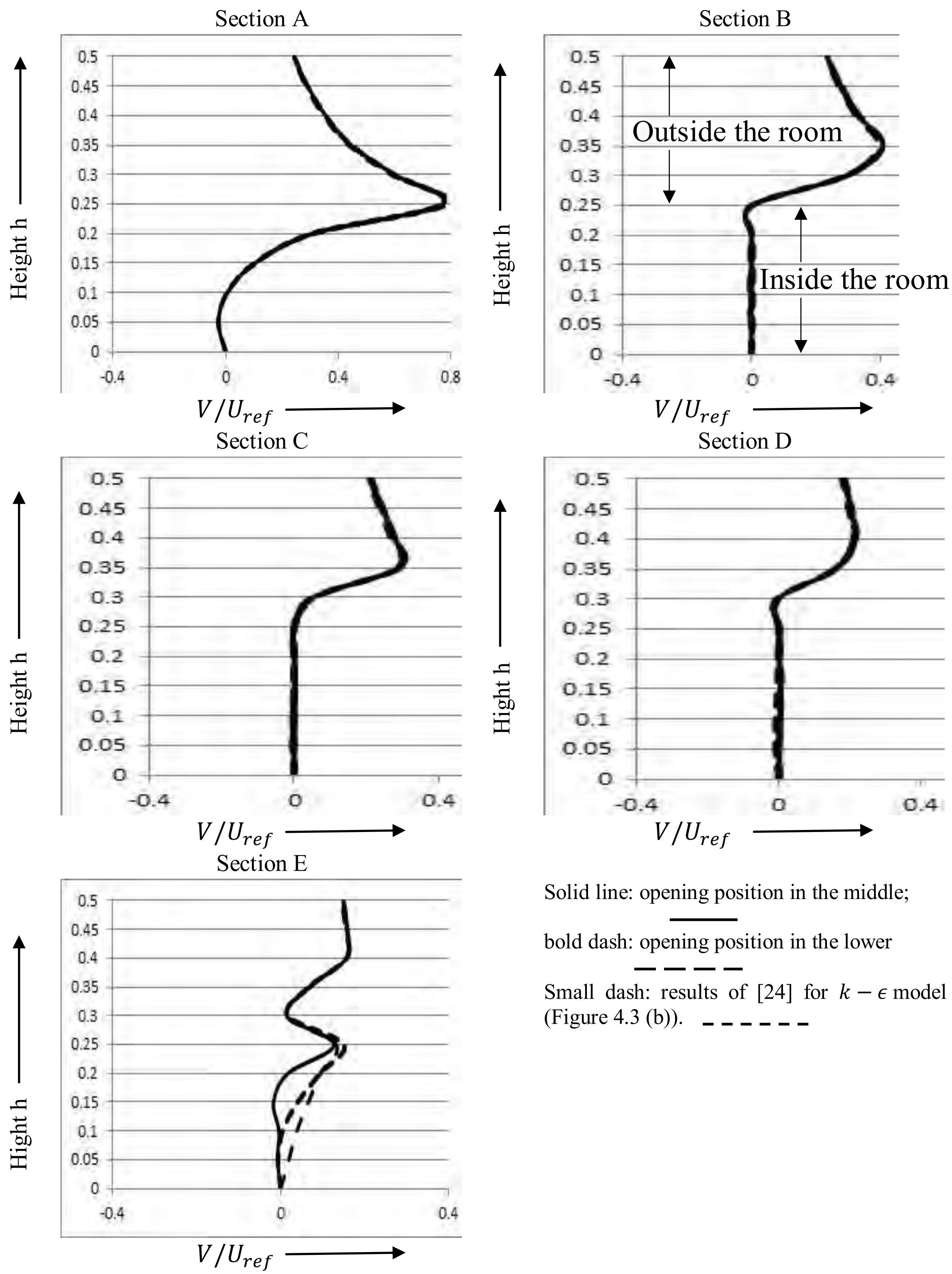


Figure 4.9(b): Single sided velocity profiles for leeward air flow for awning opening (case: 5) [velocity ratio V/U_{ref} (x) against height h (y)]

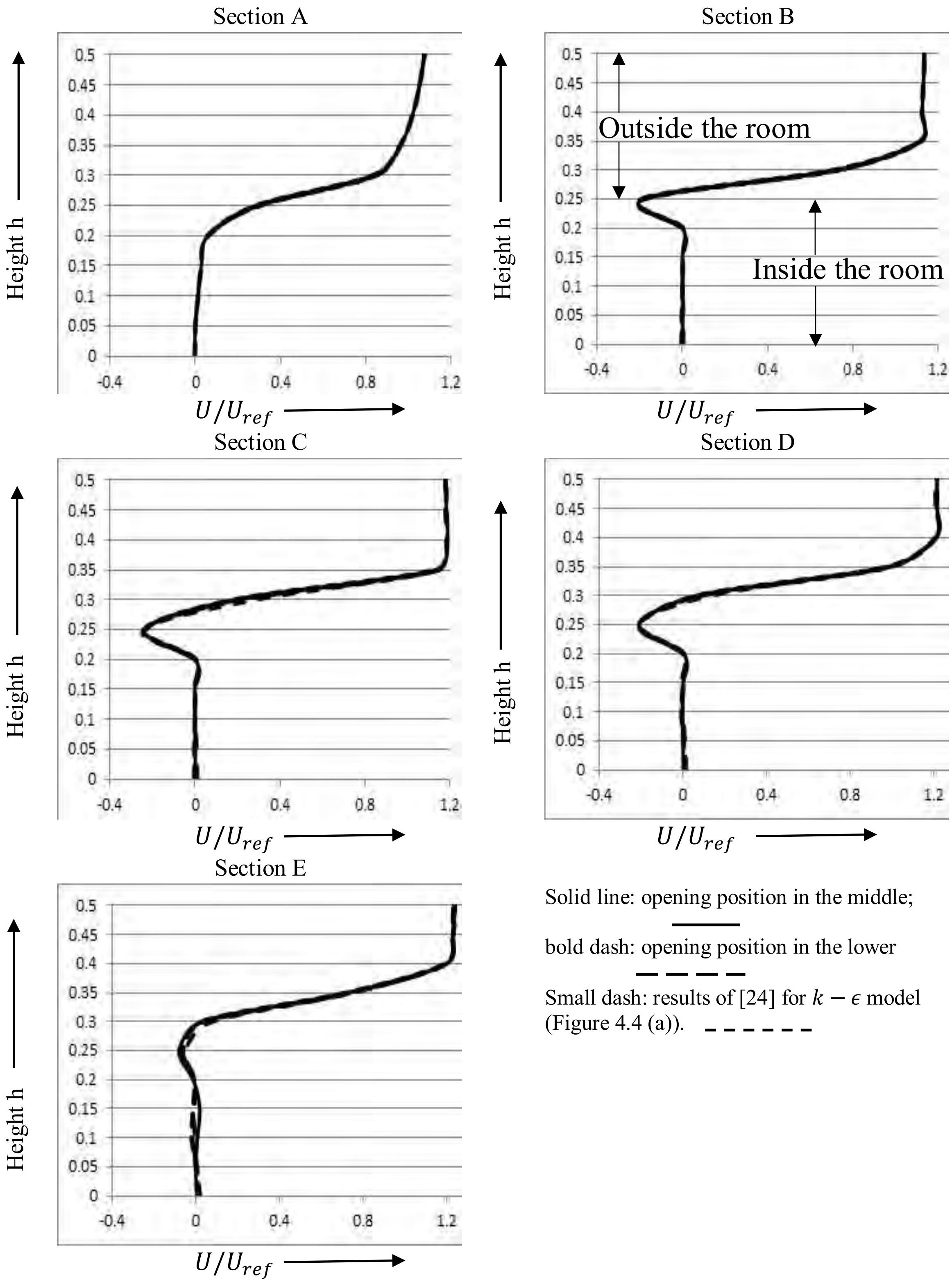


Figure 4.10 (a): Single sided velocity profiles for cross air flow for awning opening (case: 6) [velocity ratio U/U_{ref} (x) against height h (y)]

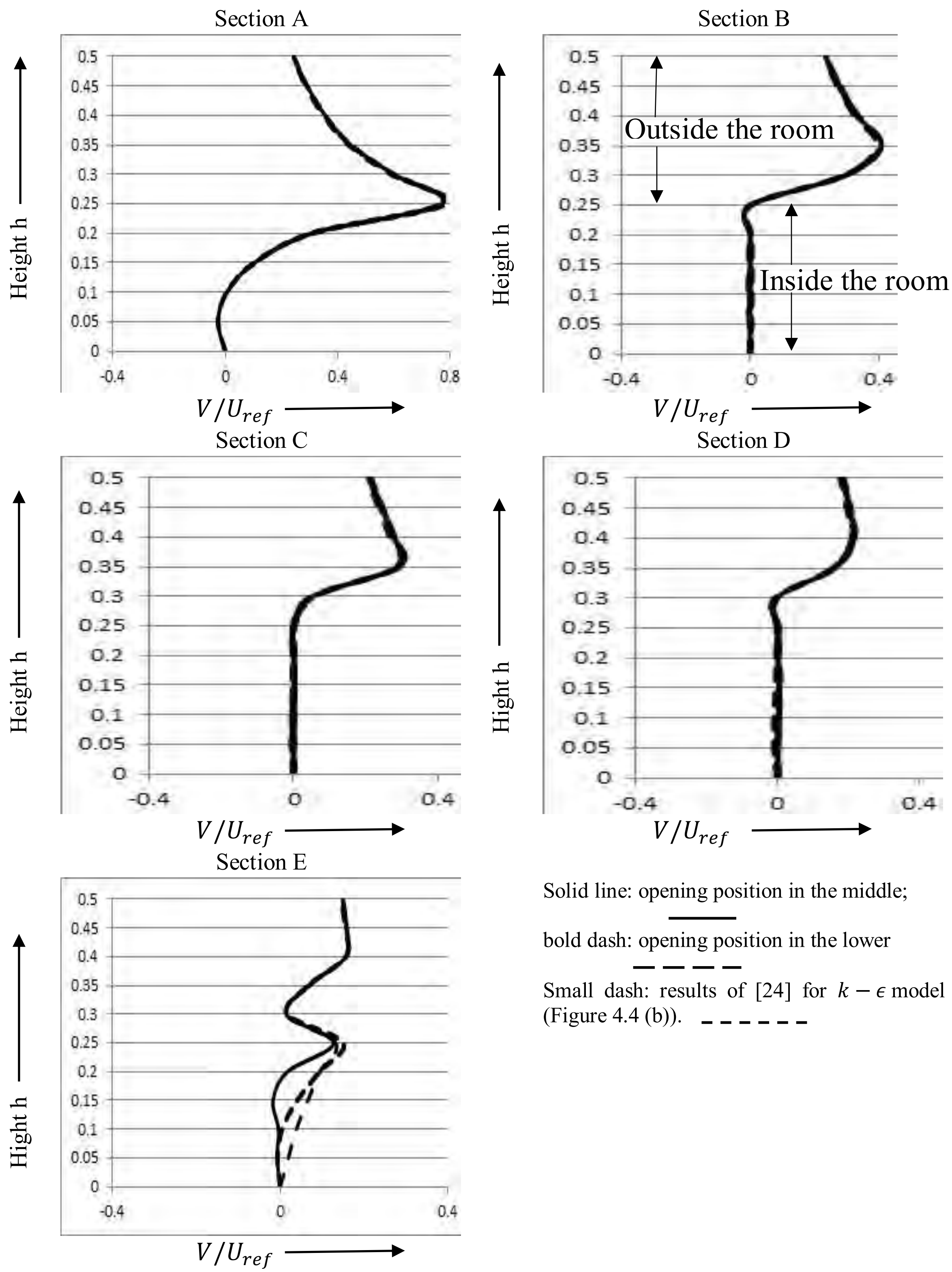
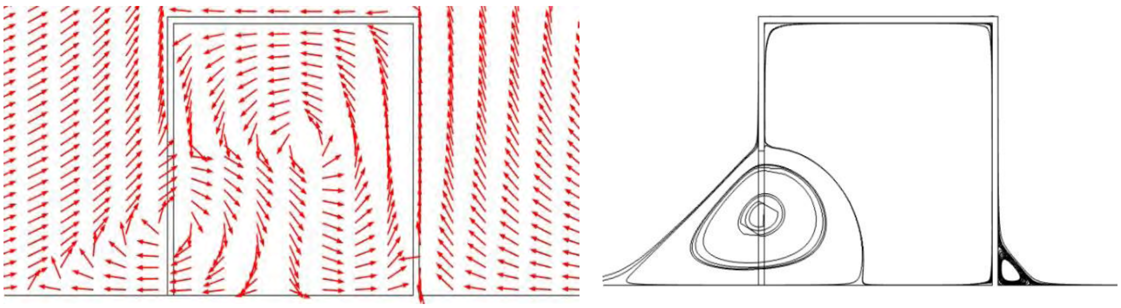


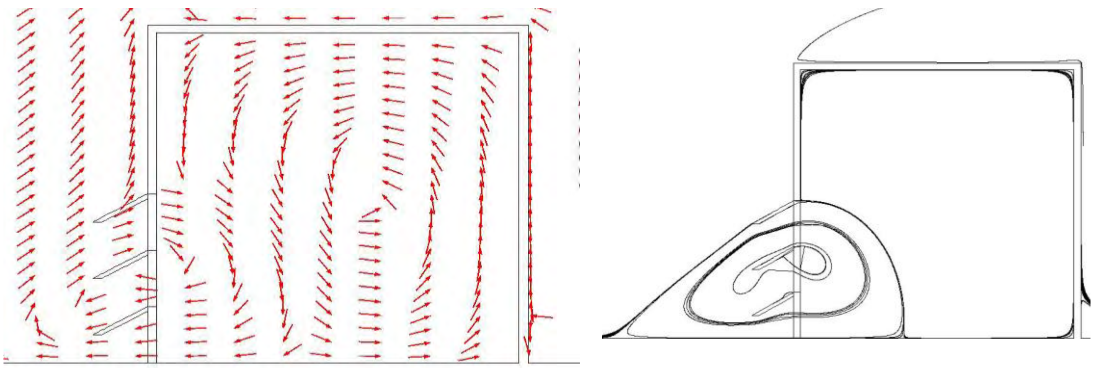
Figure 4.10(b): Single sided velocity profiles for cross air flow for awning opening (case: 6) [velocity ratio V/U_{ref} (x) against height h (y)]

Air flow distribution | Velocity stream lines

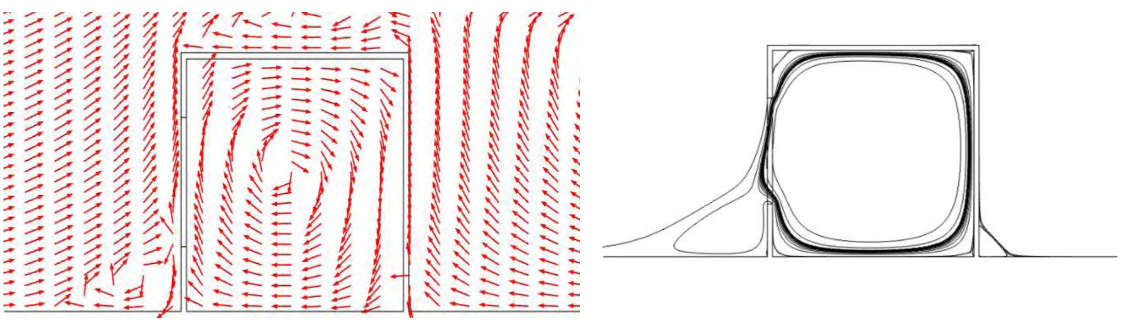
case 1(i)



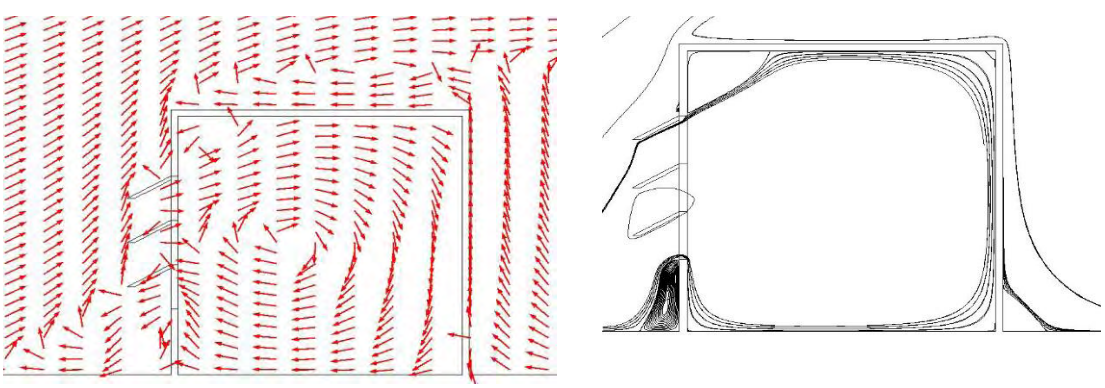
case 4(i)



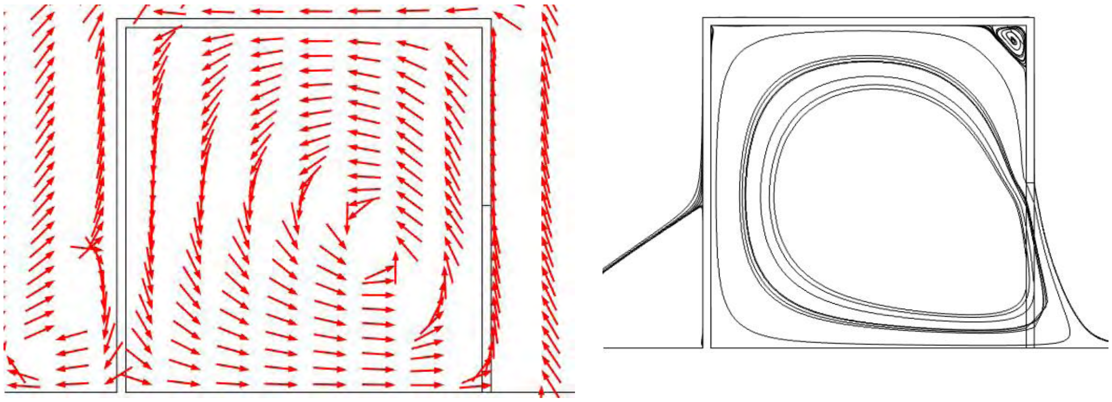
case 1(ii)



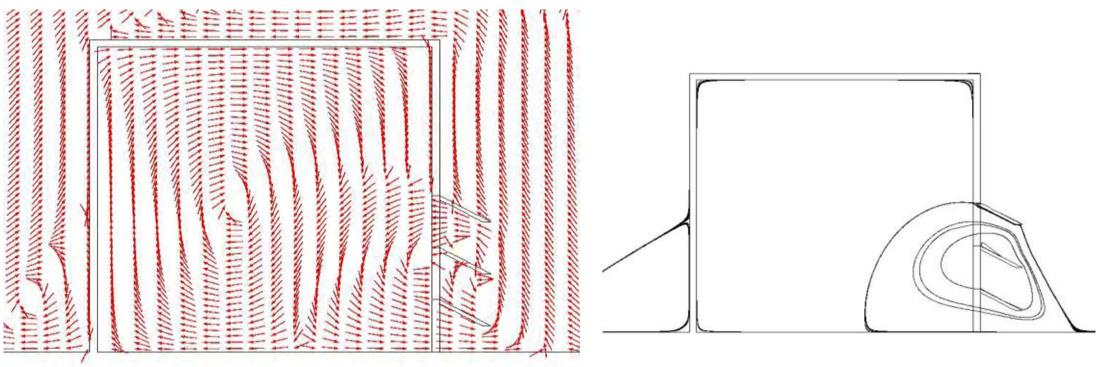
case 4(ii)



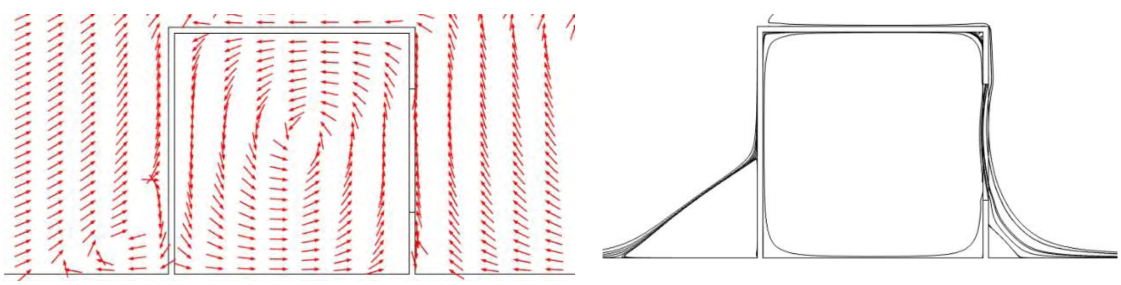
case 2(i)



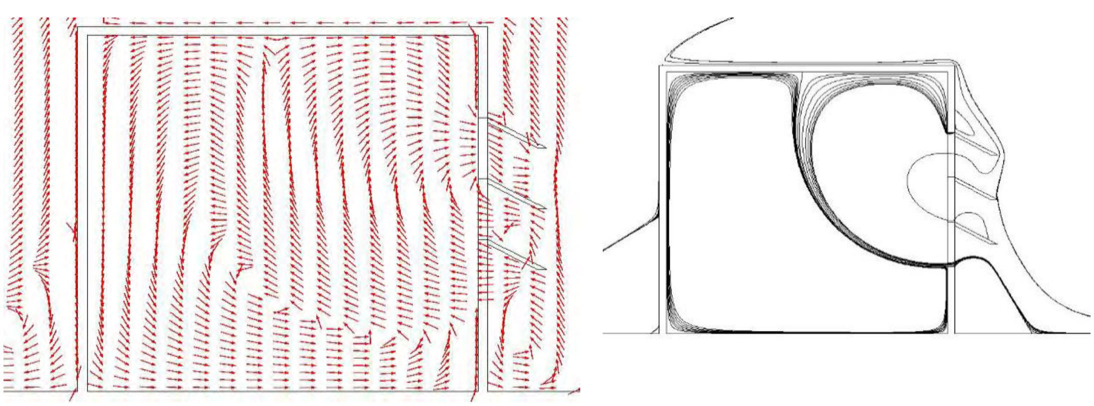
case 5(i)



case 2(ii)



case 5(ii)



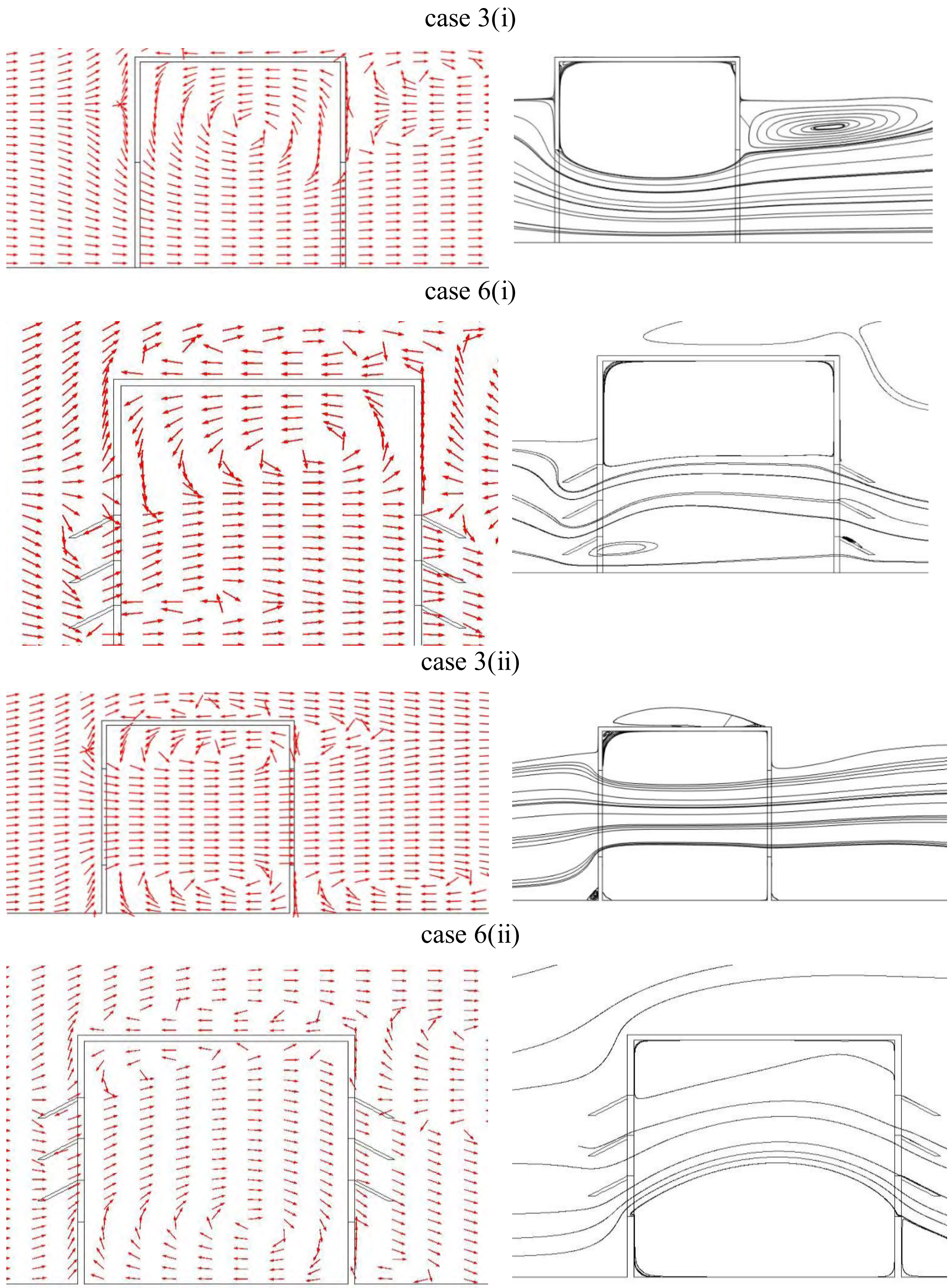


Figure 4.11: Velocity arrowline and streamlines.

