Numerical Investigation of Various Passive Control Techniques in Indoor Air Pollution

A Dissertation

Submitted for the partial fulfillment of the requirement for the award of the degree of

MASTER OF ENGINEERING

in

CIVIL ENGINEERING

By

Arunashis Mondal

Examination Roll No- M4CIV22015

Registration No- 131217 of 2015-2016

Under the Supervision of

Dr. Abhisek Roy

Professor. Shibnath Chakrabarty

JADAVPUR UNIVERSITY
FACULTY OF ENGINEERING & TECHNOLOGY
CIVIL ENGINEERING DEPARTMENT
(ENVIRONMENTAL ENGINEERING DIVISION)
KOLKATA – 700032, INDIA

2022

DECLARATION

This Dissertation titled "**Numerical Investigation of Various Passive Control Techniques in Indoor Air Pollution**" is prepared and submitted for the partial fulfillment of the requirements for the award of the degree of **Master of Engineering in Civil Engineering** course of Jadavpur University for the session2020-2021.

Arunashis Mondal

Arunashis Mondal
Roll No: 002010402015
Registration No: 131217 of 2015-2016
Examination Roll No: M4CIV22015

Date: 23/8/2022
Place: Civil Engineering Department
Jadavpur University, Kolkata

Class: M.C.E - 2nd yr
Environmental Engg. Division
Civil Engineering Department

JADAVPUR UNIVERSITY
DEPARTMENT OF CIVIL ENGINEERING
KOLKATA – 700032

RECOMMENDATION CERTIFICATE

*This is to certify that the thesis entitled "**Numerical Investigation of Various Passive Control Techniques in Indoor Air Pollution**" is prepared and submittedby **Arunashis Mondal,** who got his name registered on 21th July, 2015 for the session 2020-2022, for the partial fulfillment of the requirements for the award of **Master of Engineering in Civil Engineering** degree of **Jadavpur University** is absolutely based upon his own work under the supervision of **Dr. Abhisek Roy and Prof. Shibnath Chakrabarty** and that neither his thesis nor any part of this thesis has been submitted for any degree or any other academic award anywhere before.*

Signature of Supervisor

Abhisek Roy

Dr. Abhisek Roy

Asst. Professor
Department of Civil Engineering
Jadavpur University

Assistant Professor
Department of Civil Engineering
Jadavpur University
Kolkata-700 032

Signature of Supervisor

Prof. Shibnath Chakrabarty

Professor
Department of Civil Engineering
Jadavpur University

Head
Department of Civil Engineering
Jadavpur University
Kolkata-700 032

Countersigned by:

23/8/22

Dean

Faculty of Engineering and Technology
Jadavpur University

DEAN
Faculty of Engineering & Technology
JADAVPUR UNIVERSITY
KOLKATA-700 032

Head of the Department

Department of Civil Engineering
Jadavpur University

Head
Department of Civil Engineering
Jadavpur University
Kolkata-700 032

JADAVPUR UNIVERSITY
DEPARTMENT OF CIVIL ENGINEERING
KOLKATA – 700032

CERTIFICATE OF APPROVAL*

This is to certify that this thesis is hereby approved as an original work conducted and presented satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is implied that by this approval the undersigned do not necessarily endorse or approve any statement made, opinion expressed or conclusion drawn therein, but approve the thesis only for the purpose for which it is submitted.

Final Examination for evaluation of thesis

1)..

2)..

3)..
(Signature of Examiners)

*Only in case the thesis is approved.

ACKNOWLEDGEMENT

At the outset I would like to express my deep gratitude and kindest regards to Dr. Abhisek Roy and Prof. Shibnath Chakrabarty for invaluable and generous guidance rendered to me for the preparation of this Thesis report. This Thesis would have never been completed without their guidance, careful supervision and inspiration at all stages of the work.

I am sincerely thankful and indebted to Prof. Somnath Mukherjee, Prof. Anupam Debsarkar, Prof. Tumpa Hazra, and Asst. Prof. Ankush Majumder for their constant encouragement and continuous valuable suggestions throughout my thesis work.

I sincerely acknowledge the help of Mr. Jasimuddin Bag, Mr. Mrityunjoy Banerjee, Mr. Bhaginath Roy and Mr. Pankaj Mandal of Environmental Engineering Laboratory of Civil Engineering Department, Jadavpur University.

I would like to express my appreciation to Asst. Prof. Prasenjit Sanyal, Department of Civil Engineering, Meghnad Saha Institute of Technology; for his constant inspiration adkind supports doing the work.

Last, but not the least, I express my sincere gratitude to my classmates and my family for the encouragements and supports they provided throughout the work. This thesis would not have been possible without them.

Arunashis Mondal.

Arunashis Mondal
Class: M.C.E- 2nd yr.
Environmental Engineering
Roll No: 002010402015
Exam Roll No: M4CIV22015
Registration No: 131217 of 2015-2016

Date: 23/8/2022
Place: Civil Engineering Department
Jadavpur University, Kolkata

Contents

Chapter 1: Introduction:- 7
1.1. Air Pollution: - 7
1.1.1. Air pollution: Definition: - 7
1.1.2. Air Pollution: Episodes: - 8
1.1.3. Air Pollution legislation in India: - 9
1.2. Air Pollutants: - 10
1.2.1. Classification of air pollutants: - 10
1.3. Air Pollution Standards in India: - 12
1.4 Air pollution control: - 13
1.4.1. Types of Air Pollution Control: - 13
1.4.2. Active control of air pollution: - 13
1.4.3. Passive control of air pollution: - 14
1.5. Air pollution modeling: - 15
1.5.1. Types of modeling: - 15
Chapter 2: Literature Review: - 18
2.1. Introduction: - 18
2.2. Air flow distribution strategies: - 18
2.2.1. Introduction: - 18
2.2.2. Various types of Air flow distribution strategies: - 18
2.2.3. Displacement ventilation system: - 19
2.2.4. Mixing Ventilation: - 21
2.2.5. Underfloor Air Distribution System: - 22
2.2.6. Impinging Jet Ventilation: - 23
2.3. Indoor Air Quality: - 24
2.3.1. Introduction: - 24
2.3.2. Indoor Air Pollutants: - 25
2.4. Control of air pollution by passive control: - 25
2.4.1. Introduction: - 25
2.4.2. Various passive control methods: - 26
2.5. Computational Fluid Dynamics (CFD) Modeling in Air pollution: - 31
Chapter 3: Critical Review:- 34
Chapter 4: Objective And Scope of Study:- 35

4.1. Objective- 35
4.2. Scope of Study- 35
Chapter 5: Methodology:- 36
5.1. Numerical simulation- 36
5.2. Computational fluid dynamics (CFD) model- 36
5.3. Meshing- 42
Chapter 6: Validation of Model:- 44
Chapter-7: Results and Discussion:- 47
7.1. Variation of Windows' Position 49
7.2. Applying Green Belt in front of the Guard Room 73
7.3. PM_{10} Concentration Level Comparison between Different Windows' Positions- 97
7.4. PM_{10} Concentration Level Affected by Green Belt- 100
Chapter 8: Conclusion:- 103
Chapter 9: Future Scope of Study:- 107
Chapter 10: References:- 108

LIST OF FIGURES

FIGURE 1 DISPLACEMENT VENTILATION SYSTEM 20
FIGURE 2 DISTRIBUTION IN DISPLACEMENT VENTILATION SYSTEM 20
FIGURE 3 DISPLACEMENT VENTILATION SYSTEM VS MIXING VENTILATION SYSTEM 21
FIGURE 4 UNDER FLOOR AIR DISTRIBUTION SYSTEM (SKISTAD, 2002) 22
FIGURE 5 IMPINGING JET VENTILATION 23
FIGURE 6 IMPINGING JET VENTILATION AND MIXING VENTILATION IN LARGE-HEIGHT SPACES 23
FIGURE 7 TREES AND VEGETATION BARRIER 27
FIGURE 8 USING BOUNDARY WALL TO IMPROVE THE AIR QUALITY IN URBAN AREA 30
FIGURE 9 MATERIAL FOR PHASE-1 40
FIGURE 10 MATERIAL FOR PHASE-2 41
FIGURE 11 GENERAL SETUP 41
FIGURE 12 TOP VIEW OF MODEL 45
FIGURE 13 MESHING OF MODEL 46
FIGURE 14 PM_{10} CONCENTRATION CONTOUR 46
FIGURE 15 TOP VIEW OF THE MODEL 48
FIGURE 16 PICTORIAL VIEW OF OPPOSITE SIDE WINDOWS 49
FIGURE 17 MESHING OF THE MODEL 50
FIGURE 18 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 51
FIGURE 19 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 51
FIGURE 20 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 52
FIGURE 21 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 52
FIGURE 22 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 53
FIGURE 23 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 53
FIGURE 24 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 54
FIGURE 25 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 3 M/S 55
FIGURE 26 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 56
FIGURE 27 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 56
FIGURE 28 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 57
FIGURE 29 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 57
FIGURE 30 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 58
FIGURE 31 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 58
FIGURE 32 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 59
FIGURE 33 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 3 M/S & 5 M/S 60
FIGURE 34 PICTORIAL VIEW OF ADJACENT SIDE WINDOWS 61
FIGURE 35 MESHING OF THE MODEL 62
FIGURE 36 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 63
FIGURE 37 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 63
FIGURE 38 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 64
FIGURE 39 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 64
FIGURE 40 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 65
FIGURE 41 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 65
FIGURE 42 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 66
FIGURE 43 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 3 M/S 67
FIGURE 44 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 68
FIGURE 45 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 68
FIGURE 46 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 69
FIGURE 47 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 69
FIGURE 48 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 70
FIGURE 49 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 70
FIGURE 50 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM 71

FIGURE 51 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 3 M/S & 5 M/S ... 72
FIGURE 52 VIEW OF THE MODEL WITH GREEN BELT ... 73
FIGURE 53 MESHING OF THE MODEL ... 74
FIGURE 54 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 75
FIGURE 55 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 75
FIGURE 56 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 76
FIGURE 57 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 76
FIGURE 58 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 77
FIGURE 59 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 77
FIGURE 60 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 78
FIGURE 61 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 3 M/S ... 79
FIGURE 62 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 80
FIGURE 63 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 80
FIGURE 64 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 81
FIGURE 65 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 81
FIGURE 66 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 82
FIGURE 67 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 82
FIGURE 68 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 83
FIGURE 69 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 3 M/S & 5 M/S ... 84
FIGURE 70 TOP VIEW OF THE MODEL ... 85
FIGURE 71 MESHING OF THE MODEL ... 86
FIGURE 72 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 87
FIGURE 73 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 87
FIGURE 74 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 88
FIGURE 75 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 88
FIGURE 76 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 89
FIGURE 77 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 89
FIGURE 78 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 90
FIGURE 79 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 3 M/S ... 91
FIGURE 80 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 92
FIGURE 81 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 92
FIGURE 82 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 93
FIGURE 83 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 93
FIGURE 84 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 94
FIGURE 85 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 94
FIGURE 86 PM_{10} CONCENTRATION CONTOUR INSIDE THE ROOM ... 95
FIGURE 87 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 3 M/S & 5 M/S ... 96
FIGURE 88 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 3 M/S (DIFFERENT WINDOW POSITION OPPOSITE & ADJACENT SIDE) ... 98
FIGURE 89 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 5 M/S (DIFFERENT WINDOW POSITION OPPOSITE & ADJACENT SIDE) ... 99
FIGURE 90 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 3 M/S (WITH & WITHOUT GREEN BELT) ... 101
FIGURE 91 PM_{10} CONCENTRATION VARIATION (KG/M3) AT 5 M/S (WITH & WITHOUT GREEN BELT) ... 102
FIGURE 92 PM_{10} CONCENTRATION VARIATION (KG/M^3) AT 3 M/S (DIFFERENT WINDOW POSITION OPPOSITE & ADJACENT SIDE) ... 104
FIGURE 93 STREAMLINE AND VELOCITY ALONG +Z AXIS (WIND SPEED-3M/S) ... 105
FIGURE 94 PM_{10} CONCENTRATION VARIATION (KG/M^3) AT 3 M/S & 5 M/S ... 105
FIGURE 95 PM_{10} CONCENTRATION VARIATION (KG/M^3) AT 3 M/S (WITH & WITHOUT GREEN BELT) ... 106

List of Tables

Table 1 NAAQS (India) 2009 12
Table 2 Summary of literature review relating to dispersion of pollutants in the environment based on (Janhall, 2015) 28
Table 3 various types of passive control model 30
Table 4 PM_{10} Concentration Variation at 3m/s 54
Table 5 PM_{10} Concentration Variation when windows are in opposite side at 3m/s & 5m/s 59
Table 6 PM_{10} Concentration Variation when windows are in adjacent side at 3m/s 66
Table 7 PM_{10} Concentration Variation when windows are in adjacent side at 3m/s & 5m/s 71
Table 8 PM_{10} Concentration Variation when windows are in opposite side at 3m/s (With green belt) 78
Table 9 PM_{10} Concentration Variation when windows are in opposite side at 3m/s & 5m/s (With green belt) 83
Table 10 PM_{10} Concentration Variation when windows are in adjacent side at 3m/s (With green belt) 90
Table 11 PM_{10} Concentration Variation when windows are in adjacent side at 3m/s & 5m/s (With green belt) 95
Table 12 Comparison of PM_{10} Concentration Variation when windows are in adjacent and opposite side at 3m/s 97
Table 13 Comparison of PM_{10} Concentration Variation when windows are in adjacent and opposite side at 5m/s 99
Table 14 Comparison of PM_{10} Concentration Variation when windows are in opposite side at 3m/s (With & without green belt) 100
Table 15 Comparison of PM_{10} Concentration Variation when windows are in opposite side at 5m/s (With & without green belt) 102

List of Equations

Equation 1 Continuity equation 36
Equation 2 Momentum equation 36
Equation 3 Energy equation 37
Equation 4 Turbulent energy equation 38
Equation 5 38
Equation 6 38
Equation 7 Mean velocity equation 38
Equation 8 Turbulent dissipation rate equation 38
Equation 9 Turbulent viscosity equation 39

Abstract

A study was conducted based on effectiveness of passive control techniques (changing windows' position and applying green belt) in Guard Room (Gate No. 3) of Jadavpur University, Kolkata, India. A computational fluid dynamics (CFD), steady state computational model was used to investigate and predict the typical pollutant concentration level inside the room. PM_{10} was considered as air pollutant and tried to mitigate PM_{10} concentration level inside the room with the help of two passive control techniques. Two different wind speeds and critical wind angles were considered. It was found that if wind speed is increased, the pollution concentration inside the room also increased. Apart from that when wind angle was considered as 0º (in this case wind can directly enter into the room), pollution concentration inside the room was much more than other wind angle cases. It was also observed that applying green belt is the very useful passive control technique to reduce the pollutant concentration inside the room.

Chapter 1: Introduction:-

1.1. Air Pollution: -

Air Pollution is the presence in the atmosphere of substances or substances added directly or indirectly, generally by anthropogenic activity in such quantity and of such duration that those may affect or try to affect human beings, animals, species, vegetation, climates, materials etc. adversely.

Air pollution kills an estimated seven million people worldwide every year. **World Health Organization (WHO)** data shows that 9 out of 10 people breathe air that exceeds **WHO** guideline limits containing high levels of pollutants, with low- and middle-income countries suffering from the highest exposures (WHO, 2021). From smog hanging over cities to smoke inside the home, air pollution poses a major threat to health and climate. The combined effects of household and ambient (outdoor) air pollution cause about seven million premature deaths every year, largely as a result of increased mortality from stroke, heart disease, chronic obstructive pulmonary disease, lung cancer and acute respiratory infections.

1.1.1. Air pollution: Definition: -

As per **Organization of Economic Cooperation & Development (OECD)**, 'Air Pollution is the presence of contaminants or pollutant substances in the air that do not disperse properly and that interferes with human health or welfare, or produces other harmful environmental effects' (OECD, 1997).

As per **WHO**, 'Air Pollution is the contamination of the indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere' (WHO, 2021).

As per **H W Parker**, 'Air Pollution may be defined as the presence in the atmosphere of any substance (or combination of substances), that is detrimental to human health and welfare, offensive or objectionable to man, either externally or internally, or which by its presence will directly or indirectly adversely affect welfare of man'.

1.1.2. Air Pollution: Episodes: -

Air pollution episode is the combined effect of emissions and meteorology that gives rise to high levels of air pollution over a large area. Some examples of air pollution episodes are (Wikipedia):

a) 1930 Meuse Valley Episode:

The 1930 Meuse Valley fog happened because of industrial air pollution and climatic conditions in December that year. It killed 60 people in Belgium and approx. 6000 people became ill.

b) 1939 Saint Louis Episode:

The 1939 St. Louis smog was a severe smog episode that affected St. Louis, Missouri on November 28, 1939. Visibility was so limited that streetlights remained lit throughout the day and motorists needed their headlights to navigate city streets.

c) 1948 Donora Episode:

In 1948 Donora smog killed 20 people and caused serious respiratory problems for approx. 7,000 of the 14,000 people in Donora, Pennsylvania.

d) 1952 London Episode:

It is called Sulphur smog. Because of that smog up to 4,000 people had died and 100,000 more were made ill.

e) 1997 Indonesian forest fires Episode:

A group of forest fires occurred in 1997 in Indonesia. For those fires many South Asian countries like Myanmar, Sri Lanka, Vietnam etc. are seriously affected.

f) 2005 Malaysian Haze Episode:

It happened in Malaysia and Indonesia.

g) 2006 Southeast Asian Haze Episode:

The 2006 Southeast Asian haze was caused by uncontrolled burning from "slash and burn" cultivation in Indonesia, and affected several countries in the Southeast Asian region.

h) 1984 Bhopal Gas Tragedy Episode:

Over 500,000 people were exposed to methyl isocyanate (MIC) gas. A government affidavit in 2006 stated that the leak caused 558,125 injuries, including 38,478 temporary partial injuries and approximately 3,900 severely and permanently disabling injuries. Others estimate that 8,000 died within two weeks, and another 8,000 or more have since died from gas-related diseases.

1.1.3. Air Pollution legislation in India: -

a) 1981- The Air (Prevention and Control of Pollution) Act.
b) 1982- The Air (Prevention and Control of Pollution) Rules.
c) 1983- The Air (Prevention and Control of Pollution) (Union Territories) Rules.
d) 1994- Establishment of air quality standard (NAAQS) in India. Six air pollutants, SO_2, NO_x as NO_2, CO, suspended particulate matter (SPM), respirable particulate matter (RPM) and Pb were included in the said standard.
e) 1998- NAAQS was revised. It included NH3 as criteria air pollutant.
f) 2009- Current NAAQS in India.

1.2. Air Pollutants: -

As per **OECD**, 'Air Pollutants are substances in air that could at high enough concentrations harm human beings, animals, vegetation or material'.

Air pollutants may thus include forms of matter of almost any natural or artificial composition capable of being airborne. They may consist of solid particles, liquid droplets or gases or combinations of three forms.

1.2.1. Classification of air pollutants: -

Air pollutants are numerous, each with its own unique characteristics. It is usual to have these air pollutants classified by some design. Classification allows for the study of pollutants in sub-groups on the basis of some common characteristic of interest or concern. Some basis of classification:

a) Method of entry into atmosphere
b) Physical state of the pollutant
c) Chemical composition
d) Nature of the problem/health threat posed by the pollutant

a) Classification according to the 'Method of entry into the atmosphere': -

i) Primary air pollutant: -

Primary air pollutants are those air pollutants which are emitted into the atmosphere directly from identifiable sources, e.g., CO, NO, SO_2, primary particulate etc.

ii) Secondary air pollutants:

Secondary air pollutants are those air pollutants which are formed as a result of some reaction in the atmosphere. This reaction may occur between any combination of precursory air pollutants and/or natural components of the atmosphere e.g., NO_2, trop. O_3, H_2SO_4, HNO_3, PAN (peroxyacetyl nitrate), secondary particulate etc.

b) Classification according to the 'Physical state of pollutants': -

i) Gaseous pollutant: -

Most air pollutants (>90%) exhibit gaseous properties. They obey gas laws.

ii) Particulate pollutants: -

Any pollutant that is not gaseous is defined as a particulate pollutant, where they exist in the form of finely divided solids or liquids.

c) Classification according to 'Chemical composition': -

i) Organic (CH_4, C_6H_6, $C_{20}H_{12}$ etc.)
ii) Inorganic (CO, SO_2, NO_x etc.)

d) Classification according to the 'nature of problem or health threats': -

i) Criteria air pollutants: -

Criteria air pollutant is a term used internationally to describe air pollutants that have been regulated and are used as indicators of air quality. Criteria air pollutants are air pollutants for which a National Ambient Air Quality Standard (NAAQS) has been established. CO, SO_2, NH_3, PM2.5, PM10, Trop O_3 etc. are some criteria air pollutants.

ii) Non-criteria air pollutants: -

There are many air pollutants than criteria air pollutants, for which emission limits from industrial sources are set. Those are termed as non-criteria air pollutants.

iii) Hazardous air pollutants.

1.3. Air Pollution Standards in India: -

Pollutant	Time Weighted Average	Concentration in Ambient Air	
		Industrial, Residential, Rural and Other Areas	Ecologically Sensitive Area (notified by Central Govt.)
Sulphur Dioxide (SO_2), µg/m^3	Annual* 24 hours**	50 80	20 80
Nitrogen Dioxide (NO_2), µg/m^3	Annual* 24 hours**	40 80	30 80
Particulate Matter (size less than 10 µm) or PM_{10}, µg/m^3	Annual* 24 hours**	60 100	60 100
Particulate Matter (size less than 2.5 µm) or $PM_{2.5}$, µg/m^3	Annual* 24 hours**	40 60	40 60
(Tropospheric) Ozone (O_3), µg/m^3	8 hours* 1 hour**	100 180	100 180
Lead (Pb) µg/m^3	Annual* 24 hours**	0.50 1.0	0.50 1.0
Carbon Monoxide (CO), *mg/m^3*	8 hours* 1 hour**	02 04	02 04
Ammonia (NH_3), µg/m^3	Annual* 24 hours**	100 400	100 400
Benzene (C_6H_6), µg/m^3	Annual*	5	5
Benzo(a)Pyrene (BaP)- particulate phase only, *ng/m^3*	Annual*	1	1
Arsenic(As), *ng/m^3*	Annual*	6	60
Nickel (Ni), *ng/m^3*	Annual*	20	20

* Annual arithmetic mean of minimum 104 measurements in a year at a particular site taken twice a week 24 hourly at uniform intervals.
** 24 hourly or 8 hourly or 1 hourly monitored values, as applicable, shall be complied with 98% of the time, they may exceed the limits but not on two consecutive days of monitoring.
Source: National Ambient Air Quality Standards, Central Pollution Control Board Notification in the Gazette of India, Extraordinary, New Delhi, 18th November, 2009

Table 1 NAAQS (India) 2009

Current NAAQS of India was on 18th November, 2009 by CPCB. Prior to this, India set air quality standards first on 11th April 1994. Six air pollutants, SO_2, NO_x as NO_2, CO, suspended particulate matter (SPM), respirable particulate matter (RPM) and Pb were included in the said standard. NAAQS was revised first on 14th October, 1998 to include NH_3 as a criteria air pollutant.

1.4 Air pollution control: -

According to WHO, 4-8% of deaths occurring annually in the world are related to air pollution (Kathuria, 2002). Most of the air pollution sources are anthropogenic.

Water and air are very important things for human beings, animals, vegetation etc. The air on earth has approx. 21% oxygen, 78% nitrogen and small amounts of CO_2, SO_2 etc.

Air pollution started during the time of uncontrolled coal burning. After that due to urbanization the number of industries and vehicles increased. So, the amount of air pollutants (CO, CO_2, SO_4, NH_3, NO_X, $PM_{2.5}$, PM_{10} etc.) in the air is increasing day by day. These include adverse effects on human health, property, and atmospheric visibility.

So, air pollution control is required. Air pollution control is the technique employed to reduce or eliminate the emission into the atmosphere of substances that can harm the environment or human health.

1.4.1. Types of Air Pollution Control: -

Air pollution control has two types.

a) Active control of air pollution.
b) Passive control of air pollution.

1.4.2. Active control of air pollution: -

First of all, it is important to try to reduce the source of air pollution. If it can be done then the pollution load will be reduced. Sometimes other methods of generation of products are chosen to minimize the pollution load in air. So, source reduction study is one of the important parts of active control of air pollution.

Beside that many control devices are used in industries or vehicles to treat the emitted air to the atmosphere.

Some control devices for particulate contaminants:

a) Gravitational settling chamber
b) Inertial Collector

c) Centrifugal collector

d) Scrubbers or Wet collectors

e) Fabric filter

f) Electrostatic precipitators (ESP)

Some control devices for gaseous contaminants:

a) Adsorption

   i) Fixed bed absorber

   ii) Moving bed adsorber

   iii) Fluidized bed adsorber

b) Absorption

   i) Spray Tower

   ii)Plate Tower

   Iii) Packed Tower

   iv) Venturi scrubbers

c) Condensation

   i) Surface condenser

   ii) Contact condenser

d) Combustion

   i) Direct flame combustion

   ii) Thermal Combustion

   iii) Catalytic combustion

1.4.3. Passive control of air pollution: -

Protecting the health of growing urban populations from air pollution remains a challenge for planners and requires detailed understanding of air flow and pollutant transport in the built environment. A number of passive methods exist like porous and solid barriers, ventilation systems of buildings, boundary walls etc. These methods include trees and vegetation (porous) as well as noise barriers, low boundary walls and parked cars (solid); all of them have gained different levels of research momentum over the past decade. Green roofs, green walls, photocatalytic coating are also functioned as passive control techniques. There are some modeling techniques to assume the air quality likes Computational Fluid Dynamics (CFD) model by ANSYS, Box model, Eularian model etc. Experimental and modeling studies have provided an understanding of the potential for these barriers to improve air quality under varying urban geometrical and meteorological conditions (John Gallagher, 2015)

1.5. Air pollution modeling: -

Measurements are always better than predictions. Measurements tell us what the concentrations are at a particular location. But they cannot tell us what the concentration is going to be in future or what it is now at locations where no measurements are being made. Air Pollution models help us to understand the way air pollutants behave in the environment.
Air pollution modeling is the term used to describe using mathematical theory to understand, or predict the way pollutants behave in the atmosphere. Modeling can be used to run scenarios, to test theories and understand environmental impact under different emission rates, weather and development scenarios.
There are various reasons for using models, such as working out which sources are responsible for what proportion of concentration at any receptor, estimating population exposure on a higher spatial or temporal resolution than is practicable by measurements, targeting emission reduction on the highest contributors predicting concentration changes with time which may lead to proper strategy planning and/or policy making.

1.5.1. Types of modeling: -

There are various types of models-

a) Eularian model: -

Eulerian Models numerically solve the atmospheric diffusion equation. It works on the measurements of the properties of the atmosphere as it moves past a fixed point. Wind-vane or cup-counter anemometer is a Eulerian sensor. Eulerian Models are based on the concept of a fixed reference point, past which the air flows.

b) Lagrangian model: -

Lagrangian Models treat processes in a moving air mass or represent the process by the dispersion of fictitious particles. Tracking a neutral density balloon as it moves downwind is a Lagrangian measurement. Lagrangian Models are based on the concept of a reference point that travels with the mean flow.

c) Box model: -

It is actually based on the conservation of mass. Here the receptor is considered as a box, where the emission happens and goes through physical and chemical change.

d) Gaussian air pollution model: -

Gaussian Air Pollution Models are developed on the Gaussian (normal) distribution of wind vector (and hence pollutant concentration) fluctuation. Gaussian Models are Eulerian Models.

e) Computational fluid dynamics (CFD): -

Resolving the Navier-Stokes equation using finite difference and finite volume methods in three dimensions provides a solution to conservation of mass and momentum. Computational fluid dynamic (CFD) models use this approach to analyze flows in urban areas. In numerous situations of planning and assessment and for the near-sources region, obstacle-resolved modeling approaches are required. There are 3 types-

i) Direct Numerical simulation
ii) Large Eddy simulation
iii) Reynolds Averaged Navier-Stokes simulation

Indoor air pollution is a very important thing. Actually, a building has to be designed with a proper ventilation system. Because of increasing air pollution, proper planned buildings have to design which have less impact on indoor air pollution.

Computational fluid dynamics (CFD) is an advanced computer simulation-based program. With the help of CFD we get an overall idea about pollution concentration in indoor air. Different simulation models are made based on boundary conditions. So, we can compare various models and choose the best one.

Chapter 2: Literature Review: -

2.1. Introduction: -

Researchers have done literature review in the field of indoor environment. In section 2.2 discussions is about various airflow distribution strategies used in the room. The factor must be considered in the design of ventilation strategies which is indoor air quality for the occupied zone since they influence the comfort and well-being of the human occupants within these spaces. In section 2.3 discussions is about indoor air quality. In section 2.4 discussions is about the passive control of air pollution. In 2.5 mainly CFD modeling is discussed.