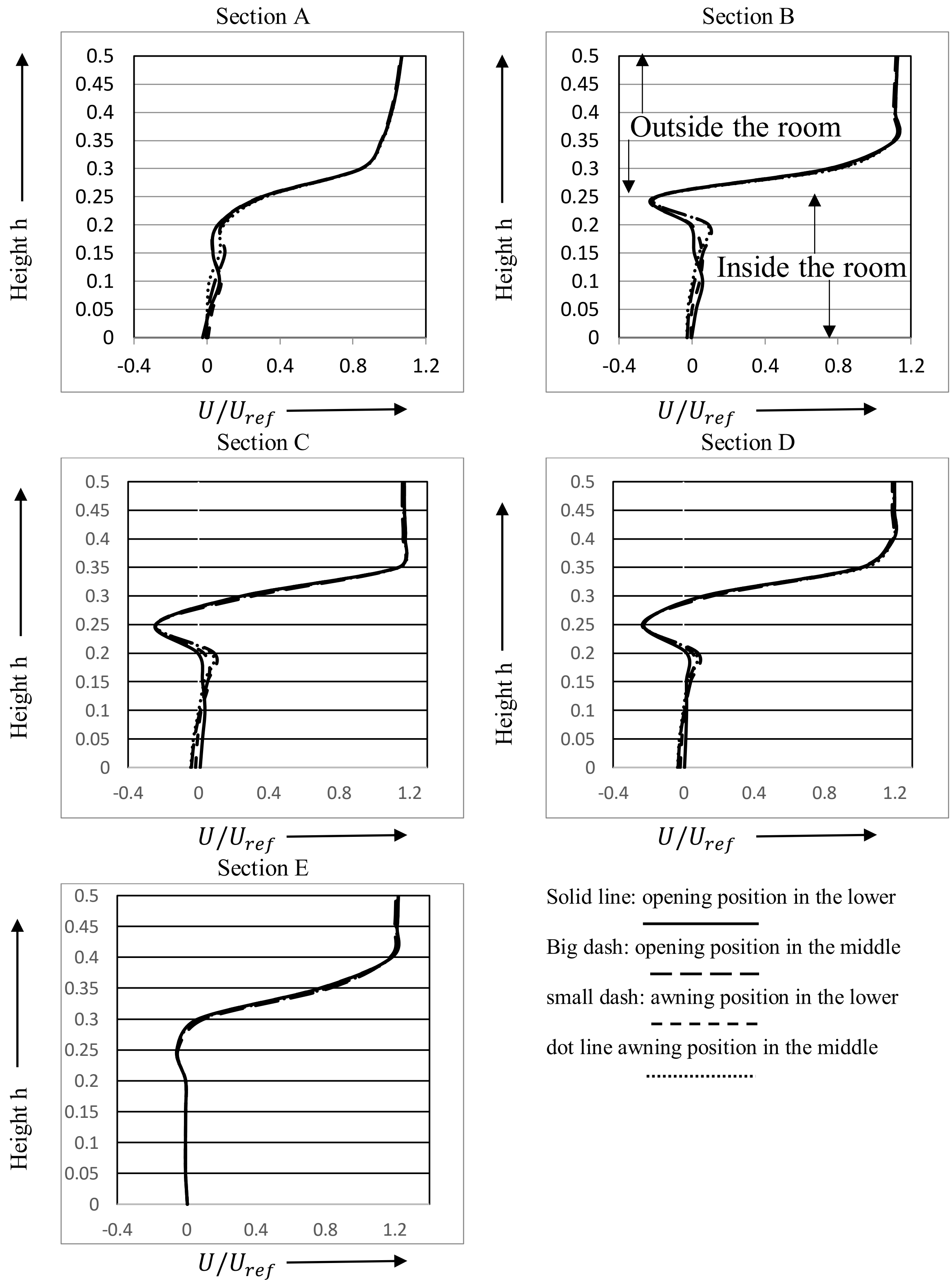


Figure 4.12 (a): Single sided velocity profiles coupling with heat flow for windward air flow (case: 1 and case: 4). [velocity ratio U/U_{ref} (x) against height h (y)]

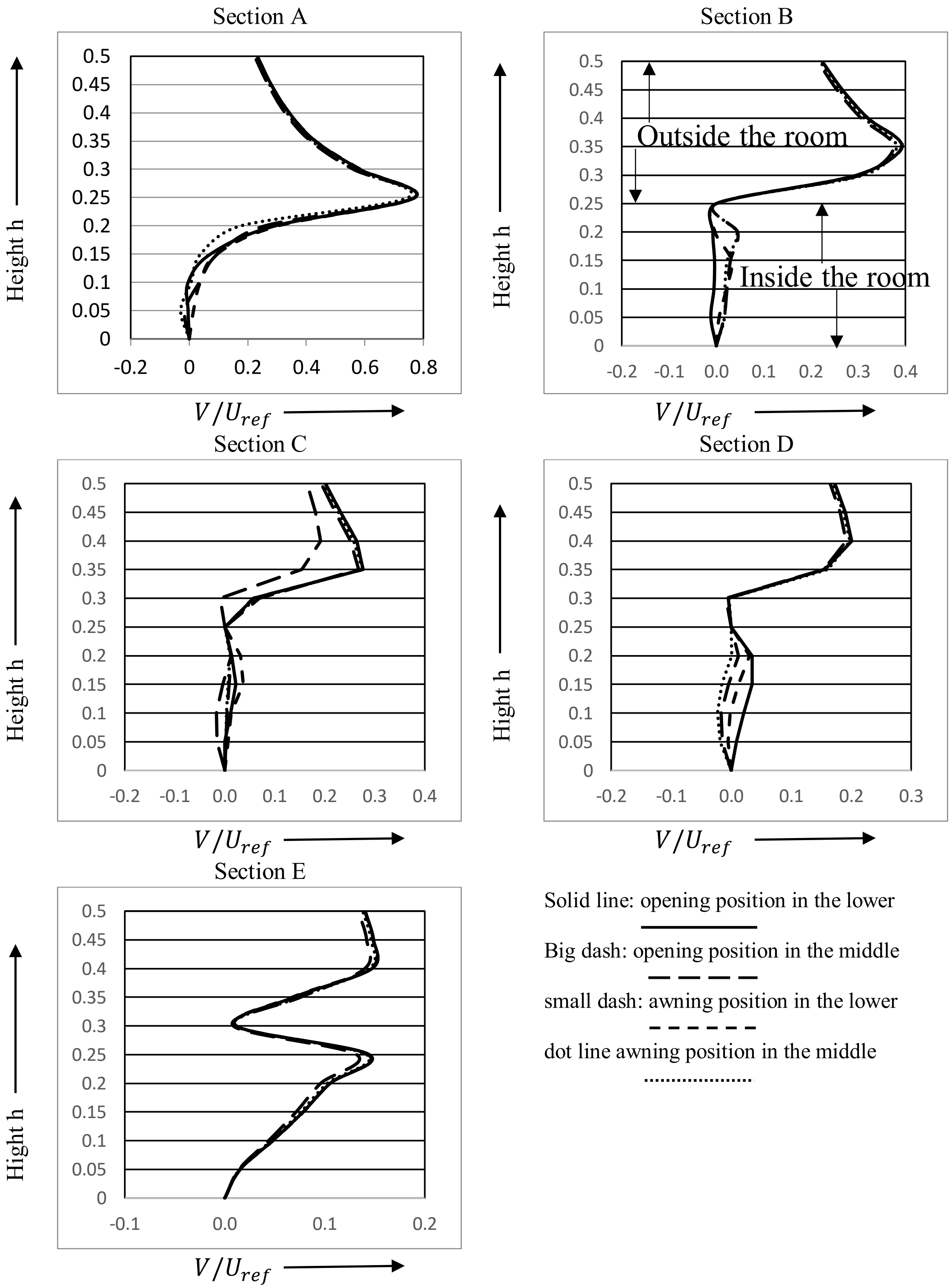


Figure 4.12 (b): Single sided velocity profiles coupling with heat flow for windward air flow (case: 1 and case: 4). [velocity ratio V/U_{ref} (x) against height h (y)]

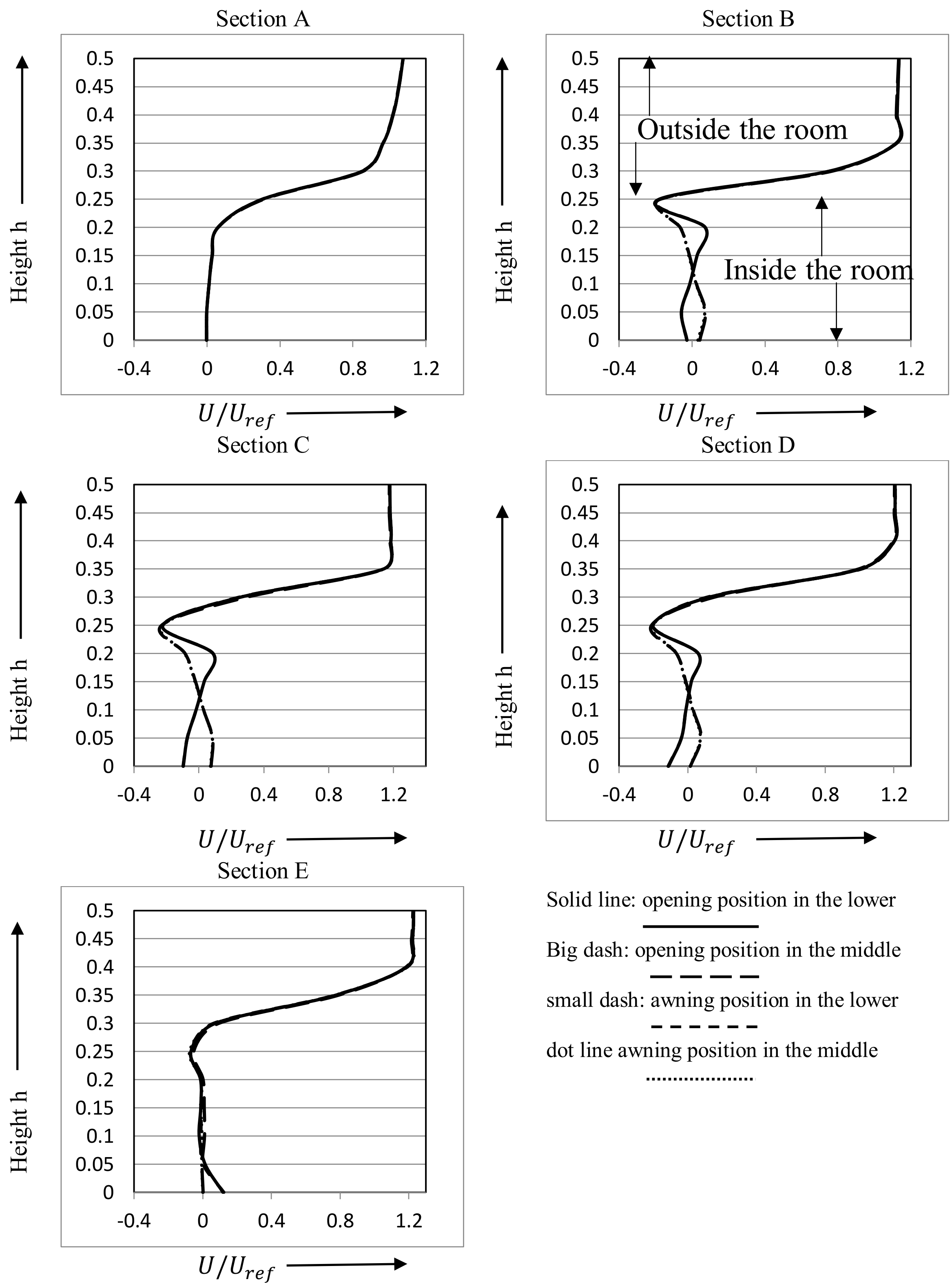


Figure 4.13 (a): Single sided velocity profiles coupling with heat flow for leeward air flow (case: 2 and case: 5). [velocity ratio U/U_{ref} (x) against height h (y)]

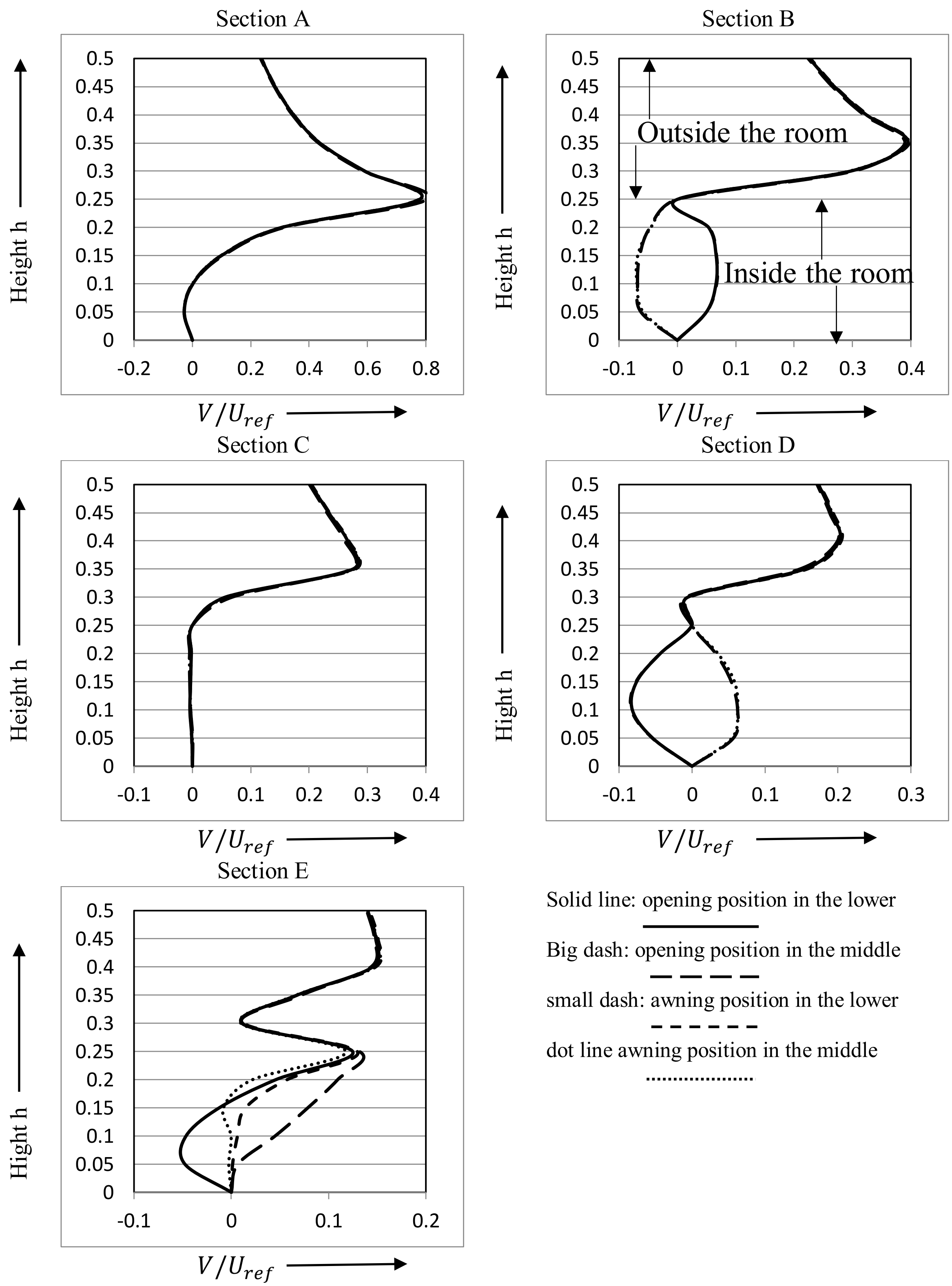


Figure 4.13 (b): Single sided velocity profiles coupling with heat flow for leeward air flow (case: 2 and case: 5). [velocity ratio V/U_{ref} (x) against height h (y)]

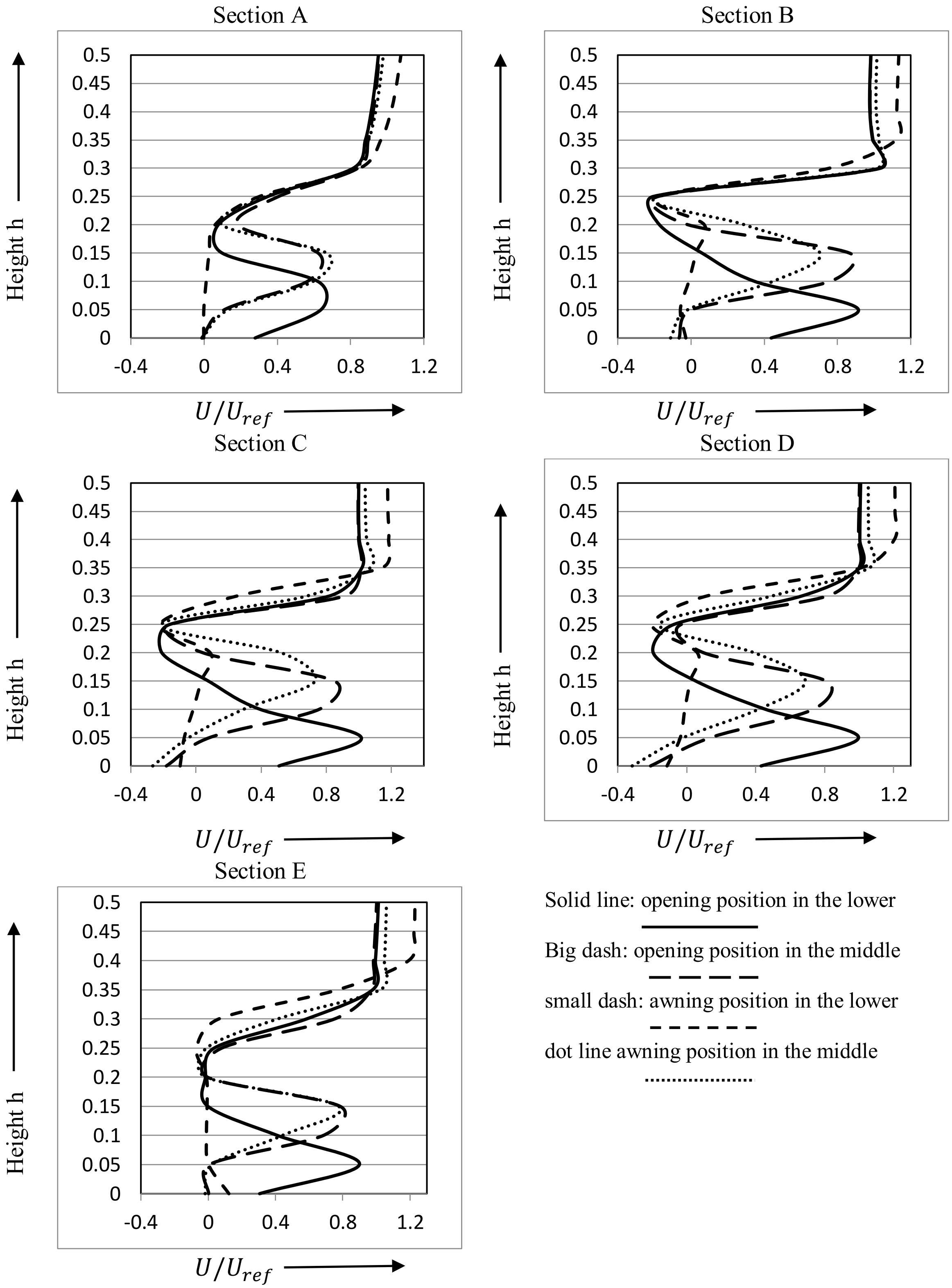


Figure 4.14 (a): Single sided velocity profiles coupling with heat flow for cross air flow (case: 3 and case: 6). [velocity ratio U/U_{ref} (x) against height h (y)]

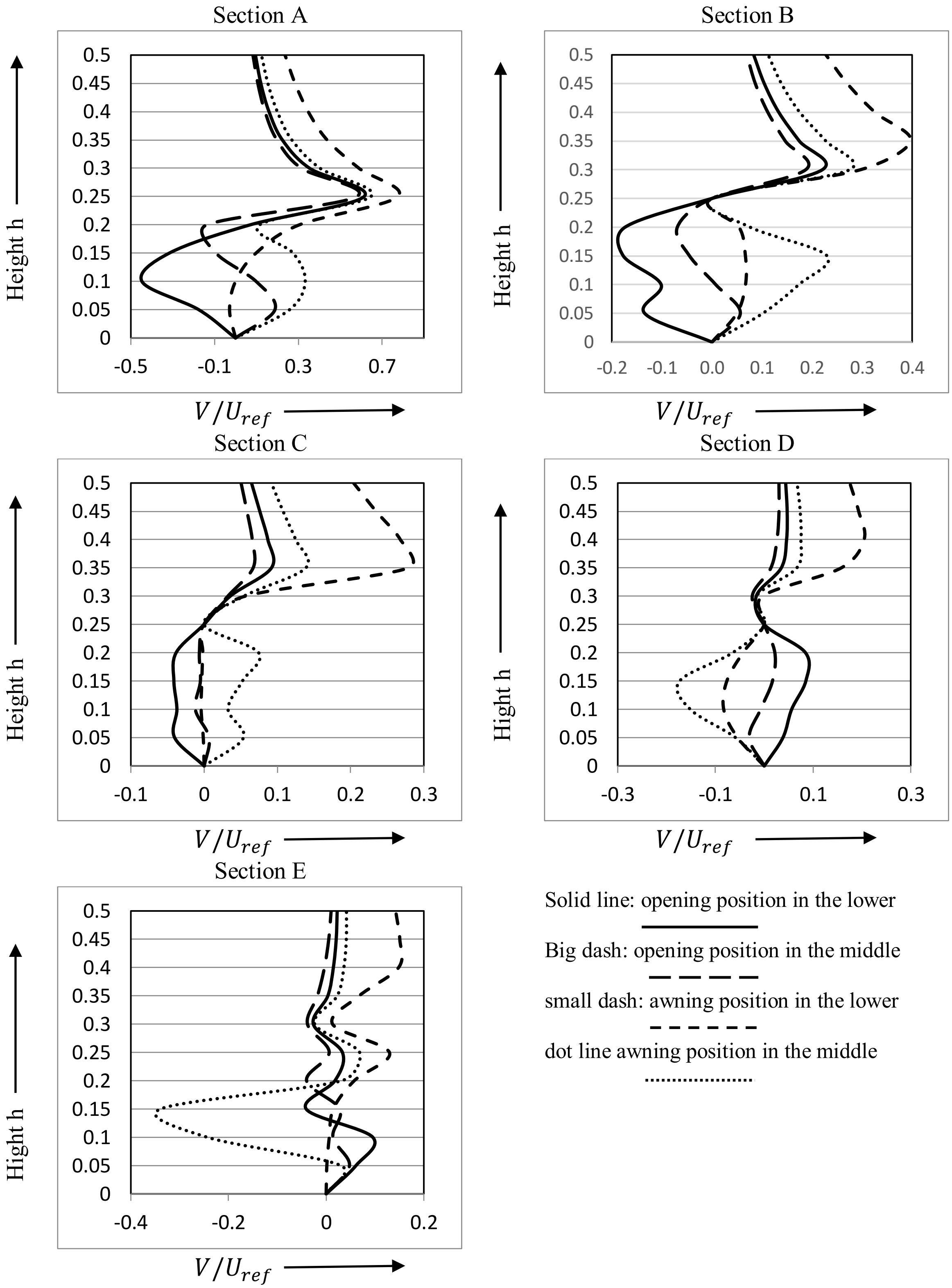


Figure 4.14 (b): Single sided velocity profiles coupling with heat flow for cross air flow (case: 3 and case: 6). [velocity ratio V/U_{ref} (x) against height h (y)]

4.2.3 Results and discussions of air velocity coupling with heat transfer for unsteady study

For the same problem, research is conducted for time dependent case to get the velocity for deferent time. Here, velocity calculated for 0, 0.1, 0.5, 1, 1.5 and 2 second and compare with stationary result. In every case it is observed that, after a few times time dependent results becomes the stationary results. In following tables (Table 4.1-Table 4.2) shows the u and v velocity component for the 5 different sections at 11 points which represents the height start from x axis (point 1) and difference between two consecutive points is 5 mm.