2.2. Air flow distribution strategies: -

2.2.1. Introduction: -

The distribution strategy of fresh air from the supply diffusers into the enclosure has an essential influence on the airflow pattern formed inside the enclosed space. Any air distribution system that enhances a healthy and comfortable environment for occupants, as well as energy efficiency, can be nominated as a good air distribution system (Karimipanah, 2008). In 2017, an extensive literature survey was done on studies of HVAC systems' performance in large rooms which found that only three types of room air distribution strategies are used in large rooms. These are displacement ventilation, mixing ventilation and under floor air distribution systems UFAD (Mateus C. d., 2017). In addition, a fourth system, impinging jet ventilation which has been evaluated only in two recent studies by (Ye X. , 2016) and (Ye X. , 2019)when it was used in the ventilation of a large space.

2.2.2. Various types of Air flow distribution strategies: -

Various types of airflow ventilation strategies are -

1) displacement ventilation

2) mixing ventilation

3) underfloor air distribution systems UFAD

4) impinging jet ventilation

2.2.3. Displacement ventilation system: -

It is a room air distribution strategy where conditioned outdoor air is supplied at a low velocity from air supply diffusers located near floor level and extracted above the occupied zone, usually at ceiling height.

Displacement ventilation was first applied in an industrial building in Scandinavia in 1978, and has frequently been used in similar applications, as well as office spaces, throughout Scandinavia since that time. By 1989, it was estimated that Displacement ventilation comprised 50% in industrial applications and 25% in offices within Nordic countries. Applications in the United States have not been as widespread as in Scandinavia. Some research has been done to assess the practicality of this application in U.S. markets due to different typical space designs and application in hot and humid climates, as well as research to assess the potential indoor environmental quality and energy-saving benefits of this strategy in the U.S. and elsewhere.

Displacement ventilation has been applied in many famous buildings such as the Suvarnabhumi International Airport in Bangkok, Thailand, the NASA Jet Propulsion Laboratory Flight Projects Center building, the San Francisco International Airport Terminal 2 etc.

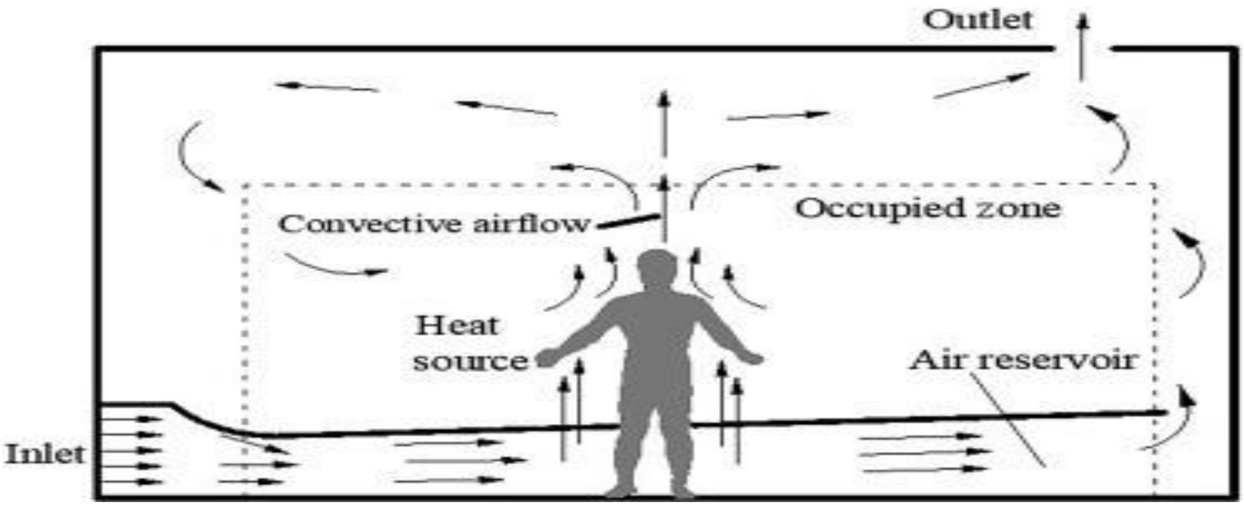


Figure 1 Displacement ventilation system

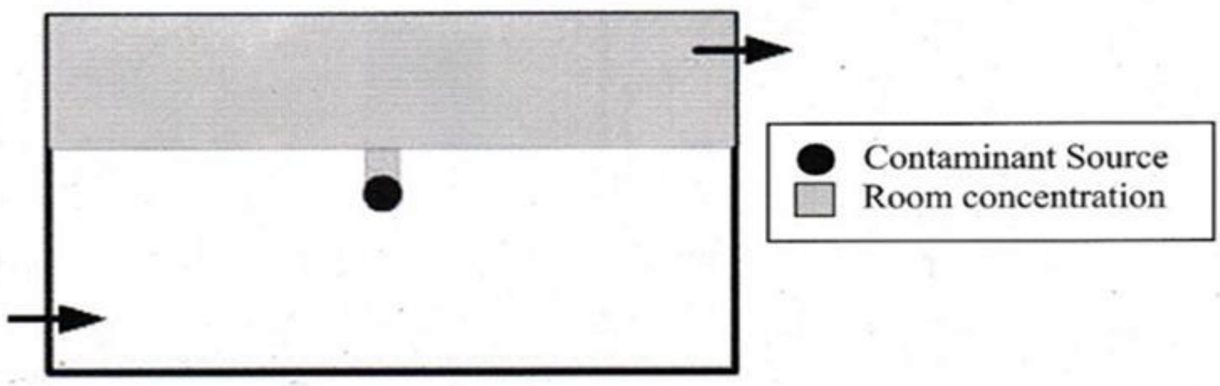


Figure 2 Distribution in displacement ventilation system

A displacement ventilation system was used in Gjovik Mountain Hall which was a purpose-built sports stadium in Norway. This building was utilized for comparing both long term and transient measurement of the air temperature distribution, airflow rates and energy consumption with predictions from CFD simulation. The results showed a favorable comparison between calculated and measured temperature and velocity fields. However, the result of the computed temperature gradient showed lower values than the measurements (IEA, 1998).

2.2.4. Mixing Ventilation: -

It is a type of ventilation system where the fresh air is mixed with impure enclosure air to provide a fresh supply of air and reduce the impurity concentrations as shown in Figure 3. The air jet is usually supplied in the top parts of the enclosure with velocity (normally > 2.0 m/s) to provide air circulation around the enclosure. The new temperature and contaminant density in the room should be uniform with this method of air supply.

(Hangan, 2001) applied a commercial CFD software to obtain the temperature and velocity distribution for a realistic model of large internal space with complex boundary conditions. These large spaces with mixing ventilation systems were located in the Miami center of performing arts, USA, and they were two large halls, an opera house and a concert hall. The results obtained demonstrated the power of the CFD software to offer the HVAC designers useful information to optimize the ventilation design for large rooms by testing different airflow distribution strategy ADS in the initial design stage.

A mixing ventilation system was used in a large lecture hall at the University of Putra Malaysia which has been used to carry out measurements of air velocity, air temperature, and relative humidity for one month. The measurements were employed as input parameters for three – dimensional CFD models to study the potential of a new specific insulator which was utilized as an insulating material placed on the lecture hall's external wall. The study concluded that the CFD simulation results showed that the system is effective in reducing the consumption of the total energy used to cool the hall by 10%. Therefore, CFD was considered to be an appropriate tool to control and identify potential problems and explore the airflow pattern and system performance (Muhieldeen, 2015)

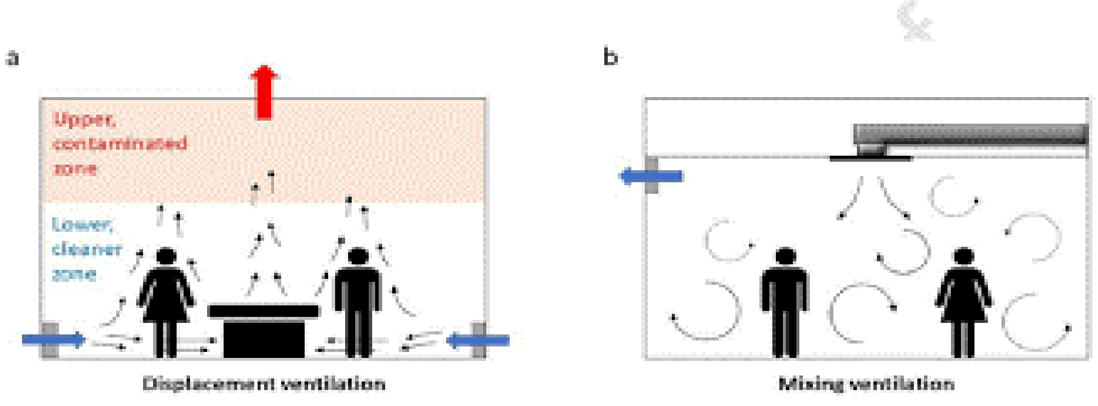


Figure 3 Displacement ventilation system vs mixing ventilation system

2.2.5. Underfloor Air Distribution System: -

Underfloor air distribution (UFAD) is an air distribution strategy for providing ventilation and space conditioning in buildings as part of the design of a HVAC system. UFAD systems use an underfloor supply plenum located between the structural concrete slab and a raised floor system to supply conditioned air through floor diffusers directly into the occupied zone of the building. UFAD is often used in office buildings, particularly highly-reconfigurable and open plan offices where raised floors are desirable for cable management. UFAD is appropriate for a number of different building types including commercials, schools, churches, airports, museums, libraries etc. Notable buildings using the UFAD system in North America include The New York Times Building, Bank of America Tower and San Francisco Federal Building. Careful considerations need to be made in the construction phase of UFAD systems to ensure a well-sealed plenum to avoid air leakage in UFAD supply plenums.

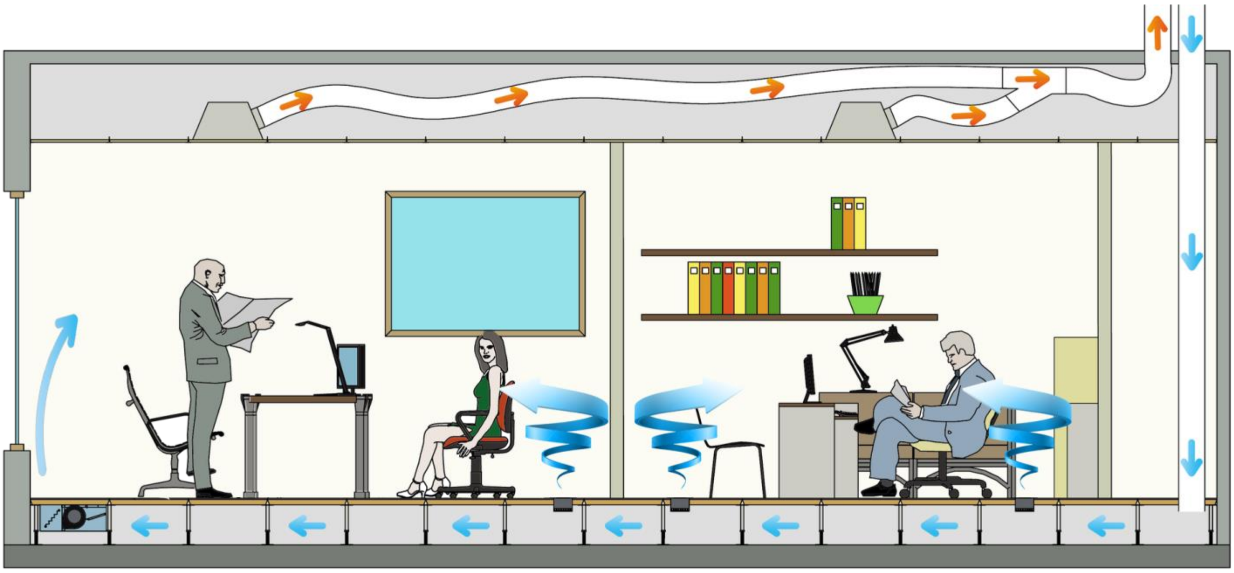


Figure 4 under floor air distribution system (Skistad, 2002)

(Fathollahzadeh, 2016) conducted a study using CFD methods to decide what produces a better performance for the under floor air distribution system in a large place. They found that different locations of the air diffusers, as well as different air supply velocities, were necessary to achieve that target. In spite of discomfort by air drafts which were induced by higher supply air velocity, UFAD was tolerated for the higher difference between room and inflow air temperatures and as a consequence, higher cooling capacity.

2.2.6. Impinging Jet Ventilation: -

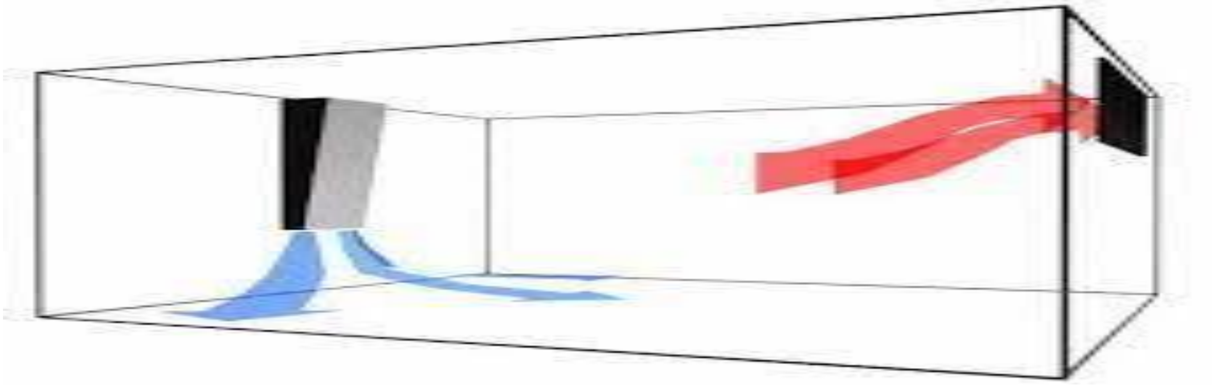


Figure 5 impinging jet ventilation

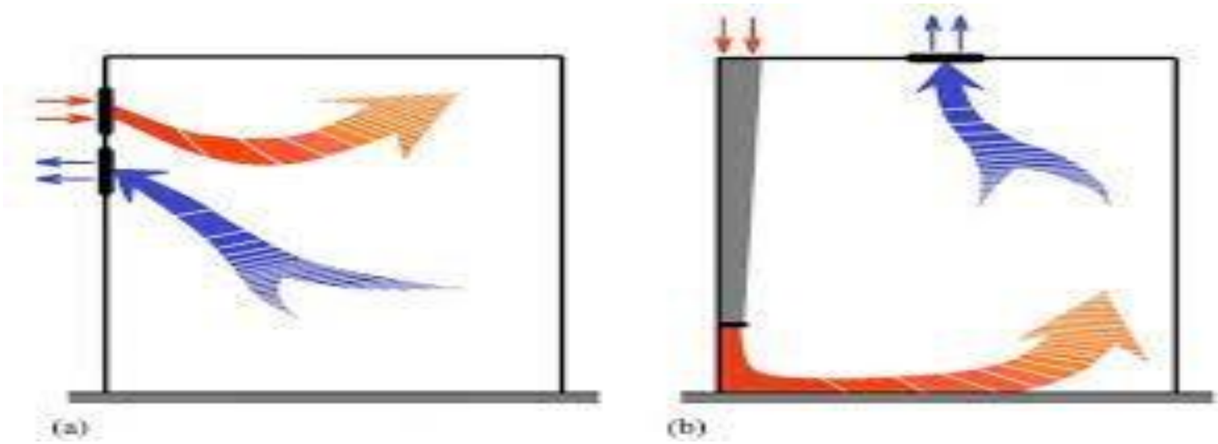


Figure 6 impinging jet ventilation and mixing ventilation in large-height spaces

Recently, a new concept, Impinging Jet Ventilation (IJV), has been introduced. By placing the supply terminal toward the floor within the impinging range, IJV successfully utilizes the advantages of MJV and DV. A supply temperature of 55F can be commonly applied. Previous studies show that IJV is particularly appropriate for space with fixed seating arrangements.

Impinging jets offer high rates of heat/mass transfer and have been used in a wide variety of applications, such as drying of paper, textiles and film, and cooling of electronic components and turbine blades; see e.g., (Hollworth, 1992) (Rundström, 2008)**),** (Macía, 2012) (Larraona, 2013) and (Li, EXPERIMENTAL INVESTIGATION OF SUBMERGED IMPINGING JET

USING CUWATER NANOFLUID, 2010) Impinging jets are also of scientific interest due to the presence of different flow regimes. The flow field of an impinging jet is generally divided into three distinct regions: free jet region, impingement region and wall jet region.

Only two studies have been carried out to evaluate the ventilation performance of the IJV system. First one was conducted numerically by (Ye X. , 2016) to study the airflow patterns and the temperature fields of the IJV and MV (Mixing Ventilation) systems used in heating modes in a large space located in Shanghai. The results show that the IJV system can distribute the warm supply air more easily into the occupied zone than the MV. They also found that the total heating energy consumption for the MV system was higher when compared with the IJV system. The same authors (Ye X. , 2019) performed numerically another study as well to predict the distribution of indoor gaseous contaminant concentration using CO2 for the same large space and ventilation systems. The results showed that the breathing zone has lower contaminant concentration for the IJV than that for the MV. The results also showed that the IJV has higher ventilation efficiency and thus is more beneficial in supplying good air quality than the MV.

2.3. Indoor Air Quality: -

2.3.1. Introduction: -

Indoor air quality is a very important thing. Air quality standards are mainly for outdoor air pollution. But old people, pregnant women, children, they mainly stay at home. Because of indoor air pollution they actually face the bad effects. There are so many sources of indoor air pollution, like organic, inorganic, environmental and also biological agents. These pollutants come from various sources, such as outdoor air, the fabric of buildings, furniture and human activities (Brohus, 1997). The contaminant concentration must be below a minimum acceptable level.

In the evaluation of indoor air quality, CO_2 concentration is regarded as a good indicator used by many designers, see e.g., (Persily, 1997)**,** (Sheng-Yi, 2011). The maximum allowable CO_2 in a room is 1000 parts per million by volume (ppm) (Awbi, 2003) and higher CO_2 concentration e.g., over 1000 ppm indicates poor ventilation and high levels of pollutants in a room. The local age of air is defined as the average time that has elapsed since the air particles at a specific location entered the room (Sandberg, 1981). It is useful in determining the length of time the outdoor air supplied to a ventilation system remains in a room (Awbi, 2003). This parameter can be regarded as a measure of freshness of the air: the "youngest" air is held at air supply inlets, whereas the "oldest" air may be at stagnation zone or in exhausts (Lin, 2005).

2.3.2. Indoor Air Pollutants: -

Indoor air pollutants are-

a) Asbestos
b) Biological Pollutants
c) Carbon Monoxide (CO)
d) Cook stoves
e) Formaldehyde/Pressed Wood Products
f) Lead (Pb)
g) Nitrogen Dioxide (NO_2)
h) Pesticides
i) Radon (Rn)
j) Indoor Particulate Matter ($PM_{2.5}$, PM_{10})
k) Secondhand Smoke/ Environmental Tobacco Smoke
l) Volatile Organic Compounds (VOCs)
m) Wood Smoke

2.4. Control of air pollution by passive control: -

2.4.1. Introduction: -

Air pollution is a very serious problem in the present days. Due to urbanization, it is increasing day by day. Of the 30 most polluted cities in the world, 21 were in India in 2019. As per a study based on 2016 data, at least 140 million people in India breathe air that is 10 times or more over the WHO safe limit and 13 of the world's 20 cities with the highest annual levels of air pollution are in India. 51% of the pollution is caused by industrial pollution, 27 % by vehicles, 17% by crop burning and 5% by fireworks. Air pollution contributes to the premature deaths of 2 million Indians every year. Emissions come from vehicles and industry, whereas in rural areas, much of the pollution stems from biomass burning for cooking and keeping warm.

So, control strategies are required to save the atmosphere. There are generally two types of control strategies-

a) Active control of air pollution
b) Passive control of air pollution

In the active control process, it is trying to remove the air pollutants by the source reduction process of air pollution. Alternative generation process is considered here. Beside those various technologies like ESP, wet scrubber, fabric filter etc. are used in industry.

When the air pollutants are controlled indirectly then it is passive control. It is generally not to help to reduce the amount of air pollutants but help to reduce the exposure in between human and air pollutants. It also gives a numerical based prediction model of air pollution to assume severity.

2.4.2. Various passive control methods: -

Various types of passive control methods have been identified to reduce exposure in between human and air pollutants in the built environment.

These methods can improve the air quality and provide healthier conditions for people (Amorim, 2013)**;** (McNabola, New Directions: passive control of personal air pollution exposure from traffic emissions in urban street canyons, 2010).

Various types of methods are:

a) Porous Barrier: -

Green infrastructure as a porous media can make a barrier between traffic emissions and nearby populations. These porous barriers can help filtration and deposition of pollutants, particularly different sizes of airborne particulates, thus affecting local pollutant concentration in a different manner to gaseous pollutants (Janhall, 2015). Trees and vegetation are one type of porous barrier.

1) Trees and vegetation: -

Trees and vegetation affect localized pollutant deposition and offer additional benefits of filtering out particulate pollutants. Previous investigations have explored and quantified the macro-scale impacts of trees and vegetation on air pollution in the built environment (Janhall, 2015)**;** (Nowak, 2006)**;** (Heikki Setäläa, 2013)**;** (M. Tallis, 2011)**;** (P.E. Vos, 2013). (Janhall, 2015) reviewed multiple studies that measured changes in pollutant concentrations in the presence of vegetation at both urban and local scales: eleven modeling investigations, six wind tunnel experiment studies, six sets of field experiments, with several studies adopting a combination of modeling and field measurements.

Figure 7 Trees and vegetation barrier

Environment	Impact	Details	References
Street canyon	vegetation characteristics	vegetation type crown size porosity leaf density tree spacing	(Amorim et al., 2013b; Buccolieri et al., 2009; Buccolieri et al., 2011; Gromke, 2011; Gromke et al., 2008; Gromke and Ruck, 2007, 2012; Ng and Chau, 2012; Wania et al., 2012)
	air flow	vortices development wind speed wind direction vehicular turbulence	(Amorim et al., 2013a; Buccolieri et al., 2011; Gromke et al., 2008; Gromke and Ruck, 2012; Ng and Chau, 2012; Salmond et al., 2013; Wania et al., 2012)
	street geometry	street aspect ratio monitoring location	(Buccolieri et al., 2009; Buccolieri et al., 2011; Gromke and Ruck, 2012; Wania et al., 2012)
Highway	vegetation characteristics	vegetation type porosity leaf density tree spacing	(Al-Dabbous and Kumar, 2014; Baldauf et al., 2008; Brantley et al., 2014; Hagler et al., 2012; Mao et al., 2013)
	air flow	wind speed wind direction	(Al-Dabbous and Kumar, 2014; Hagler et al., 2012; Mao et al., 2013; Steffens et al., 2012)
	road geometry	road layout monitoring location	(Al-Dabbous and Kumar, 2014; Baldauf et al., 2008)

Table 2 Summary of literature review relating to dispersion of pollutants in the environment based on (Janhall, 2015).

b) Solid Barrier: -

There is a list of solid barriers which are involved to reduce the air pollution concentration in the atmosphere. These solid barriers are-

1) Noise Barrier
2) Low boundary wall
3) Parked car

The differences between a noise barrier and the other solid barriers are: (a) height difference: the noise barrier is typically more than 4-5 m tall, compared to a Low Boundary Wall (LBW) or parked car of 1-2 m or less in height, respectively, (b) LBWs and parked cars are often adjacent to low-speed roadways while noise barriers are often located along high-speed highways.

Here the low boundary wall is important. Initial studies on LBWs were done along a boardwalk in Dublin, Ireland (W. King, 2009)**;** (McNabola, Reducing pedestrian exposure to environmental pollutants: A combined noise exposure and air quality analysis approach, 2009). The investigations examined the influence of a boundary wall constructed between a boardwalk and an adjacent road with three lanes of one-directional traffic. (McNabola, Reducing pedestrian exposure to environmental pollutants: A combined noise exposure and air quality analysis approach, 2009) found that an LBW acted as a baffle, which when located along the outer edge of footpaths or in the center of the canyon, promoted pollutant dispersion in a street canyon. A subsequent investigation by (W. King, 2009) noted the clear benefits of the boardwalk on air and noise pollution as the segregation of human and vehicular traffic increased the distance between the source and the receptor.

The results from the air quality sampling study by (McNabola, Reducing pedestrian exposure to environmental pollutants: A combined noise exposure and air quality analysis approach, 2009) measured reductions of between 35% and 57% in personal pollutant exposure for pedestrians walking along the boardwalk as opposed to the adjacent footpath. A generic computational modeling investigation by (McNabola, Reducing pedestrian exposure to environmental pollutants: A combined noise exposure and air quality analysis approach, 2009; McNabola, New Directions: passive control of personal air pollution exposure from traffic emissions in urban street canyons, 2010) calculated reductions in personal pollutant exposure of up to 40% and 75% in perpendicular and parallel wind conditions, respectively.

A subsequent study by (Gallagher, 2012) found that footpath LBWs (i.e., a low wall on the outer edge of the footpath) models ranged from a 19% increase to a 30% reduction on the leeward footpath and reductions of 26% to 50% on the windward footpath. Following this, (Gallagher, 2012) assessed LBWs in a real-world investigation and found reductions in pollutant concentrations of up to 35% to a maximum increase of 25% on the footpaths in varying wind conditions.

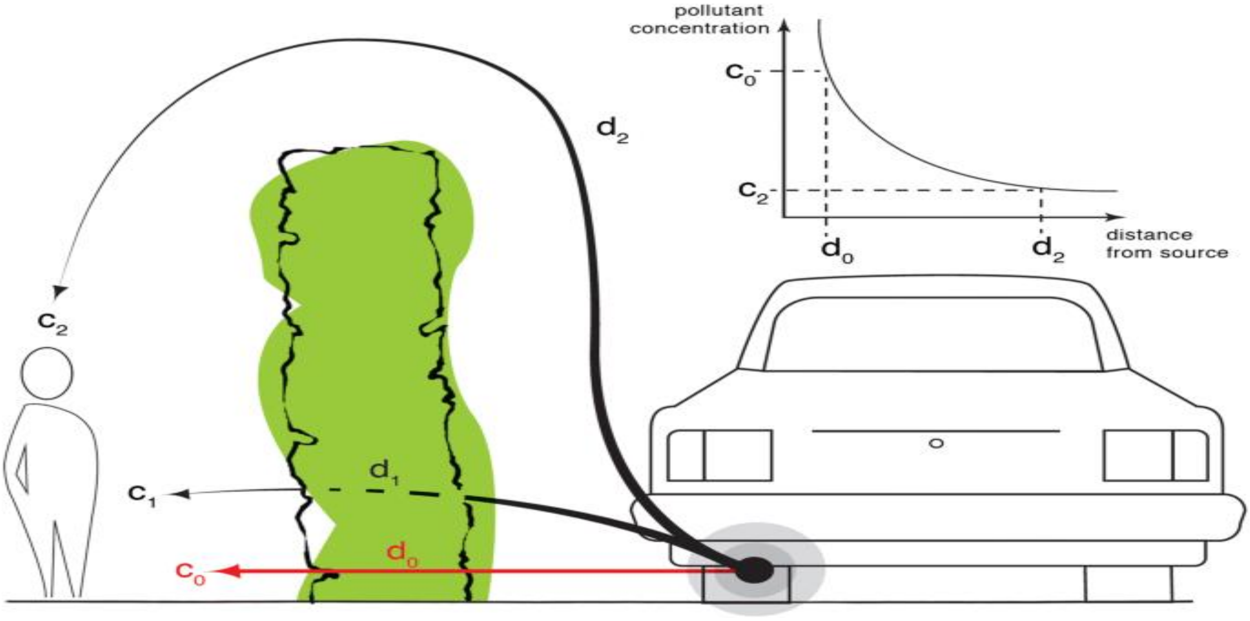


Figure 8 Using boundary wall to improve the air quality in urban area

Here C_0, C_1, C_2 is the air pollution concentration in distance of d_0, d_1, d_2 respectively.