Table 4.1: Velocity component for case 4(ii)

	Section A: u velocity (m/s)						Section A: v velocity (m/s)					
Time (s)	0.1	0.5	1	1.5	2	Stationary Results	0.1	0.5	1	1.5	2	Stationary Results
point 1	-0.016	0.009	0.003	0.003	0.004	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
point 2	0.011	-0.009	0.000	-0.001	-0.001	0.002	0.0194	0.0063	-0.0121	-0.0147	-0.0142	-0.0292
point 3	0.004	-0.010	-0.009	-0.009	-0.009	0.012	0.0067	-0.0082	-0.0070	-0.0069	-0.0068	0.0062
point 4	-0.024	0.006	0.010	0.010	0.010	0.070	-0.0103	-0.0033	0.0003	0.0006	0.0008	0.0388
point 5	-0.022	0.086	0.086	0.086	0.086	0.093	-0.0583	0.1484	0.1498	0.1498	0.1499	0.1760
point 6	0.438	0.345	0.345	0.345	0.345	0.321	0.8462	0.7675	0.7679	0.7675	0.7675	0.7480
point 7	0.897	0.863	0.863	0.862	0.862	0.848	0.5896	0.5627	0.5629	0.5628	0.5628	0.5630
point 8	0.961	0.968	0.968	0.968	0.968	0.962	0.4074	0.4194	0.4194	0.4195	0.4196	0.4200
point 9	1.018	1.020	1.021	1.021	1.021	1.014	0.3215	0.3354	0.3352	0.3354	0.3355	0.3336
point 10	1.054	1.050	1.051	1.051	1.051	1.045	0.2619	0.2749	0.2744	0.2747	0.2748	0.2742
point 11	1.075	1.071	1.072	1.072	1.072	1.067	0.2143	0.2288	0.2280	0.2283	0.2283	0.2281
	Section B: u velocity (m/s)						Section B: v velocity (m/s)					
Time (s)	0.1	0.5	1	1.5	2	Stationary Results	0.1	0.5	1	1.5	2	Stationary Results
point 1	-0.012	-0.014	-0.016	-0.012	-0.010	-0.028	0.000	0.000	0.000	0.000	0.000	0.000
point 2	-0.025	-0.037	-0.026	-0.019	-0.016	-0.023	0.005	0.016	0.010	0.006	0.005	0.017
point 3	-0.041	-0.022	-0.010	-0.010	-0.011	0.003	-0.011	0.023	0.012	0.005	0.004	0.018
point 4	0.072	0.039	0.019	0.010	0.006	0.040	0.064	0.025	0.011	0.007	0.006	0.023
point 5	-0.012	0.041	0.025	0.023	0.023	0.086	0.014	0.009	0.008	0.008	0.009	0.044
point 6	-0.208	-0.159	-0.158	-0.158	-0.158	-0.189	0.000	0.000	0.000	0.000	0.000	0.000
point 7	0.960	0.825	0.826	0.825	0.825	0.805	0.353	0.318	0.320	0.320	0.320	0.312
point 8	1.146	1.113	1.114	1.114	1.114	1.109	0.359	0.377	0.378	0.378	0.378	0.382
point 9	1.113	1.117	1.118	1.118	1.118	1.112	0.274	0.310	0.311	0.311	0.311	0.313

point 10	1.122	1.122	1.124	1.123	1.123	1.119	0.229	0.260	0.260	0.260	0.260	0.260
point 11	1.133	1.128	1.130	1.130	1.130	1.124	0.192	0.220	0.219	0.219	0.219	0.219
Section C: u velocity (m/s)							Section C: v velocity (m/s)					
Time (s)	0.1	0.5	1	1.5	2	Stationary Results	0.1	0.5	1	1.5	2	Stationary Results
point 1	-0.011	-0.018	-0.015	-0.011	-0.010	-0.044	0.000	0.000	0.000	0.000	0.000	0.000
point 2	-0.011	-0.029	-0.023	-0.017	-0.015	-0.029	-0.007	-0.014	-0.011	-0.007	-0.004	0.002
point 3	-0.003	-0.012	-0.008	-0.009	-0.010	0.002	-0.019	-0.035	-0.020	-0.012	-0.007	0.003
point 4	0.013	0.029	0.016	0.007	0.004	0.032	-0.009	-0.037	-0.017	-0.011	-0.007	0.007
point 5	0.006	0.025	0.020	0.019	0.019	0.075	0.001	-0.013	-0.009	-0.006	-0.005	0.011
point 6	-0.269	-0.217	-0.221	-0.221	-0.221	-0.239	0.000	0.000	0.000	0.000	0.000	0.000
point 7	0.379	0.325	0.324	0.323	0.323	0.272	0.054	0.067	0.069	0.069	0.069	0.062
point 8	1.241	1.142	1.144	1.143	1.143	1.143	0.250	0.270	0.271	0.271	0.271	0.275
point 9	1.173	1.171	1.174	1.173	1.173	1.170	0.205	0.255	0.256	0.256	0.257	0.258
point 10	1.163	1.169	1.171	1.171	1.171	1.167	0.176	0.226	0.225	0.226	0.226	0.227
point 11	1.169	1.169	1.171	1.171	1.171	1.166	0.152	0.197	0.196	0.197	0.197	0.197
Section D: u velocity (m/s)							Section D: v velocity (m/s)					
Time (s)	0.1	0.5	1	1.5	2	Stationary Results	0.1	0.5	1	1.5	2	Stationary Results
point 1	-0.004	-0.008	0.000	0.000	-0.003	-0.034	0.000	0.000	0.000	0.000	0.000	0.000
point 2	-0.003	-0.007	-0.007	-0.007	-0.008	-0.023	-0.004	-0.012	-0.011	-0.008	-0.007	-0.018
point 3	-0.001	0.004	-0.004	-0.005	-0.006	-0.001	-0.007	-0.018	-0.020	-0.014	-0.013	-0.023
point 4	0.003	0.010	0.005	0.003	0.003	0.024	-0.005	-0.008	-0.016	-0.016	-0.015	-0.015
point 5	0.003	-0.001	0.006	0.009	0.011	0.067	-0.002	-0.001	-0.007	-0.010	-0.010	0.001
point 6	-0.246	-0.208	-0.213	-0.213	-0.213	-0.226	0.000	0.000	0.000	0.000	0.000	0.000
point 7	0.220	0.167	0.165	0.163	0.163	0.130	-0.023	-0.005	-0.004	-0.003	-0.003	-0.004
point 8	1.206	1.036	1.041	1.039	1.039	1.036	0.135	0.156	0.158	0.159	0.159	0.161
point 9	1.213	1.188	1.192	1.191	1.191	1.191	0.140	0.194	0.195	0.195	0.196	0.198
point 10	1.191	1.196	1.199	1.199	1.199	1.195	0.118	0.186	0.185	0.186	0.186	0.187
point 11	1.190	1.197	1.200	1.200	1.200	1.195	0.101	0.170	0.168	0.168	0.169	0.169
Section E: u velocity (m/s)							Section E: v velocity (m/s)					
Time (s)	0.1	0.5	1	1.5	2	Stationary Results	0.1	0.5	1	1.5	2	Stationary Results
point 1	0.070	-0.001	0.004	0.003	0.003	0.004	0.000	0.000	0.000	0.000	0.000	0.000
point 2	-0.102	0.009	-0.006	-0.005	-0.005	-0.006	-0.089	-0.071	0.013	0.011	0.011	0.015
point 3	-0.095	-0.006	-0.006	-0.006	-0.006	-0.006	0.452	-0.071	0.044	0.040	0.039	0.046
point 4	-0.019	-0.010	-0.005	-0.005	-0.005	-0.006	0.746	-0.029	0.073	0.068	0.067	0.076
point 5	0.046	-0.012	-0.006	-0.006	-0.006	-0.006	0.699	0.025	0.099	0.095	0.094	0.103
point 6	0.016	-0.061	-0.051	-0.053	-0.054	-0.057	0.472	0.093	0.135	0.134	0.134	0.142

point 7	0.165	0.102	0.101	0.100	0.100	0.075	0.051	-0.001	0.010	0.011	0.011	0.011
point 8	1.071	0.832	0.839	0.837	0.837	0.809	0.088	0.075	0.080	0.080	0.080	0.075
point 9	1.245	1.175	1.181	1.181	1.181	1.182	0.086	0.142	0.142	0.143	0.143	0.145
point 10	1.220	1.206	1.213	1.213	1.213	1.209	0.118	0.186	0.185	0.186	0.186	0.187
point 11	1.209	1.215	1.220	1.221	1.221	1.216	0.101	0.170	0.168	0.168	0.169	0.169

Table 4.2: Velocity component for case 4(i)

Section A: u velocity (m/s)							Section A: v velocity (m/s)					
Time (s)	0.1	0.5	1	1.5	2	Stationary Results	0.1	0.5	1	1.5	2	Stationary Results
point 1	-0.011	-0.022	-0.025	-0.025	-0.026	0.005	0.000	0.000	0.000	0.000	0.000	0.000
point 2	0.023	-0.028	-0.022	-0.022	-0.022	0.031	0.014	0.001	-0.002	-0.002	-0.002	0.015
point 3	-0.046	0.043	0.042	0.041	0.041	0.078	0.003	0.015	0.014	0.014	0.014	0.038
point 4	0.034	0.034	0.034	0.034	0.034	0.032	-0.011	0.099	0.098	0.098	0.098	0.094
point 5	0.092	0.061	0.061	0.061	0.061	0.059	0.390	0.316	0.315	0.315	0.315	0.303
point 6	0.303	0.313	0.312	0.312	0.312	0.296	0.960	0.795	0.794	0.794	0.793	0.771
point 7	0.848	0.856	0.855	0.855	0.855	0.843	0.656	0.584	0.585	0.584	0.584	0.585
point 8	0.942	0.966	0.965	0.965	0.965	0.958	0.455	0.432	0.433	0.433	0.433	0.432
point 9	1.002	1.020	1.019	1.019	1.019	1.012	0.355	0.343	0.344	0.344	0.344	0.342
point 10	1.049	1.051	1.050	1.050	1.050	1.045	0.291	0.280	0.280	0.281	0.281	0.280
point 11	1.081	1.074	1.074	1.074	1.074	1.067	0.241	0.232	0.233	0.233	0.233	0.233

Section B: u velocity (m/s)							Section B: v velocity (m/s)					
Time (s)	0.1	0.5	1	1.5	2	Stationary Results	0.1	0.5	1	1.5	2	Stationary Results
point 1	-0.001	-0.012	-0.016	-0.015	-0.014	-0.005	0.000	0.000	0.000	0.000	0.000	0.000
point 2	0.002	-0.009	-0.006	-0.004	-0.004	0.000	0.001	-0.019	-0.018	-0.020	-0.021	0.006
point 3	0.000	0.022	0.023	0.021	0.019	0.042	0.002	-0.013	-0.017	-0.018	-0.018	0.021
point 4	-0.001	-0.006	-0.004	-0.003	-0.003	0.055	0.000	0.002	-0.004	-0.005	-0.004	0.032
point 5	-0.001	-0.001	-0.003	-0.003	-0.002	-0.001	0.000	0.000	-0.001	-0.001	-0.001	-0.003
point 6	-0.189	-0.173	-0.174	-0.174	-0.174	-0.202	0.000	0.000	0.000	0.000	0.000	0.000
point 7	0.682	0.766	0.762	0.761	0.761	0.747	0.281	0.300	0.300	0.300	0.300	0.298
point 8	1.149	1.120	1.119	1.119	1.119	1.114	0.419	0.388	0.390	0.390	0.390	0.393

point 9	1.115	1.121	1.121	1.121	1.121	1.116	0.323	0.318	0.320	0.320	0.320	0.321
point 10	1.124	1.126	1.125	1.126	1.125	1.121	0.264	0.265	0.266	0.267	0.267	0.267
point 11	1.142	1.133	1.134	1.134	1.134	1.127	0.221	0.223	0.224	0.224	0.224	0.223

Section C: u velocity (m/s)							Section C: v velocity (m/s)					
Time (s)	0.1	0.5	1	1.5	2	Stationary Results	0.1	0.5	1	1.5	2	Stationary Results
point 1	0.000	-0.003	0.001	0.004	0.006	-0.017	0.000	0.000	0.000	0.000	0.000	0.000
point 2	0.000	0.000	0.003	0.006	0.007	-0.005	0.001	-0.003	-0.005	-0.006	-0.006	0.007
point 3	0.000	0.003	0.005	0.003	0.001	0.015	0.001	0.000	0.000	-0.001	-0.002	0.013
point 4	0.000	0.000	-0.004	-0.006	-0.006	0.058	0.000	0.001	0.003	0.002	0.000	0.036
point 5	0.000	-0.001	-0.003	-0.004	-0.004	0.030	0.000	0.000	0.001	0.000	0.000	0.031
point 6	-0.261	-0.225	-0.227	-0.226	-0.226	-0.245	0.000	0.000	0.000	0.000	0.000	0.000
point 7	0.176	0.302	0.298	0.297	0.297	0.248	0.043	0.062	0.063	0.063	0.063	0.057
point 8	1.246	1.147	1.145	1.144	1.144	1.135	0.296	0.273	0.275	0.275	0.275	0.277
point 9	1.194	1.180	1.180	1.179	1.179	1.175	0.254	0.260	0.263	0.263	0.263	0.264
point 10	1.176	1.175	1.175	1.176	1.175	1.170	0.214	0.229	0.231	0.231	0.231	0.231
point 11	1.182	1.173	1.174	1.175	1.175	1.170	0.185	0.200	0.201	0.201	0.201	0.201

Section D: u velocity (m/s)							Section D: v velocity (m/s)					
Time (s)	0.1	0.5	1	1.5	2	Stationary Results	0.1	0.5	1	1.5	2	Stationary Results
point 1	0.000	0.000	0.001	0.003	0.005	-0.019	0.000	0.000	0.000	0.000	0.000	0.000
point 2	0.000	0.000	0.001	0.003	0.004	-0.010	0.000	-0.001	0.001	0.004	0.005	-0.005
point 3	0.000	0.000	0.001	0.000	-0.001	0.005	0.000	0.000	0.003	0.006	0.006	-0.002
point 4	0.000	0.000	-0.001	-0.002	-0.004	0.029	0.000	0.000	0.002	0.004	0.004	0.012
point 5	0.000	0.000	-0.001	-0.002	-0.002	0.051	0.000	0.000	0.001	0.001	0.001	0.031
point 6	-0.198	-0.208	-0.211	-0.211	-0.211	-0.226	0.000	0.000	0.000	0.000	0.000	0.000
point 7	0.080	0.150	0.146	0.145	0.145	0.117	-0.063	-0.009	-0.007	-0.007	-0.007	-0.006
point 8	1.048	1.015	1.010	1.009	1.009	1.004	0.142	0.152	0.155	0.156	0.156	0.154
point 9	1.240	1.198	1.199	1.198	1.198	1.195	0.192	0.196	0.199	0.200	0.200	0.200
point 10	1.213	1.203	1.204	1.205	1.204	1.200	0.164	0.186	0.189	0.189	0.189	0.190
point 11	1.210	1.202	1.204	1.204	1.204	1.199	0.139	0.170	0.172	0.172	0.172	0.173

Section E: u velocity (m/s)							Section E: v velocity (m/s)					
Time (s)	0.1	0.5	1	1.5	2	Stationary Results	0.1	0.5	1	1.5	2	Stationary Results
point 1	0.074	-0.004	0.004	0.003	0.003	0.004	0.000	0.000	0.000	0.000	0.000	0.000
point 2	-0.108	0.013	-0.006	-0.005	-0.005	-0.006	-0.048	-0.081	0.012	0.011	0.010	0.015

point 3	-0.104	-0.002	-0.006	-0.006	-0.006	-0.007	0.583	-0.101	0.043	0.040	0.039	0.048
point 4	-0.024	-0.011	-0.005	-0.005	-0.005	-0.006	0.901	-0.065	0.072	0.068	0.067	0.078
point 5	0.045	-0.016	-0.006	-0.006	-0.006	-0.006	0.871	0.001	0.098	0.095	0.094	0.105
point 6	0.113	-0.065	-0.051	-0.053	-0.053	-0.056	0.599	0.090	0.132	0.132	0.132	0.143
point 7	0.019	0.095	0.091	0.091	0.091	0.067	0.101	0.000	0.010	0.011	0.011	0.011
point 8	0.702	0.797	0.790	0.789	0.789	0.768	0.078	0.067	0.073	0.073	0.073	0.068
point 9	1.268	1.183	1.185	1.184	1.184	1.183	0.163	0.140	0.145	0.146	0.146	0.146
point 10	1.261	1.214	1.218	1.218	1.218	1.213	0.119	0.145	0.148	0.148	0.148	0.148
point 11	1.246	1.221	1.225	1.225	1.225	1.220	0.084	0.138	0.139	0.140	0.140	0.140

4.3 Ventilation Rate

From equation (5) noted in chapter 3, the expected ventilation rate for single sided is
$Q_{ss} = 2.73 \times 10^{-3}\ m^3/s.$

And using equation (6) and (7), the expected ventilation rate for cross ventilation is
$Q_{CR} = 4.416 \times 10^{-2}\ m^3/s.$

Table 4.3 compares the ventilation rate provided by the simulation with the expected values previously defined, the values obtained by this research presents better results than the results obtained by [24] using $k - \epsilon$ method. Anyway, for a correct interpretation of these data it is important to remember that the expected ventilation rates have not been obtained through experimental measurements, but they are given by empirical relationships which have by now shown a good accuracy, but which may be affected by some limitations. From this table it is clear that, awning opening allows more air enter into the room than normal openings and that's why more ventilation rate is accounted.

Table 4.3: Ventilation rate comparison

Case	Present study result Ventilation rate [m^3/s]	Previous obtained result Evola [24] Ventilation rate [m^3/s]
Without coupling with heat		
Case 1(i)	3.1698×10^{-2}	3.75×10^{-3}
Case 2(i)	8.4285×10^{-4}	1.48×10^{-3}
Case 3(i)	5.08×10^{-2}	5.08×10^{-2}

Case 1(ii)	2.1327×10^{-2}	
Case 2(ii)	1.5168×10^{-3}	
Case 3(ii)	1.0048×10^{-2}	
Case 4(i)	2.6410×10^{-3}	
Case 4(ii)	2.9004×10^{-3}	
Case 5(i)	1.2117×10^{-4}	
Case 5(ii)	1.1992×10^{-4}	
Case 6 (i)	0.88970×10^{-2}	
Case 6 (ii)	2.1875×10^{-2}	
Coupling with heat		
Case 4(i)	2.8387×10^{-2}	
Case 4(ii)	1.7684×10^{-2}	
Case 5(i)	1.4902×10^{-2}	
Case 5(ii)	1.8629×10^{-2}	
Case 6 (i)	7.4826×10^{-2}	
Case 6 (ii)	7.5865×10^{-2}	

Chapter 5
Results and discussions: Heat transfer

Natural ventilation systems do not only provide fresh air, but also affect the indoor thermal environment a lot. Since the research focuses on thermal comfort, we have to pay attention to the quality of the indoor environment. For thermally comfort, Heat transfer rates in a room with an opening are studied, where for these studies, the opening is a window/doorway. With an adiabatic wall, the heat transfer only occurs at the opening. To feel comfortable in a thermal sense, a human has to be able to release a well-defined amount of Heat**.** These kinds of discussion will be discussed in this section.

5.1 Introduction

Only by knowing the air temperature in the room, thermal comfort cannot be determined. There is a known statistic that more than 50% of all thermal energy exchanges through radiation between a human body and the environment. A human body is continuously exchanging radiant heat with all objects that surrounds it due to temperature difference between them. Mean Radiant Temperature (MRT) of a space is really the measure of the combined effects of temperatures of surfaces within that space on human body. The more surface area, the more effect the surface temperature has on the individual. Thus MRT, changes with location inside the room corresponding to air temperature which provides thermal comfort. In general if MRT drops by 1°C, air temperature has to be raised by 1 - 1.5°C.

ASHRAE defined the thermal comfort for human body as the human mood that expresses satisfaction with the surrounding environment (ASHRAE Standard 55). One of the main goal of the ventilation designers should maintaining this thermal comfort for occupants of buildings or other enclosures. The keys of thermal comfort are heat conduction, convection, radiation, and evaporative heat loss. Thermal comfort is maintained when the heat generated by human metabolism is allowed to dissipate, thus maintaining thermal equilibrium with the surroundings. Any heat gain or loss beyond this generates a sensation of discomfort. It has been long recognized that the sensation of feeling hot or cold is not just dependent on air temperature alone. Most people will feel comfortable at room temperature, colloquially a range of temperatures around 20 to 22 °C, but this may vary greatly between people and depending on factors such as movement level, outfit, and humidity. The main factors that influence thermal comfort are those that determine heat gain and loss, namely metabolic rate, outfit insulation, air temperature, mean radiant temperature, air speed and relative humidity.

5.2 Results and discussions of temperature distribution

The graphs in Figure 5.1 -5.3 display the temperature distribution profile vertically of numerical of the designed evaluated for ventilation of the 5 section. Figure 5.1, 5.2 and 5.3 stands for windward, Leeward and Cross openings and awning opening case respectively. Figure 5.4 shows the thermal surface for case 4(i). In this study any other heat source or mechanical system does not into account. Only natural source is take into account. For all cases, the lower temperatures are close to the air inlet. It can be observed that a large area of the room has temperatures 303.15 K, and between 298K and 303 K (for leeward case), also a thermal stratification can be observed in the top of the room. However, the ASHRAE Standard 55 states that occupants may feel uncomfortable due to contact with floor surfaces that are too warm or too cool, giving an allowable range of floor temperatures between 292 K and 303 K. Figure 5.5 and Figure 5.6 shows the isothermal contours for different time (for 2D) and isothermal surfaces (for 3D) for case4 (i) respectively. Figure 5.7 shows the temperature distribution for case 4(i). Table 5.1 shows the average temperature enters into the room through openings for different time. It can be conclude that, for all case, awning openings are giving more thermal comfort then openings.

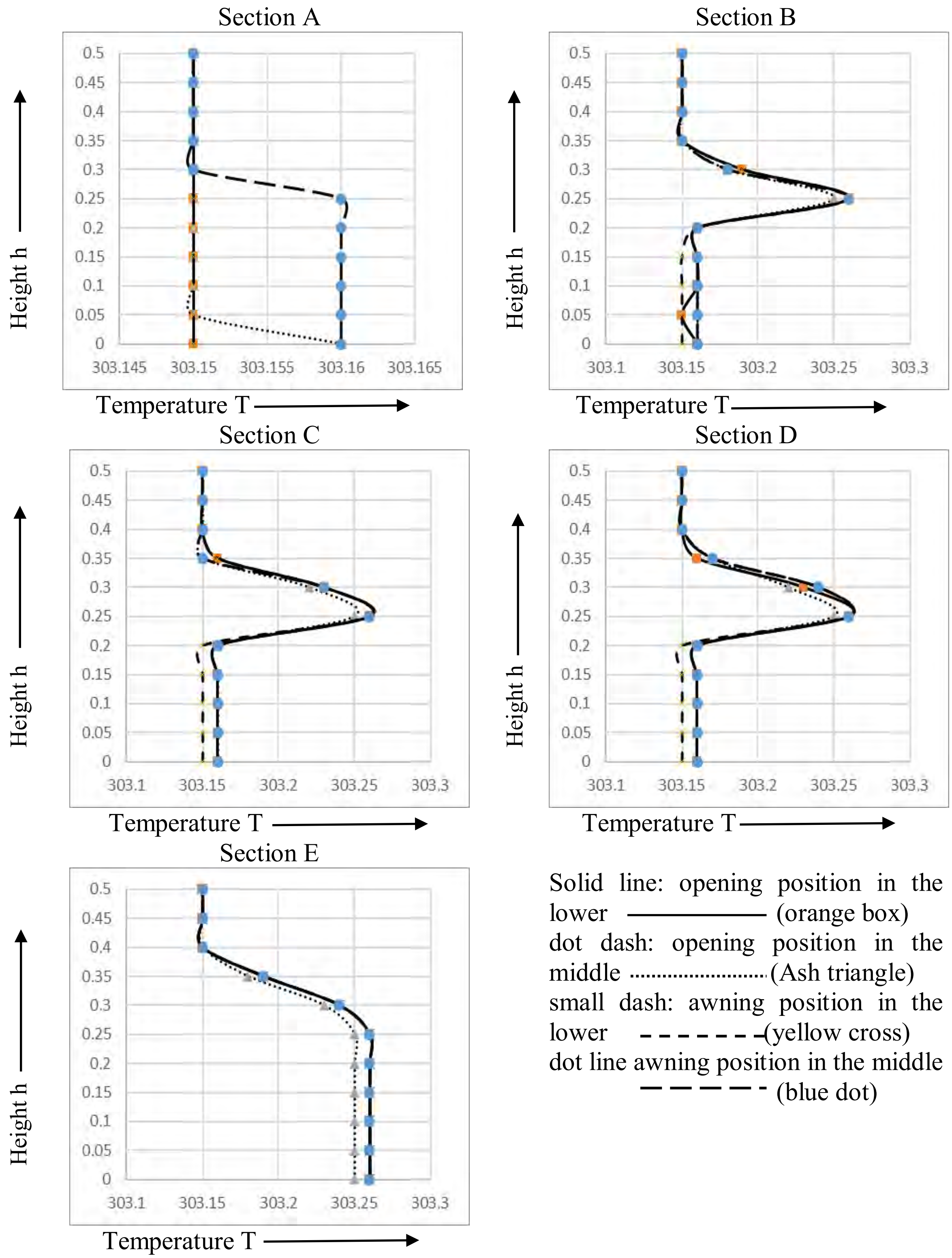


Figure 5.1: Temperature distribution in different section around and inside the room for case: 1 and case: 4. [Temperature T (x) against height h (y)]