Passive method		Study type				Pollutant[a]				
Barrier type	Method	Measurement	Modelling	Wind Tunnel	Combined	PM	CO^b	NO_x	VOCs	References
Porous	Trees and vegetation	✓	✓	✓	✓	✓	✓	✓	✓	(Abhijith and Gokhale, 2015; Al-Dabbous and Kumar, 2014; Amorim et al., 2013a; Amorim et al., 2013b; Baldauf et al., 2008; Brantley et al., 2014; Buccolieri et al., 2009; Buccolieri et al., 2011; Gromke, 2011; Gromke et al., 2008; Gromke and Ruck, 2007, 2012; Hagler et al., 2012; Mao et al., 2013; Ng and Chau, 2012; Salmond et al., 2013; Steffens et al., 2012; Wania et al., 2012)
Solid	Noise barrier	✓	✓	✓	✓	✓	✓		✓	(Baldauf et al., 2008; Bowker et al., 2007; Finn et al., 2010; Hagler et al., 2012; Hagler et al., 2011; Jeong, 2014; Ning et al., 2010; Schulte et al., 2014; Steffens et al., 2014; Steffens et al., 2013)
	Low boundary wall	✓	✓		✓	✓	✓	✓	✓	(Gallagher et al., 2012, 2013; King et al., 2009; McNabola et al., 2008, 2009)
	Parked cars	✓	✓		✓		✓	✓		(Abhijith and Gokhale, 2015; Gallagher et al., 2011, 2013)

Table 3 various types of passive control model

2.5. Computational Fluid Dynamics (CFD) Modeling in Air pollution: -

Nowadays due to advanced technology, the computational fluid dynamics (CFD) method is the advanced one. It is actually a prediction simulation model which helps assume the indoor air quality of a building, effectiveness of the ventilation system etc. Rapid advancements in the computational fluid dynamics (CFD) bring nowadays interest of many researchers to apply numerical modeling for prediction of indoor environment quality.

In terms of air quality study, (Nielsen, 2011) was the first ones to apply the CFD technique to the field of heating, ventilating and air conditioning. They measured and calculated the velocity characteristics of ventilated rooms by laser-Doppler anemometry.

(Li, Hood performance and capture efficiency of kitchens: A review, 2019) studied the capture efficiency of a kitchen range hood in a confined domain by a two-zone mixing model. The results showed that the capture efficiency equals the ratio of captured flow rate to the total plume flow rate at the front canopy height.

Researcher (Akoua, 2003) analyzed the impact of volatile organic compounds emission on the concentration field in a ventilated room using a method of combining experiment and numerical simulation (Fluent 6.0).

Researcher (Livchak, 2005) compared traditional mixing ventilation systems and thermal displacement ventilation systems in a typical kitchen by using a CFD model.

(Ioannis K. Panagopoulos1*, 2011) made a CFD simulation study of VOC and Formaldehyde indoor air pollution dispersion in an apartment as part of an indoor pollution management plan.

Researcher (Zhenlei Chen, Air quality and thermal comfort analysis of kitchen environment with CFD simulation and experimental calibration, 2020) analyzed air quality and thermal comfort of the kitchen environment with CFD simulation and experimental calibration.

Researcher (Lin C. , 2006)analyzed the particle deposition and distribution in a chamber by using the Lagrangian method.
Researcher (Tham, 2016) reviewed the challenge and development of indoor air quality and its effect on humans in the last three decades.

Researcher (Jeanjean, 2017) modeled the impact of trees on vehicular emissions in the urban environment using CFD.

Researcher (Alzaid, 2019) conducted the experimental and numerical investigation of air distribution in a large air-conditioned space building.

In June 2019, (Madsen, 2019) did the CFD modeling of pollutant transport with the help of ANSYS.

Researcher (Boonthanom, 2019) has done a CFD case study of pollution dispersion in the street and effect of $PM_{2.5}$ deposition.

In 2019, (Zhen, 2020) has designed an integrated low-energy ventilation system to improve indoor air quality and thermal comfort of primary school buildings in the cold climate zone of China.

Researcher (Bjerg, 2011) has done the CFD analysis of the efficiency of air cleaning in pig production. The analyses, including CFD-methods, showed that evacuating and cleaning of 10% of the total ventilation capacity from the pit may reduce the ammonia emission of the system by 73%, and the ammonia concentration in the room is significantly reduced. In a similar production system without pit ventilation cleaning of 10% of the ventilation capacity reduced the ammonia emission with 41% compared to no cleaning. In addition, analyses illustrated that CFD methods can be a very useful tool in the development of improved and more efficient ventilation systems in this case.

In India (S, 2005) has done one evaluation of CFD model PANAIR for air pollution dispersion of industrial stack emissions in Mumbai. The performance of PANAIR shows that it can serve as a useful integrated package for industries like RCF, for policy decisions, prediction of accidental releases, monitoring site selection and other management purposes.

Researcher (Mr. Rahul Kumar, 2016) have analyzed the CFD model of pollution dispersion in complex domains. The detailed study of different shapes of building and hills, and the effect of distance between hill and building are done. The attempt is made here to find the optimum distance from the pollutant source so that the building will face a minimum level of pollution.

Chapter 3: Critical Review:-

Experimental measurements of quantities describing conditions in the indoor environment with people are very difficult and sometimes not even possible to perform in real-life conditions with humans. When the experimental work is not possible, then the modeling is very important. Prediction of contaminant inhalation, indoor air quality and airborne infection risk requires a reliable modeling of the human interaction with the surrounding. In an indoor environment, occupants interact closely with their surroundings as a source of various contaminants and airflow obstacles. All this causes any computational prediction of the indoor environment state to take into account people's presence in the considered space. Rapid advancements in the computational fluid dynamics (CFD) bring nowadays interest of many researchers to apply numerical modeling for prediction of indoor environment quality.

So, it is a new research area which has very high demand and necessity. Actually, this kind of research helps to improve indoor air quality. Such knowledge is needed by engineers and architects for selecting appropriate ventilation systems and control strategies to minimize indoor contaminant exposures.

But in Kolkata, despite having the worst air quality, the air pollution modeling with the help of CFD related work is not too much.

Chapter 4: Objective And Scope of Study:-

4.1. Objective-

The main objective of this thesis is the numerical investigation of various control techniques to mitigate PM_{10} concentration level of the Guard room of Jadavpur University Gate No-3 (Kolkata, India) with the help of CFD (ANSYS, Fluent).

Two types of passive control techniques are used.

a) Changing windows’ position.
b) Applying green belt in front of Guard room.

4.2. Scope of Study-

a) A proper road side room (room belongs to Jadavpur University) will be selected.
b) Size of room, size of windows will be measured.
c) PM_{10} concentration inside the room will be measured by Portable Air Quality Monitor Pollution Meter.
d) A road survey will be conducted in Raja Subodh Chandra Mullick road, Kolkata and PM_{10} load will be calculated (according to CPCB vehicle emission factor guideline).
e) A model of selected room will be designed in ANSYS FLUENT 2020 software.
f) Various passive control techniques (changing windows’ position and applying green belt) will be applied in model.
g) Effect of passive control techniques in the room will be analyzed.

Chapter 5: Methodology:-

5.1. Numerical simulation-

The numerical simulation uses the commercial CFD, CFX package to perform the analysis. The program has been validated for the simulation of displacement and mixing ventilation for many types of indoor spaces such as offices, classrooms and workshops by (Lin C. , 2006). Numerical simulation involves the solution to the Reynolds averaged Navier–Stokes equations and the mass conservation equation. Various types of turbulence models can be used for CFD codes, depending on the type of application. Direct numerical simulation (DNS) is considered to be the most accurate for modeling turbulent effects. LES are also used mostly for large-scale simulations. The turbulence models assume mean values of velocity rather than the actual velocity, which is difficult to simulate. Two other popular turbulence models include the k– e model and the re-normalized (RNG) k– e model. The k–e model is used in this simulation.

5.2. Computational fluid dynamics (CFD) model-

h) The governing equations for the turbulent motion of air are expressed as:

$$\frac{\partial u_i}{\partial x_i} = 0$$

Equation 1 Continuity equation

$$\frac{\partial(\rho u_i)}{\partial t} + \frac{\partial(\rho u_i u_j)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \mu \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \frac{\partial\left(-\rho \overline{u_i' u_j'}\right)}{\partial x_j}$$

Equation 2 Momentum equation

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho h u_i)}{\partial x_i} = \frac{(k + k_t)\partial^2 u_j}{\partial x_i \partial x_j} + S_h$$

Equation 3 Energy equation

Eqns. (1)–(3) are the continuity, momentum, and energy equations, respectively, where ***u*** is the fluid velocity; ***i, j*** 1, 2, and 3 are the ***x-, y-,* and *z*-directions,** respectively; ***p*** is the pressure; ***t*** is the time; ***ρ*** is the density; ***μ*** is the dynamic viscosity coefficient; $-\rho\overline{u_i' u_j'}$ is the Reynolds

Stresses; ***h*** is the enthalpy with $h = \int_{T_{ref}}^{T} C_p dT$, ***Cp*** is the heat capacity, ***T*** is the temperature, $\boldsymbol{T_{ref}}$ **= 298.15 K** is the reference temperature; **Kt=** $C_p\mu_t/\mathrm{Pr}_t$ $\mathbf{Pr_t}$ is the Plante number; is the source term; ***k*** is the turbulent kinetic energy per unit mass of fluid (Zhenlei Chen, Air quality and thermal comfort analysis of kitchen environment with CFD, 2020).

i) **The k-epsilon (k−ϵ)** model for turbulence is the most common to simulate the mean flow characteristics for turbulent flow conditions. It belongs to the **Reynolds-averaged Navier Stokes (RANS)** family of turbulence models where all the effects of turbulence are modelled.

It is a two-equation model. That means that in addition to the conservation equations, it solves two transport equations (PDEs), which account for the history effects like convection and diffusion of turbulent energy. The two transported variables are turbulent kinetic energy (k), which determines the energy in turbulence, and turbulent dissipation rate (ϵ), which determines the rate of dissipation of turbulent kinetic energy.

The k−ϵ model is shown to be reliable for free-shear flows, such as the ones with relatively small pressure gradients, but might not be the best model for problems involving adverse pressure gradients, large separations, and complex flows with strong curvatures.

There exist different variations of the k-epsilon model such as **Standard**, **Realizable**, **RNG**, (Teodosiu, 2015) etc. each with certain modifications to perform better under certain conditions of the fluid flow. Here **Realizable k-epsilon model** is considered.

Mathematical Representation

The turbulent energy is given by

$$k = \frac{3}{2}(UI)^2$$

Equation 4 Turbulent energy equation

Where **U** is the mean flow velocity and **I** is the turbulence intensity.

The turbulence intensity gives the level of turbulence and can be defined as follows:

$$I = \frac{u'}{U}$$

Equation 5

Where **u′** is the root-mean-square of the turbulent velocity fluctuations given as:

$$u' = \sqrt{\frac{1}{3}\left({u'_x}^2 + {u'_y}^2 + {u'_z}^2\right)} = \sqrt{\frac{2}{3}k}$$

Equation 6

The mean velocity **U** can be calculated as follows:

$$U = \sqrt{{U_x}^2 + {U_y}^2 + {U_z}^2}$$

Equation 7 Mean velocity equation

The **turbulent dissipation rate** can be calculated using the following formula:

$$\epsilon = {C_\mu}^{\frac{3}{4}} \frac{k^{\frac{3}{2}}}{l}$$

Equation 8 Turbulent dissipation rate equation

Where Cμ is the turbulence model constant which usually takes the value 0.09, k is the turbulent energy; l is the turbulent length scale. The turbulence dissipation rate is considered as 0.8.

The turbulence length scale describes the size of large energy-containing eddies in a turbulent flow.

The turbulent viscosity $\boldsymbol{\nu_t}$ is, thus, calculated as:

$$\nu_t = 0.09\,\frac{k^2}{\epsilon}$$

Equation 9 Turbulent viscosity equation

(https://www.simscale.com/docs/simulation-setup/global-settings/k-epsilon/, 2021)

The turbulent viscosity is considered as 1.

j) Inlet Turbulence-

To realistically model a given problem, it is important to define the turbulence intensity at the inlets. Here are a few examples of common estimations of the incoming turbulence intensity:

- **High-turbulence (between 5% and 20%):** Cases with high velocity flow inside complex geometries. Examples: heat exchangers, flow in rotating machinery like fans, engines, etc.
- **Medium-turbulence (between 1% and 5%)**: Flow in not-so-complex geometries or low speed flows. Examples: flow in large pipes, ventilation flows, etc.
- **Low-turbulence (well below 1%):** Cases with fluids that stand still or highly viscous fluids, very high-quality wind tunnels. Examples: external flow across cars, submarines, aircraft, etc.

It is considered that turbulence is **medium-turbulence**.

k) Multiphase Model-

Eularian multiphase model is considered. Eularian parameter is dense discrete phase model (Yuting Ma, 2015).

One phase is **air (considered as property of fluid, also Phase-1)**. Another phase is **inert particle phase (Phase-2)**.

l) Materials-

Material for Phase-1:

Air (considered as property of fluid) is considered.

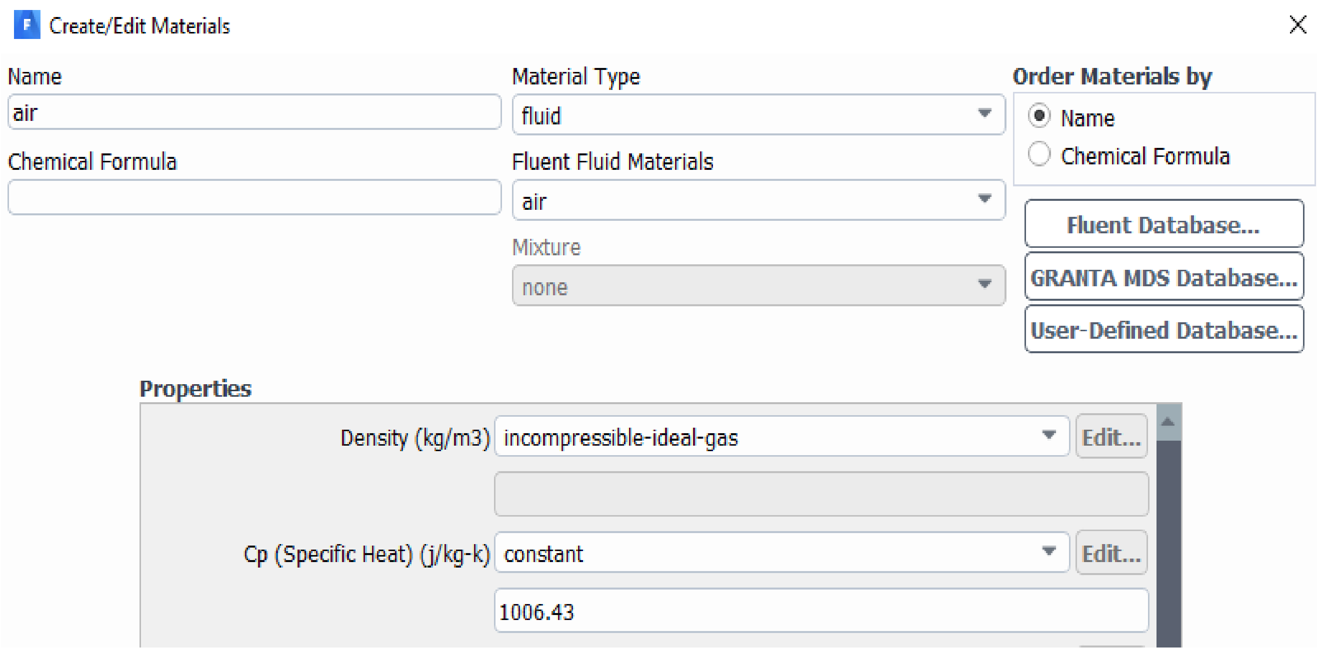


Figure 9 Material for Phase-1

Material for Phase-2:

Fuel-oil-liquid is considered as Fluent inert particle material.

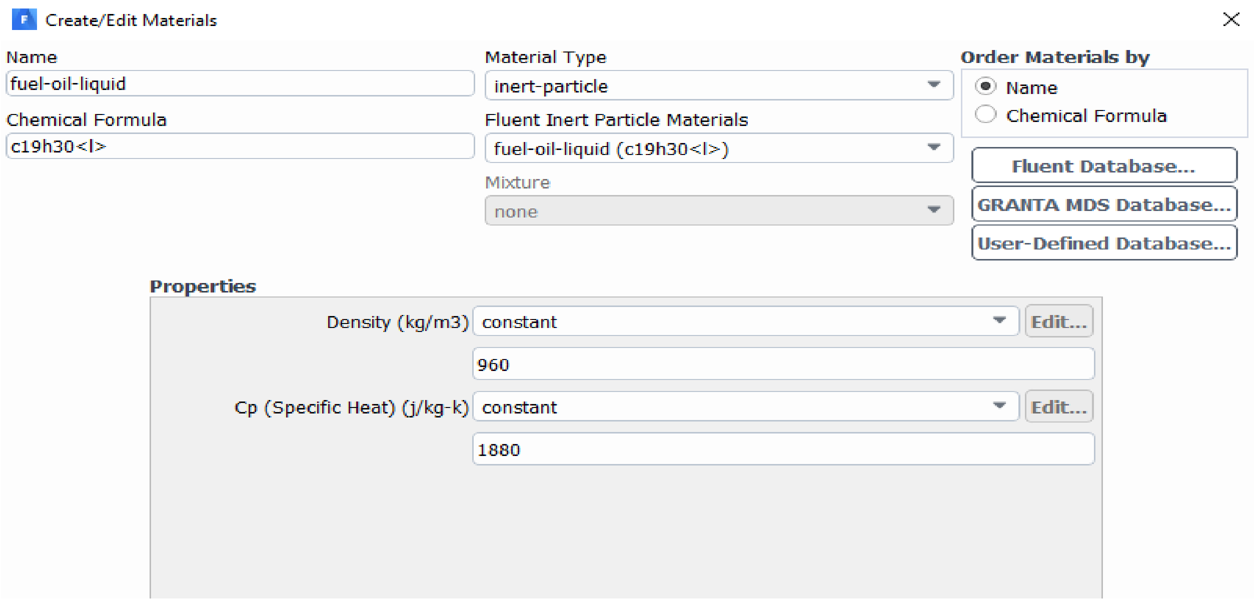


Figure 10 Material for Phase-2

m) General Setup of Model:

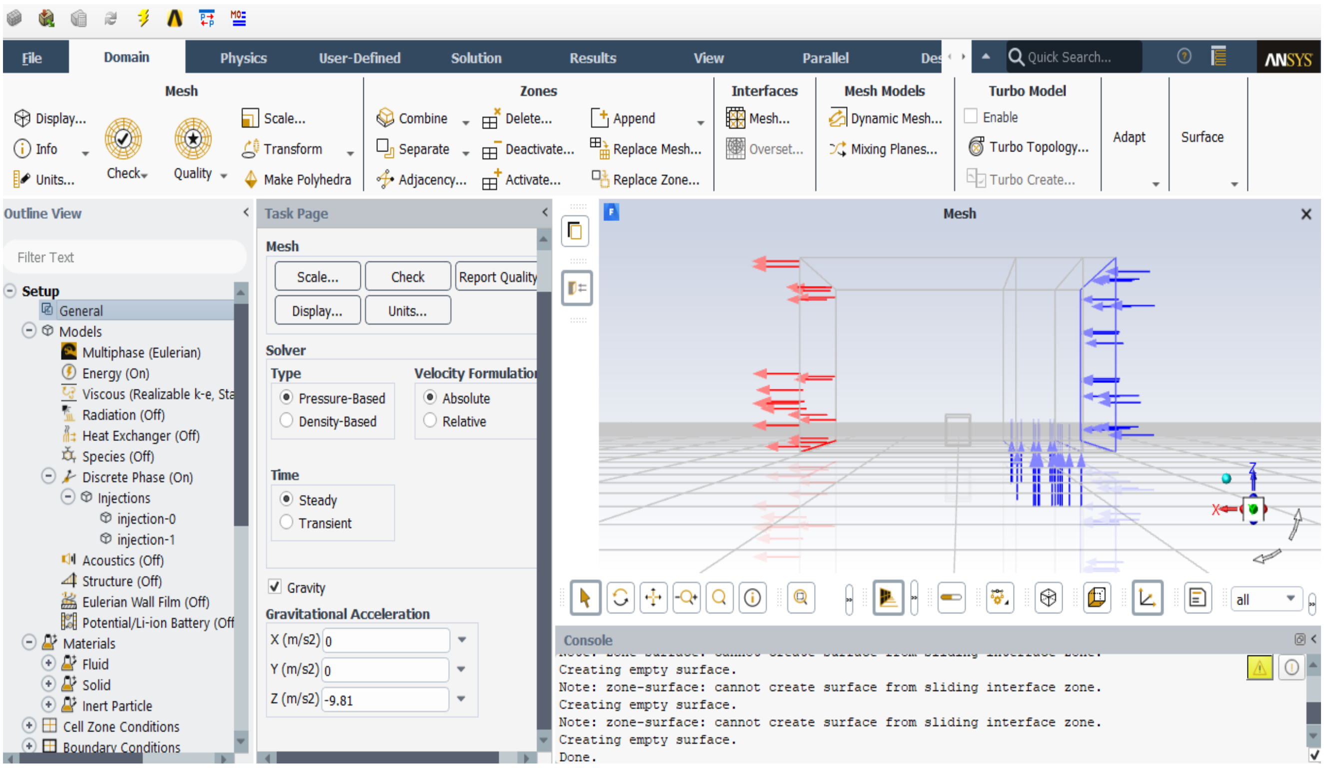


Figure 11 General setup

Calculations are based on **Steady State condition** (Zhenlei Chen, Air quality and thermal comfort analysis of kitchen environment with CFD, 2020).

The air is considered as **incompressible flow gas**. That's why **pressure based solver** is used. It is known that, for incompressible flow, density is assumed to be constant hence flow equations are computed based on pressure equations.

5.3. Meshing-

ANSYS is software to perform Finite Element Analysis.

Finite Element Analysis consists of the following steps:

1. Preprocessing
   a. **Discretization**
   b. Apply constraints
2. Processing
3. Post processing

This **discretization** is the process of dividing up the model into elements consisting of nodes. The processing phase solves equations for these nodes and obtains results.

Meshing is discretization. It is the most important part of an analysis and can determined the efficiency and effectiveness of an analysis. Therefore, a lot of time is given to meshing of complex models. If it is not meshed, we won't get the finite elements and there won't be a "Finite Element" Analysis.

So, meshing is the core of finite element analysis.

Mesh Parameter Quality-

I. Element Quality-

The mesh element quality is a dimensionless quantity between 0 and 1, where 1 represents a perfectly regular element, in the chosen quality measure, and 0 represents a degenerated element. So, 0 represents worst and 1 represents best.

II. Skewness-

The Skewness is defined as the difference between the shape of the cell and the shape of an equilateral cell of equivalent volume. Its' range is 0 to 1. 0 means best and 1 means worst.

III. Jacobian Ratio-

Jacobian (also called Jacobian Ratio) is a measure of the deviation of a given element from an ideally shaped element. The jacobian value ranges from -1 to +1, where +1 represents a perfectly shaped element.

Tetrahedral meshing is used for modeling.

Chapter 6: Validation of Model:-

<u>Dimension of Guard Room-</u>

The **length and width of the room is 3 m. and height is 3 m. The depth of wall is 300mm.**

<u>Windows' Position and Size-</u>

The guard room at gate no 3 has 3 windows. The size of each window is same. **The height of window is 1.15 m and width is 1 m.** It is considered that **the door of that room is closed**.

<u>Speed and Direction of Wind-</u>

Wind speed and direction were measured on 16^{th} March, 2022. The measured wind speed was **3 m/s** and wind direction was **North-West (NW Wind) (45º Angle variation).**

<u>Observation-</u>

Portable Air Quality Monitor Pollution Meter was used for PM_{10} concentration measurement. The observed concentration level was **45 µg/m^3**.

<u>Details of the Model-</u>

The **'ANSYS FLUENT 2020'** software was used. The **domain height is 18 m (6×height of room),** (Revuz, 2012). There are **two inlet (one is surface inlet and another is road inlet) and one outlet.** The **length and width of domain is 33 m**. The guard room and the road in placed inside the domain following proper dimensions. **In model width of the road is 7m and the distance between the room and road is 4.57m.**

<u>Applying the PM_{10} pollution load-</u>

It is already said that there are two inlets one is surface inlet and another is road inlet.

A road survey was successfully conducted on 16^{th} March, 2022 and the vehicle pollution load was calculated as **2.5644×10^{-6} kg/s.** This value is used in road inlet.

Apart from vehicle source, a certain amount of PM_{10} already exists in our environment. So, here **0.001 kg/s** value is considered and this value is used in **surface inlet**.

Applying the velocity power law-

The **velocity power law** is used in surface inlet. The formula is-

$$\frac{V}{V0} = \left(\frac{Z}{Z0}\right)^{P}$$

Here 'P' = 0.2 and 'Z_0'= 2m

'V_0' is initial velocity which is considered as 3 m/s.

View of Model-

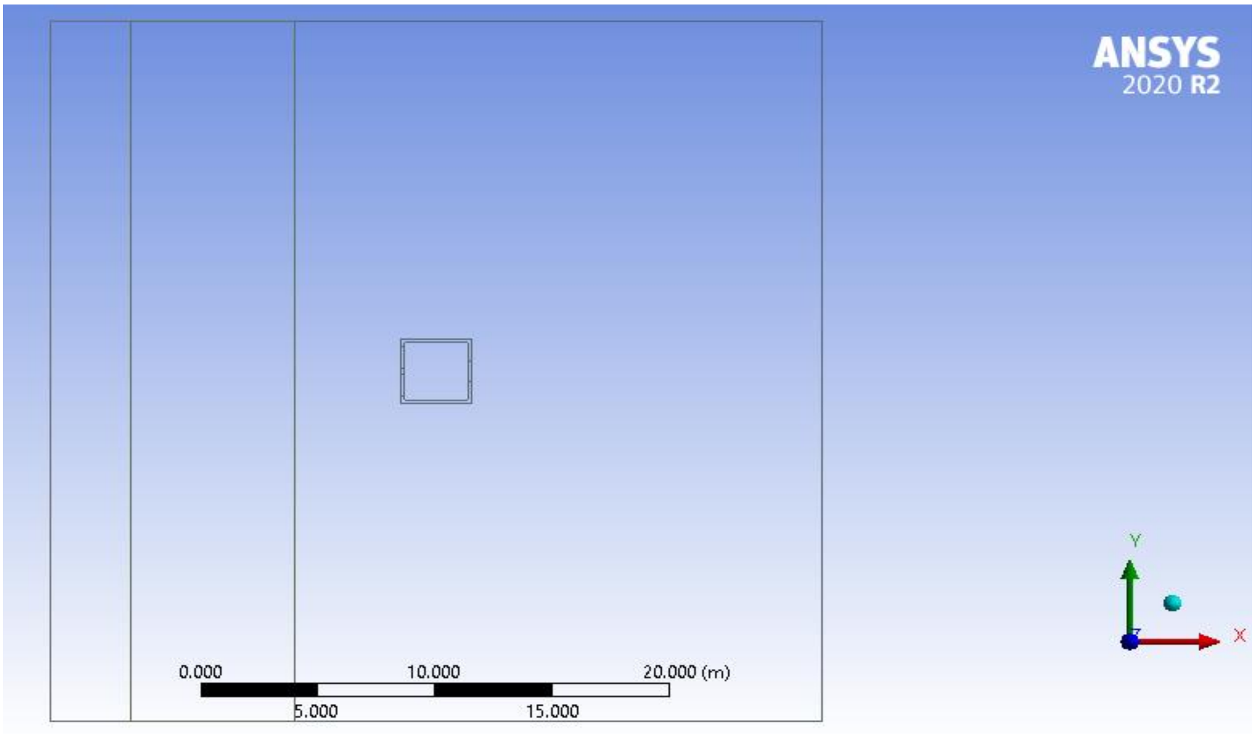


Figure 12 Top View of Model

Meshing of Model-

Here, **tetrahedral meshing** is used.