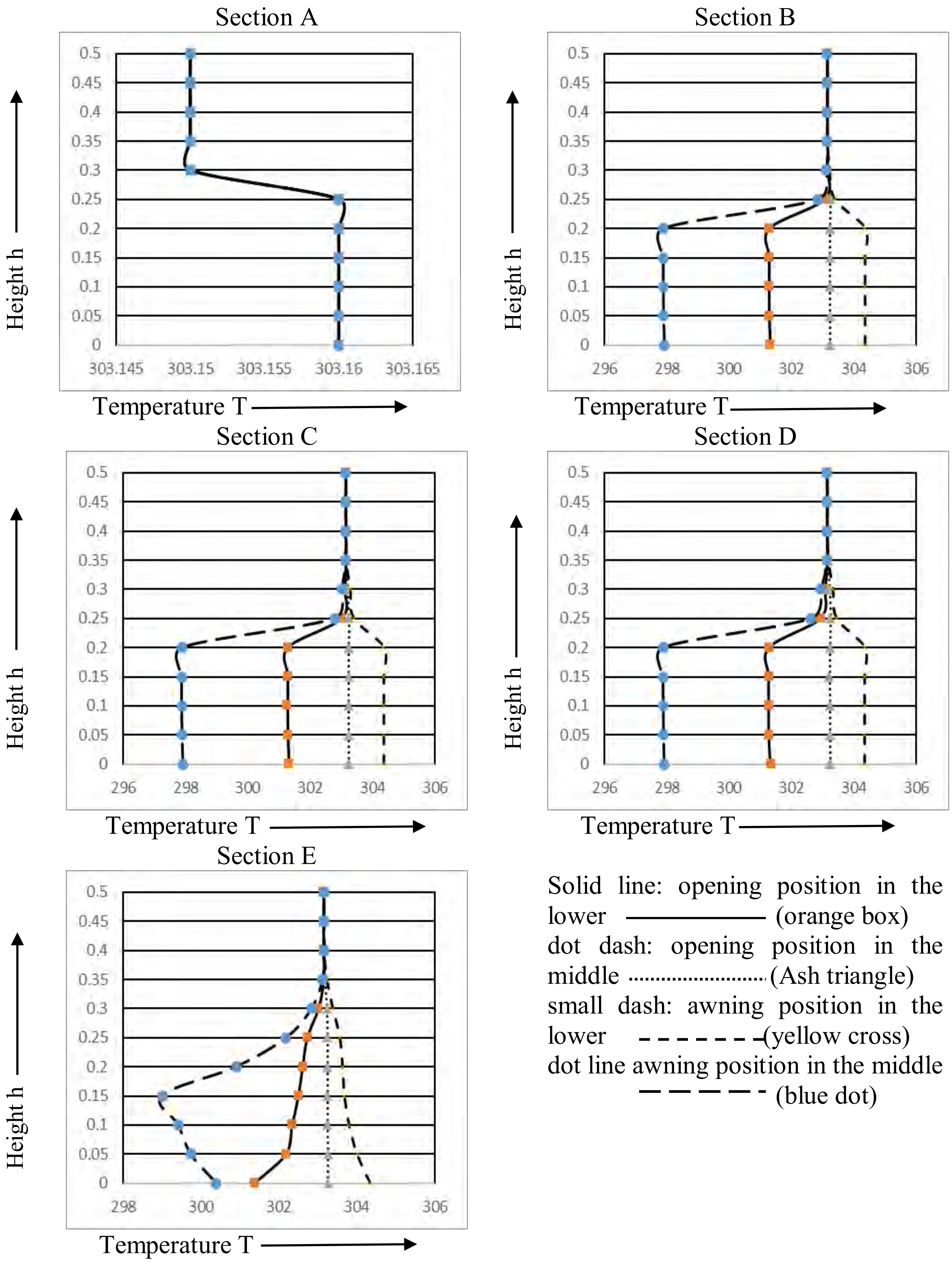


Figure 5.2: Temperature distribution in different section around and inside the room for case: 2 and case: 5. [Temperature T (x) against height h (y)]

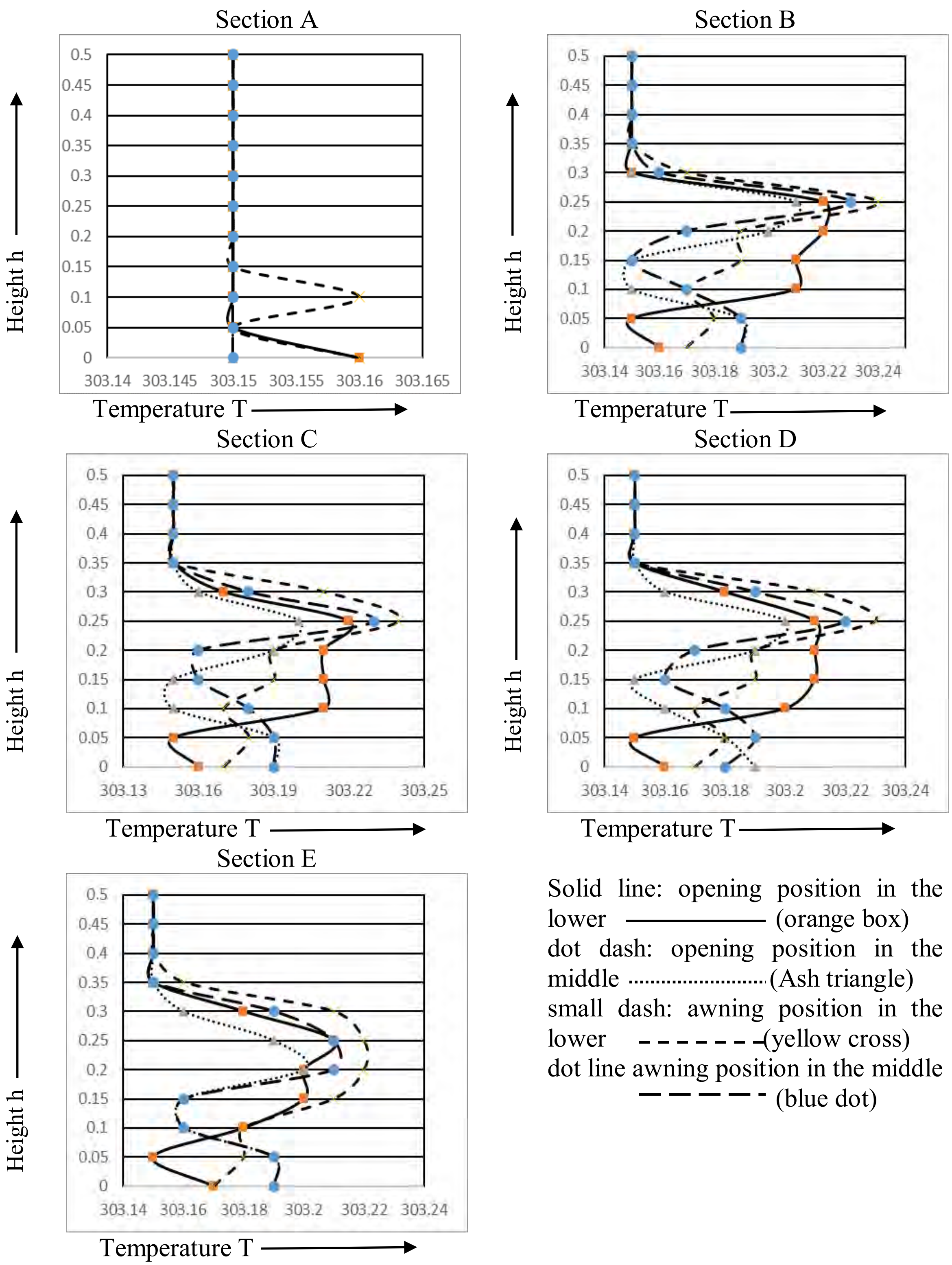


Figure 5.3: Temperature distribution in different section around and inside the room for case: 3 and case: 6. [Temperature T (x) against height h (y)]

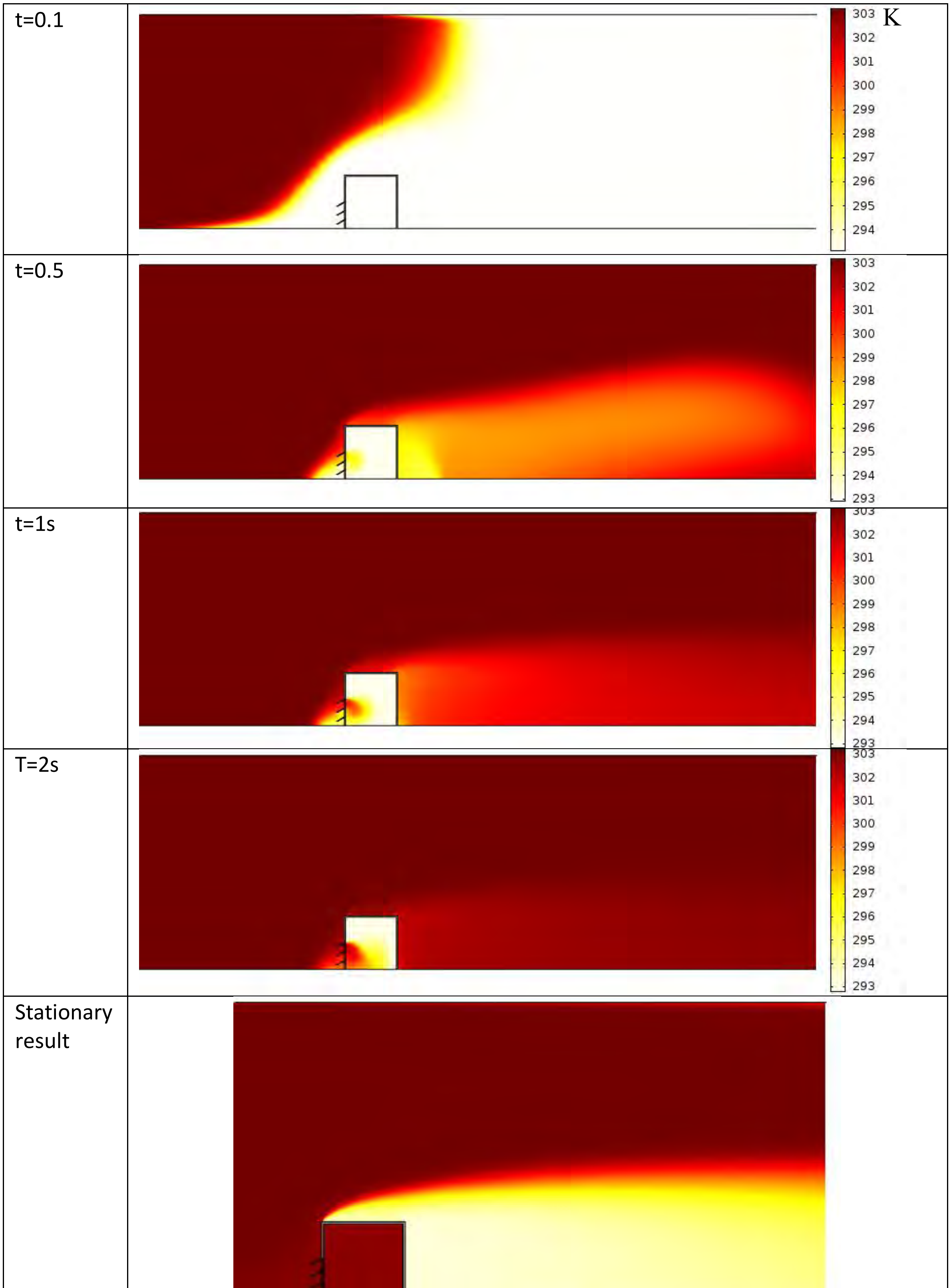


Figure 5.4: Time dependent result and stationary results for thermal surface for case 4(i)

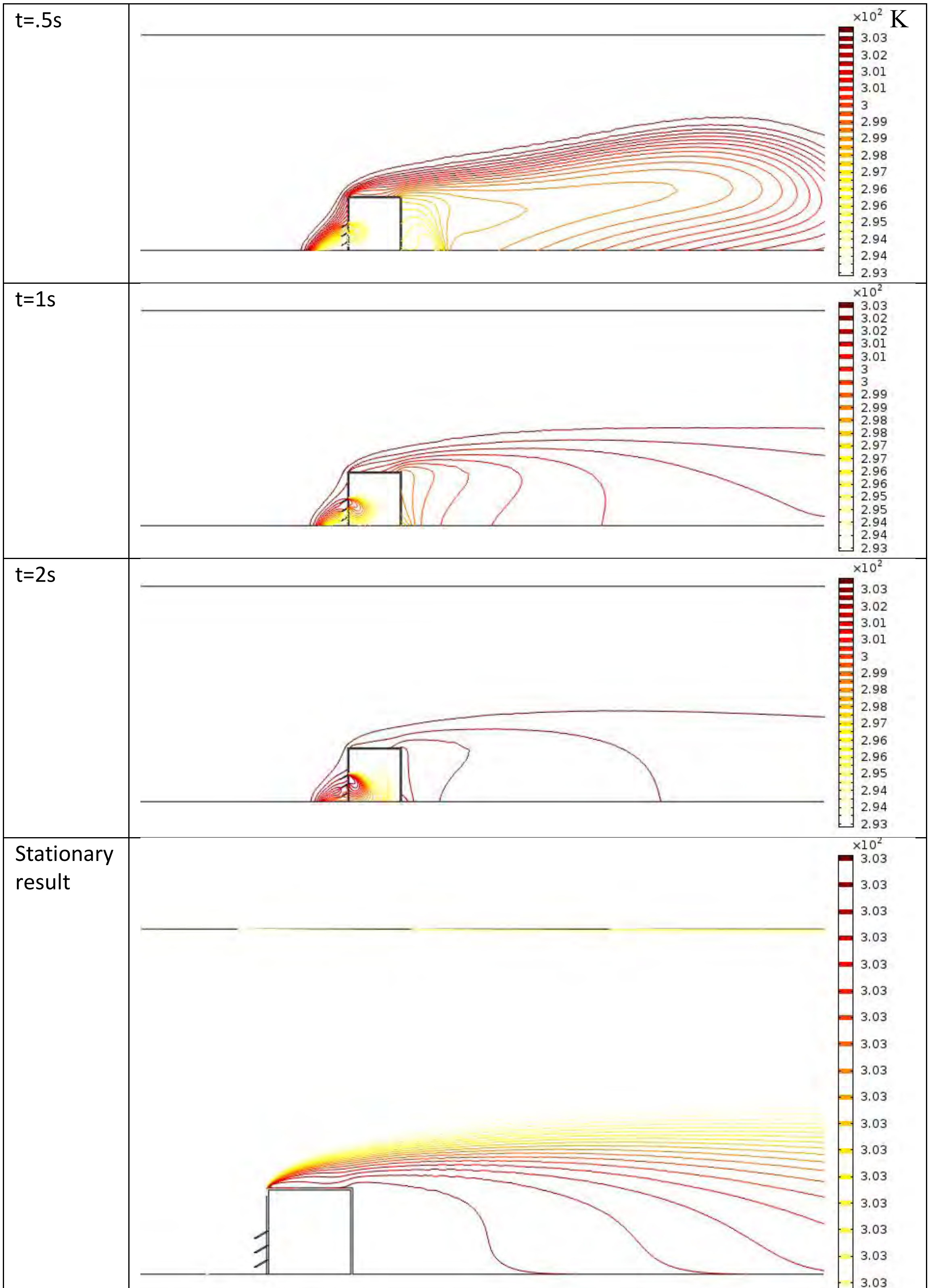


Figure 5.5: Time dependent result and stationary results for isothermal contours for case 4(i)

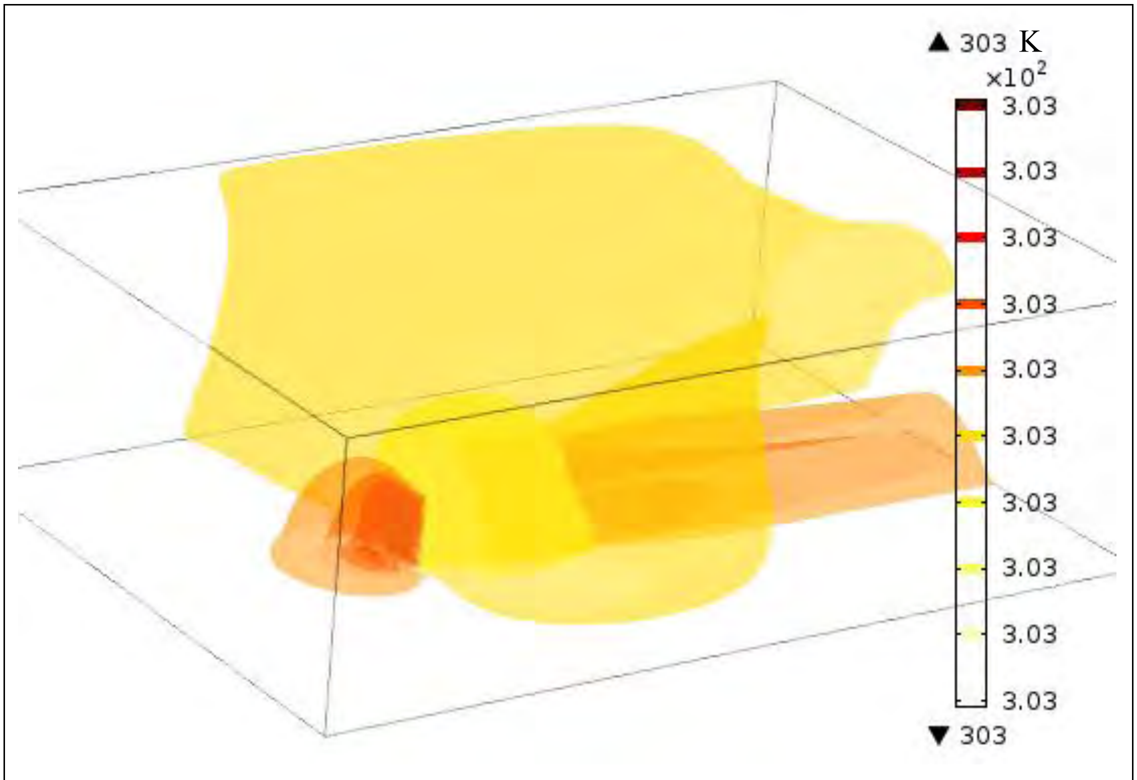


Figure 5.6: Results for isothermal surface for case 4(i) in 3D.

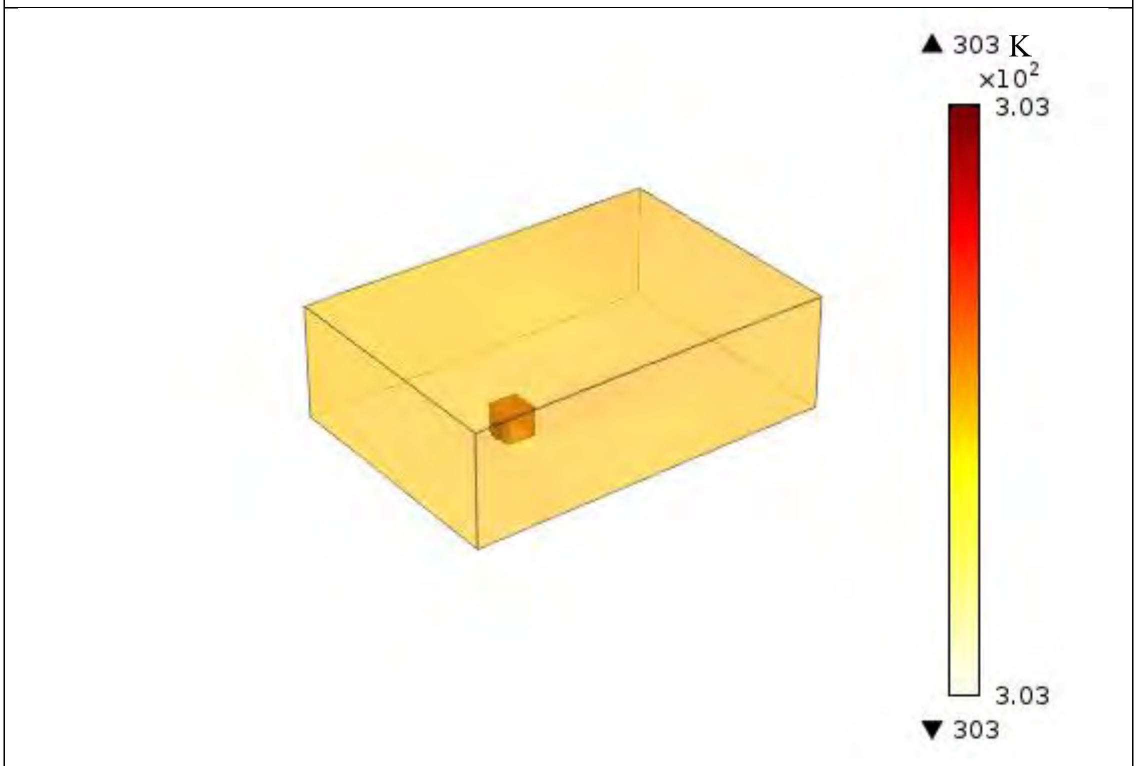


Figure 5.7: Temperature distribution on the whole environment (Case 4(i))

Table 5.1: Average velocity enters into the room for different time

Case	Time (s)	Temperature (K)
Case 1(i)	0	293.15
	.5	296.77
	1	299.21
	1.5	300.26
	2	300.82
Case 2(i)	0	293.15
	.5	294.75
	1	296.13
	1.5	297.64
	2	298.54
Case 4(i)	0	293.15
	.5	295.18
	1	297.91
	1.5	299.77
	2	300.72
Case 4(ii)	0	293.15
	.5	295.23
	1	297.85
	1.5	298.44
	2	299.13
Case 5(ii)	0	293.15
	.5	293.85
	1	295.21
	1.5	296.87
	2	298.39

From the Figures 5.1 -5.3 and Table 5.1, it is clear that in all cases, temperature inside the room maintains the ASHRAE [15] (Table 1.2) standard.

Chapter 6
Conclusion

Natural ventilation is a suitable process to save energy consumed in buildings mostly for heating and cooling purposes. Throughout the analytical work with natural ventilation made in linking with this thesis, a lot of outcomes have been found, but at the same time also a lot of new scopes have appeared that need to be analyzed further in the future. The summery of this thesis will be discussed in this chapter.

6.1 Introduction

During this research, it was difficult to collect data and to develop a suitable program. At the end, solving this difficulties and finding suitable solutions and outcomes with some recommendation. Which is discussed in this chapter.

6.2 Conclusion

Ventilation is required for living people inside a room, either it should be mechanical or natural ventilation. Among them natural ventilation is a useful system to reduce the consumption of energy in official or residential buildings mostly for heating and cooling purposes. Natural ventilation does not depend on a mechanical ventilating system, the ambient situations (outdoor temperature, wind, etc.) and internal spatial arrangements are important issues to consider for planning natural ventilating in buildings.

In this research, a single room with an opening was studied using computational fluid dynamics. Velocity and temperature profiles' predictions for at the opening were initially validated with the experiments and numerical solutions presented by Mahajan [16] and Schaelin *et al*. [17] respectively. In this study, wind driven natural ventilation are calculated by finite element method using $k-\epsilon$ where as Evola *et al.*[24] used finite volume method using RNG and $k-\epsilon$ model. Reynolds averaged Navier–Stokes approach has been applied to wind driven natural ventilation in a cubic building and current study used 2D and 3D simulations to model six different configurations were considered: single-sided ventilation with an opening on the windward wall, single-sided ventilation with an opening on the leeward wall, openings on opposite wall (cross ventilation), single-sided ventilation with an awning opening on the windward wall, single-sided ventilation with an awning opening on the leeward wall and awning openings on opposite wall (cross ventilation) and two window position lower and middle of the room included the room and sufficient ambient environment surrounding the room in order not to disturb the air flow around the building. The models were accomplished using standard two-equation $k-\epsilon$ model. As a result, distribution of the velocity inside and around the building was calculated, as well as the ventilation rate; all the results were then compared to experimental data provided in literature and well established empirical expressions for the prediction of the ventilation rate. Obtained numerical results show a good similarity with the previous data especially for single sided ventilation. The profiles of vertical velocity component and streamlines are showed good agreement and the discrepancy between calculated and expected ventilation rate lies under 10% and sometimes get better results in few case.

Findings of this study are written below:

- Awning opening on the windward side rather than on the leeward side (opening and awning opening), when dealing with single sided ventilation in a better air movement and heat exchange inside the building; hence in larger ventilation rate.
- In the case of cross ventilation, awning openings gives better results than openings in sense of air movement and heat exchange.
- The streamlines showed that the ambient air entered through the opening/awning opening more smoothly, and cooled the room faster.
- The spatially averaged velocity exceeded the maximum acceptable velocity by ASHRAE guidelines, and average temperature in the room was never able to achieve comfortable conditions.

Recommendations of this study are written below:

- $k-\epsilon$ model is used to obtained results but there are more model like RNG and Large-eddy simulation. Some authors have previously dealt with wind driven natural ventilation by means of large-eddy simulation and RNG model. These models will be added as a comparative study for further improvement of this study in future work.

- In literature different opinions have been expressed about this point, thus raising the need of further experimental investigations.

6.3 Possible future works based on this thesis

The present study can be extended by considering the following cases:

- Non dimensional equation/format can be consider to extend this study.
- For different ambient temperature and temperature dependent physical properties like viscosity, Prandtl number with different physics like heat generation, stress work may be considered.
- RNG model and Large-eddy simulation can be used for comparative study.
- This work can be extended by considering furniture, internal heat source like TV, Refrigerator, burner etc. for real scenario.