Quality of meshing-

Jacobian Ration of mesh- 1.0058

Skewness- 0.23942

Element Quality- 0.79982

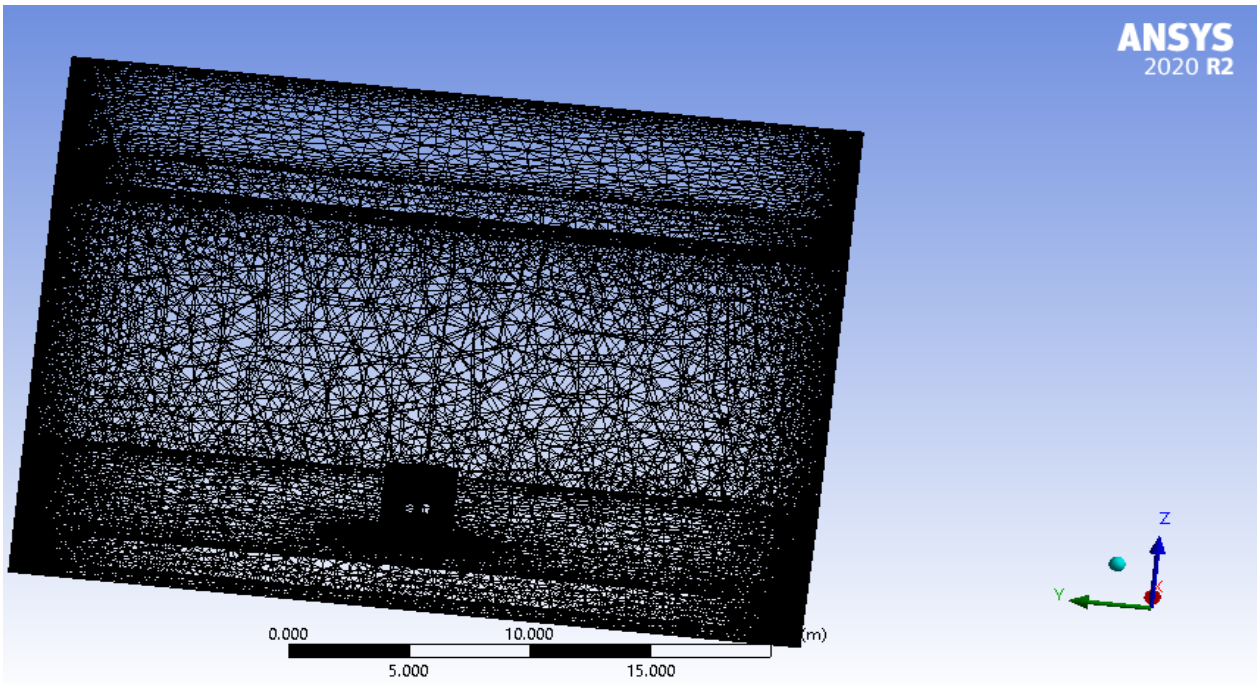


Figure 13 Meshing of Model

Result-

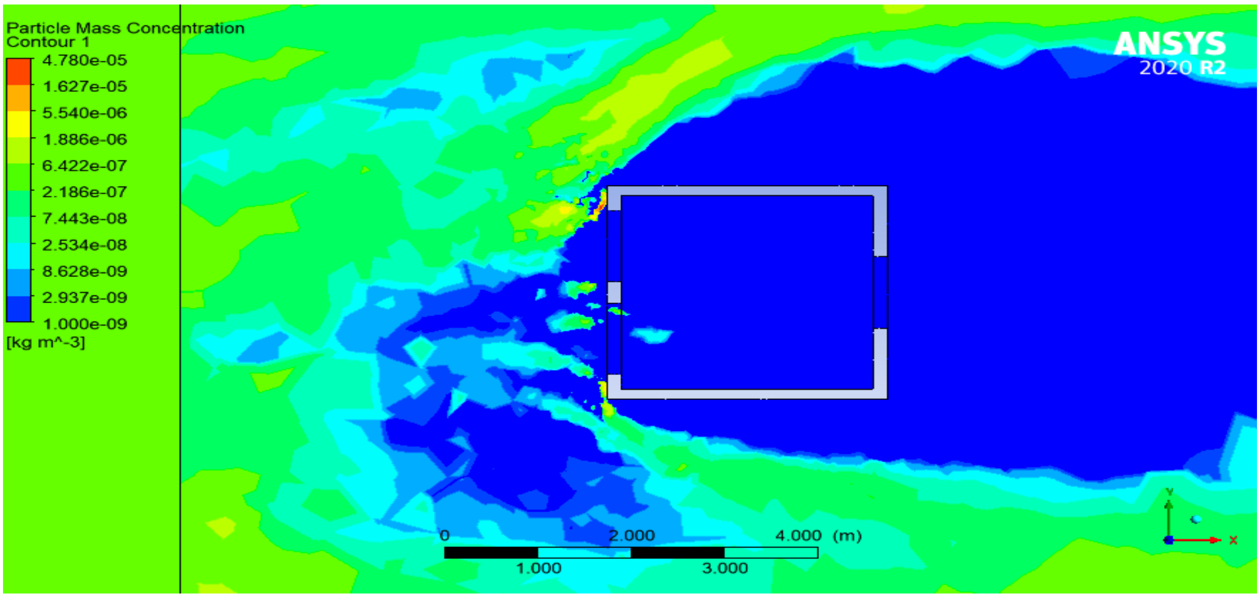


Figure 14 PM_{10} Concentration Contour

It is observed that according to 'ANSYS FLUENT 2020', the range of PM_{10} concentration inside the room is from 2.534×10^{-8} kg/m^3 to 7.443×10^{-8} kg/m^3.

So, the observed value belongs to the above maintained range.

Chapter-7: Results and Discussion:-

It is all known that **'ANSYS FLUENT'** is very important and useful software across the world for modeling and simulation purpose. Here some passive control techniques tried to use based on the **guard room of Jadavpur University Gate No-3**. Because that room is located beside a very busy road **(Raja Subodh Chandra Mullick Road, Kolkata-700032).** So, various kinds of air pollutants like **CO, NO_x, SO_2, $PM_{2.5}$, PM_{10}** etc. are very effective on that place and those are very harmful for our body. Here **PM_{10} is considered as criteria air pollutant.** It is tried to mitigate the level of **PM_{10}** of the guard room using passive control techniques with the help of **'ANSYS FLUENT 2020'** software.

The **length and width of the room is 3 m. and height is 3 m. The depth of wall is 300mm.** actually there are 3 windows, but it is considered that two windows which are always open. So, models are based on two windows. **The height of window is 1.15 m and width is 1 m.** It is considered that the door of that room is closed.

There is a **7 m width road (Raja Subodh Chandra Mullick Road, Kolkata-700032)** in-front of that guard room. The kerb distance is 4.57 m.

There are a lot of passive control techniques available. **Here two types of passive control techniques are used.**

1. **Position variation of window (Window sizes unchanged).**
2. **Applying the Green Belt.**

Direction of wind-

Actually the road is located in the west side of the guard room. So it is considered that the west wind is critical in that case and also considered wind angle variations of **0º,5º,10º,15º,20º,25º,30º**. Here **0º, 5º, 10º, 15º wind is considered as west wind** and **20º, 25º, 30º wind is north-west wind.**

Speed of Wind-

The wind speed is considered as **3 m/s** and **5 m/s**.

Details of the Model-

The **domain height is 18 m (6×height of room),** (Revuz, 2012)**.**There are **two inlet (one is surface inlet and another is road inlet) and one outlet.** The **length and width of domain is 33 m**. The guard room and the road in placed inside the domain following proper dimensions. **In model width of the road is 7m and the distance between the room and road is 4.57m.**

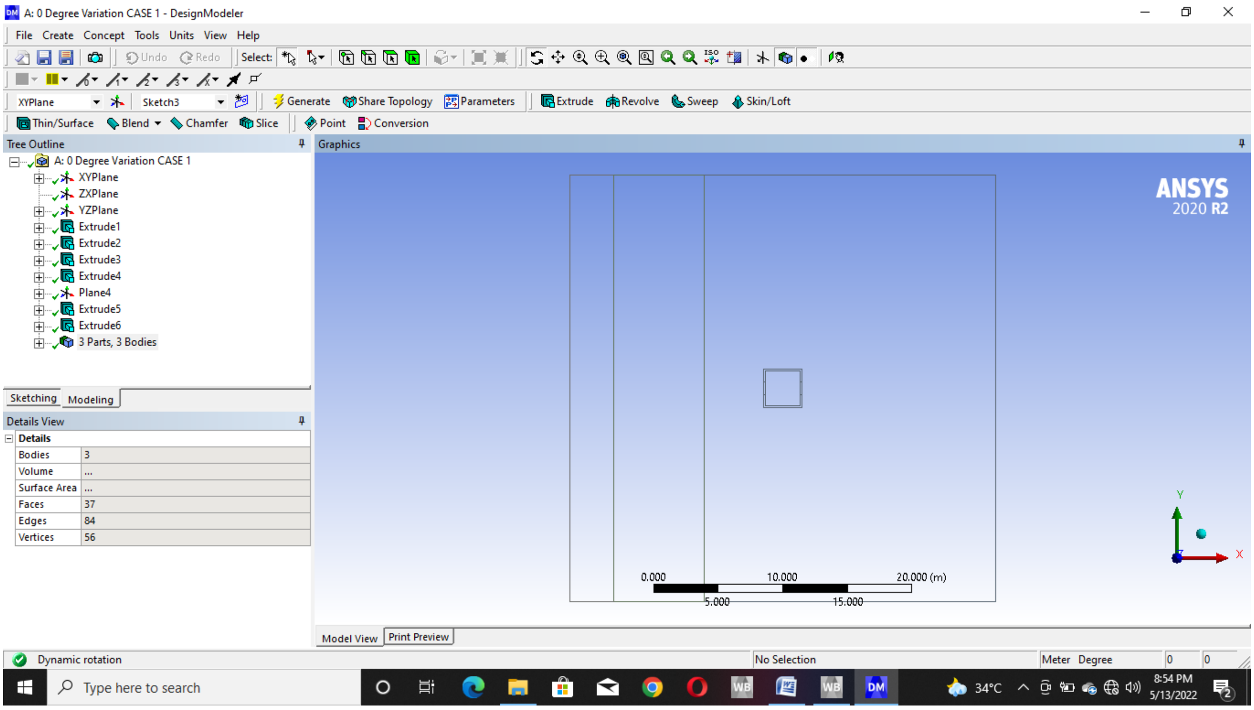


Figure 15 Top view of the model

<u>Applying the PM_{10} pollution load-</u>

It is already said that there are two inlets one is surface inlet and another is road inlet.

A road survey was successfully conducted and the vehicle pollution load was calculated as **2.5644×10^{-6} kg/s.** This value is used in road inlet.

Apart from vehicle source, a certain amount of PM_{10} already exists in our environment. So, here **0.001 kg/s** value is considered and this value is used in **surface inlet**.

<u>Applying the velocity power law-</u>

The **velocity power law** is used in surface inlet. The formula is-

$$\frac{V}{V0} = \left(\frac{Z}{Z0}\right)^{P}$$

Here 'P' = 0.2 and 'Z_0'= 2m

'V_0' is initial velocity which is considered as 3 m/s and 5 m/s.

<u>Contour Height-</u>

In this study all of the contours are in 1.5 m height from ground (Z=1.5m).

7.1. Variation of Windows' Position

<u>3D Model of Guard Room of Jadavpur University Gate No. 3-</u>

<u>CASE–1-</u>

The positions of windows are in **opposite wall of the guard room.**

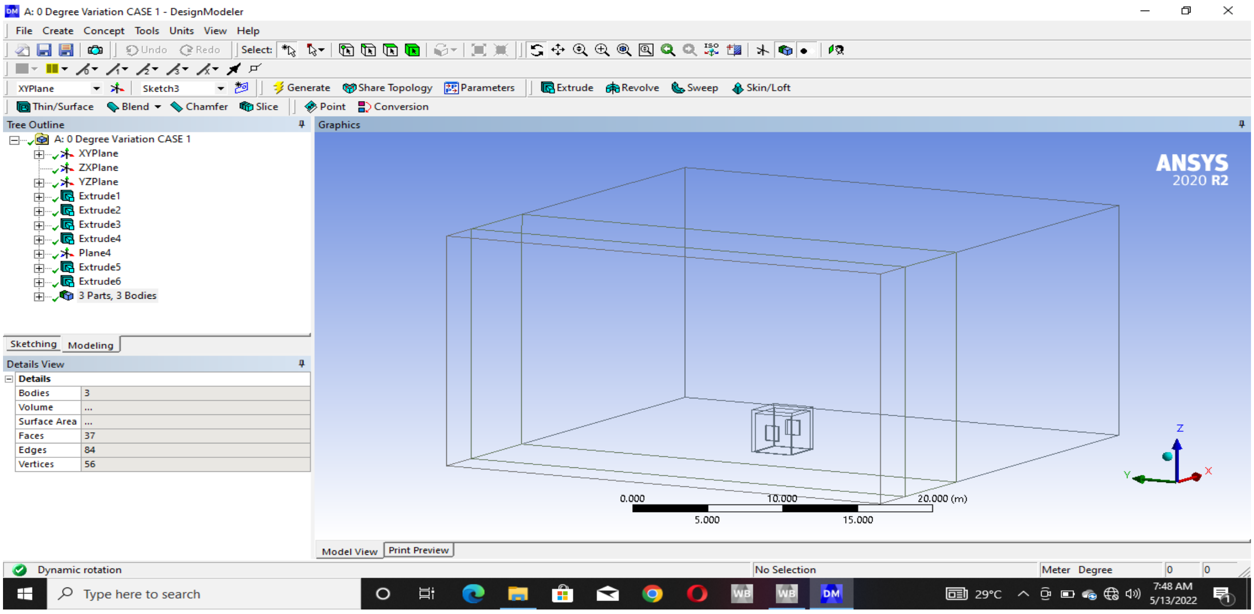


Figure 16 Pictorial View of opposite side windows

<u>Meshing of Model-</u>

Tetrahedral meshing is used.

Quality of meshing-

Jacobian Ration of mesh- 1.0062

Skewness- 0.23972

Element Quality- 0.79683

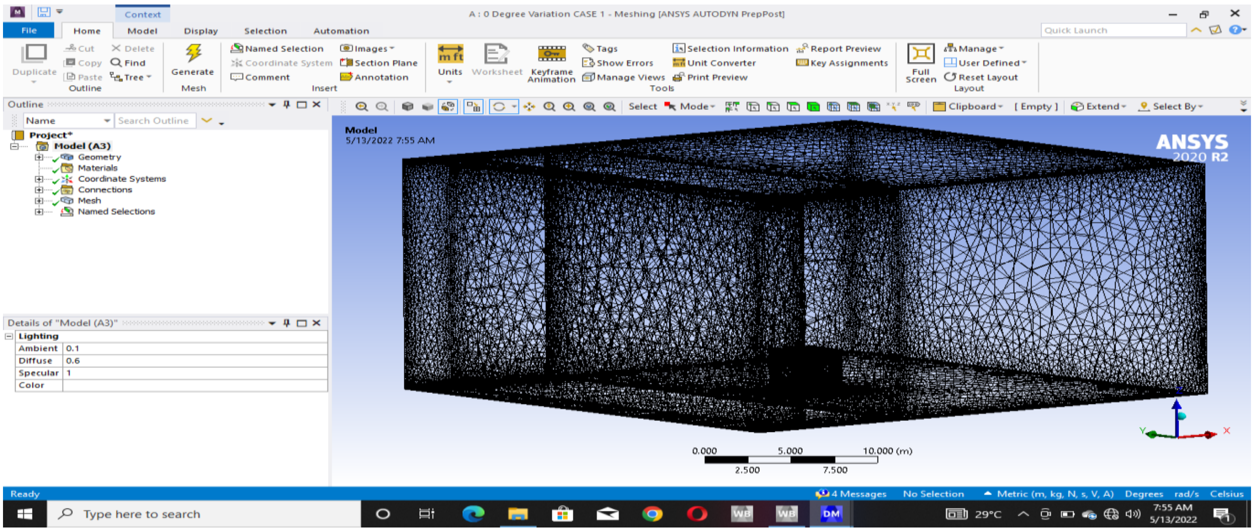


Figure 17 Meshing of the Model

Wind Speed 3 m/s-

It is considered that the speed of ‘west wind’ is 3 m/s. Various angle variation of west wind and their effects on PM_{10}.