Reference

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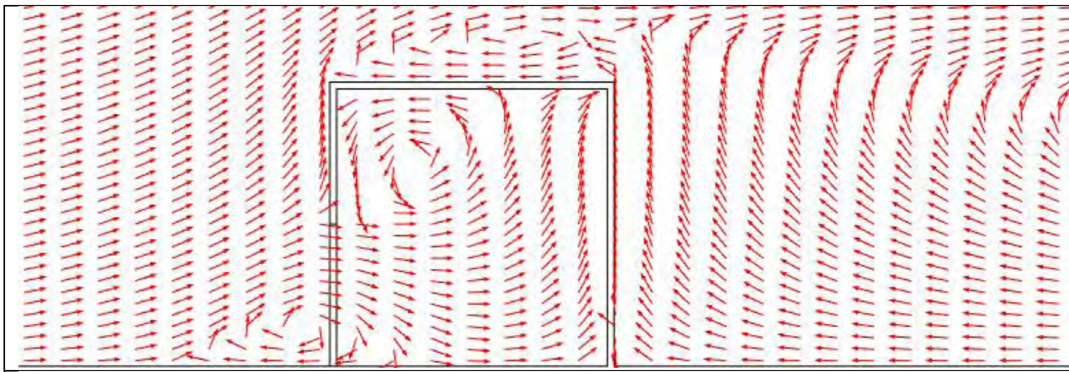
Two dimensional CFD simulation

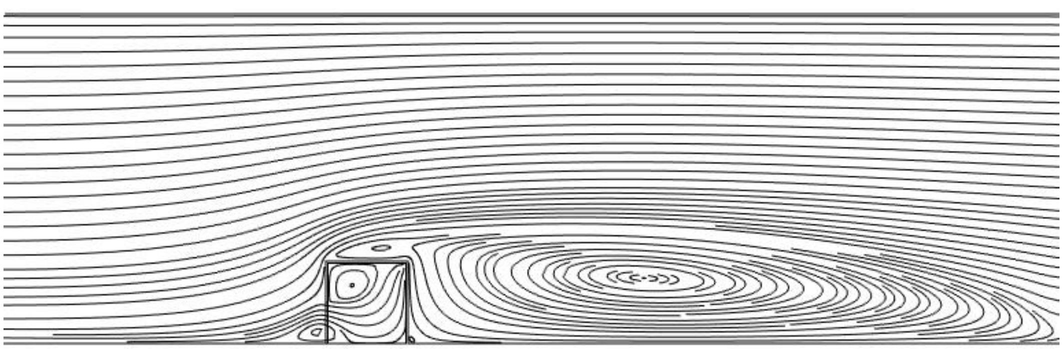
Two-dimensional CFD simulations were performed in order to investigate the impact of the opening facing the approaching wind and temperature on the room.

Coupling With Heat (Stationary):

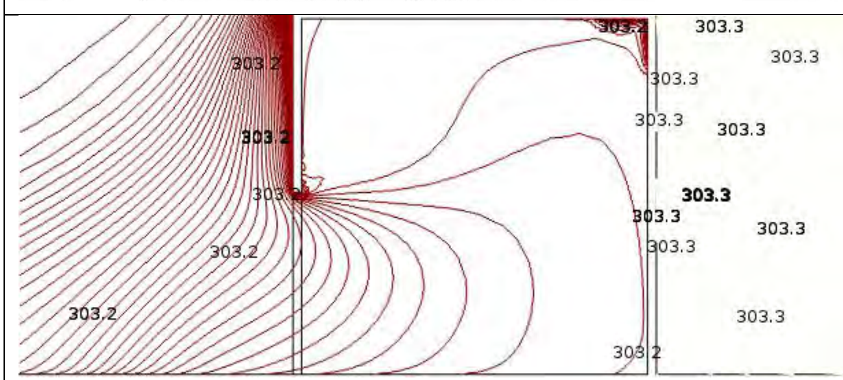
Case 1(i):



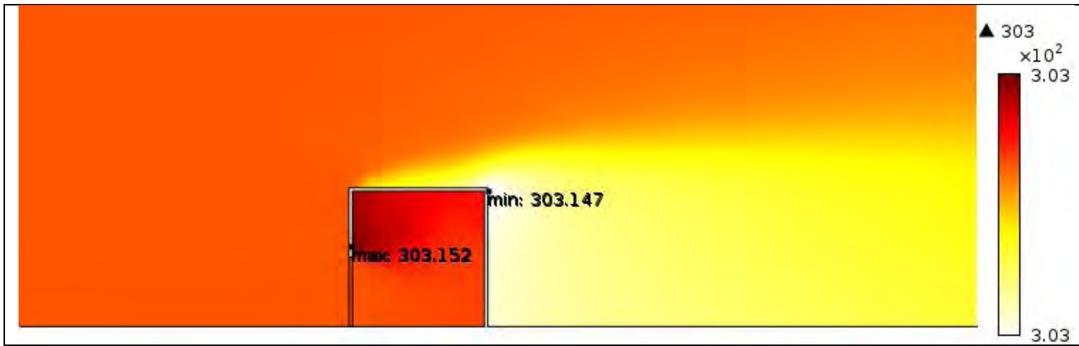
Arrow line inside the room



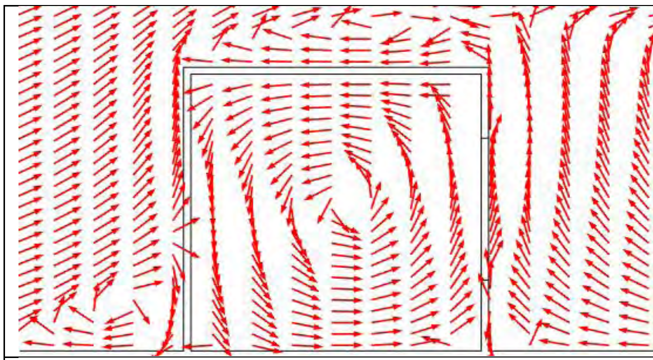
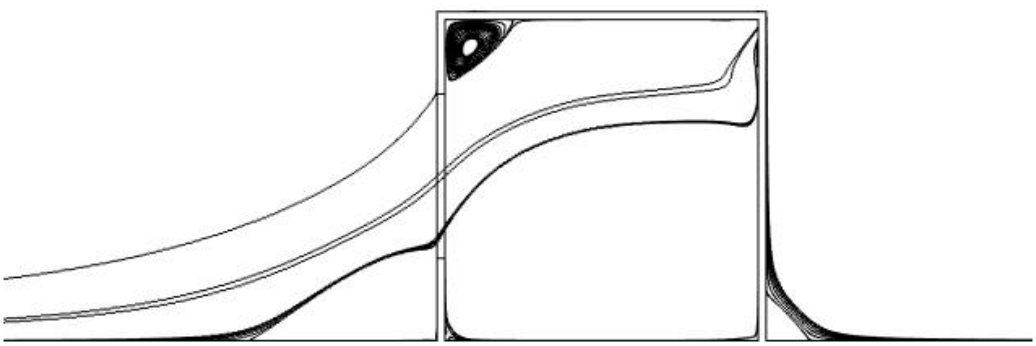
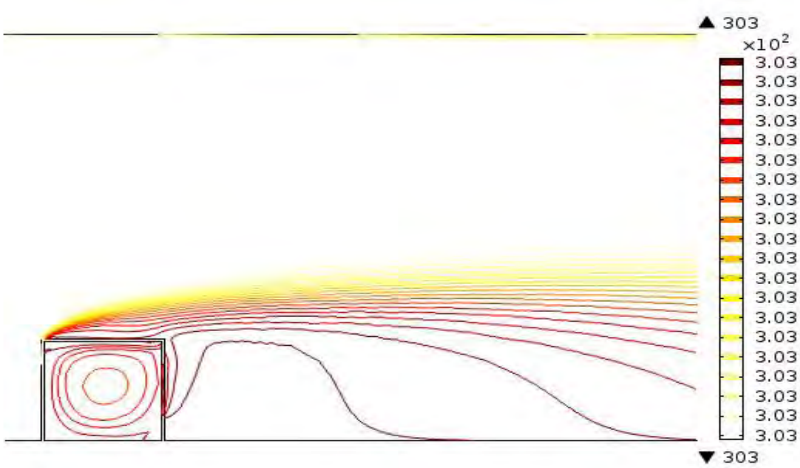
Stream line

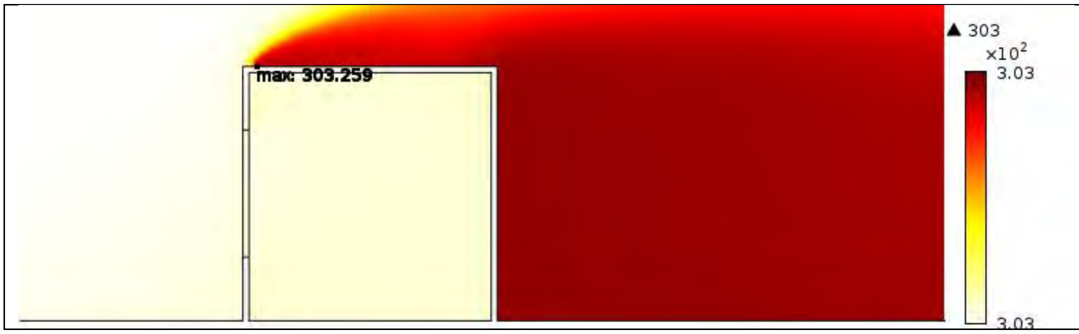


Isothermal contour

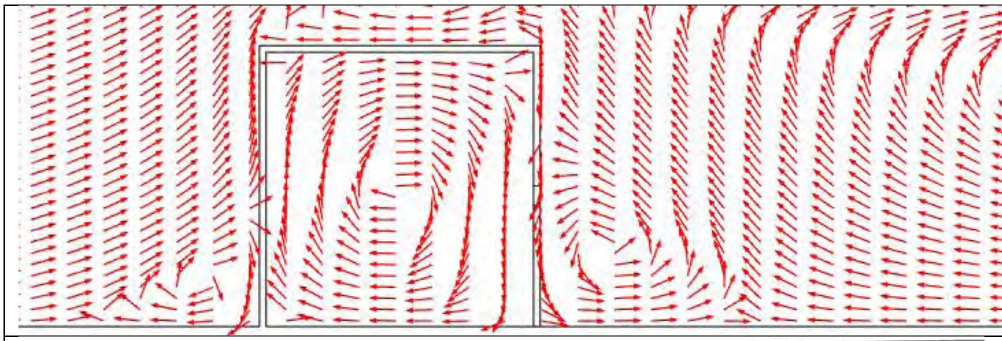
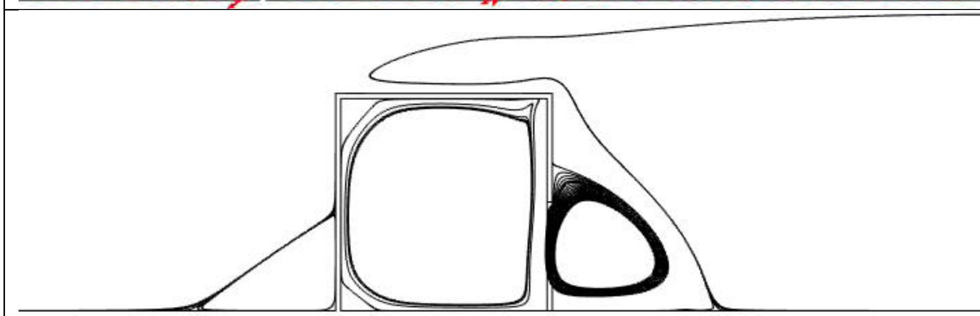
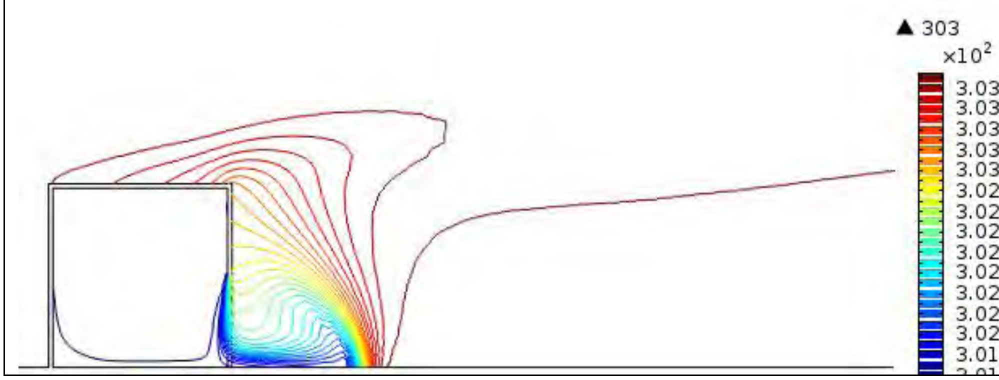
	Temperature distribution and max and min temperature

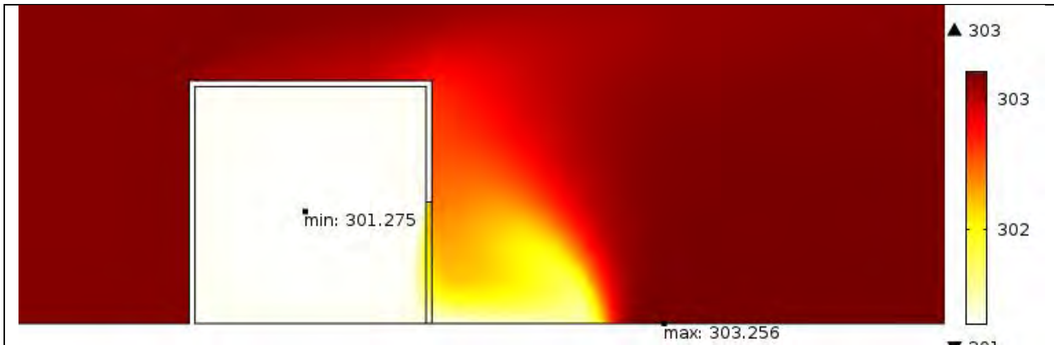
Case 1(ii):

	Arrow line inside the room
	Stream line
	Isothermal contour

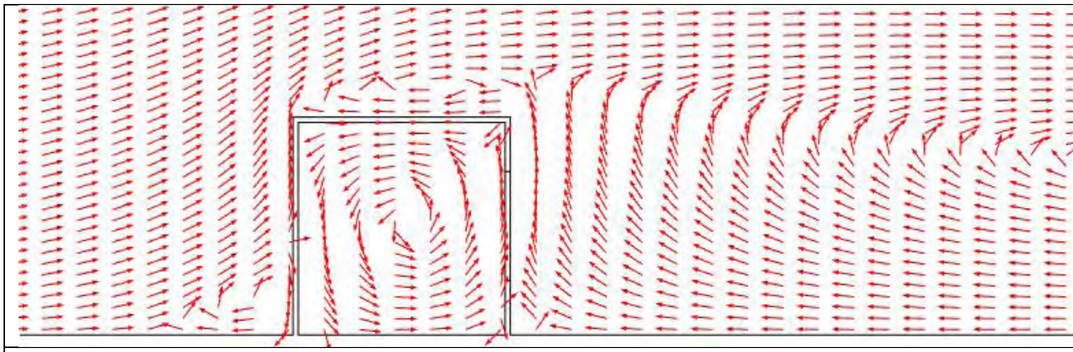
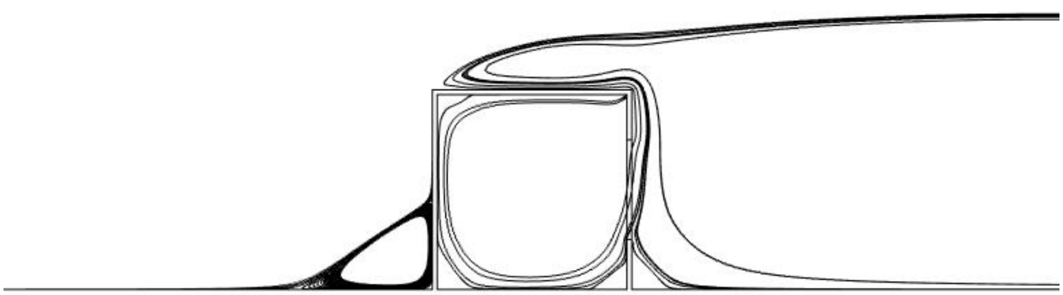
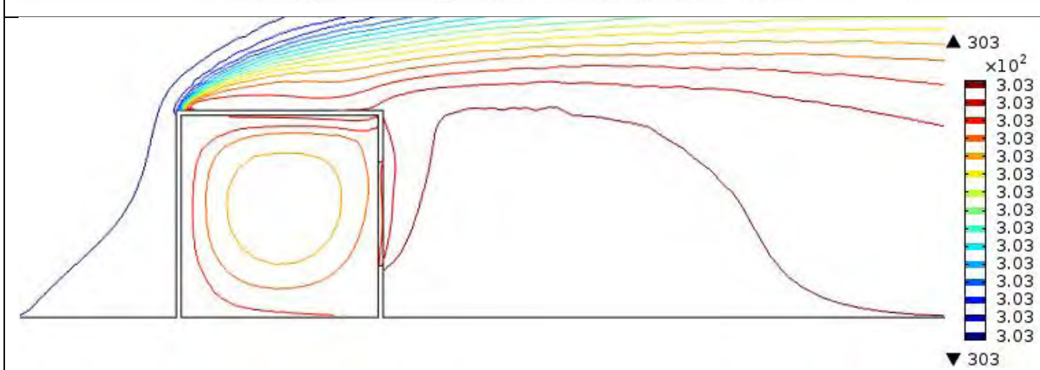
	Temperature distribution and max and min temperature

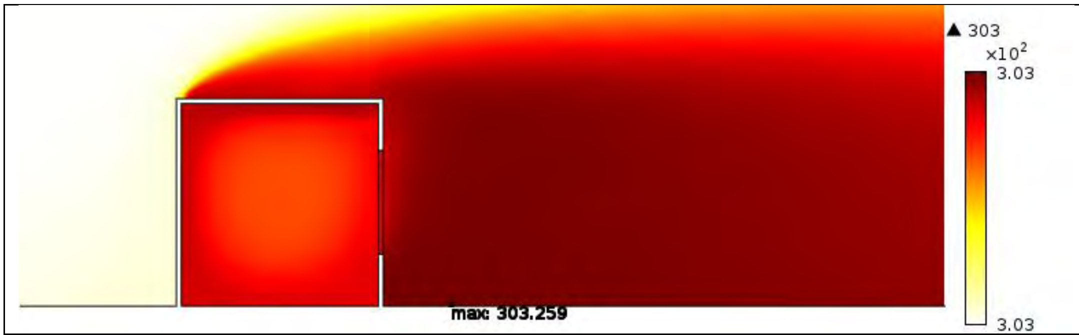
Case 2(i):

	Arrow line inside the room
	Stream line
	Isothermal contour

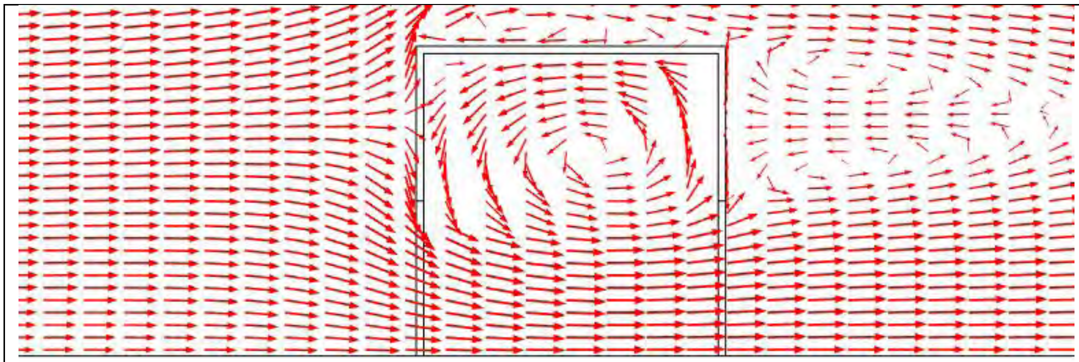
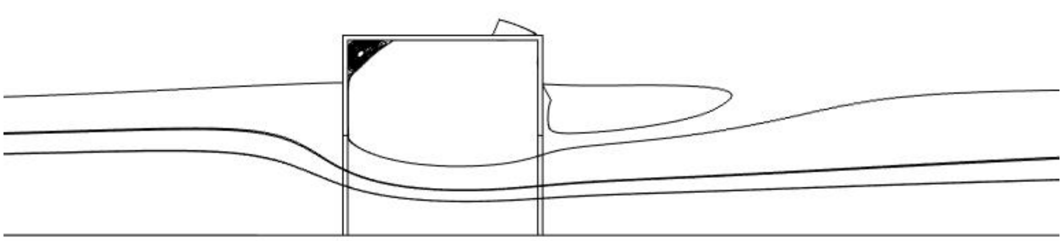
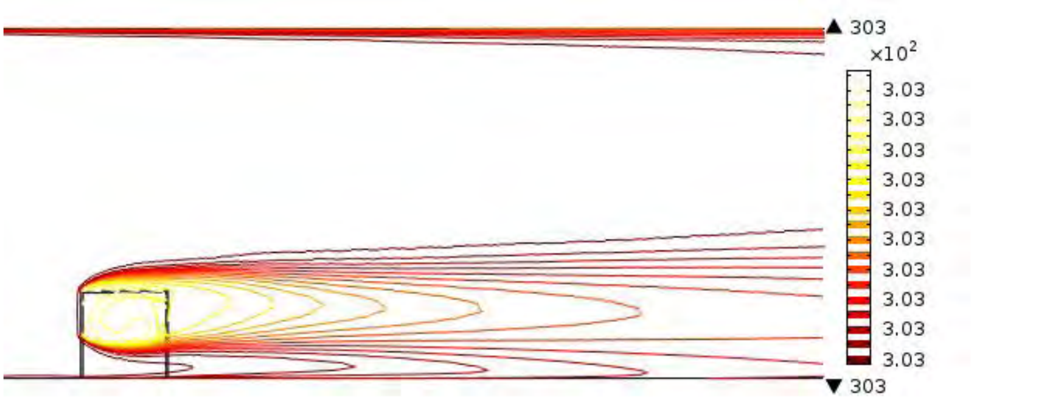
	Temperature distribution and max and min temperature

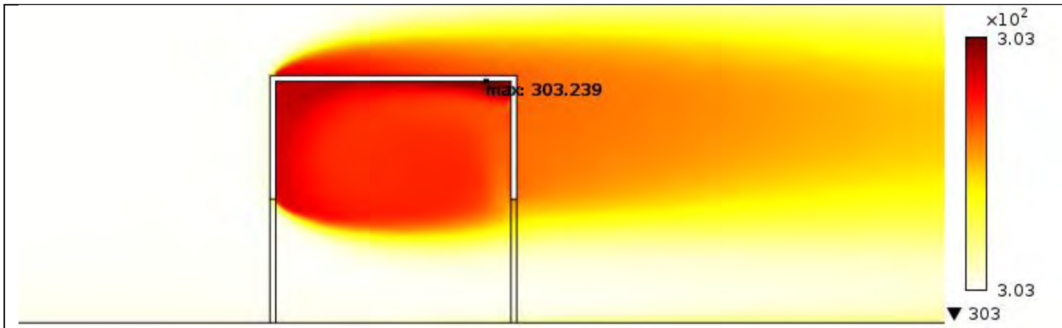
Case 2(ii):

	Arrow line inside the room
	Stream line
	Isothermal contour

	Temperature distribution and max and min temperature

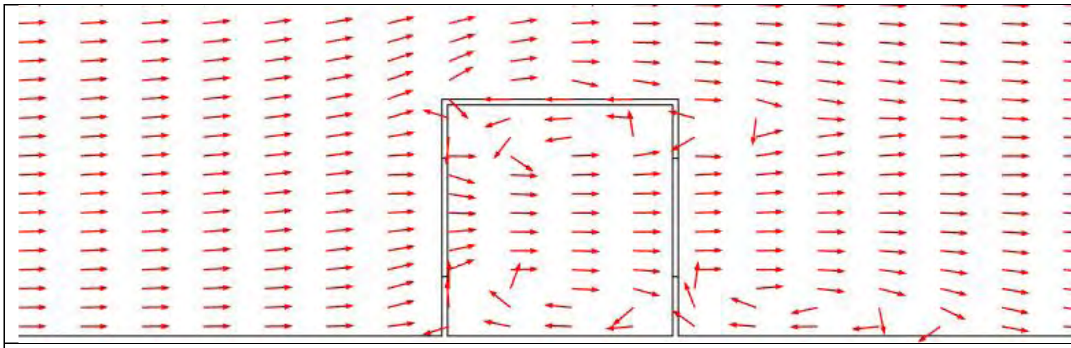
Case 3(i):

	Arrow line inside the room
	Stream line
	Isothermal contour

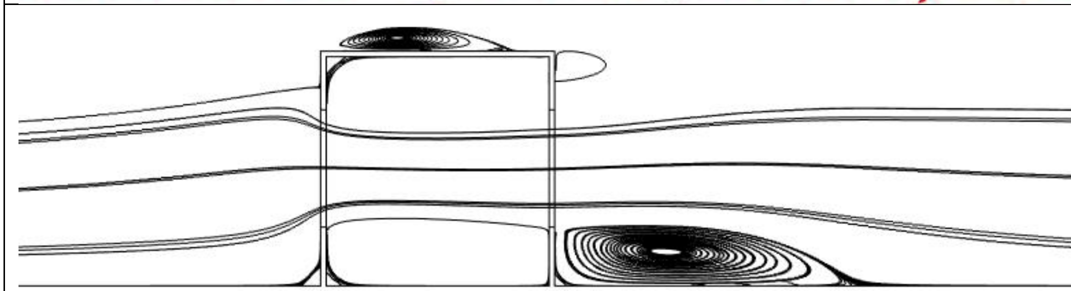


Temperature distribution and max and min temperature

Case 3(ii):