PM $_{10}$ concentration in that particular guard room are shown below-

1) 0 Degree Angle Variation-

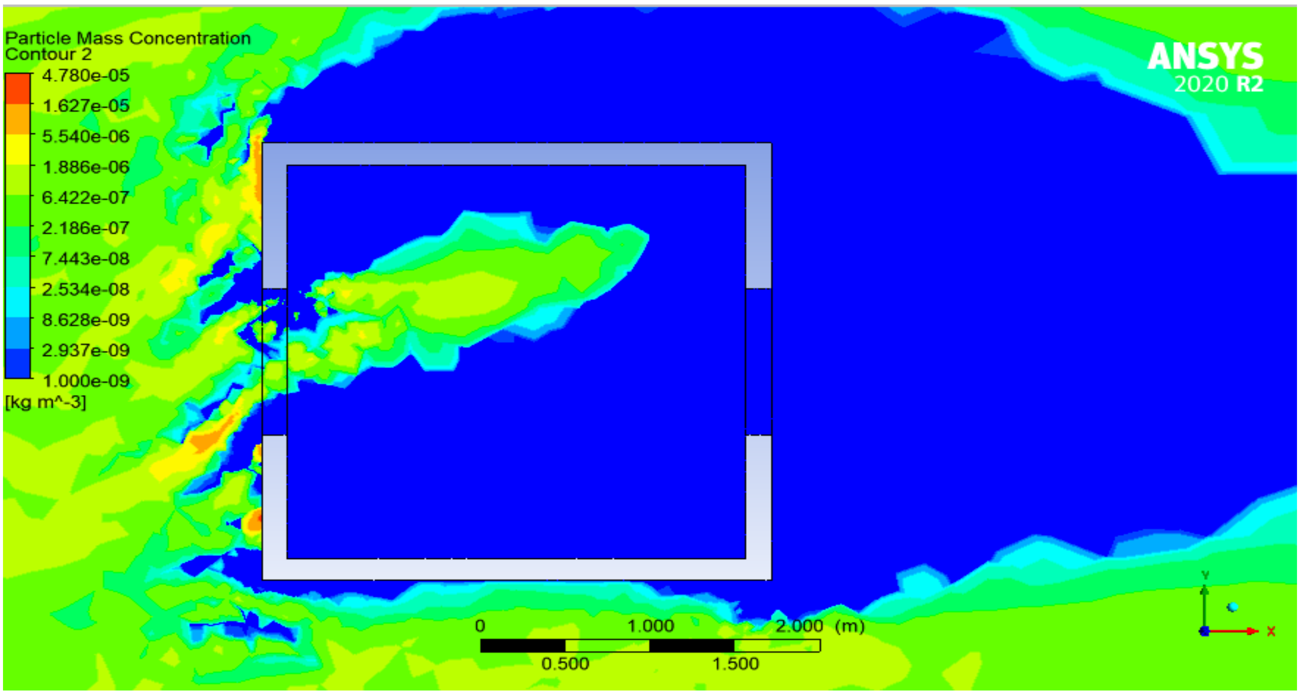


Figure 18 PM_{10} concentration contour inside the room

2) 5 Degree Angle Variation -

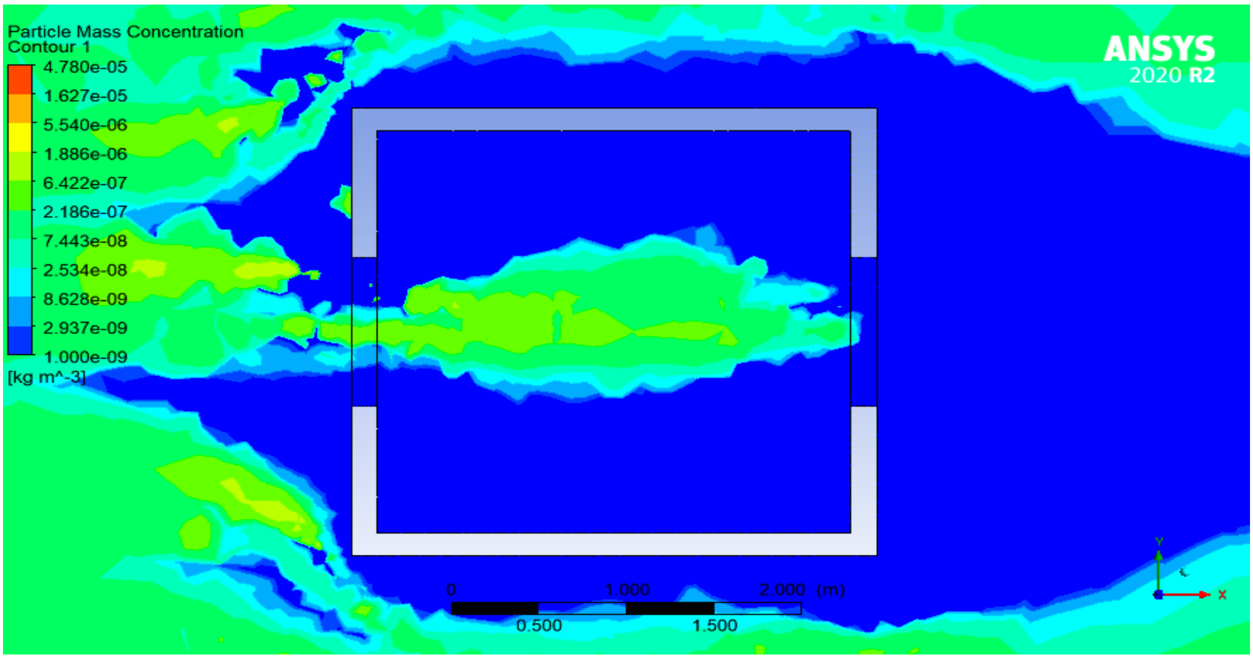


Figure 19 PM_{10} concentration contour inside the room

3) 10 Degree Angle Variation –

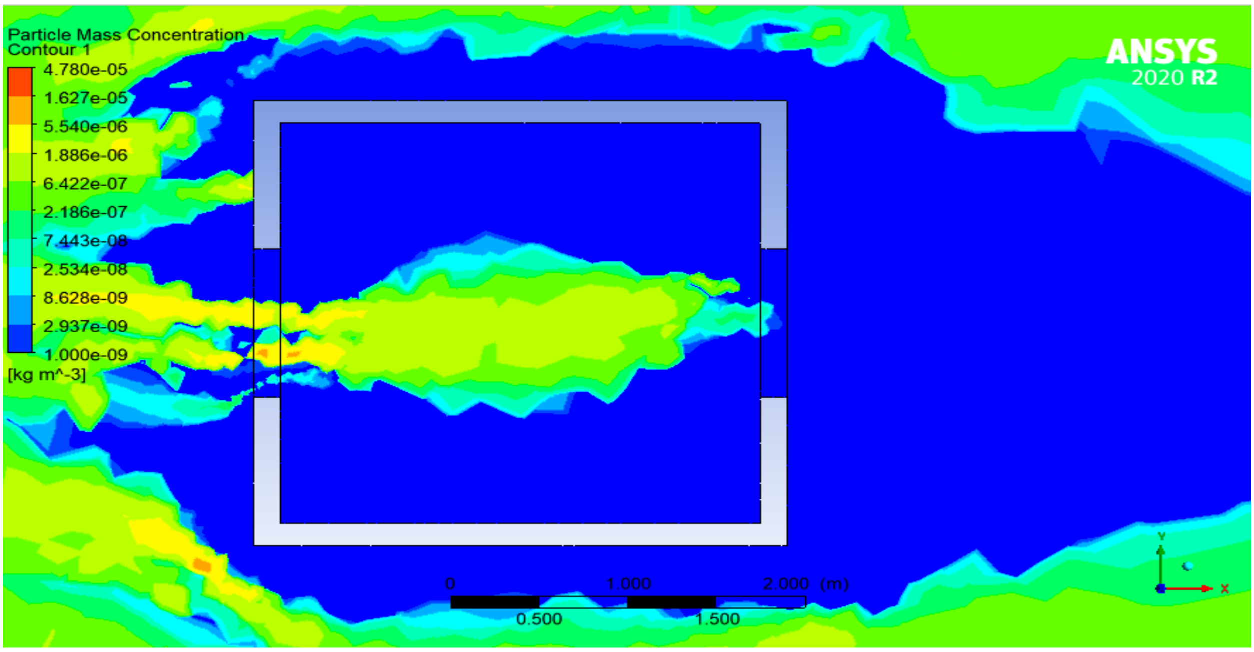


Figure 20 PM_{10} concentration contour inside the room

4) 15 Degree Angle Variation-

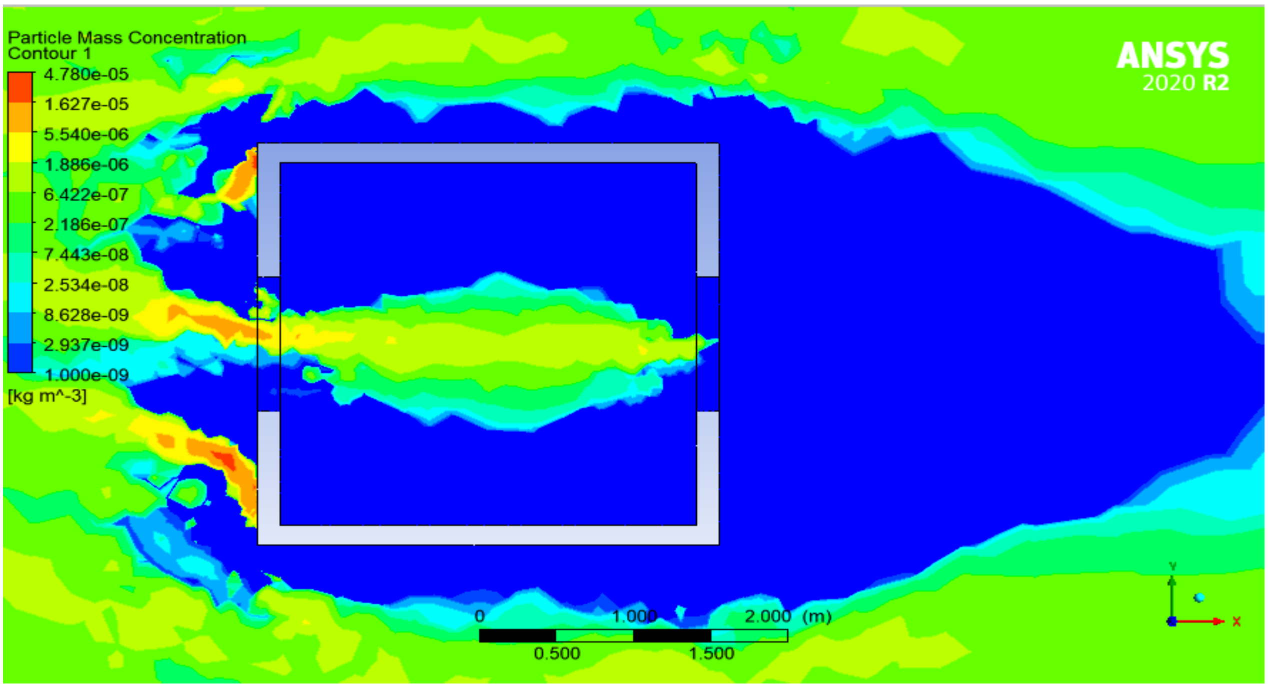


Figure 21 PM_{10} concentration contour inside the room

5) 20 Degree Angle Variation –

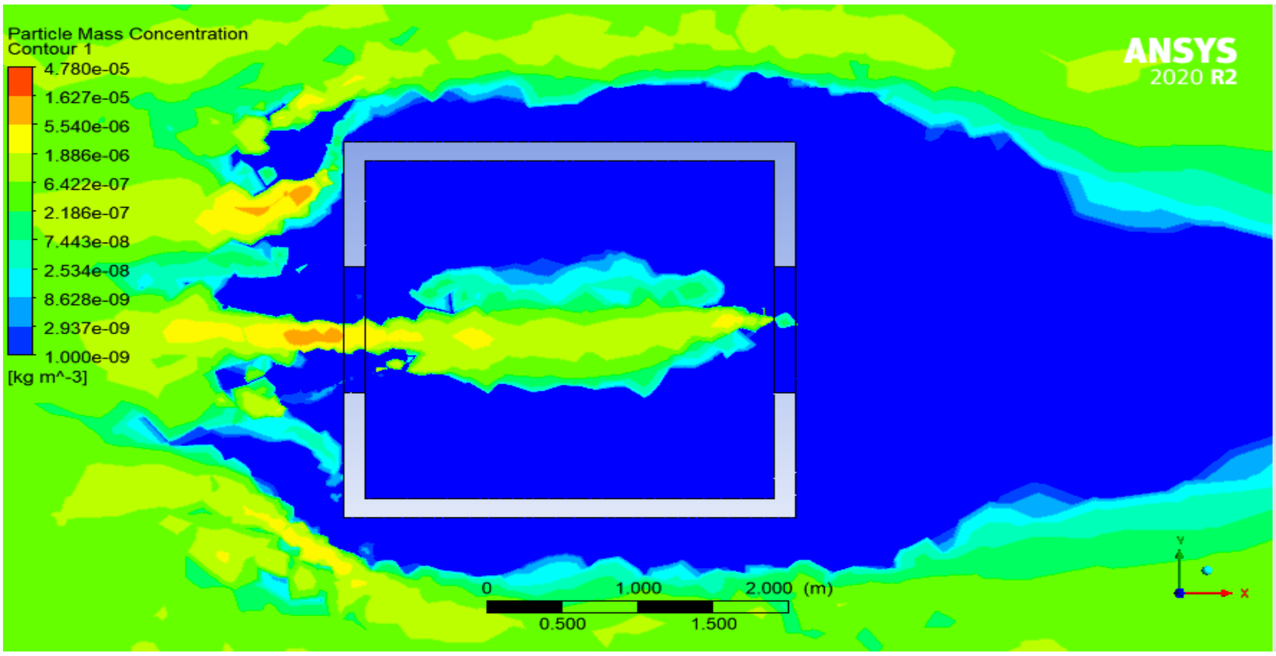


Figure 22 PM_{10} concentration contour inside the room

6) 25 Degree Angle Variation-

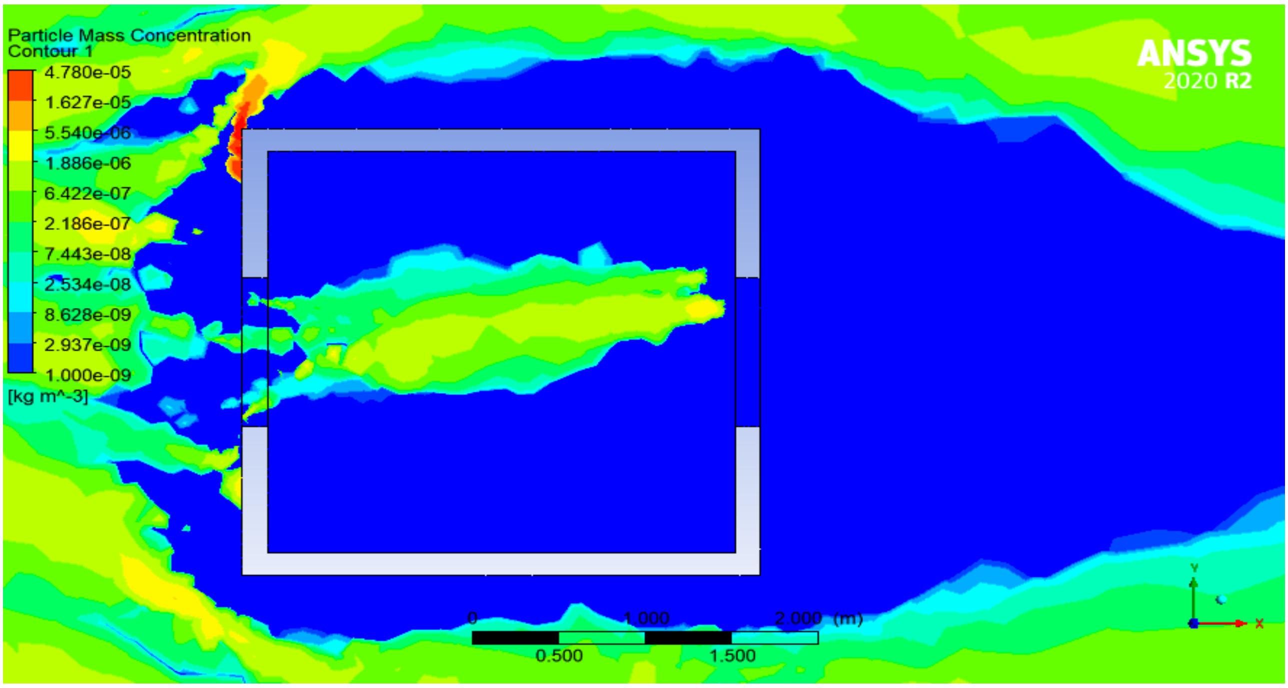


Figure 23 PM_{10} concentration contour inside the room

7) 30 Degree Angle Variation-

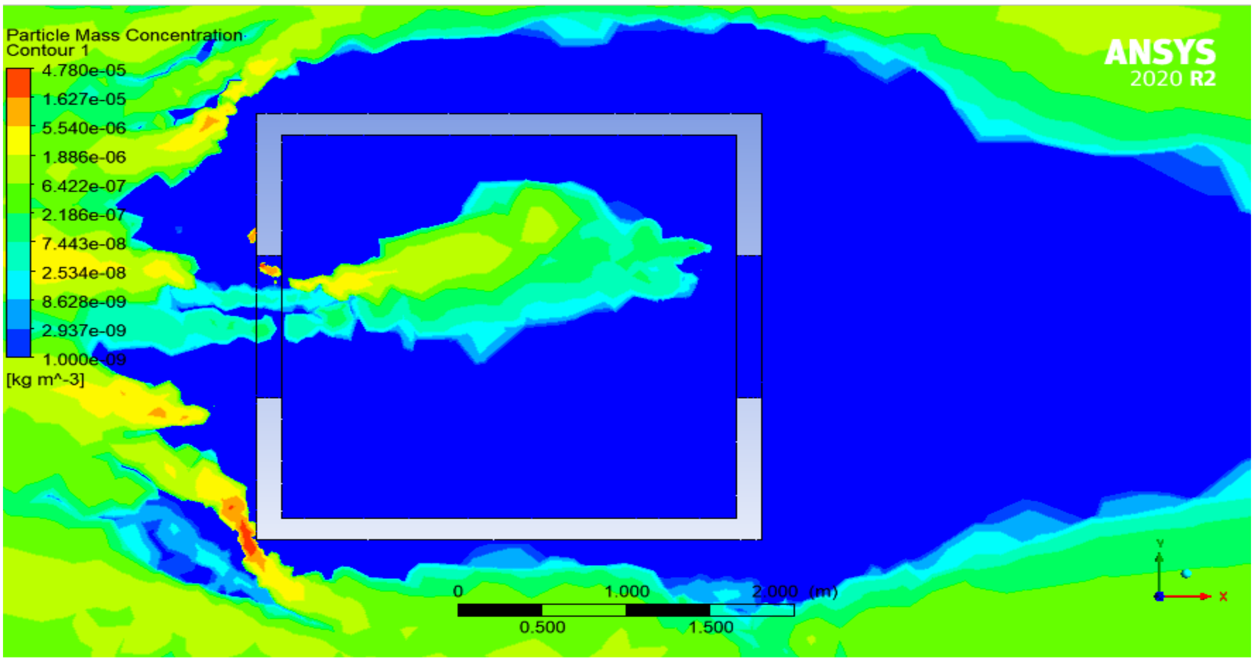


Figure 24 PM_{10} concentration contour inside the room

The highest values of PM_{10} concentration inside the room with respect to various wind angles are shown below.

Angle Variation	PM_{10} Concentration Variation (kg/m^3) 3 m/s
0 Degree	5.48×10^{-06}
5 Degree	5.41×10^{-06}
10 Degree	4.89×10^{-06}
15 Degree	4.67×10^{-06}
20 Degree	4.40×10^{-06}
25 Degree	4.31×10^{-06}
30 Degree	3.90×10^{-06}

Table 4 PM_{10} Concentration Variation at 3m/s

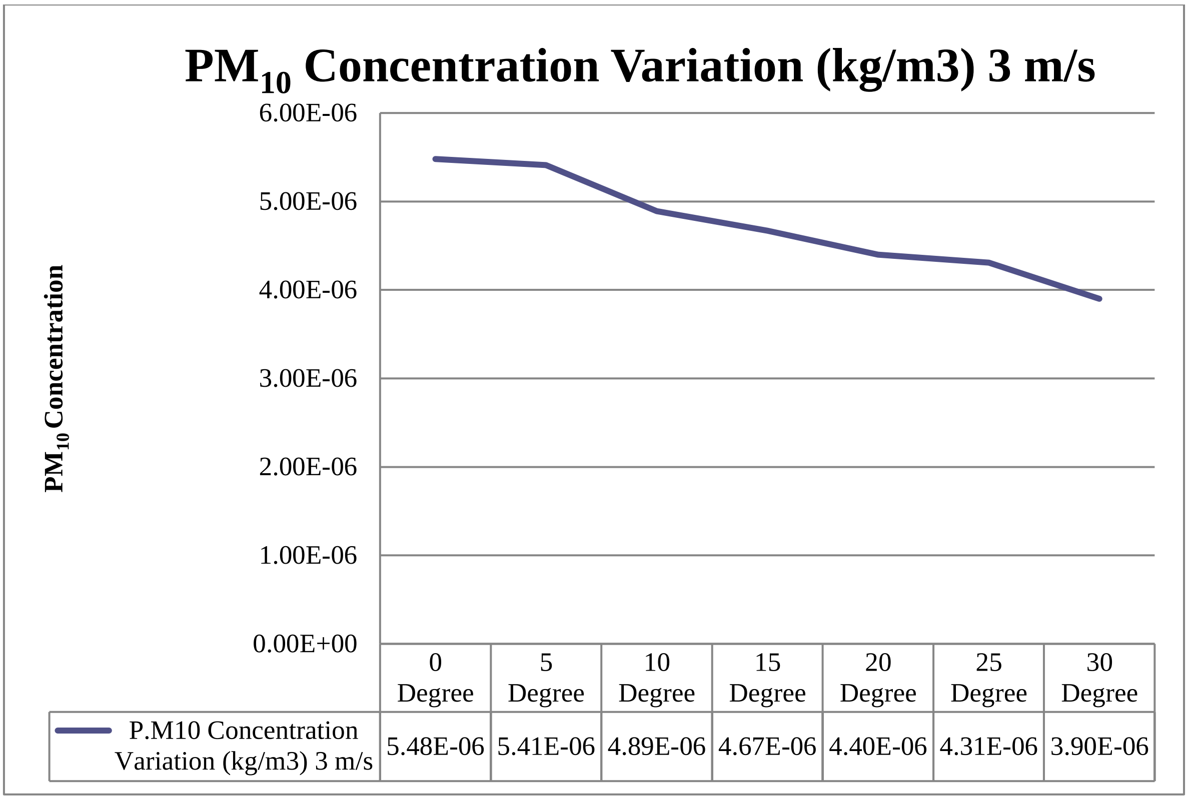


Figure 25 PM_{10} Concentration Variation (kg/m3) at 3 m/s

- It is observed that when the wind speed is constant and angle variation is increased, PM_{10} concentration level inside the room is decreased. Because when wind angle is 0 degree, the west wind is parallel to X axis. So, the effect of wind is maximum. When wind angle is increased gradually, the wind can't enter the room directly. So, the effect of wind is decreased gradually.

Wind Speed 5 m/s-

It is considered that the speed of 'west wind' is 5 m/s. Various angle variation of west wind and their effects on PM_{10} concentration in that particular guard room are shown below-