Arrow line inside the room



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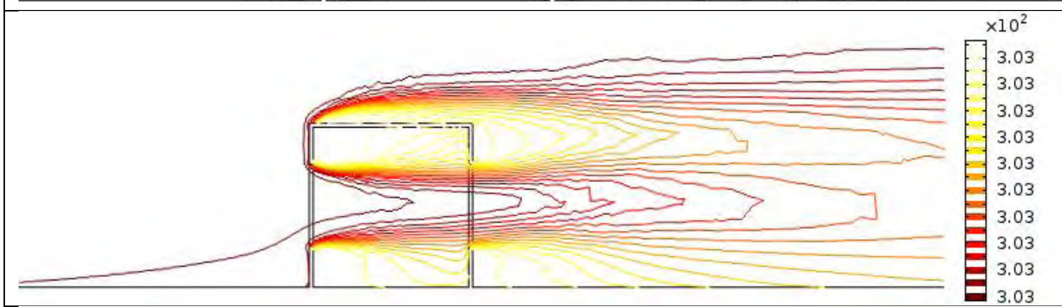
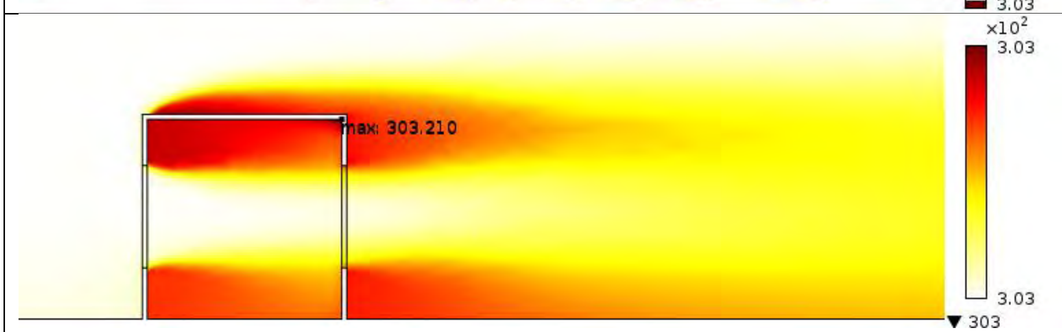


Isothermal contour



Temperature distribution and max and min temperature

Case 4(i):

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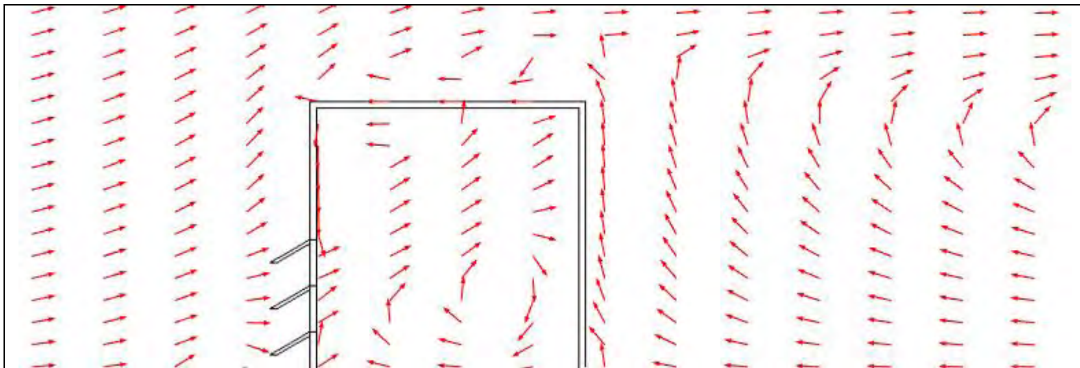
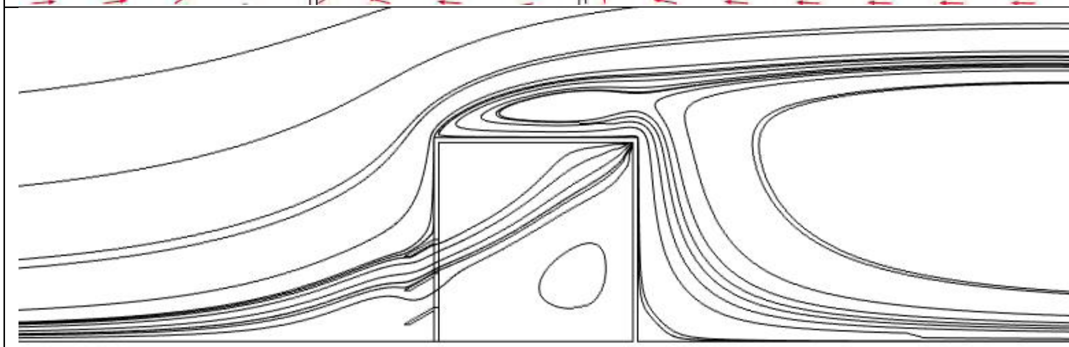
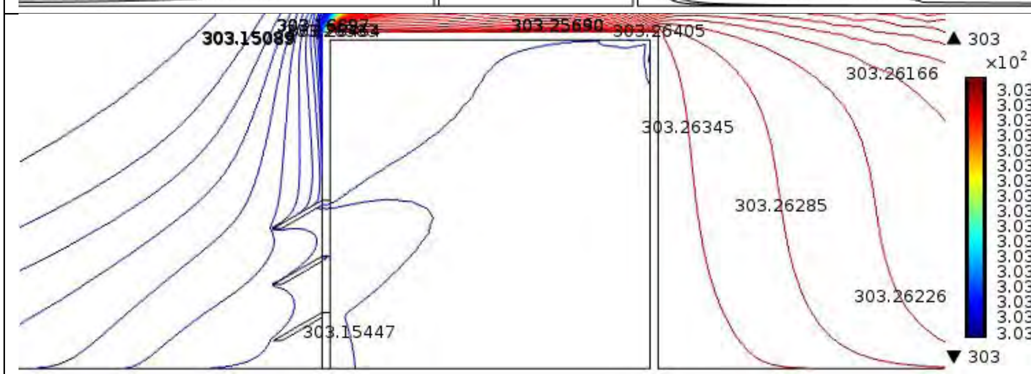
<tr><td></td><td>Arrow line inside the room</td></tr>
<tr><td></td><td>Stream line</td></tr>
<tr><td>
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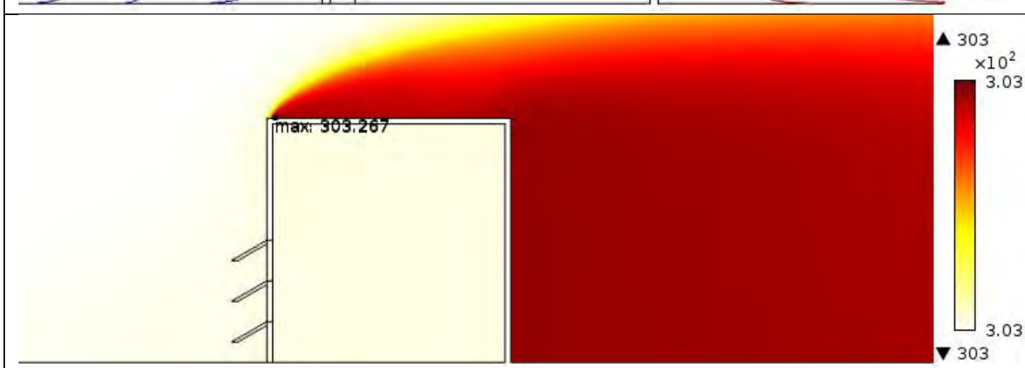
<tr><td>
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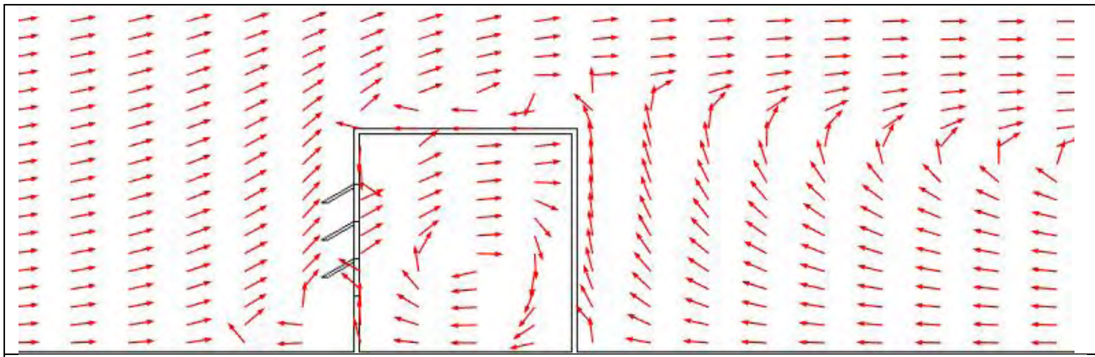
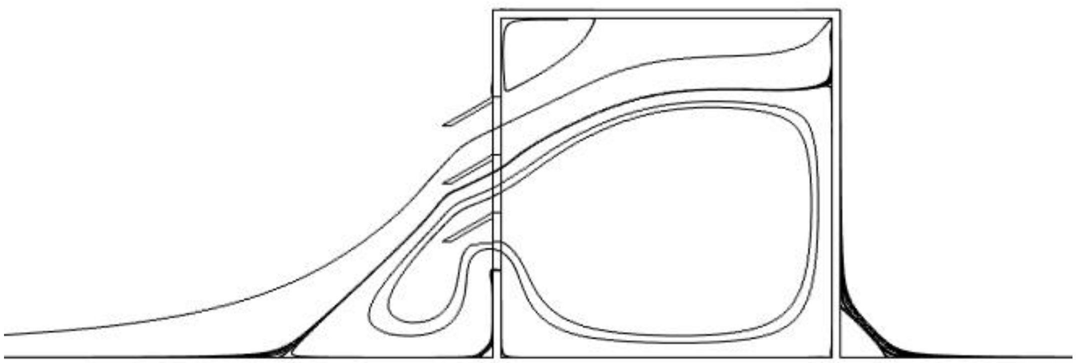
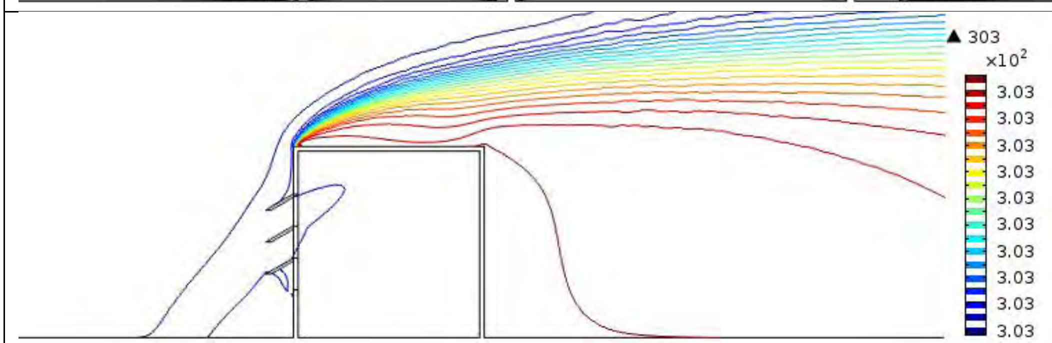
Case 4(ii):



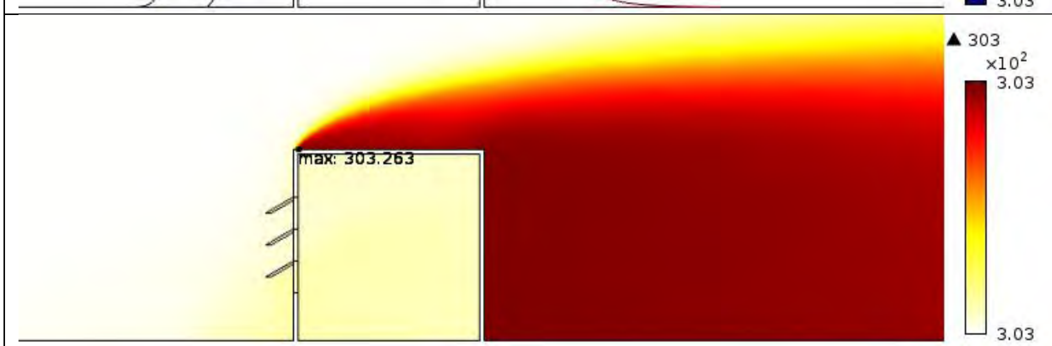
Arrow line inside the room



Stream line

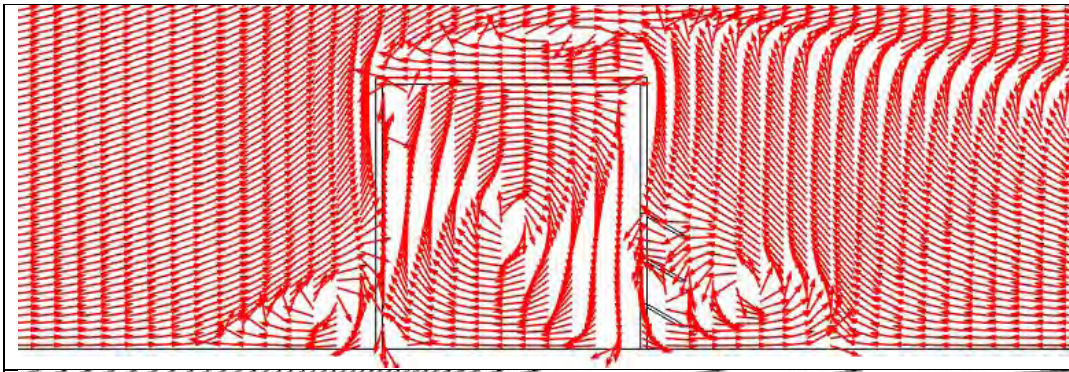


Isothermal contour

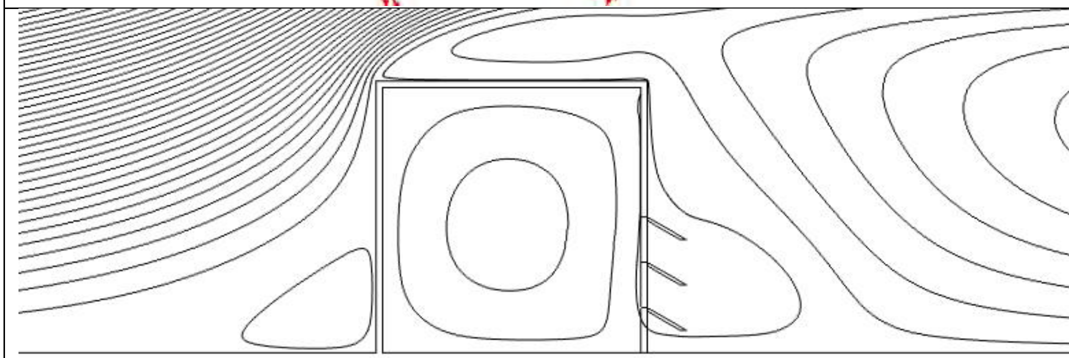


Temperature distribution and max and min temperature

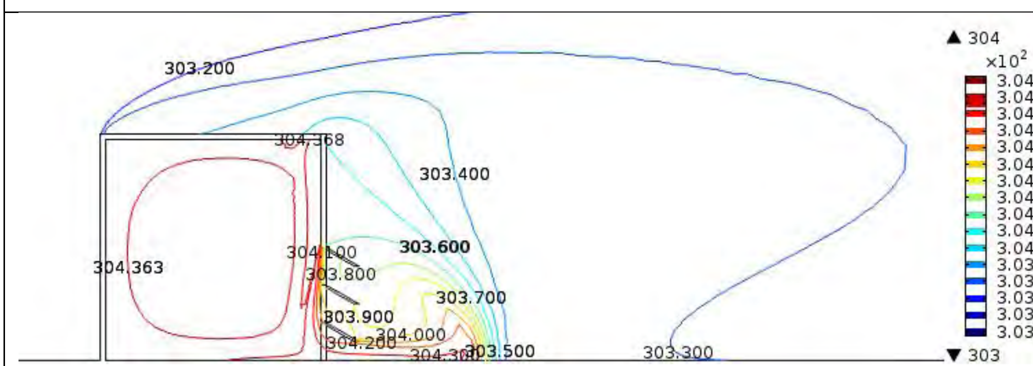
Case 5(i):



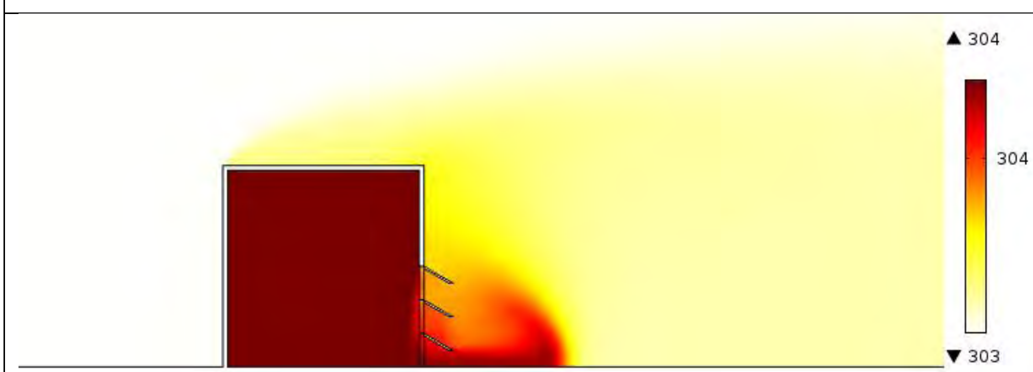
Arrow line inside the room



Stream line

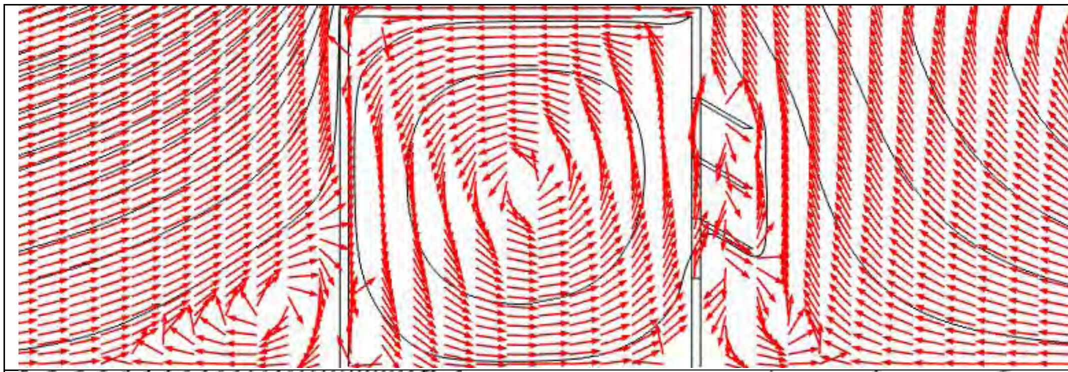
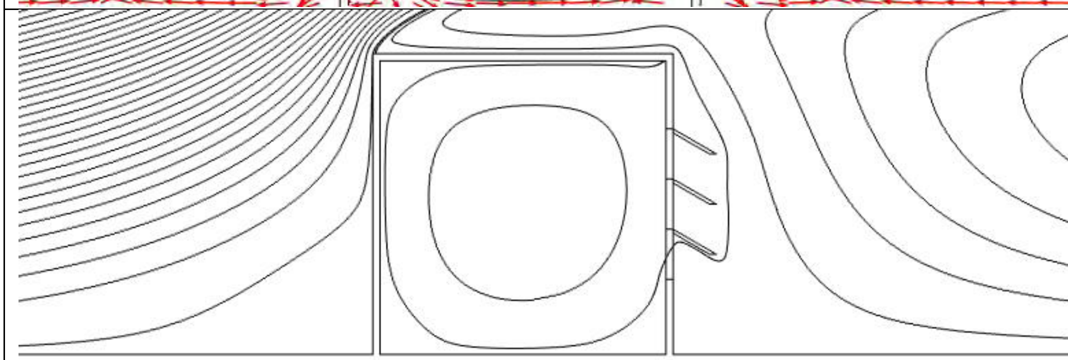
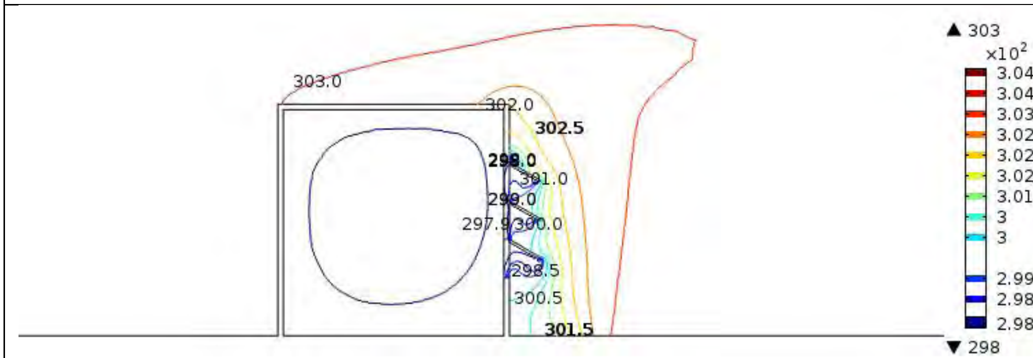
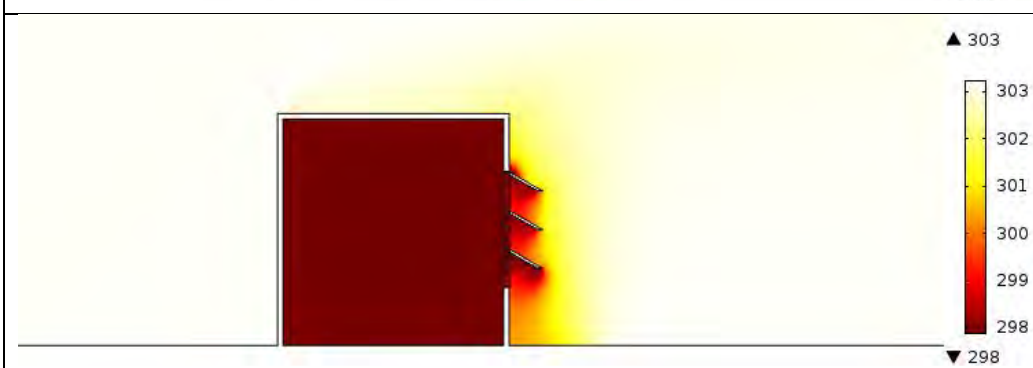


Isothermal contour

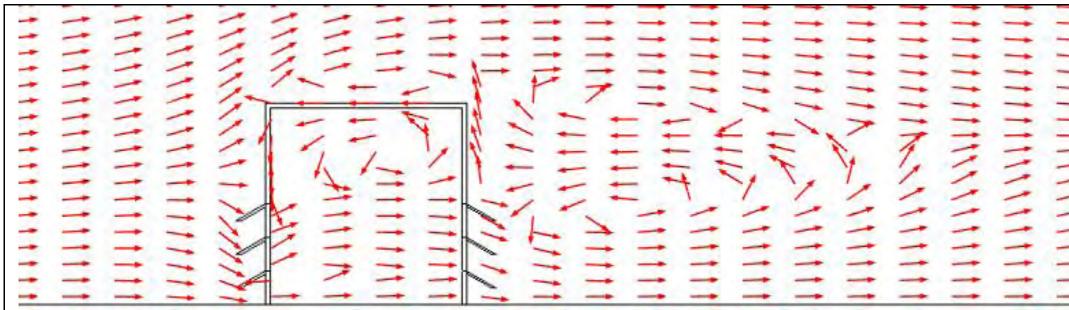
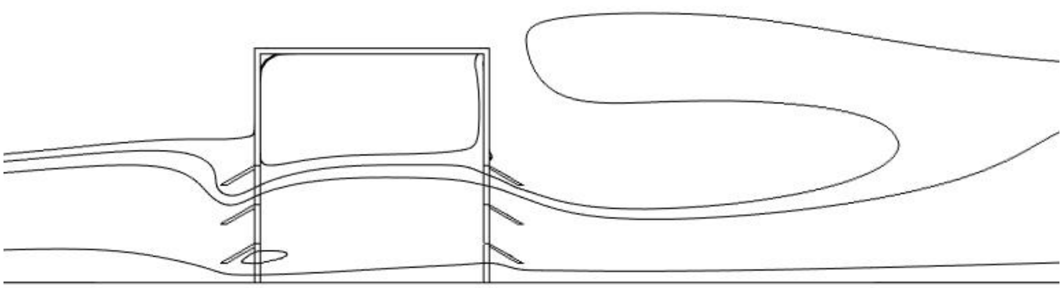
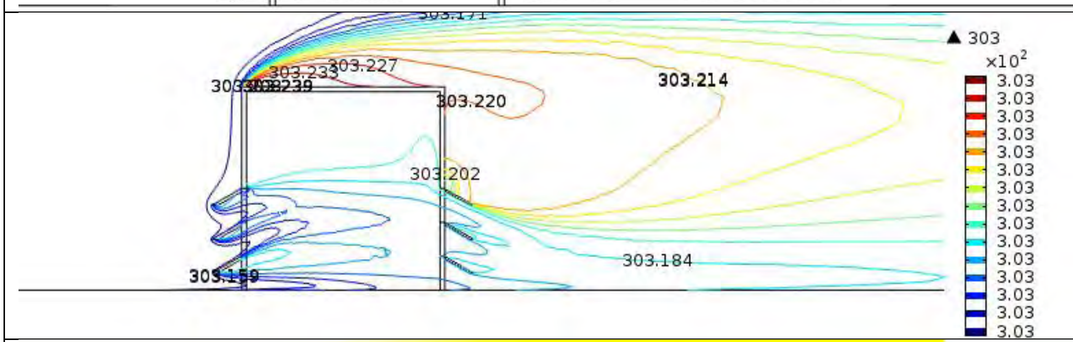
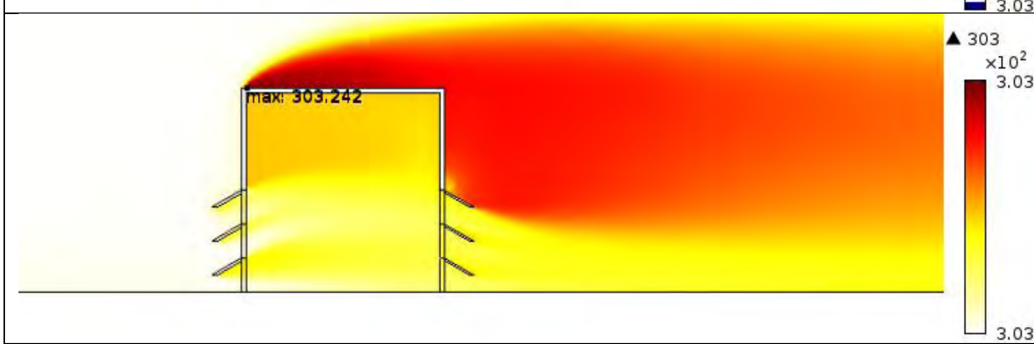


Temperature distribution

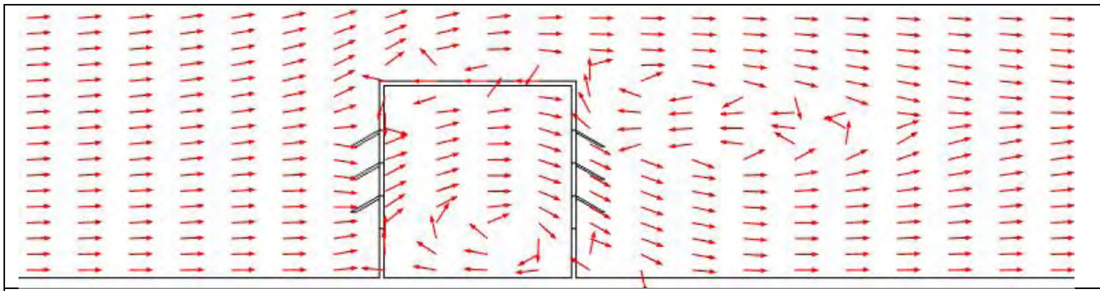
Case 5(ii):

	Arrow line inside the room
	Stream line
	Isothermal contour
	Temperature distribution and max and min temperature

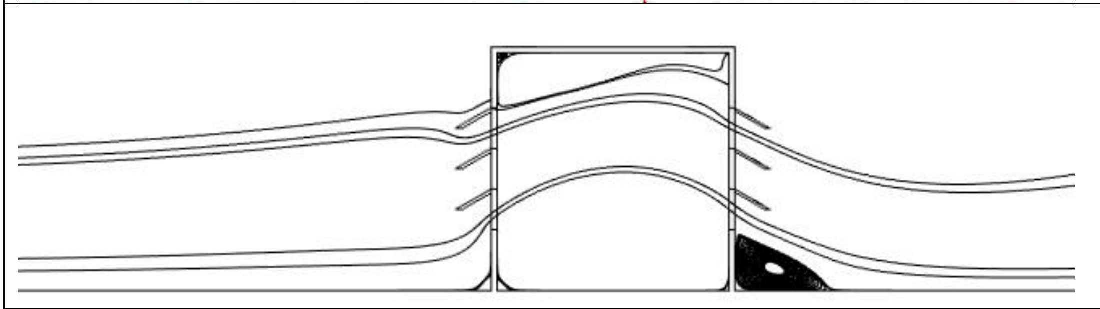
Case 6(i):

	Arrow line inside the room
	Stream line
	Isothermal contour
	Temperature distribution

Case 6(ii):



Arrow line inside the room



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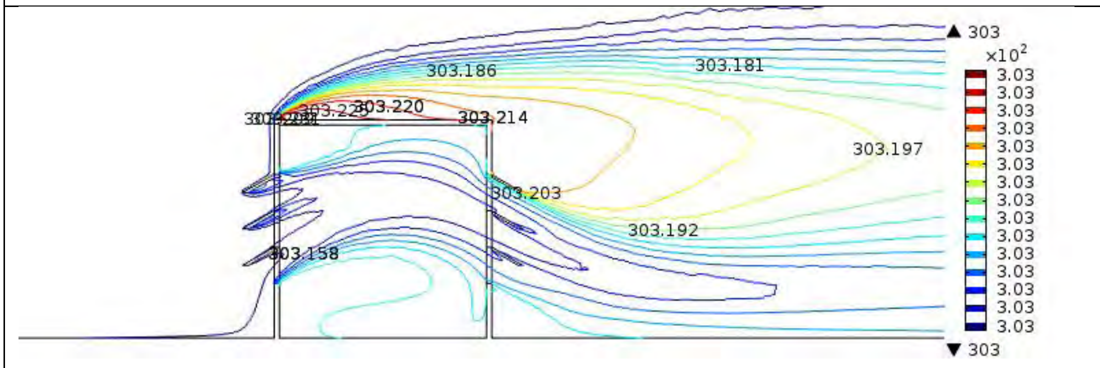
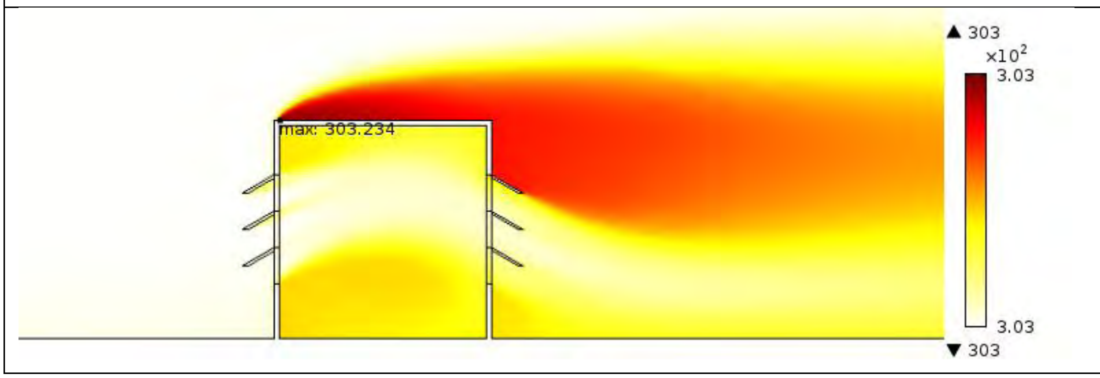


Isothermal contour



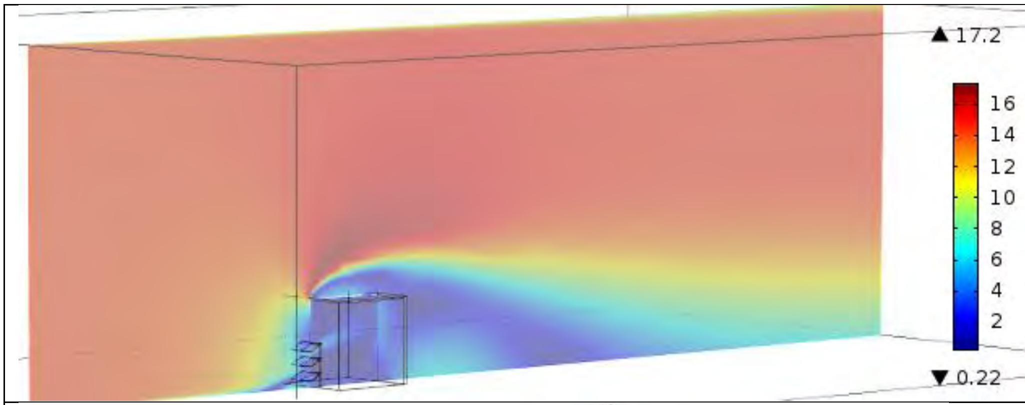
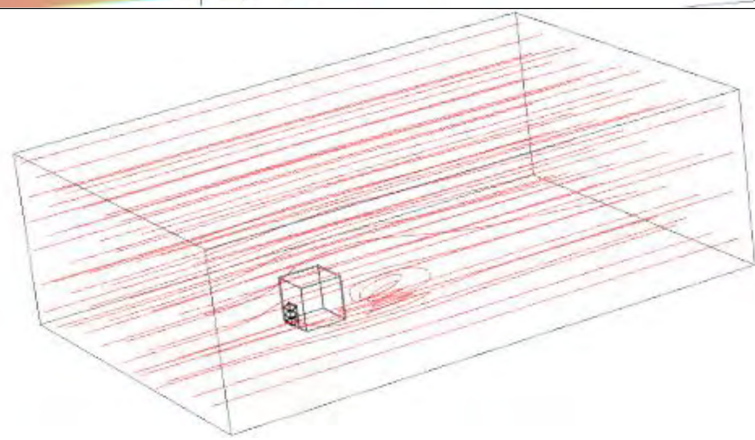
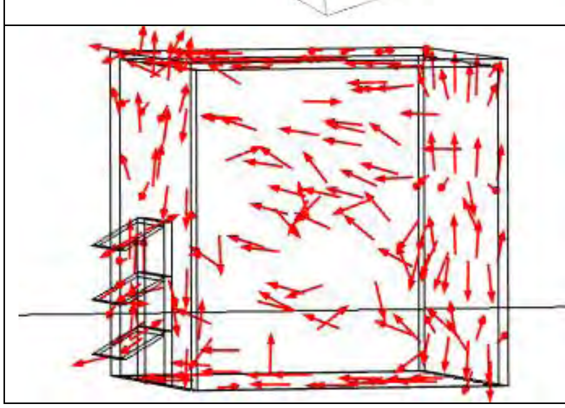
Temperature distribution and max and min temperature

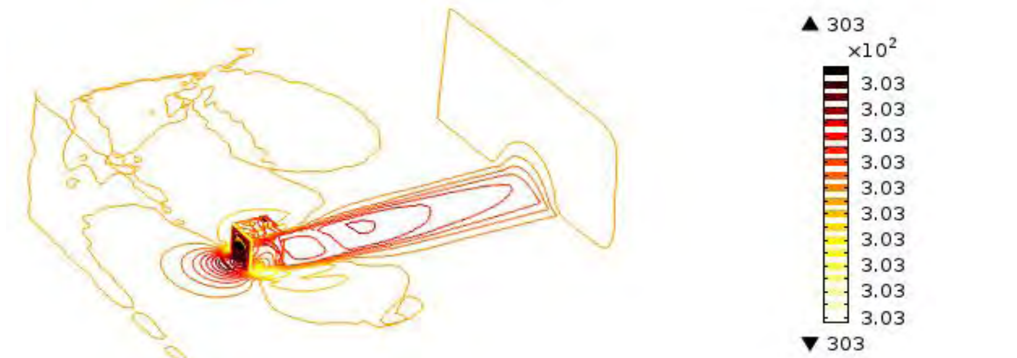
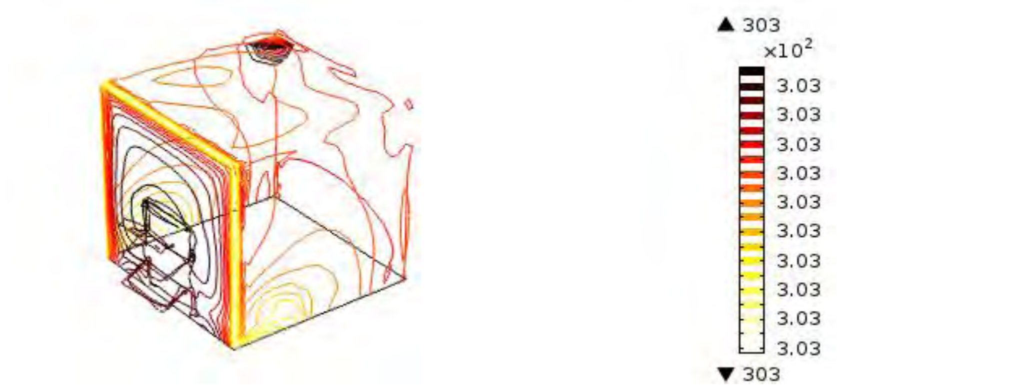
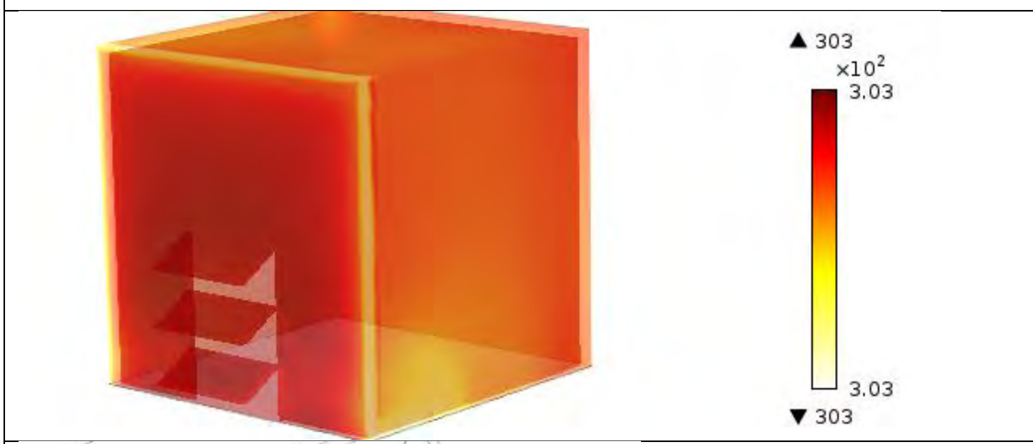
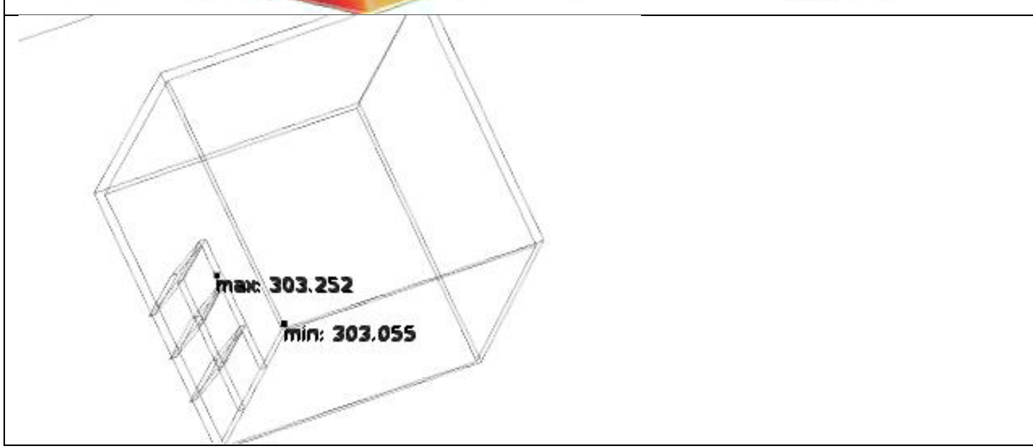
Three dimensional CFD simulation

Three-dimensional CFD simulations were performed in order to get realistic scenario of the flow field within the environment.

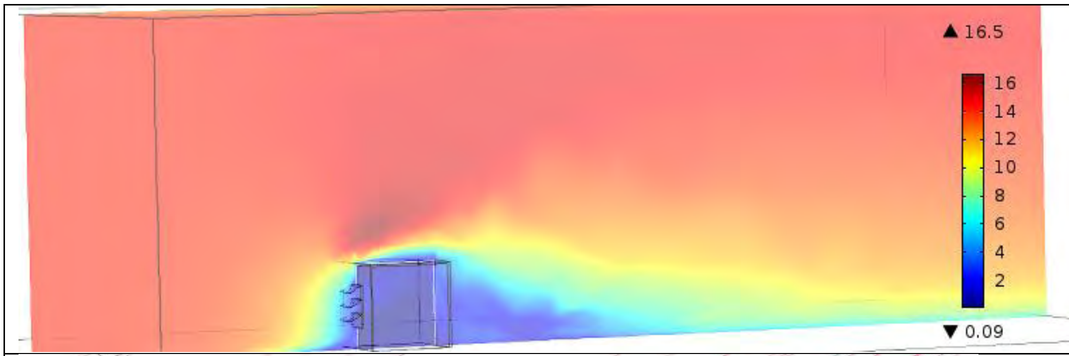
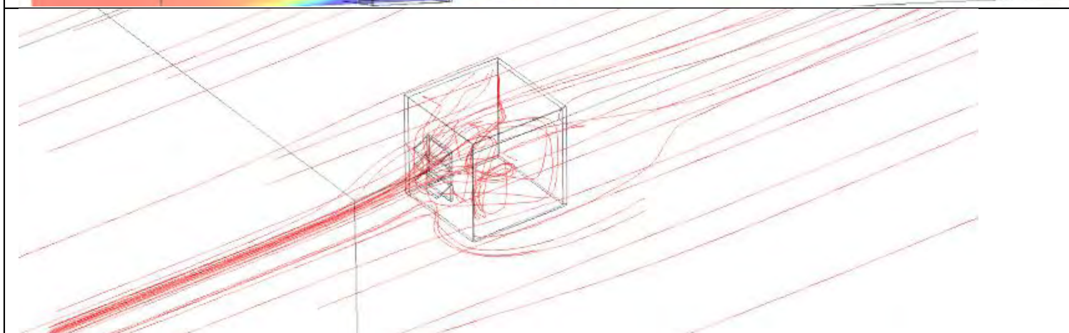
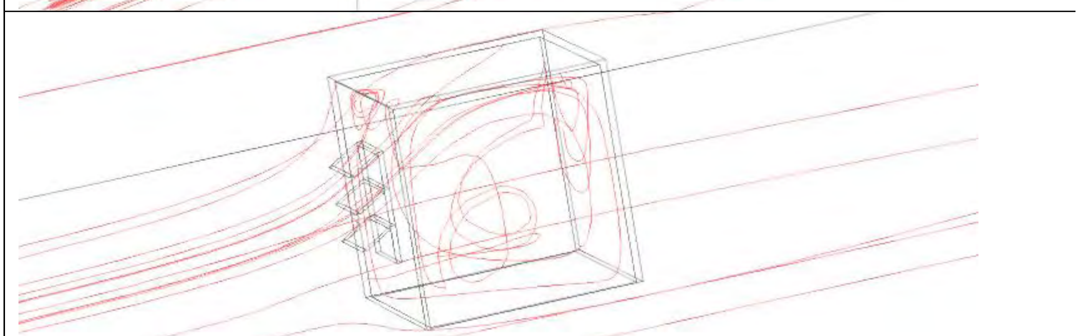
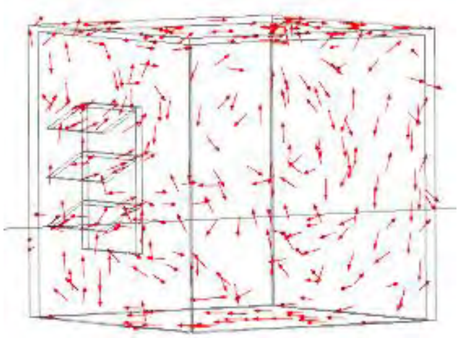
Coupling with Heat

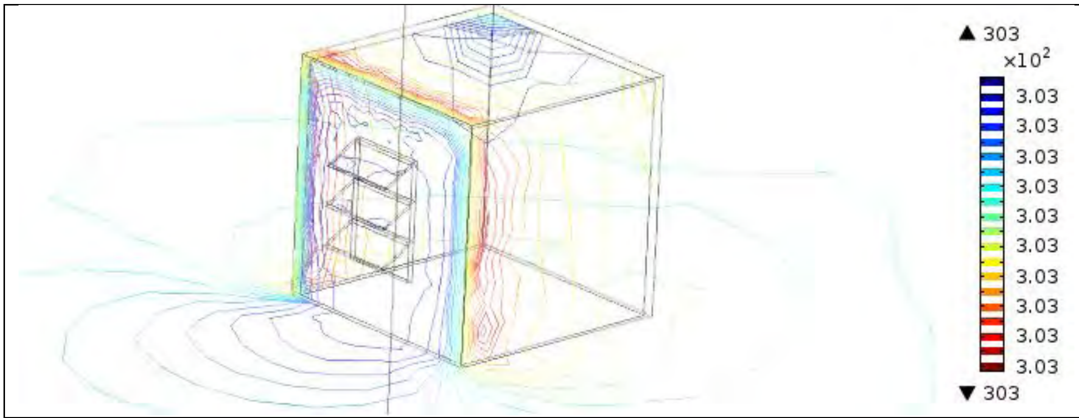
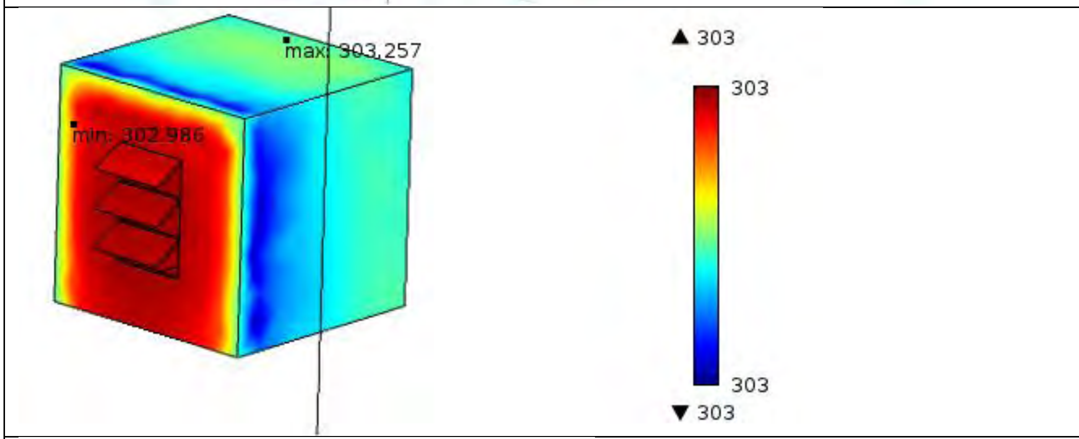
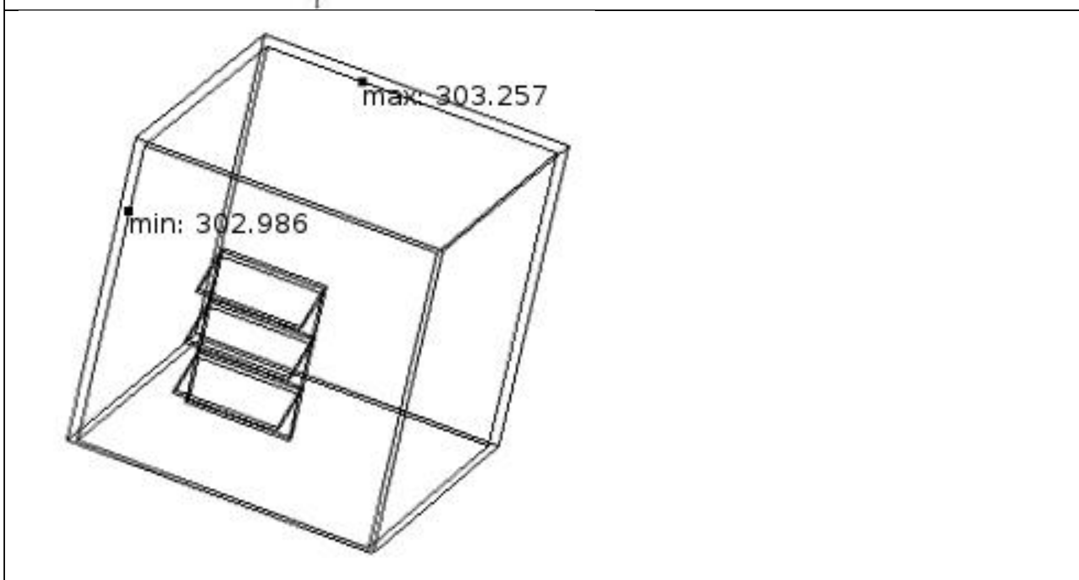
Case 4(i):

	Velocity Surface
	Stream line
	Arrow line inside the room

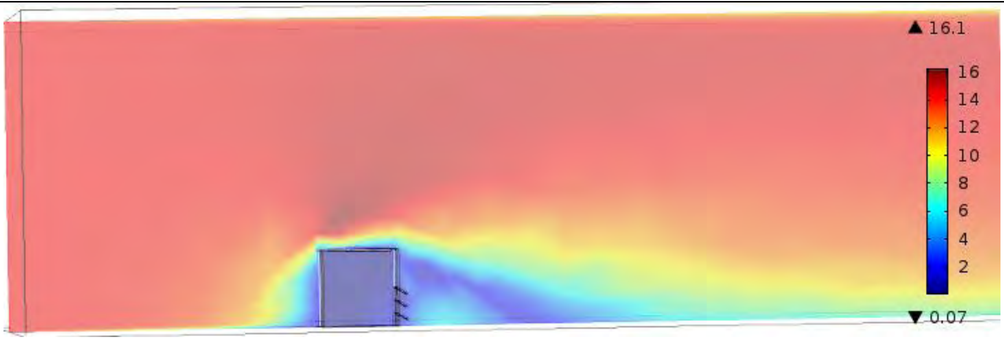
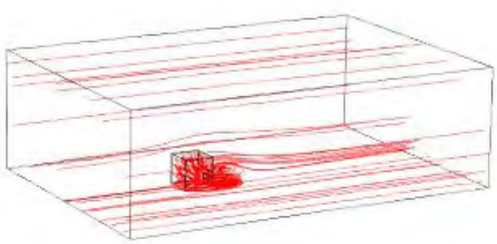
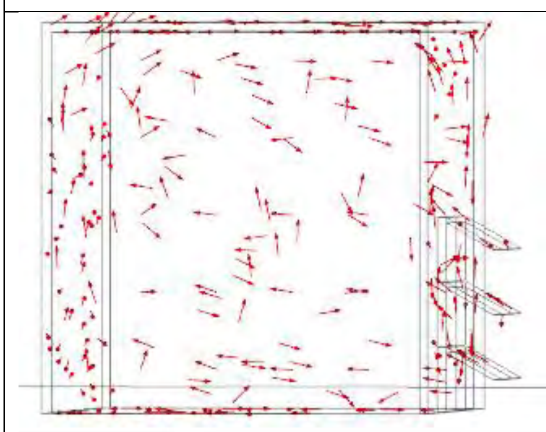
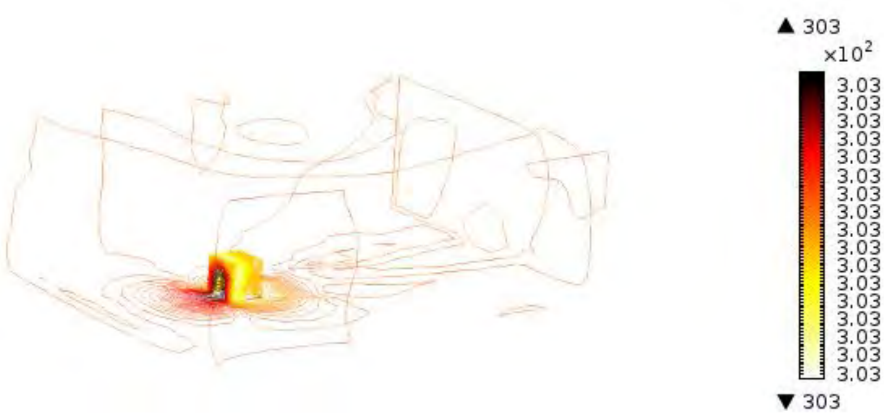
	Isothermal contour on the total environment
	Isothermal contour of the room
	Temperature Distribution inside the room
	Maximum and minimum temperature