1) <u>0 Degree Angle Variation-</u>

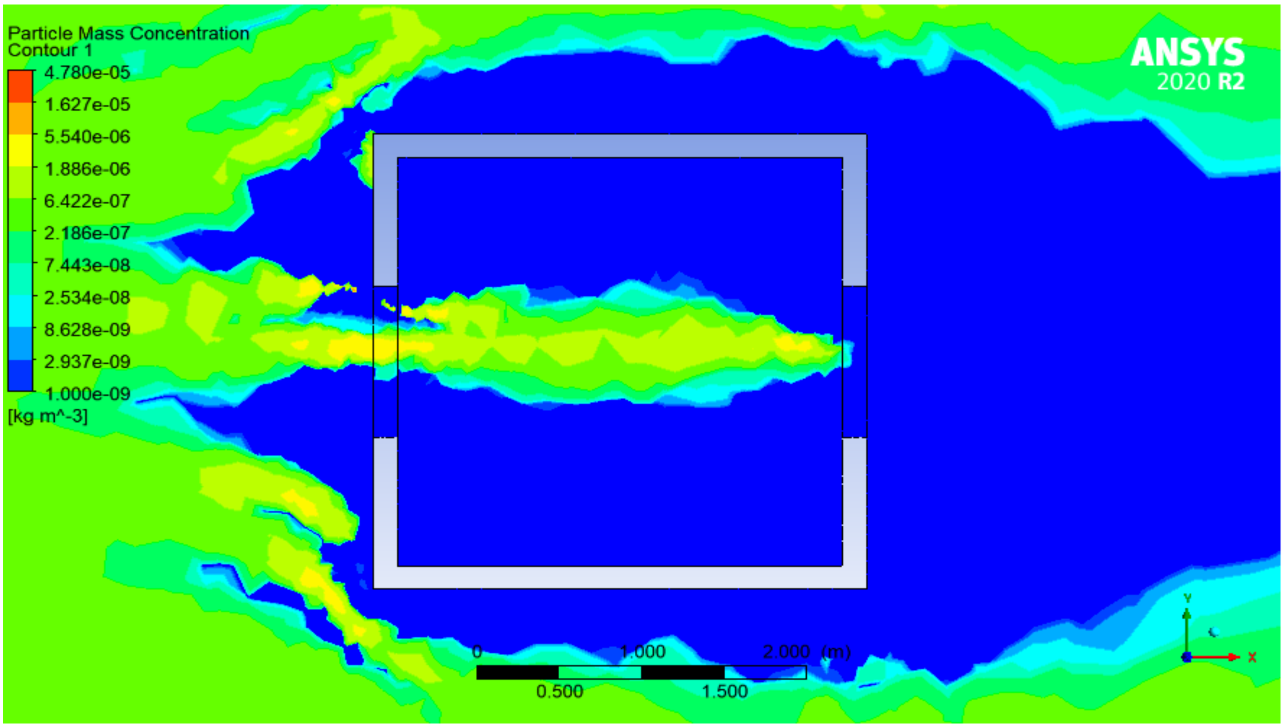


Figure 26 PM_{10} concentration contour inside the room

2) <u>5 Degree Angle Variation-</u>

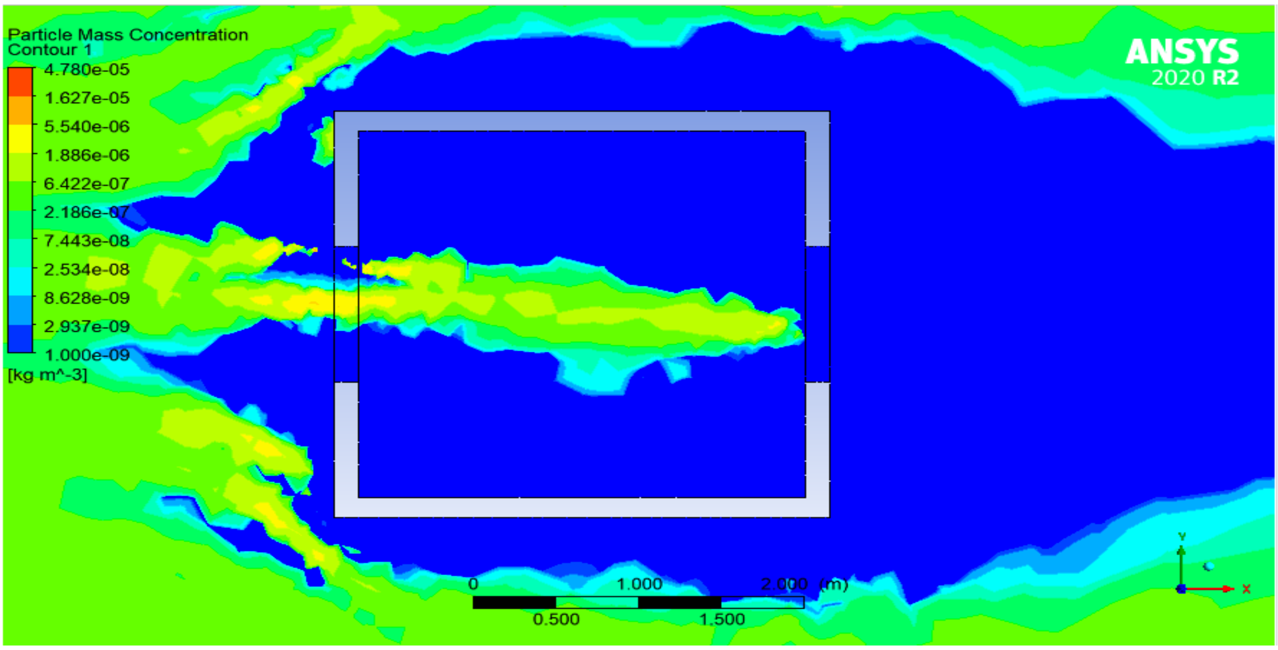


Figure 27 PM_{10} concentration contour inside the room

3) 10 Degree Angle Variation-

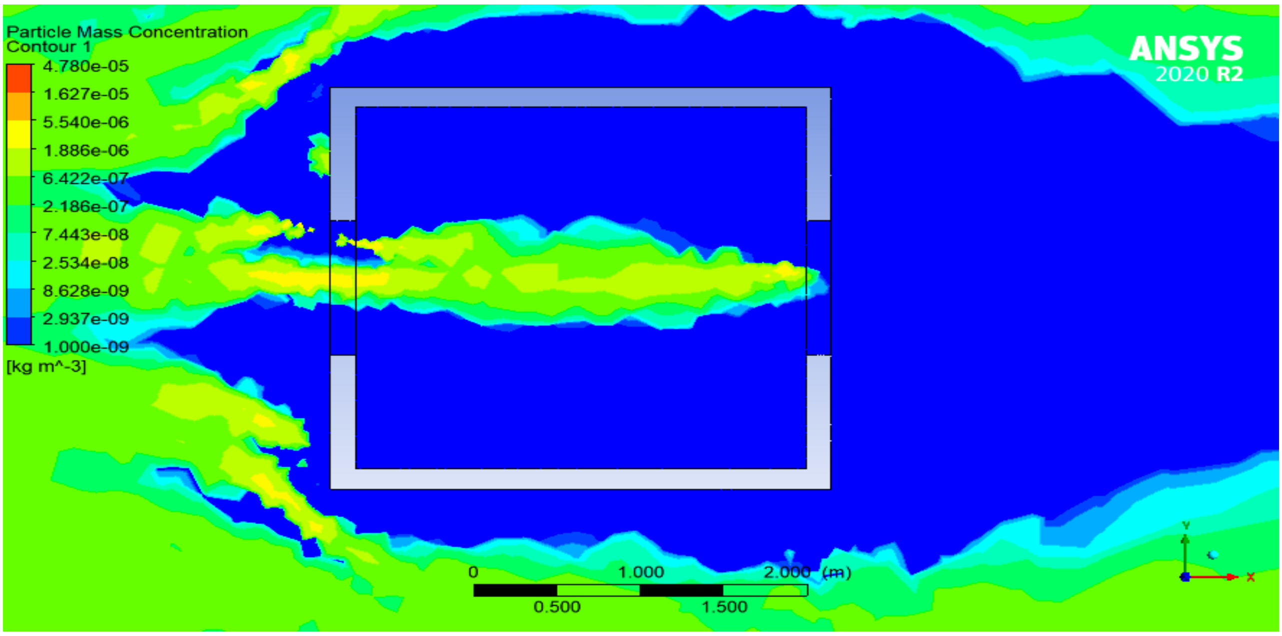


Figure 28 PM_{10} concentration contour inside the room

4) 15 Degree Angle Variation-

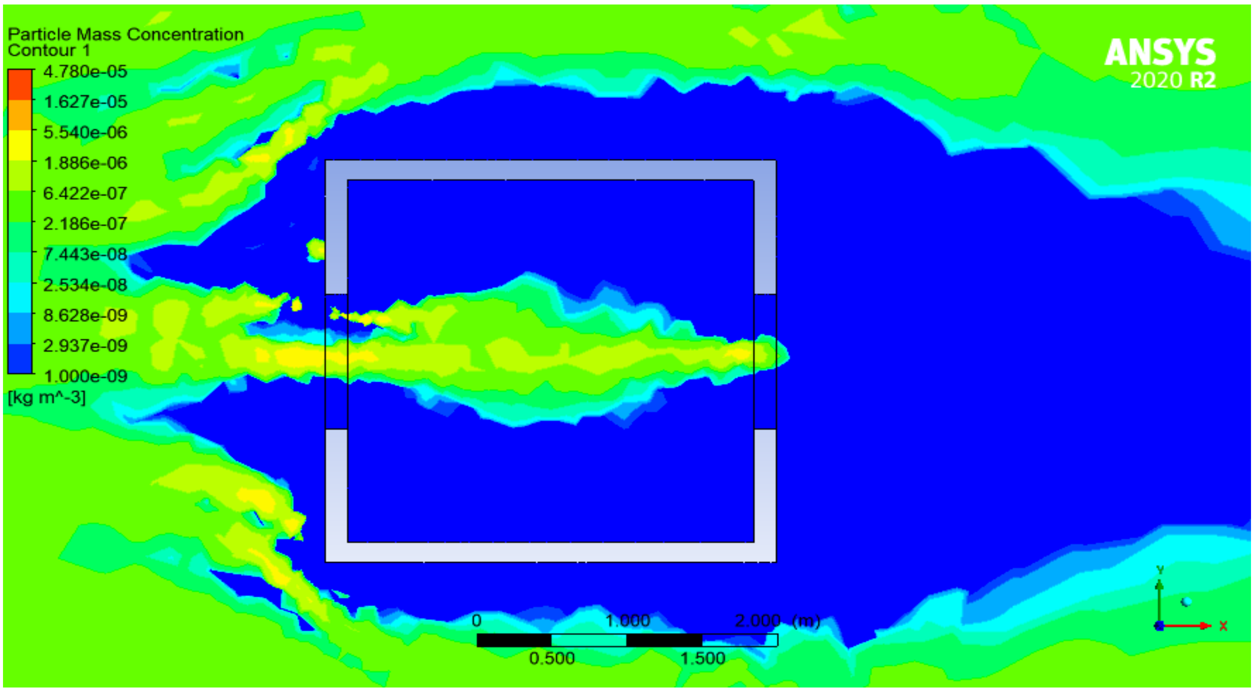


Figure 29 PM_{10} concentration contour inside the room

5) 20 Degree Angle Variation-

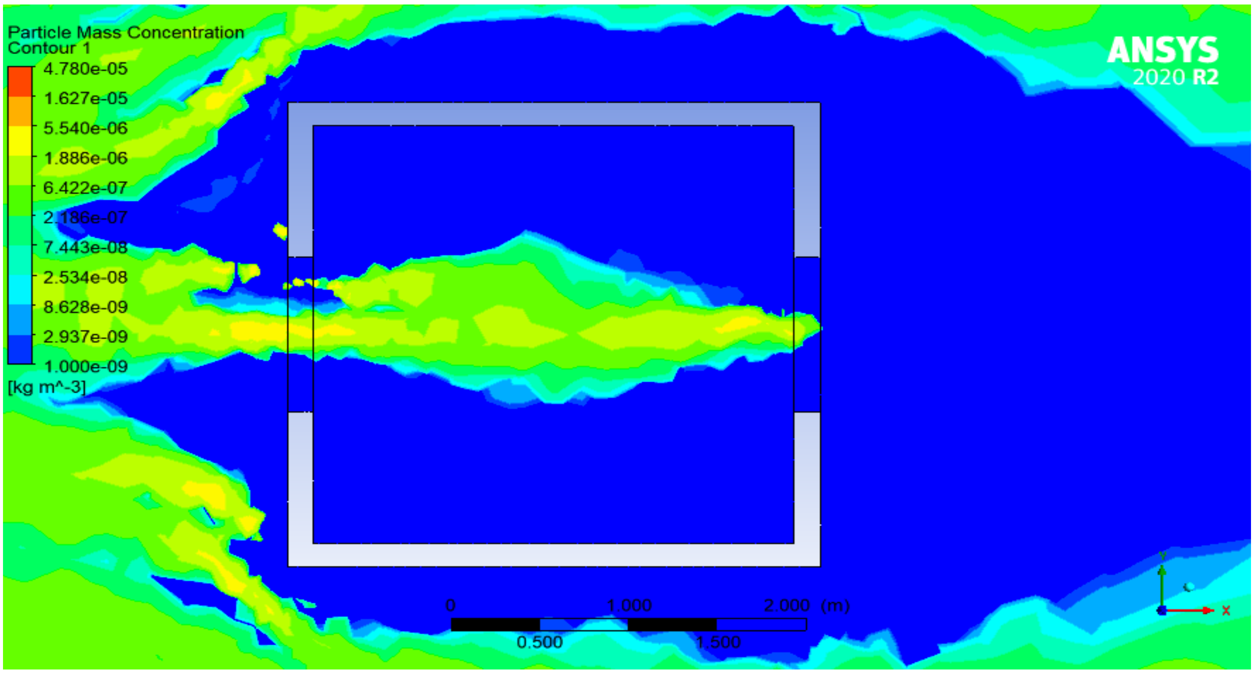


Figure 30 PM_{10} concentration contour inside the room

6) 25 Degree Angle Variation-

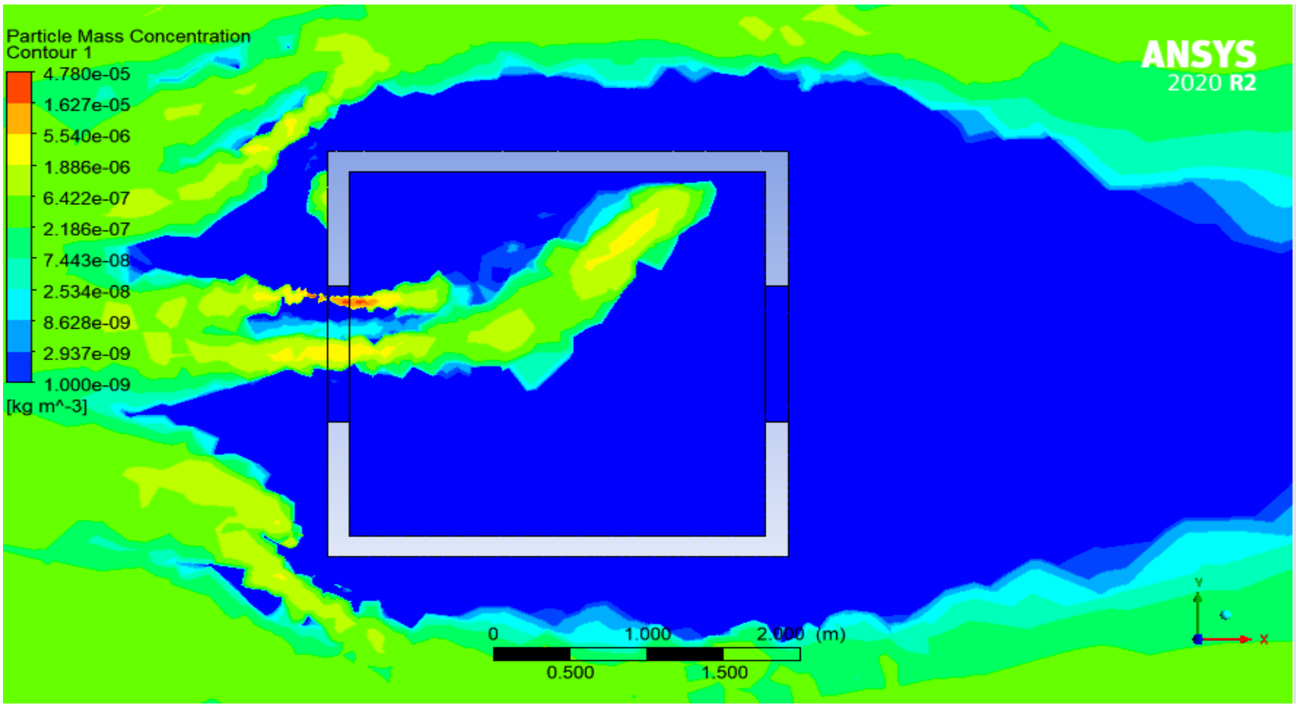


Figure 31 PM_{10} concentration contour inside the room

7) 30 Degree Angle Variation-

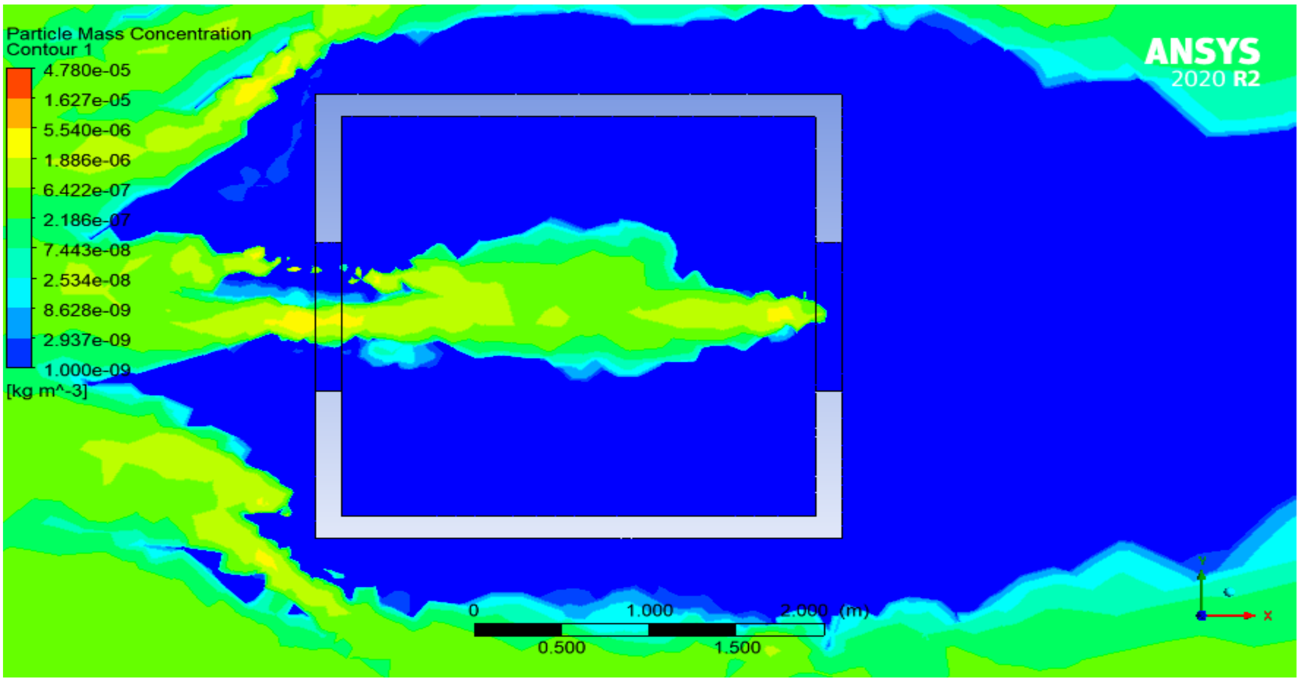
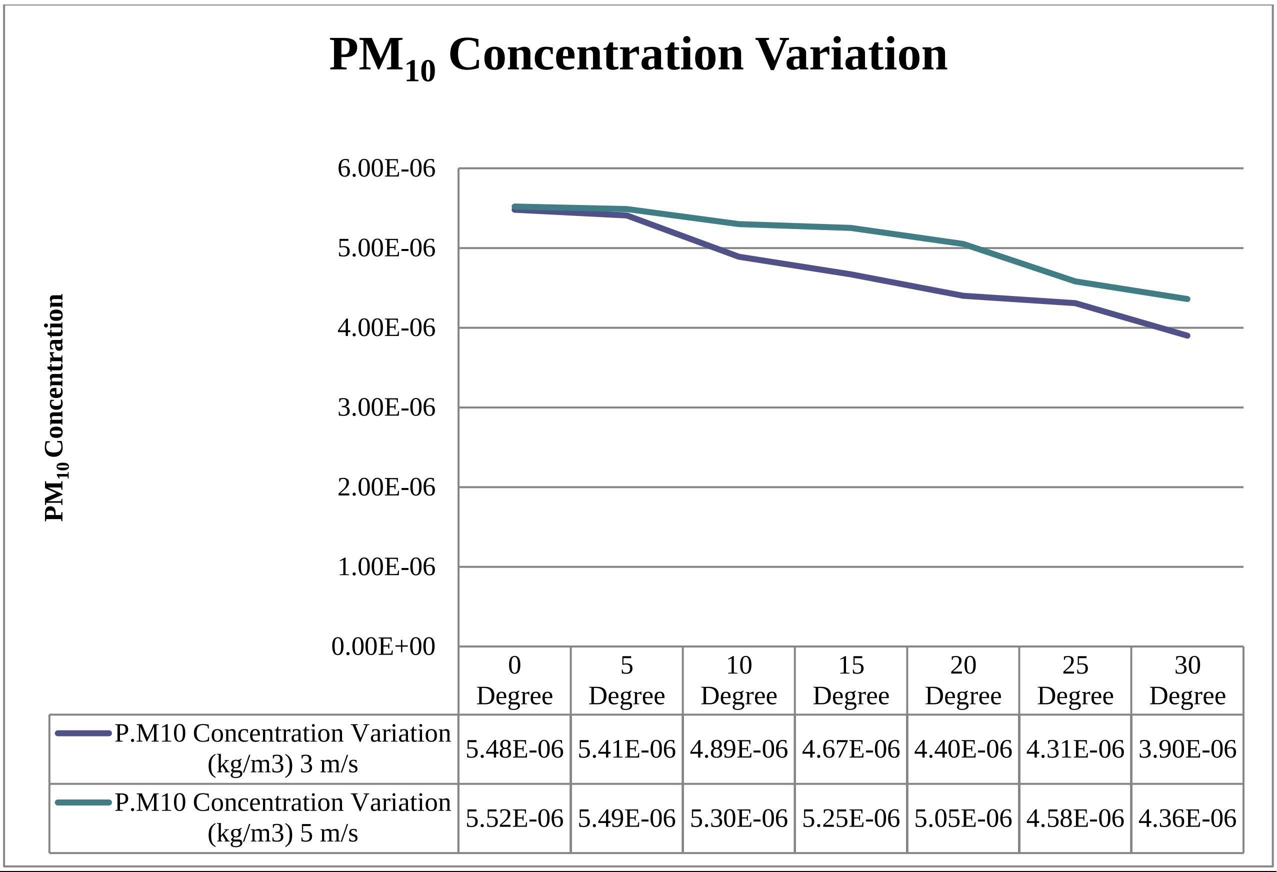


Figure 32 PM_{10} concentration contour inside the room

The highest values of PM_{10} concentration inside the room with respect to various wind angles are shown below.

Angle Variation	PM_{10} Concentration Variation (kg/m^3) 3 m/s	PM_{10} Concentration Variation (kg/m^3) 5 m/s
0 Degree	5.48×10^{-06}	5.52×10^{-06}
5 Degree	5.41×10^{-06}	5.49×10^{-06}
10 Degree	4.89×10^{-06}	5.30×10^{-06}
15 Degree	4.67×10^{-06}	5.25×10^{-06}
20 Degree	4.40×10^{-06}	5.05×10^{-06}
25 Degree	4.31×10^{-06}	4.58×10^{-06}
30 Degree	3.90×10^{-06}	4.36×10^{-06}

Table 5 PM_{10} Concentration Variation when windows are in opposite side at 3m/s & 5m/s



	0 Degree	5 Degree	10 Degree	15 Degree	20 Degree	25 Degree	30 Degree
P.M10 Concentration Variation (kg/m3) 3 m/s	5.48E-06	5.41E-06	4.89E-06	4.67E-06	4.40E-06	4.31E-06	3.90E-06
P.M10 Concentration Variation (kg/m3) 5 m/s	5.52E-06	5.49E-06	5.30E-06	5.25E-06	5.05E-06	4.58E-06	4.36E-06

Figure 33 PM_{10} Concentration Variation (kg/m3) at 3 m/s & 5 m/s

It is observed that when the wind speed is constant and angle variation is increased, PM_{10} concentration level inside the room is decreased.

CASE-2 –

The positions of windows are in adjacent side wall of the guard room.

Model-

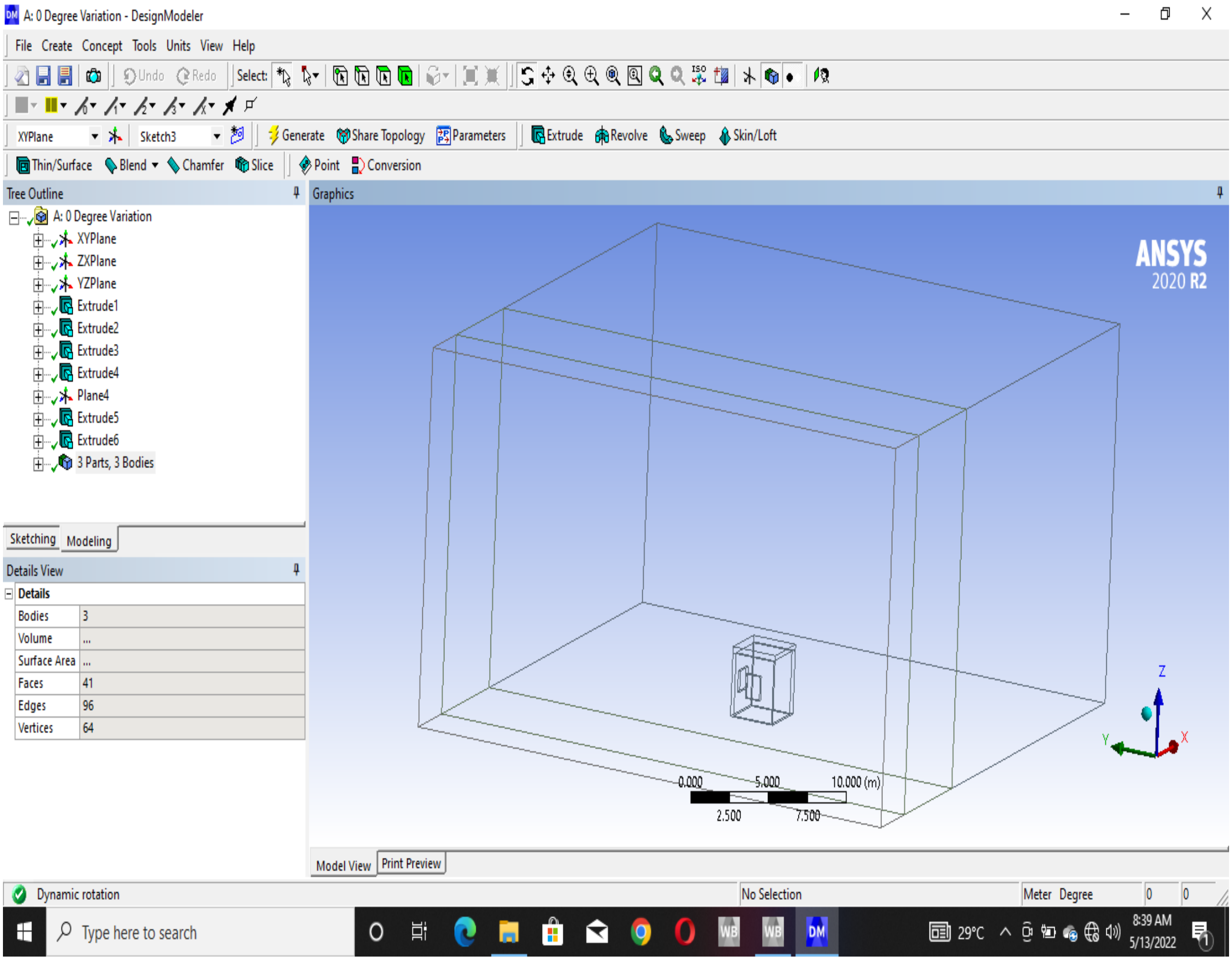


Figure 34 Pictorial View of adjacent side windows

Meshing-

Here, tetrahedral meshing is used.

Quality of meshing-

Jacobian Ration of mesh- 1.0058

Skewness- 0.23959

Element Quality- 0.80104

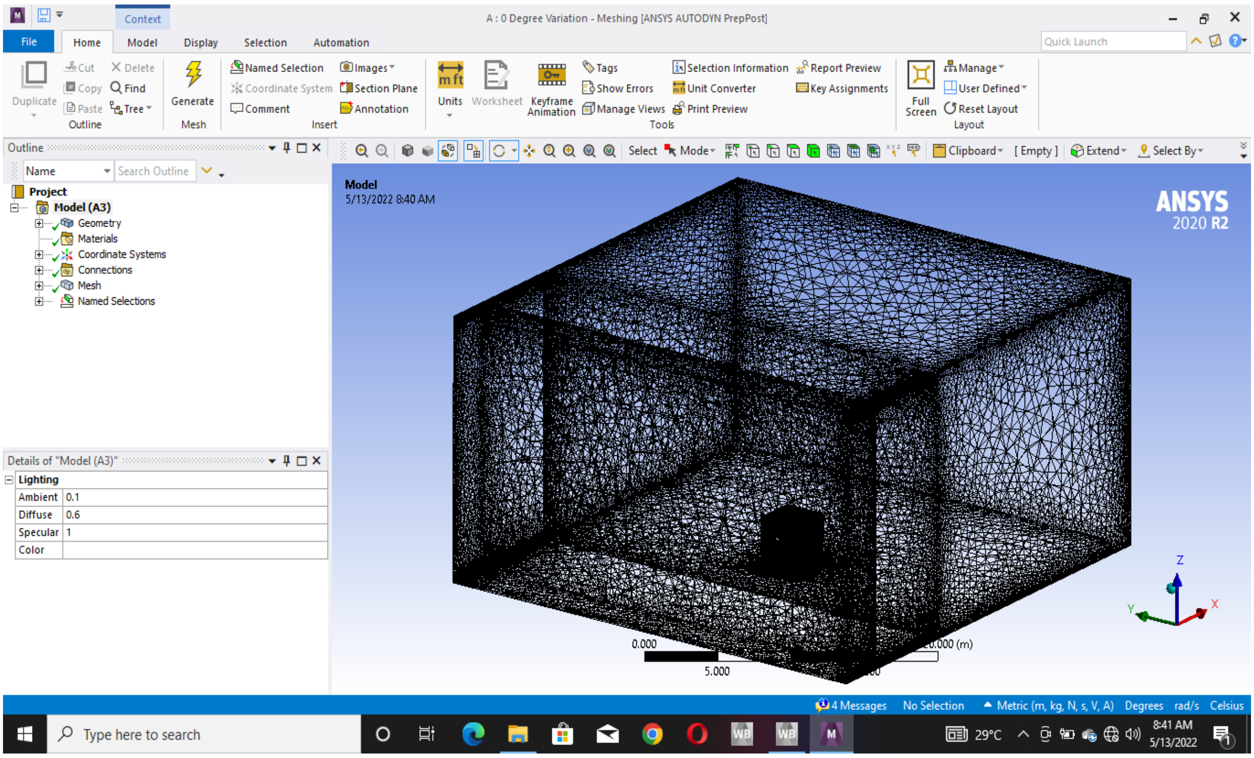


Figure 35 Meshing of the model

Wind Speed – 3m/s

It is considered that the speed of ‘west wind’ is 3 m/s. Various angle variation of west wind and their effects on PM_{10} concentration in that particular guard room are shown below-

1) <u>0 Degree Angle Variation-</u>

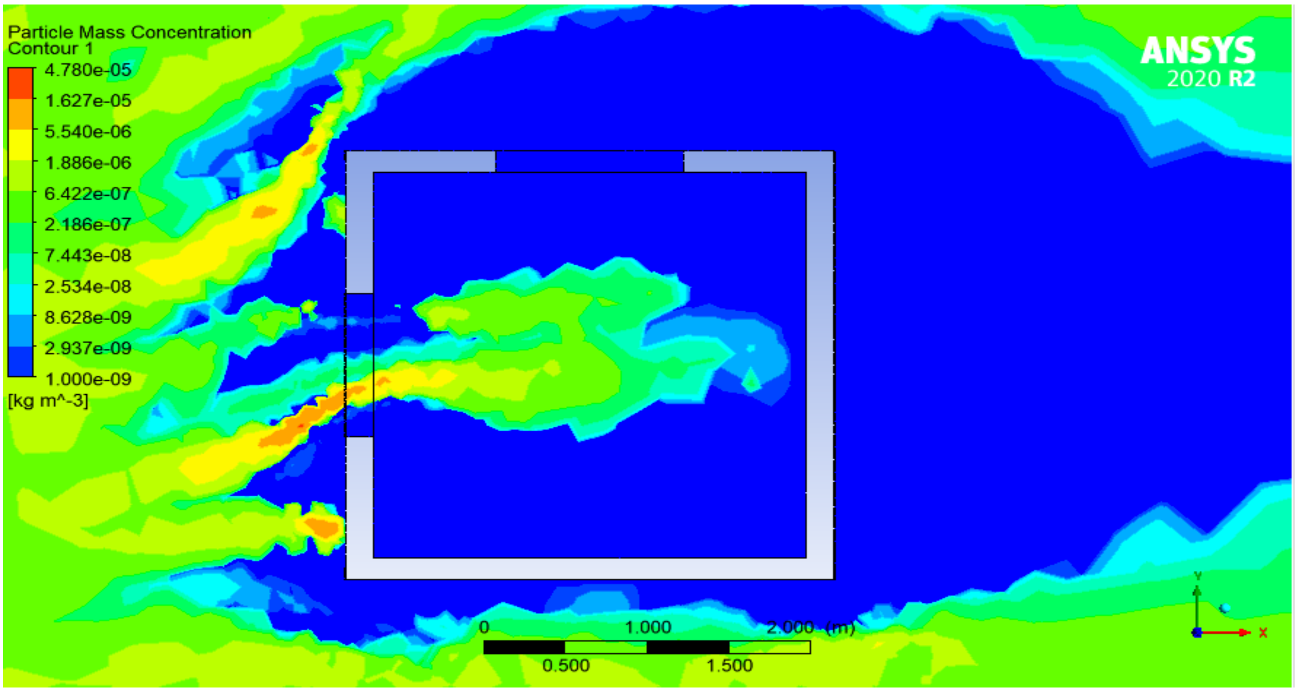


Figure 36 PM_{10} concentration contour inside the room

2) <u>5 Degree Angle Variation-</u>

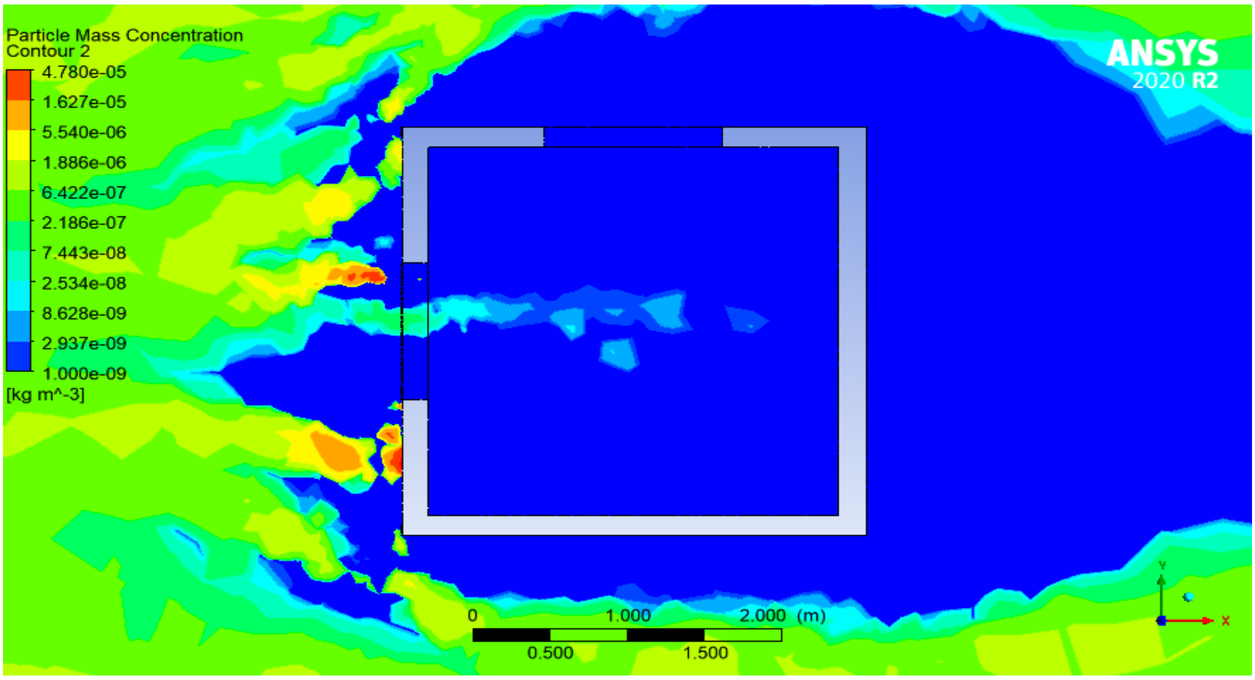


Figure 37 PM_{10} concentration contour inside the room

3) 10 Degree Angle Variation-

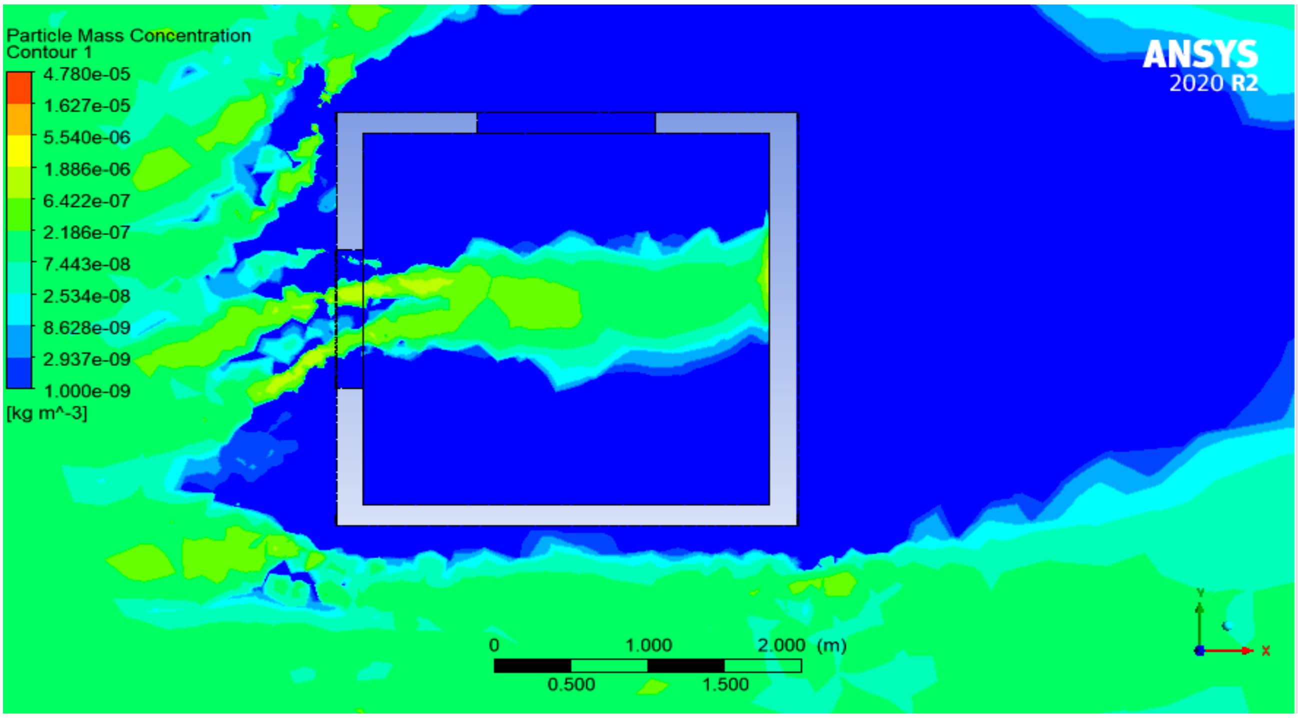


Figure 38 PM_{10} concentration contour inside the room

4) 15 Degree Angle Variation-

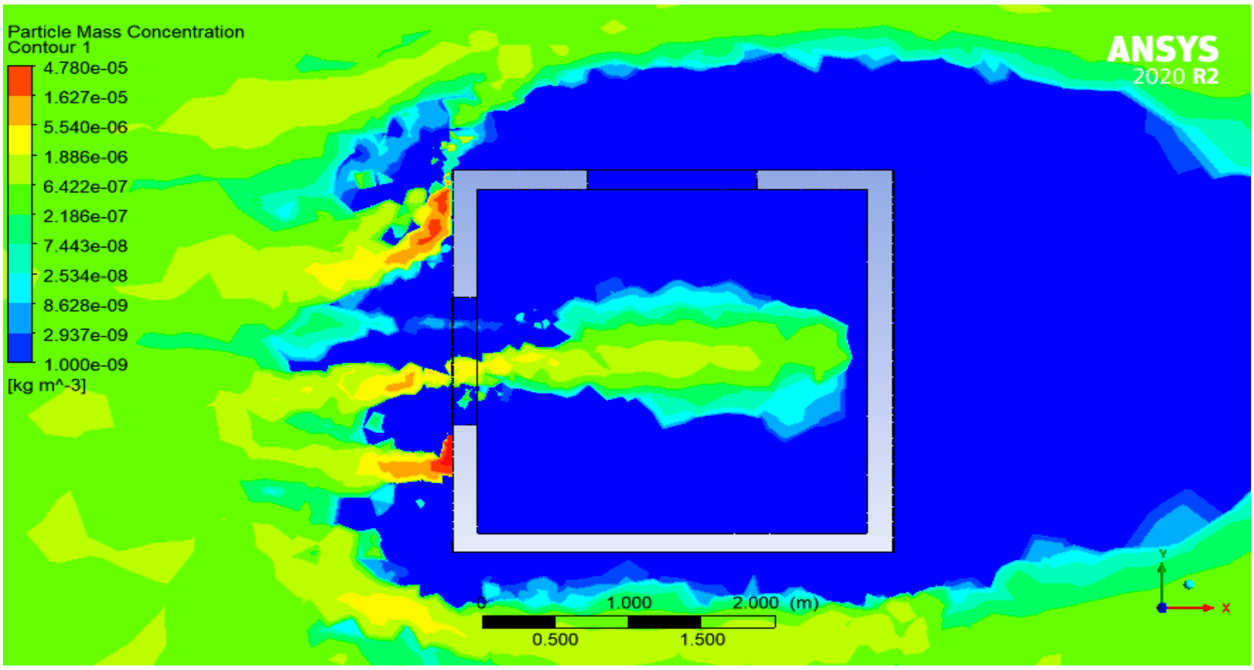


Figure 39 PM_{10} concentration contour inside the room

5) 20 Degree Angle Variation-

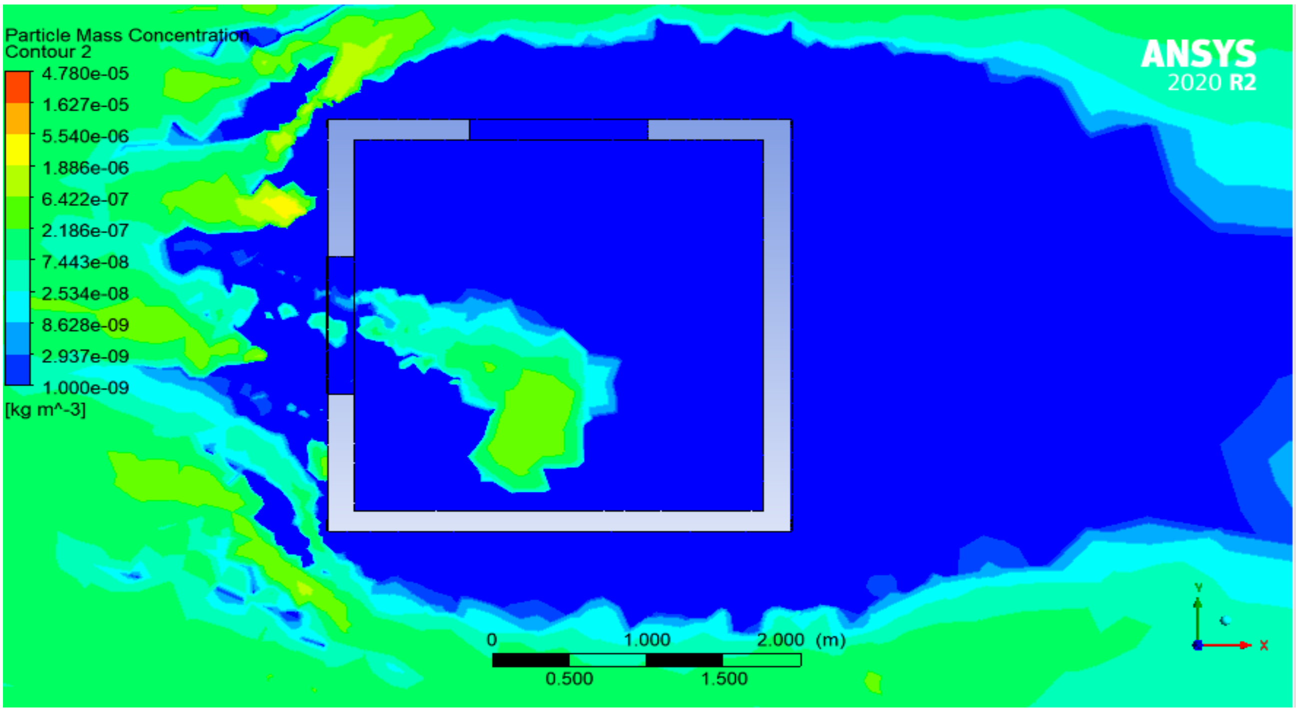


Figure 40 PM_{10} concentration contour inside the room

6) 25 Degree Angle Variation-

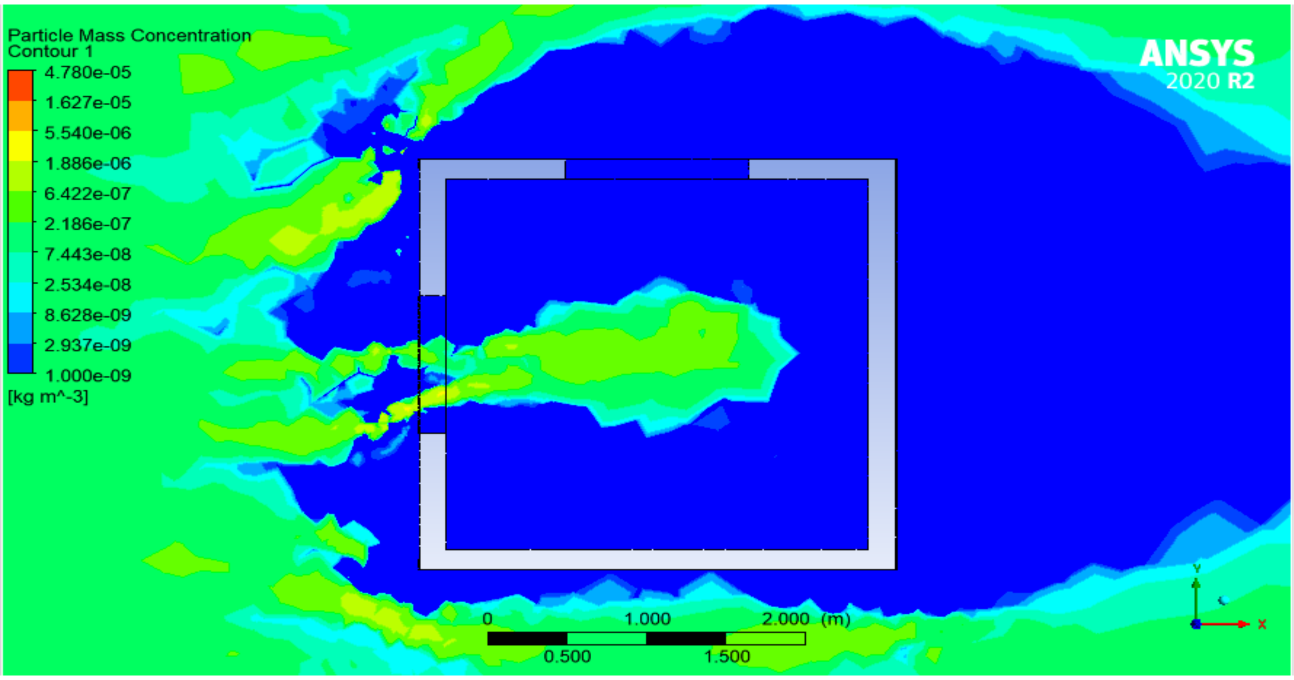


Figure 41 PM_{10} concentration contour inside the room

7) 30 Degree Angle Variation-

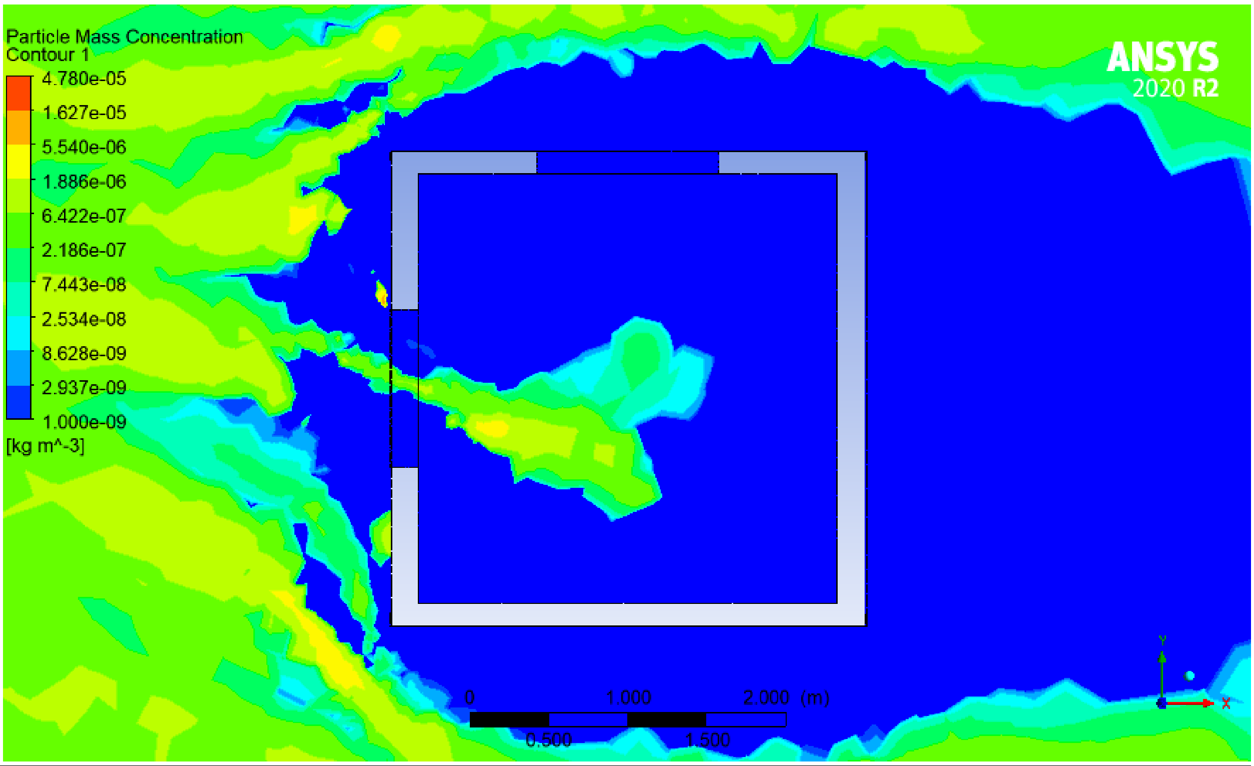
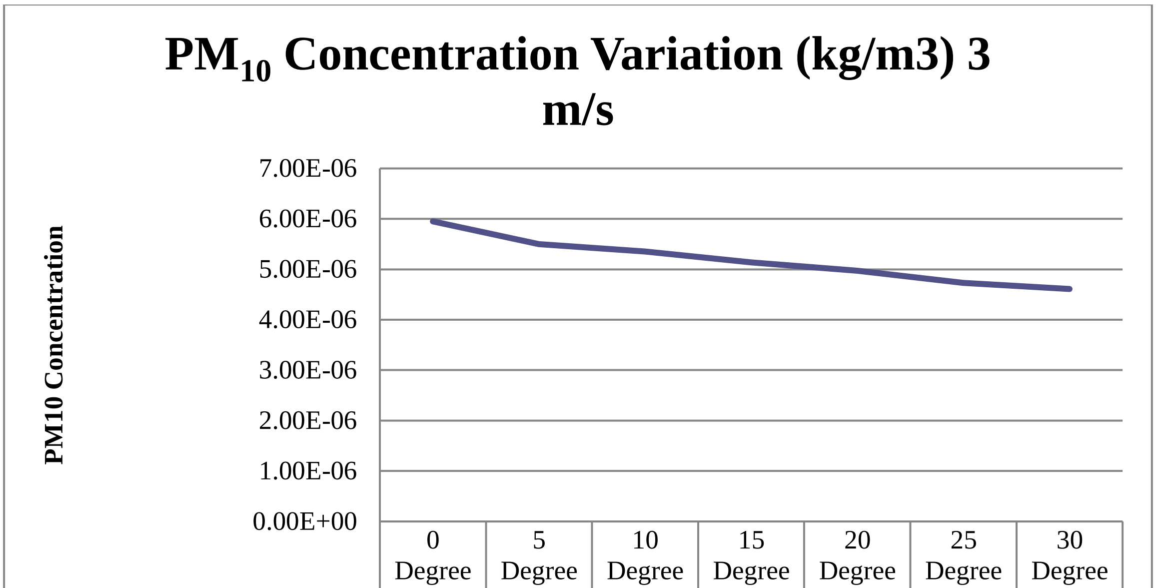


Figure 42 PM10 concentration contour inside the room

The highest values of PM_{10} concentration inside the room with respect to various wind angles are shown below.

Angle Variation	PM_{10} Concentration Variation (kg/m^3) 3 m/s
0 Degree	5.95×10^{-06}
5 Degree	5.50×10^{-06}
10 Degree	5.35×10^{-06}
15 Degree	5.14×10^{-06}
20 Degree	4.97×10^{-06}
25 Degree	4.73×10^{-06}
30 Degree	4.61×10^{-06}

Table 6 PM10 Concentration Variation when windows are in adjacent side at 3m/s



	0 Degree	5 Degree	10 Degree	15 Degree	20 Degree	25 Degree	30 Degree
P.M10 Concentration Variation (kg/m3) 3 m/s	5.95E-06	5.50E-06	5.35E-06	5.14E-06	4.97E-06	4.73E-06	4.61E-06

Figure 43 PM_{10} Concentration Variation (kg/m3) at 3 m/s

For Case-2, it is observed that when the wind speed is constant and angle variation is increased, PM_{10} concentration level inside the room is decreased.

Wind Speed- 5 m/s

It is considered that the speed of ‘west wind’ is 5 m/s. Various angle variation of west wind and their effects on PM_{10} concentration in that particular guard room are shown below-

1) <u>0 Degree Angle Variation-</u>

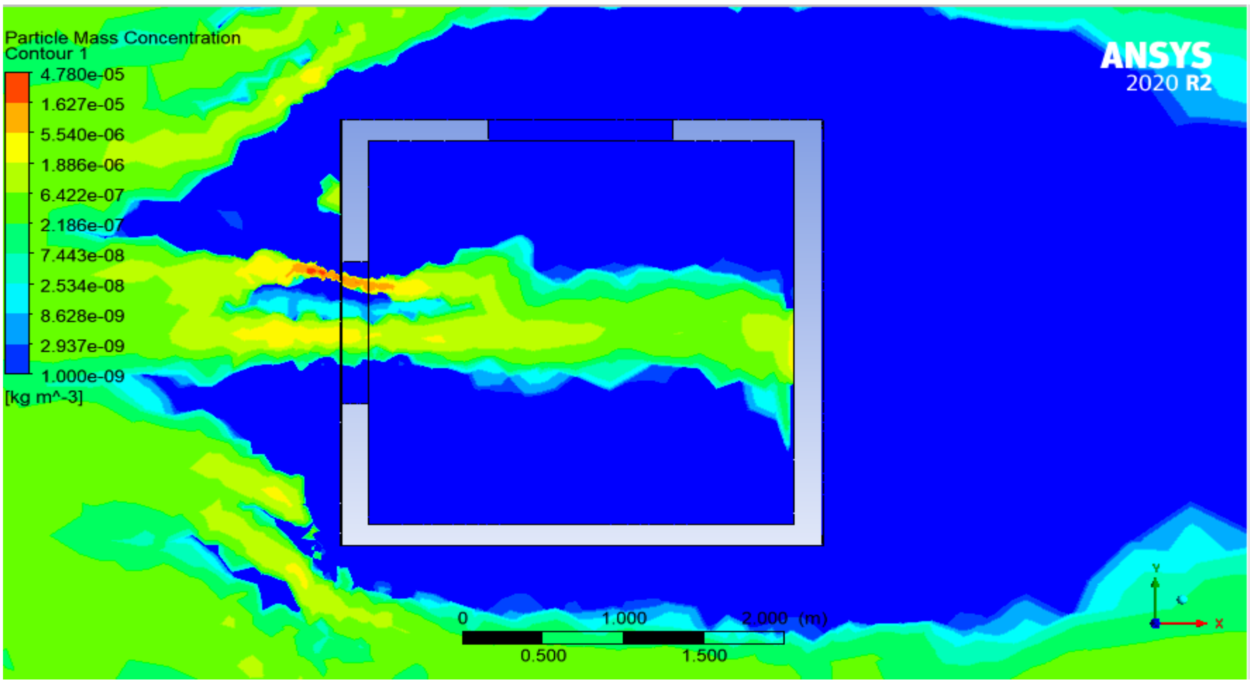


Figure 44 PM_{10} concentration contour inside the room

2) <u>5 Degree Angle Variation-</u>

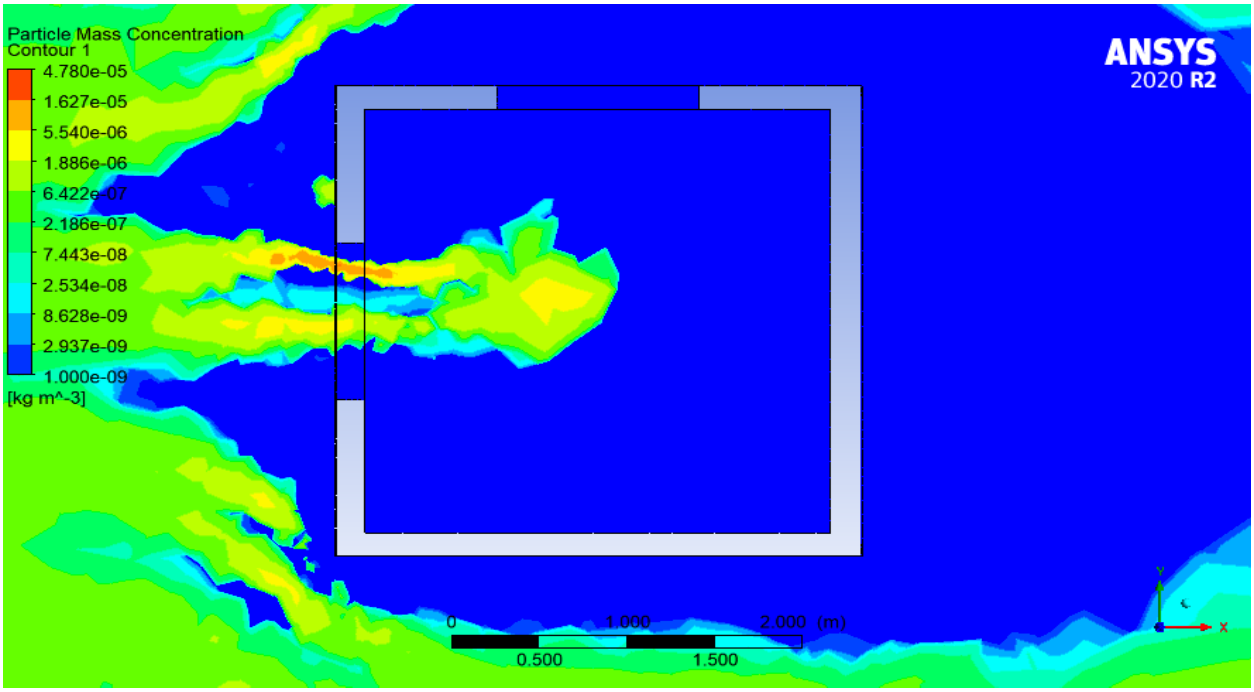


Figure 45 PM_{10} concentration contour inside the room

3) 10 Degree Angle Variation-

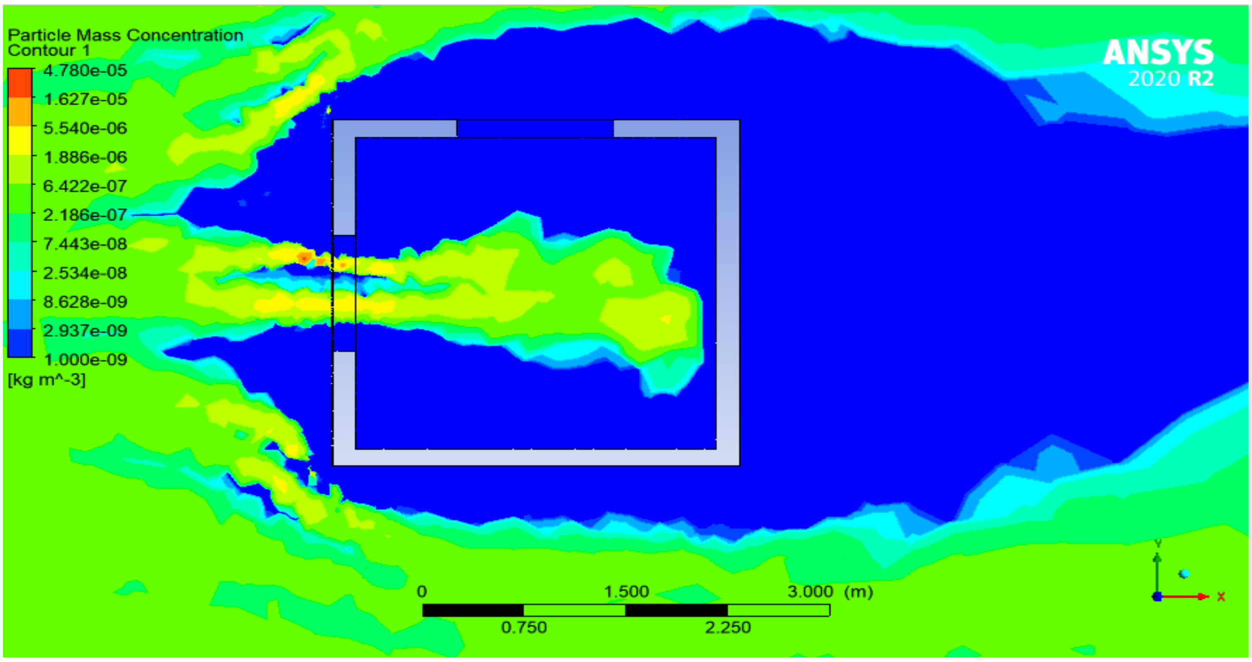


Figure 46 PM_{10} concentration contour inside the room

4) 15 Degree Angle Variation-

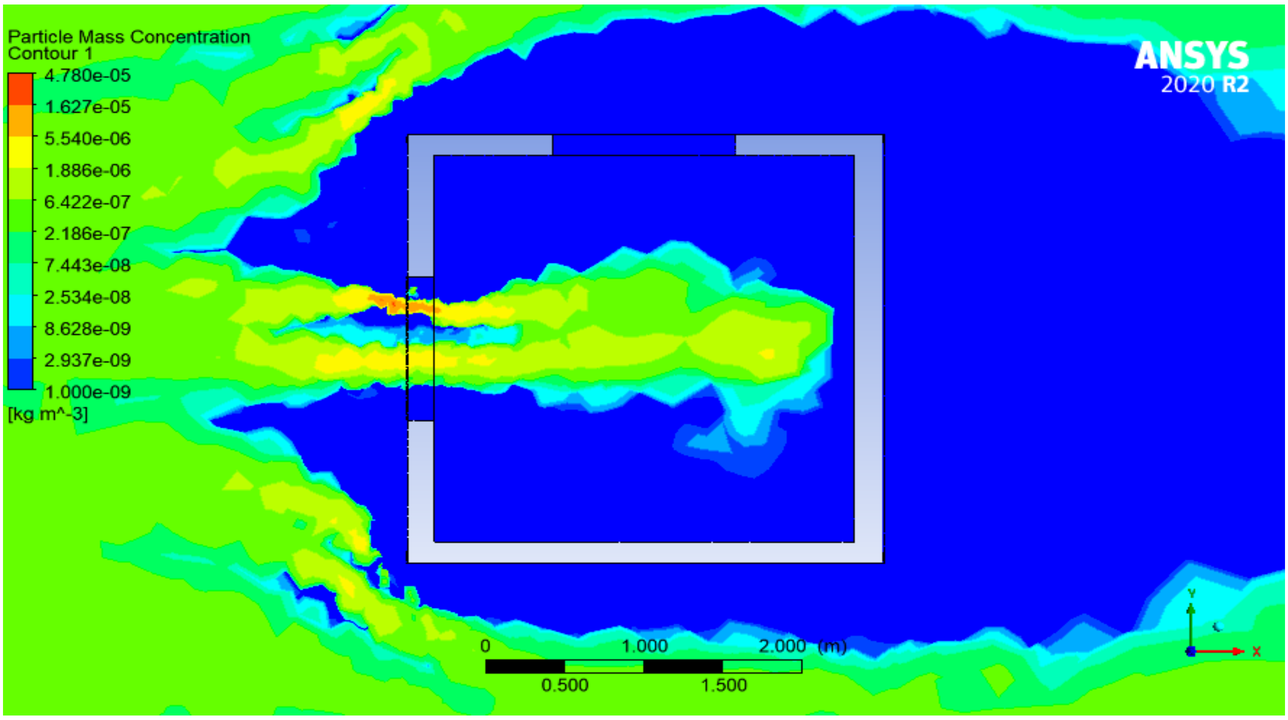


Figure 47 PM_{10} concentration contour inside the room

5) 20 Degree Angle Variation-

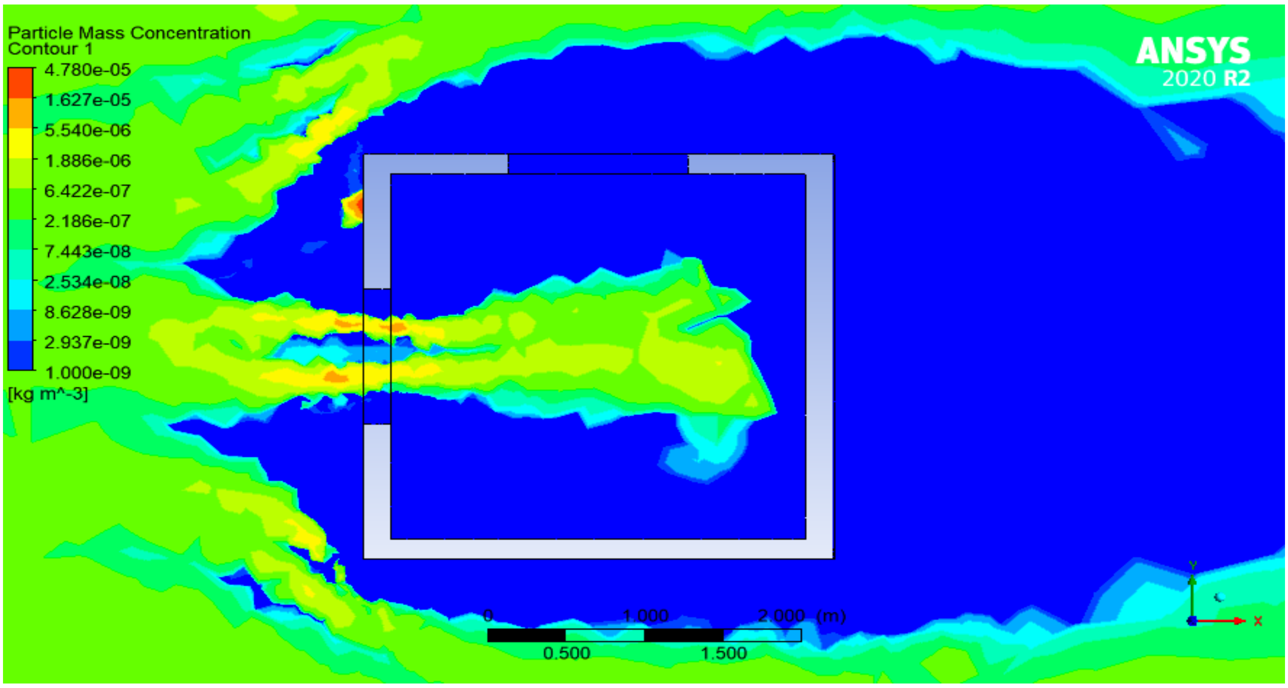


Figure 48 PM_{10} concentration contour inside the room

6) 25 Degree Angle Variation-

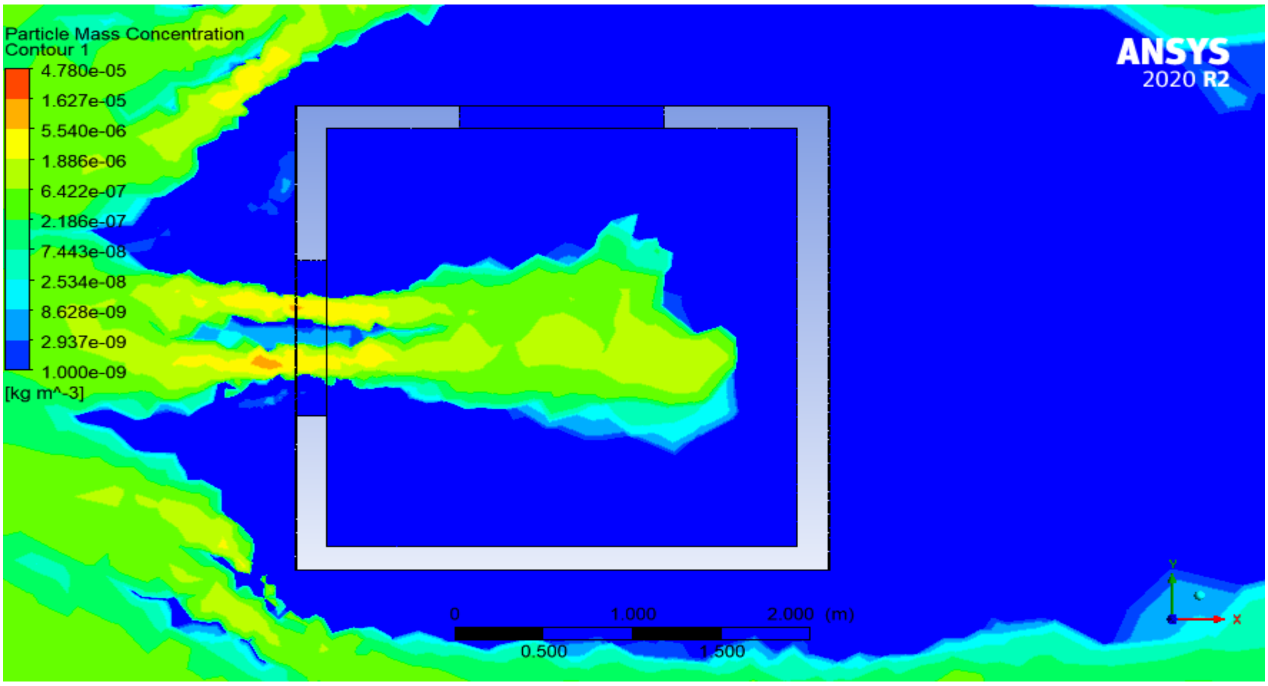


Figure 49 PM_{10} concentration contour inside the room

7) 30 Degree Angle Variation-

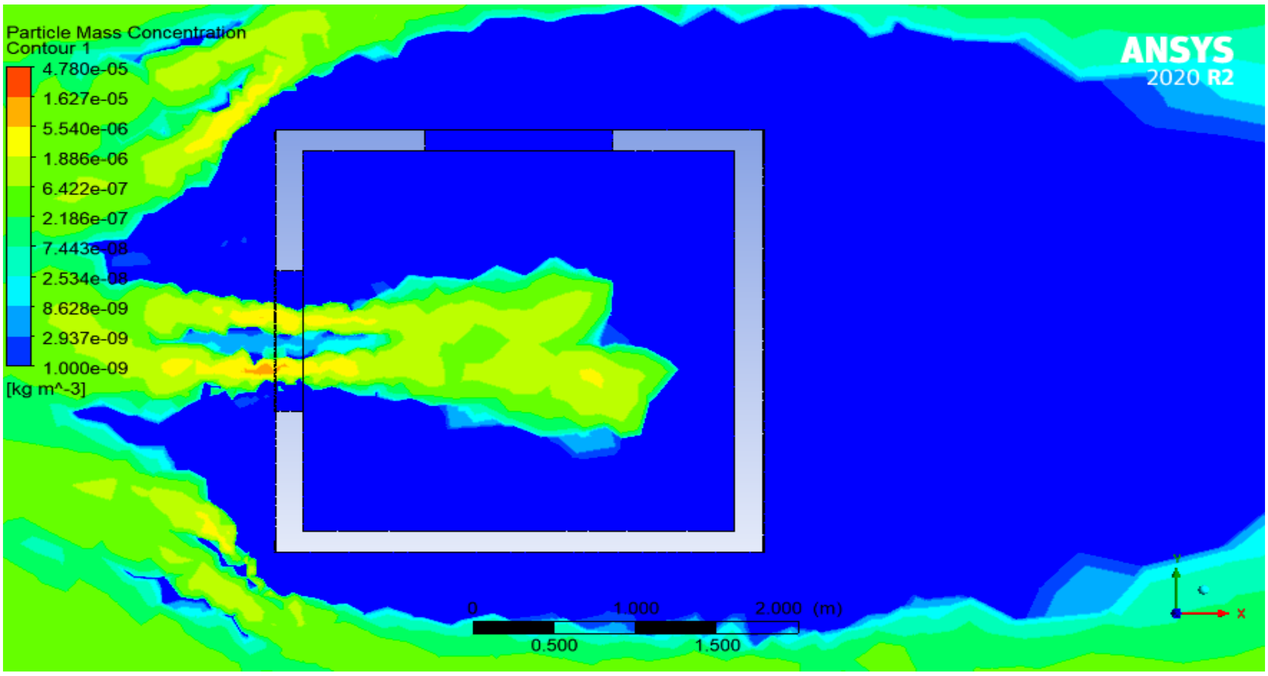
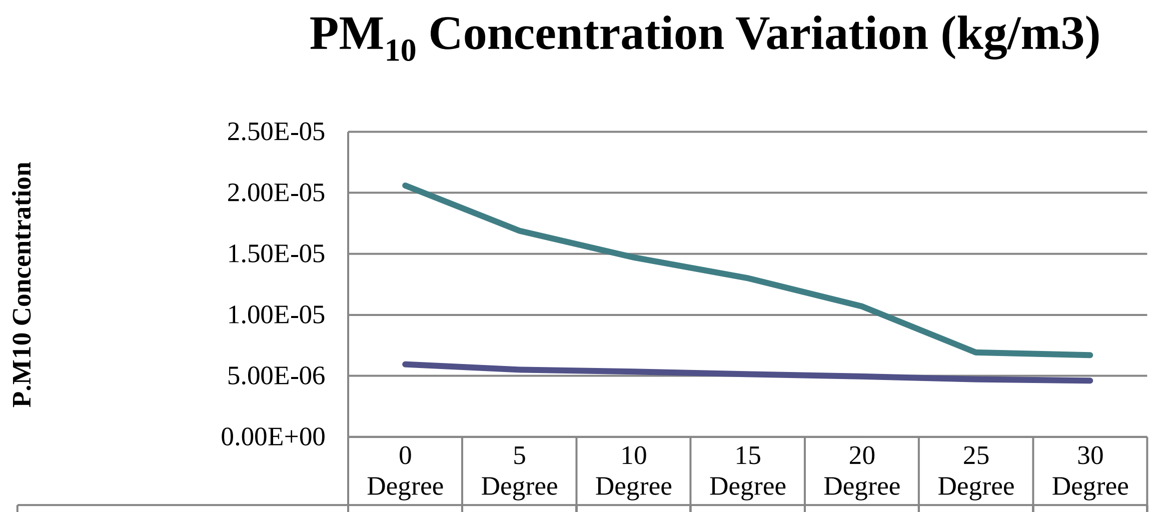


Figure 50 PM_{10} concentration contour inside the room

The highest values of PM_{10} concentration inside the room with respect to various wind angles are shown below.