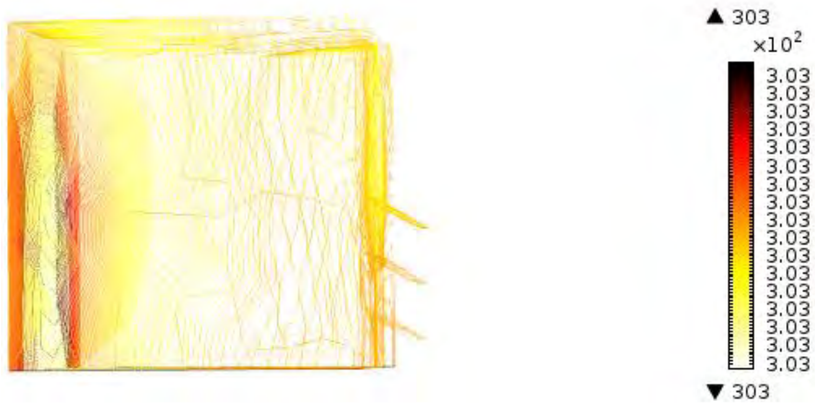
Case 4(ii):

	Velocity Surface
	Stream line
	
	Arrow line inside the room

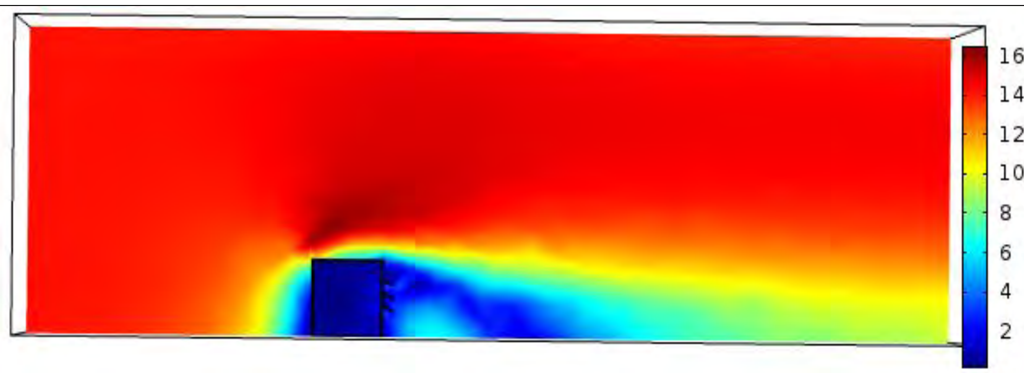
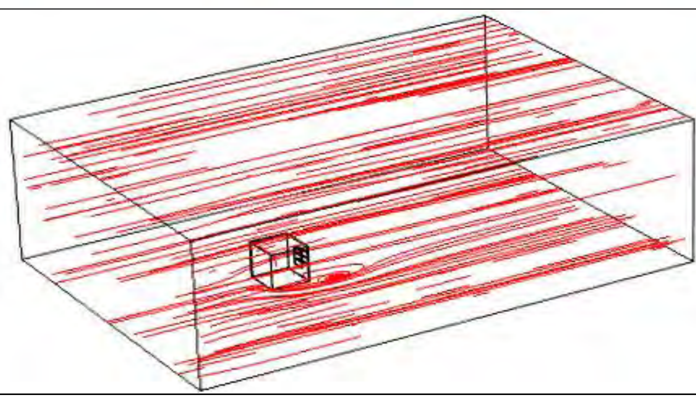
	Isothermal contour on the total environment
	Temperature Distribution inside the room
	Maximum and minimum temperature

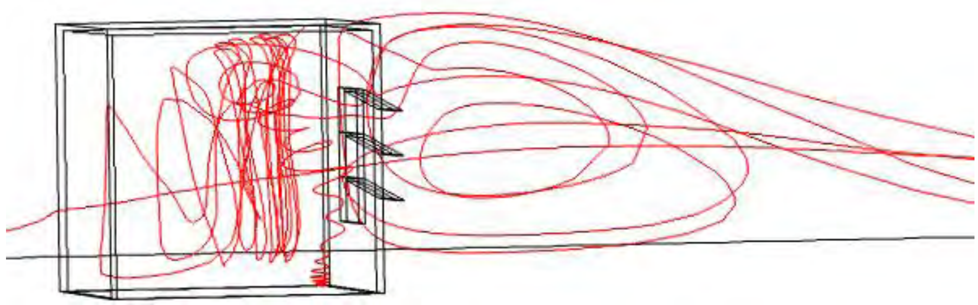
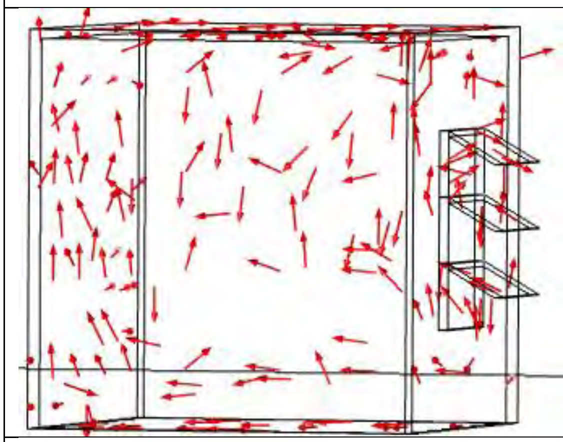
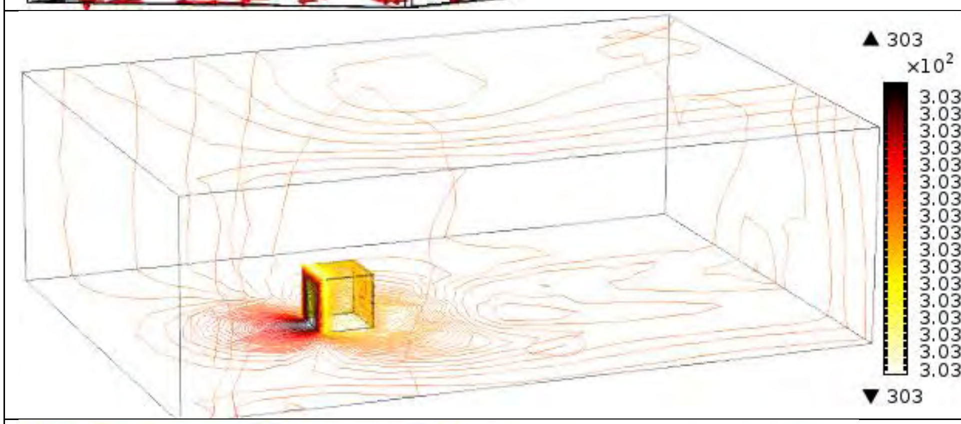
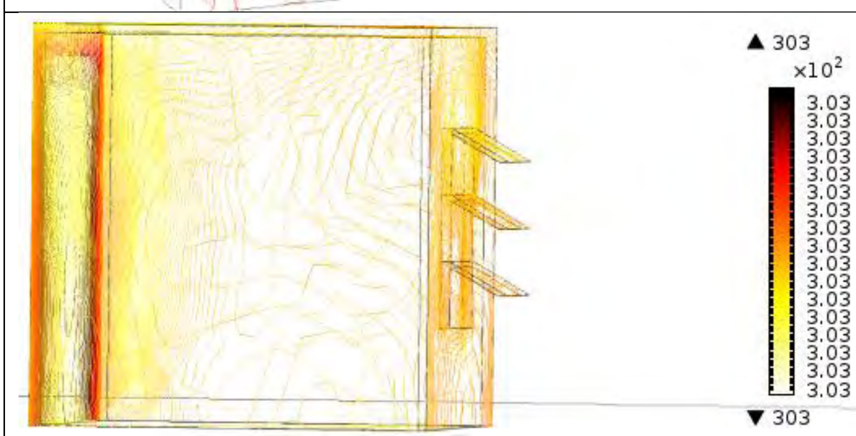
Case 5(i):

	Velocity Surface
	Stream line
	Arrow line inside the room
	Isothermal contour on the total environment

	Isothermal contour of the room
	Temperature Distribution inside the room with max min temperature

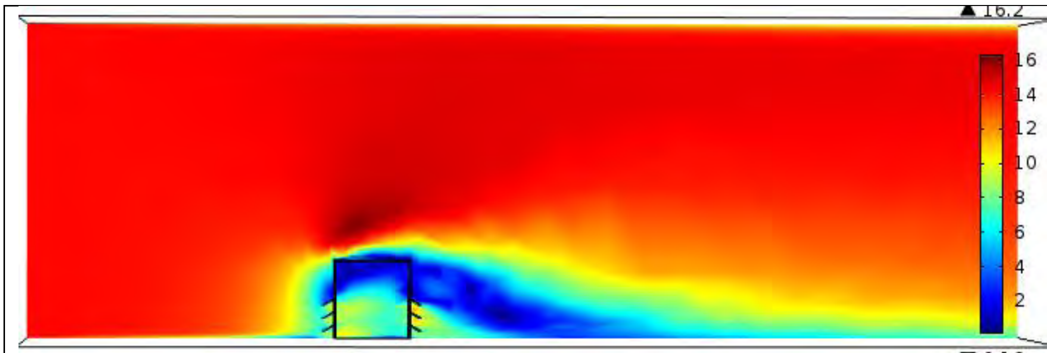
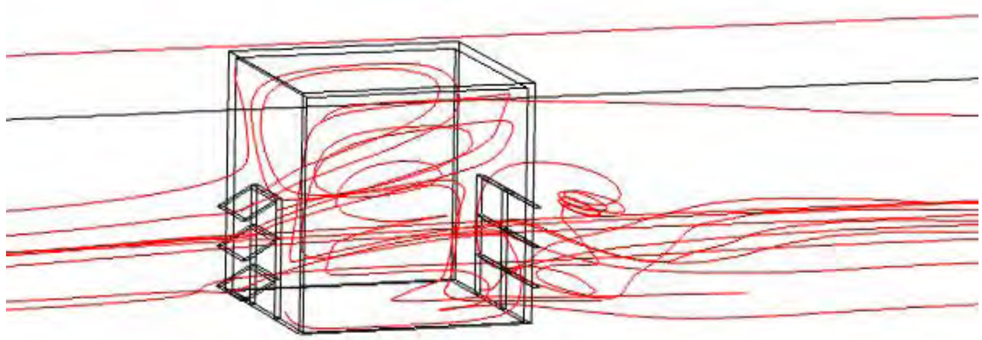
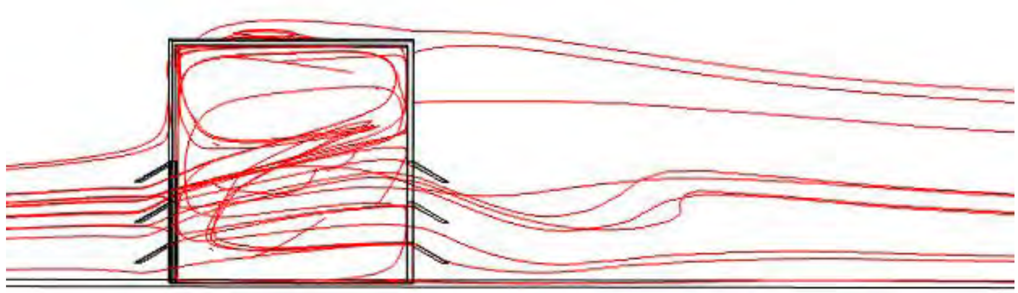
Case 5(ii):

	Velocity Surface
	

	Stream line
	Arrow line inside the room
	Isothermal contour on the total environment
	Isothermal contour of the room

	Temperature Distribution inside the room with max min temperature

Case 6(i):

	Velocity Surface
	Stream line
	

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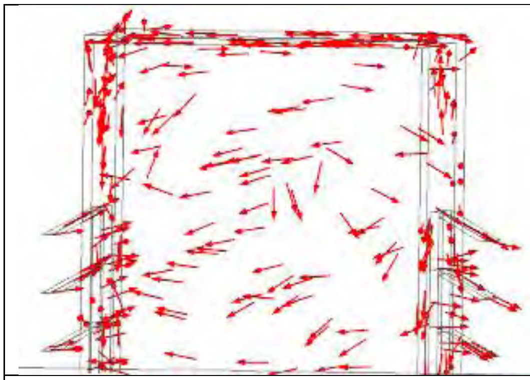
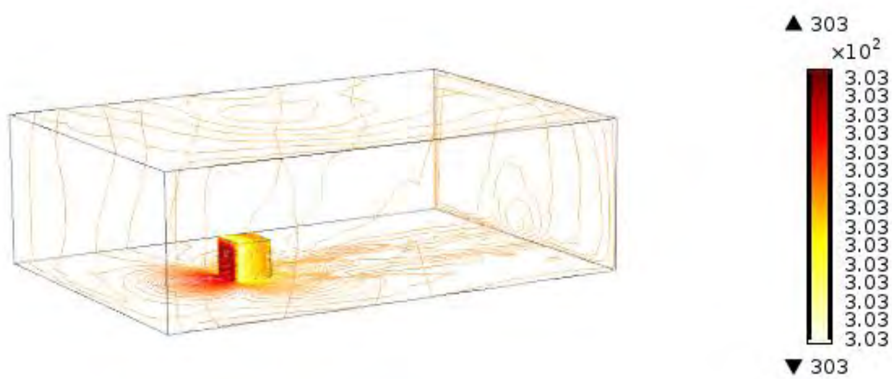
<tr><td></td><td>Arrow line inside the room</td></tr>
<tr><td>
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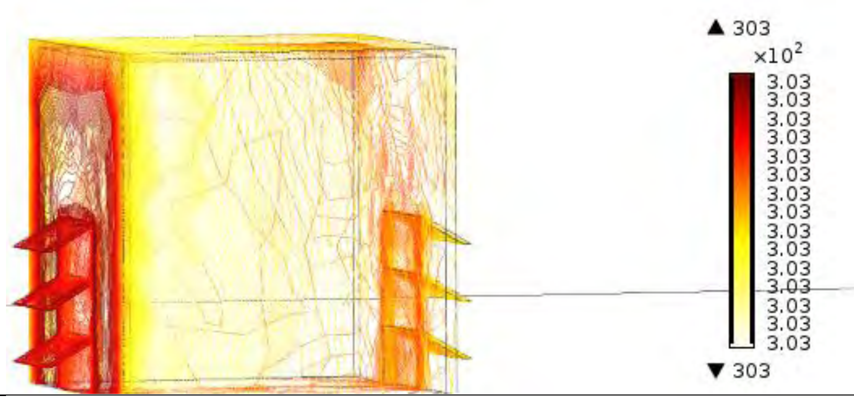
<tr><td>
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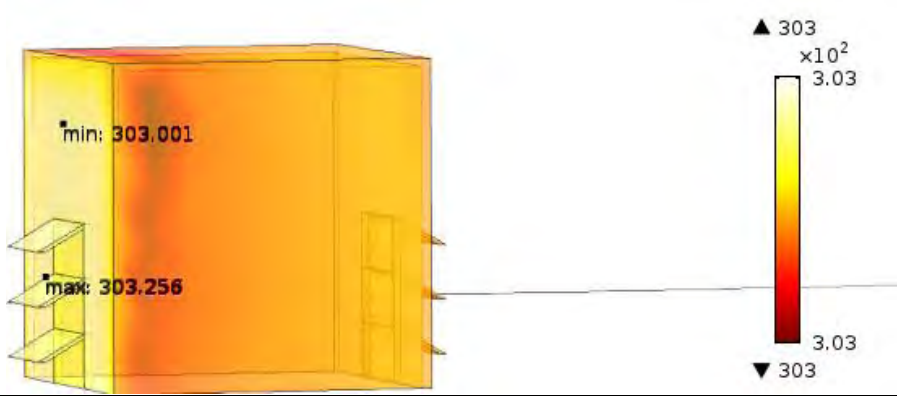
<tr><td>
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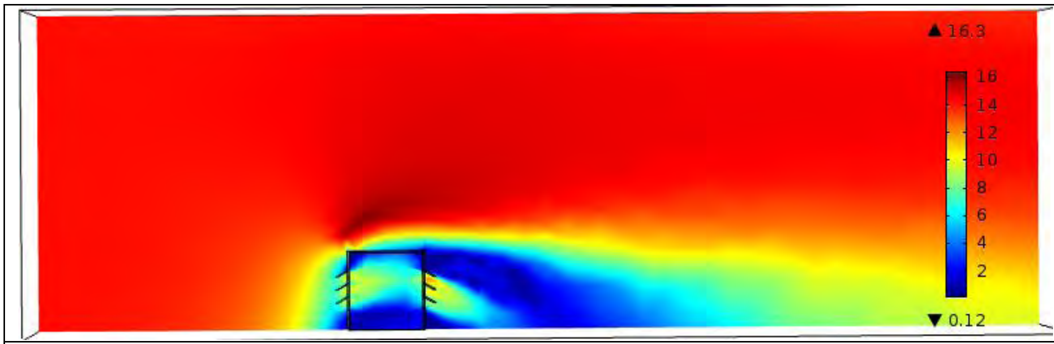
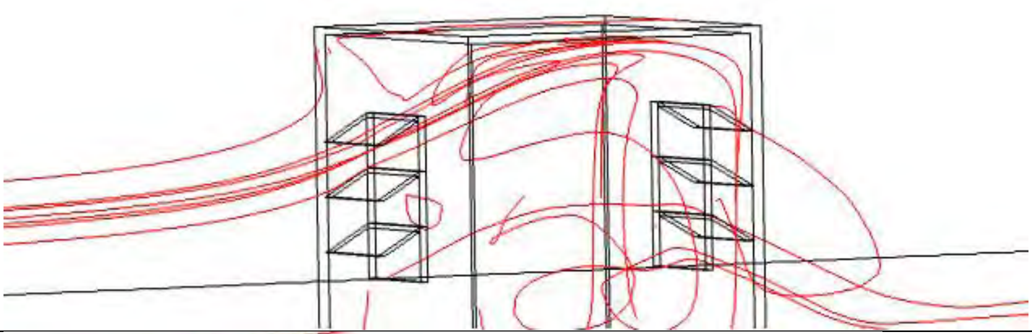
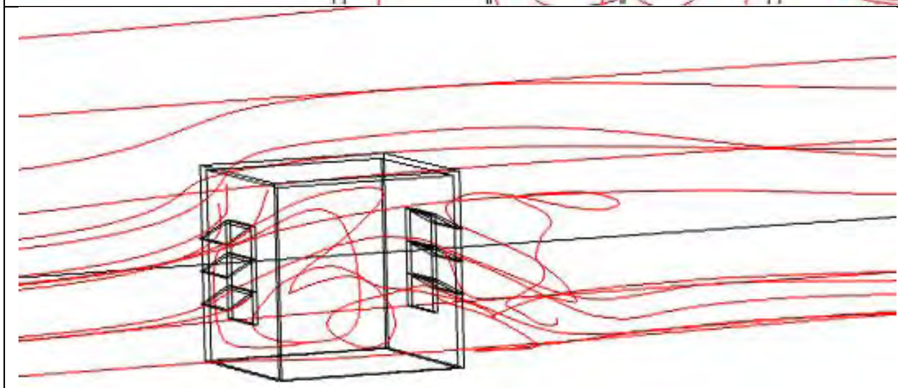
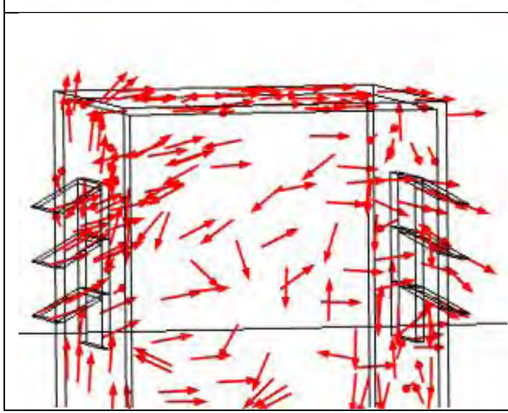
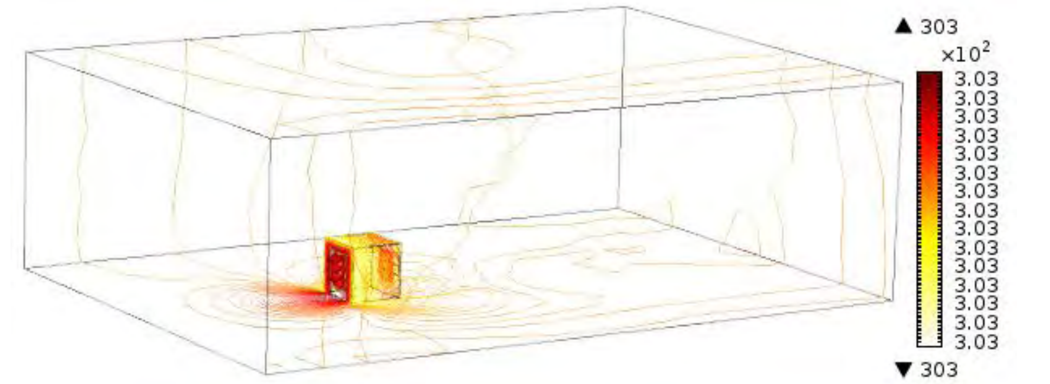
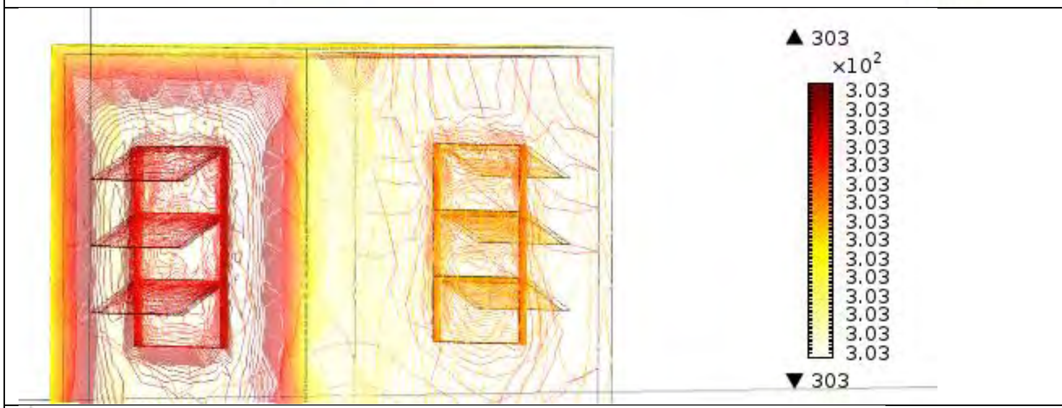
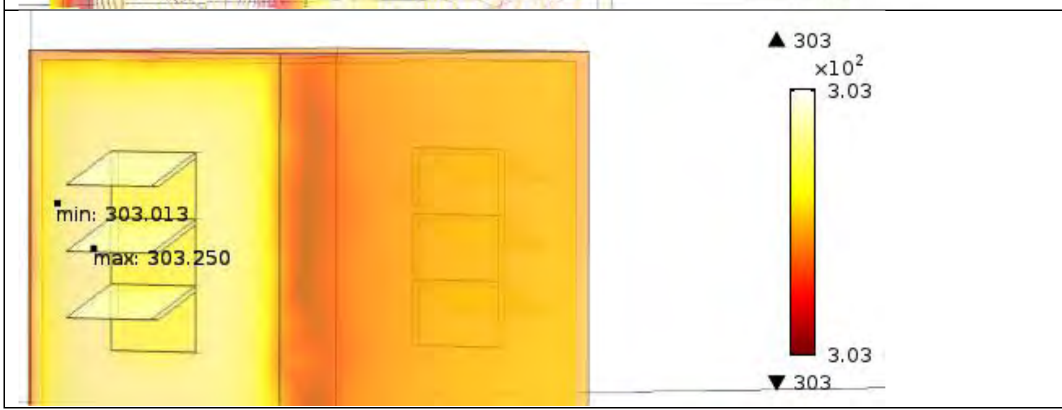
Case 6(ii):

	Velocity Surface
	Stream line
	
	Arrow line inside the room

	Isothermal contour on the total environment
	Isothermal contour of the room
	Temperature Distribution inside the room with max min temperature