Angle Variation	PM_{10} Concentration Variation (kg/m^3) 3 m/s	PM_{10} Concentration Variation (kg/m^3) 5 m/s
0 Degree	5.95×10^{-06}	2.06×10^{-05}
5 Degree	5.50×10^{-06}	1.69×10^{-05}
10 Degree	5.35×10^{-06}	1.47×10^{-05}
15 Degree	5.14×10^{-06}	1.30×10^{-05}
20 Degree	4.97×10^{-06}	1.07×10^{-05}
25 Degree	4.73×10^{-06}	6.93×10^{-06}
30 Degree	4.61×10^{-06}	6.70×10^{-06}

Table 7 PM_{10} Concentration Variation when windows are in adjacent side at 3m/s & 5m/s



	0 Degree	5 Degree	10 Degree	15 Degree	20 Degree	25 Degree	30 Degree
P.M10 Concentration Variation (kg/m3) 3 m/s	5.95E-06	5.50E-06	5.35E-06	5.14E-06	4.97E-06	4.73E-06	4.61E-06
P.M10 Concentration Variation (kg/m3) 5 m/s	2.06E-05	1.69E-05	1.47E-05	1.30E-05	1.07E-05	6.93E-06	6.70E-06

Figure 51 PM_{10} Concentration Variation (kg/m3) at 3 m/s & 5 m/s

- In case-2 when the variation of wind angle is increased, the PM_{10} concentration level inside the room is slightly deceased.
- Apart from that it is observed that in both the cases (Case-1, Case-2), when wind speed is increased from 3 m/s to 5 m/s, the PM_{10} concentration level inside the guard room is generally increased.
- It is also observed that the PM_{10} concentration level inside the room for Case-1(Windows positions are in opposite side) is less than Case-2(Windows positions are in adjacent side).

7.2. Applying Green Belt in front of the Guard Room

The tree belt is considered in front of Jadavpur University Gate no. 3 guard room and will check its effect on PM_{10} concentration level in-side the room with the help of ANSYS 2020 software.

It is considered that-

Diameter of each tree- 0.06 m

Height of each tree- 1.5 m

Here tree is considered as a solid media.

CASE-1 –

In this case, windows are located in opposite side wall of the guard room. A green belt following the above mentioned dimension is applied.

MODEL-

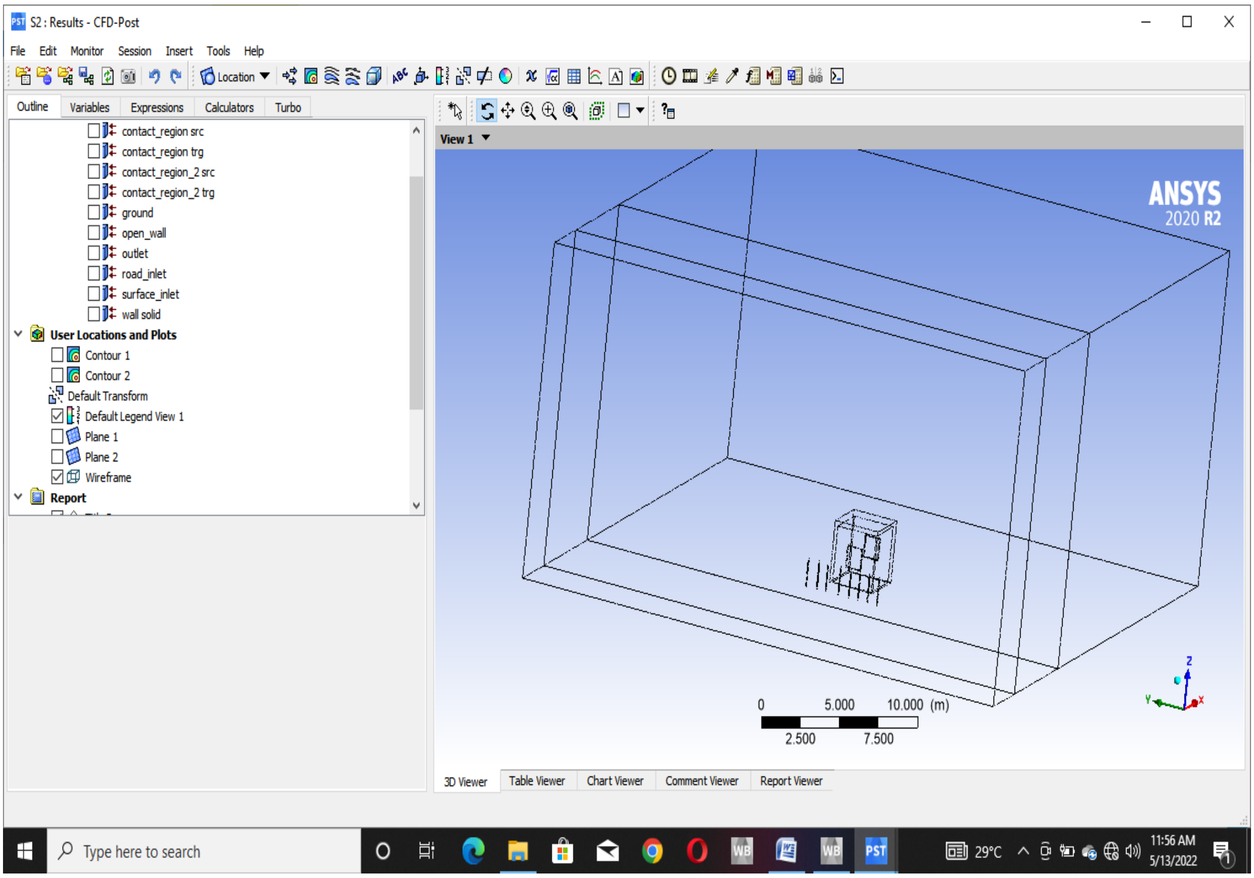


Figure 52 View of the Model with Green Belt

MESHING-

Here, tetrahedral meshing is considered.

Quality of meshing-

Jacobian Ration of mesh- 1.004

Skewness- 0.23717

Element Quality- 0.81063

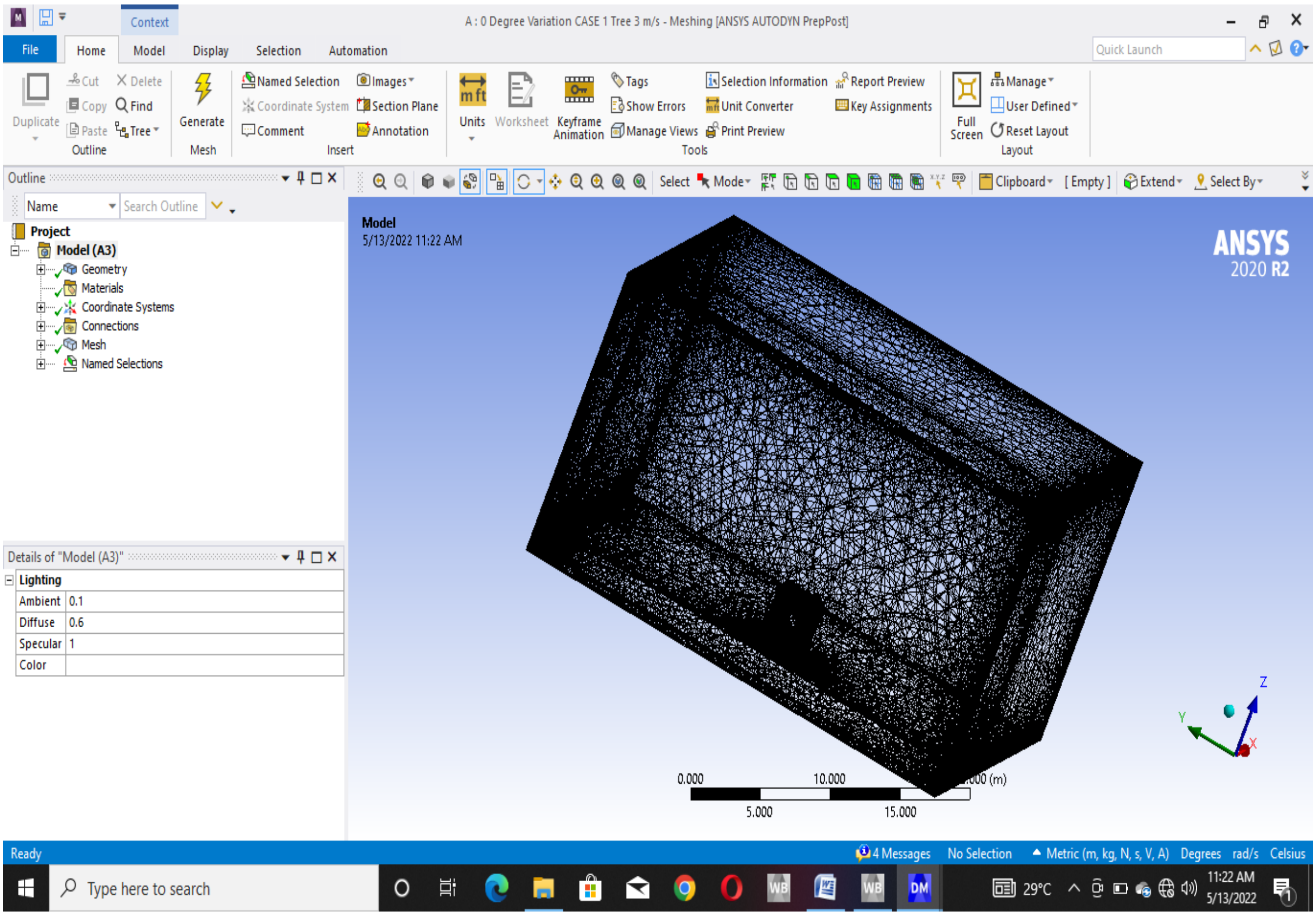


Figure 53 Meshing of the model

Wind Speed- 3 m/s-

The applied 'West Wind' speed is considered as 3 m/s. PM_{10} concentration contour with the respect of various wind angle inside the room are shown below.

1) <u>0 Degree Angle Variation-</u>

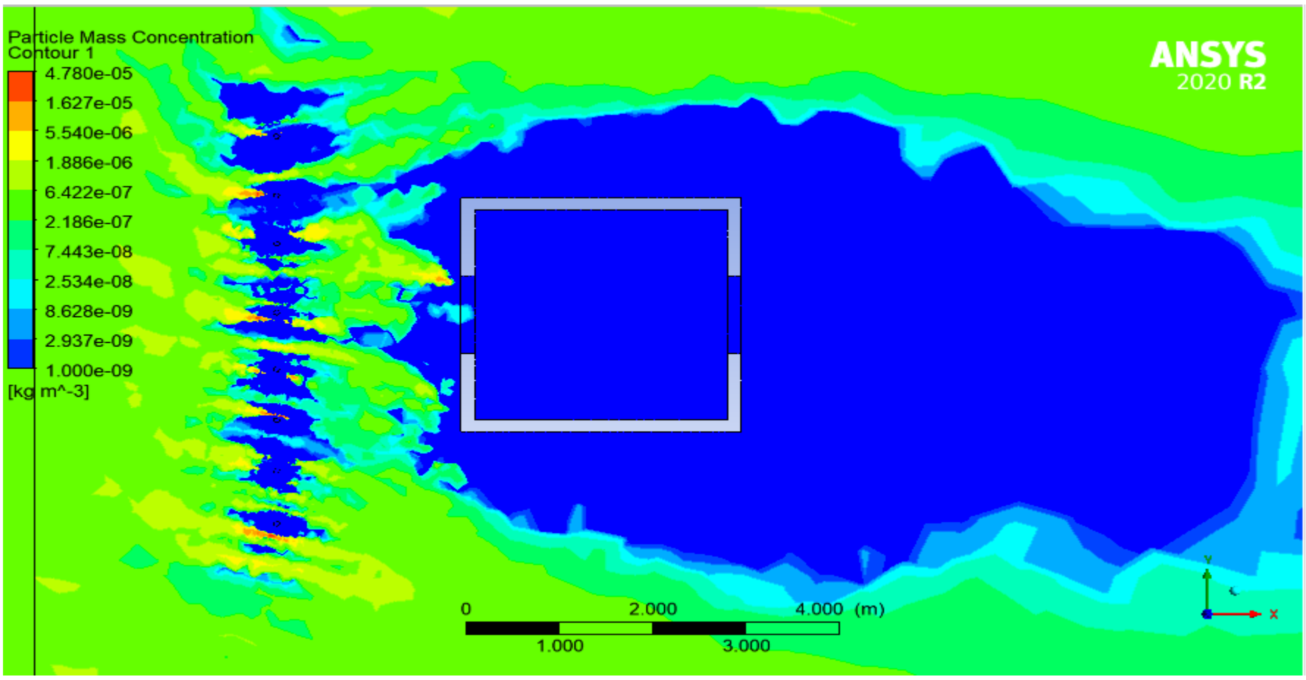


Figure 54 PM_{10} concentration contour inside the room

2) <u>5 Degree Variation-</u>

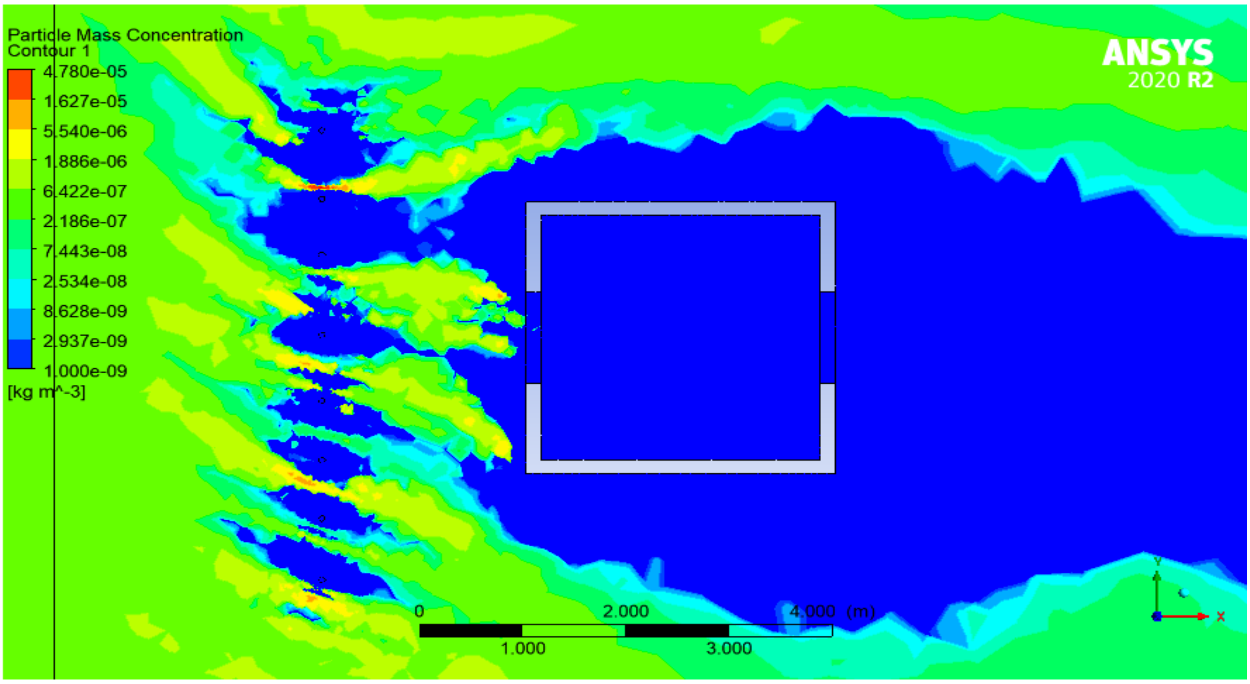


Figure 55 PM_{10} concentration contour inside the room

3) <u>10 Degree Variation-</u>

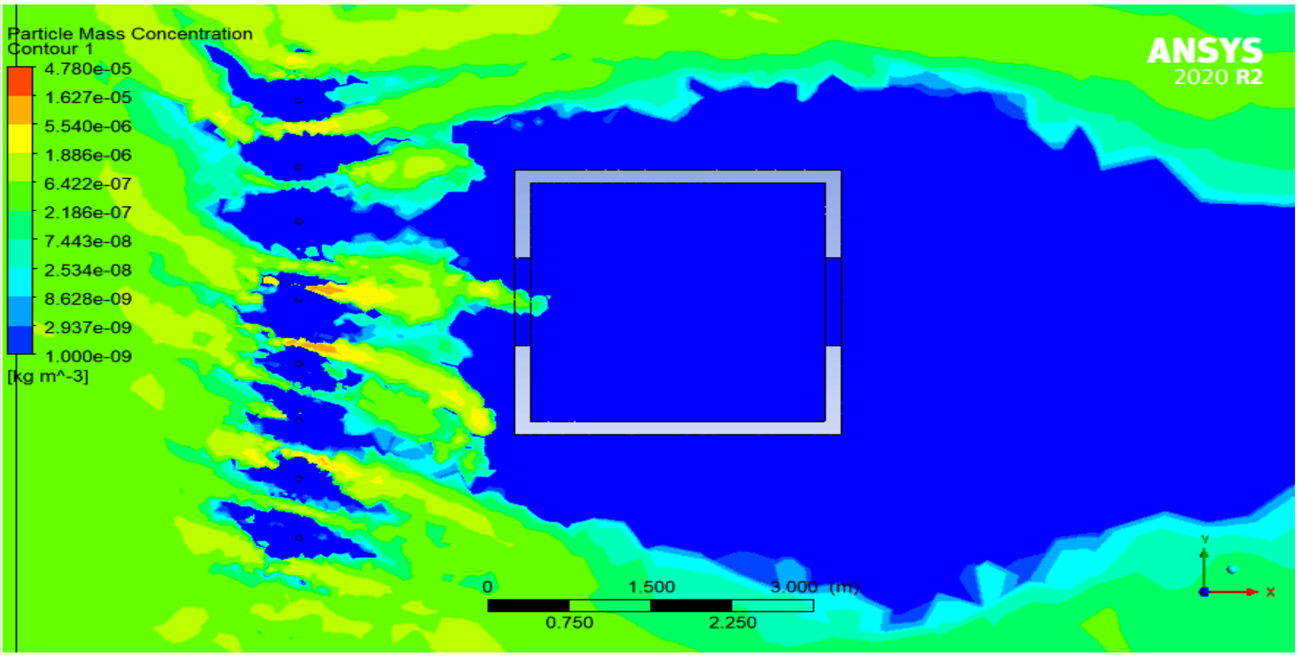


Figure 56 PM_{10} concentration contour inside the room

4) <u>15 Degree Angle Variation-</u>

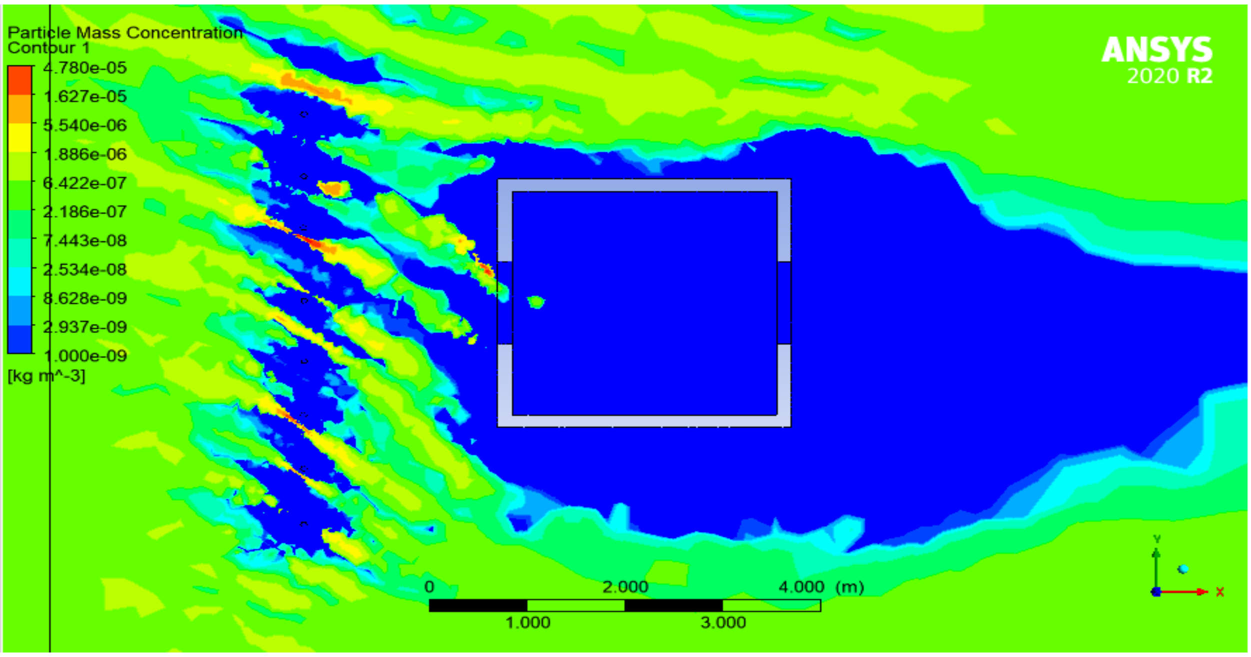


Figure 57 PM_{10} concentration contour inside the room

5) 20 Degree Angle Variation-

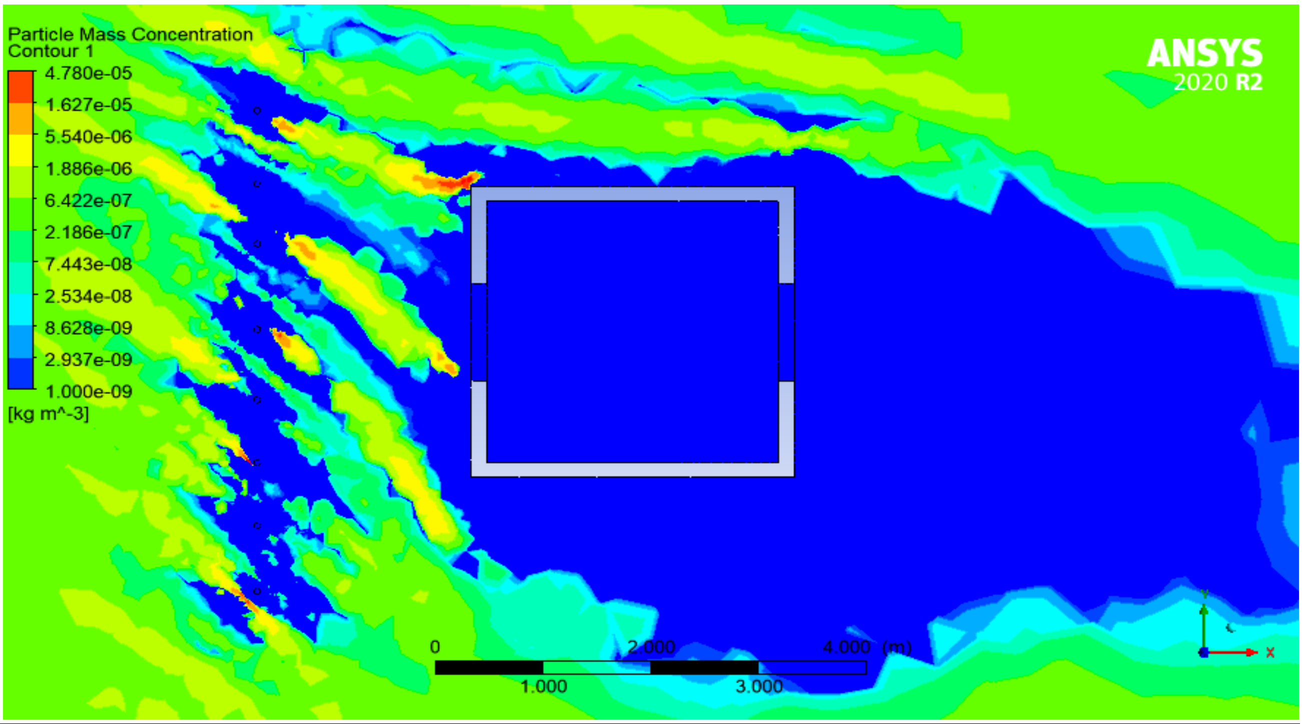


Figure 58 PM_{10} concentration contour inside the room

6) 25 Degree Angle Variation-

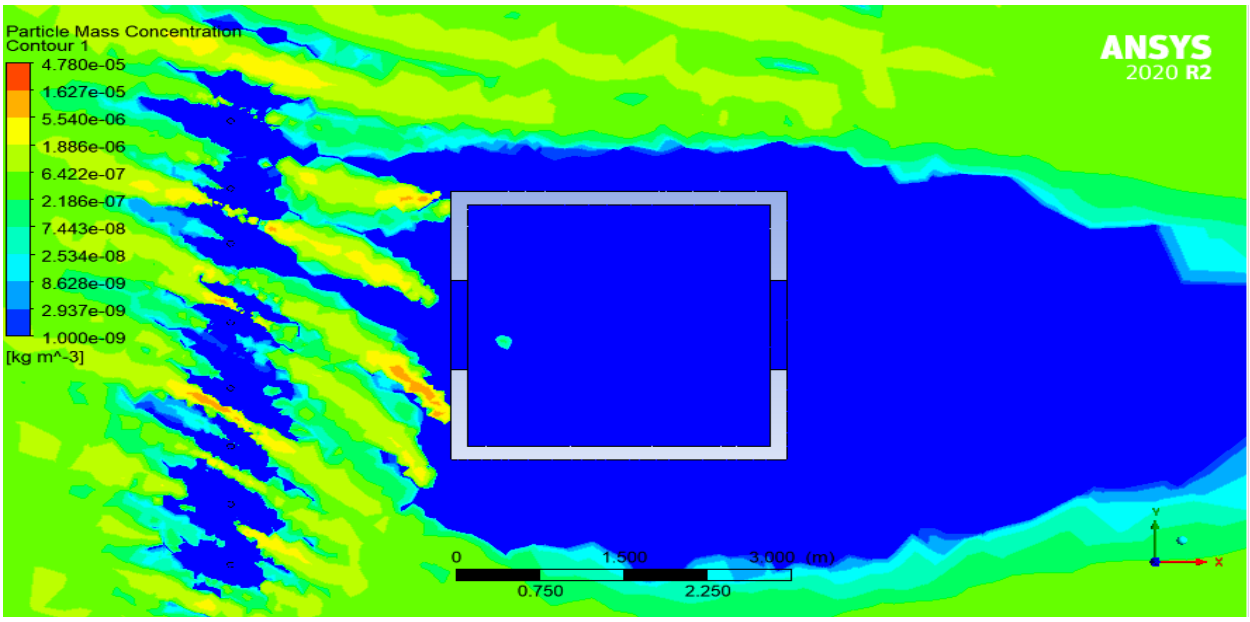


Figure 59 PM_{10} concentration contour inside the room

7) 30 Degree Angle Variation-

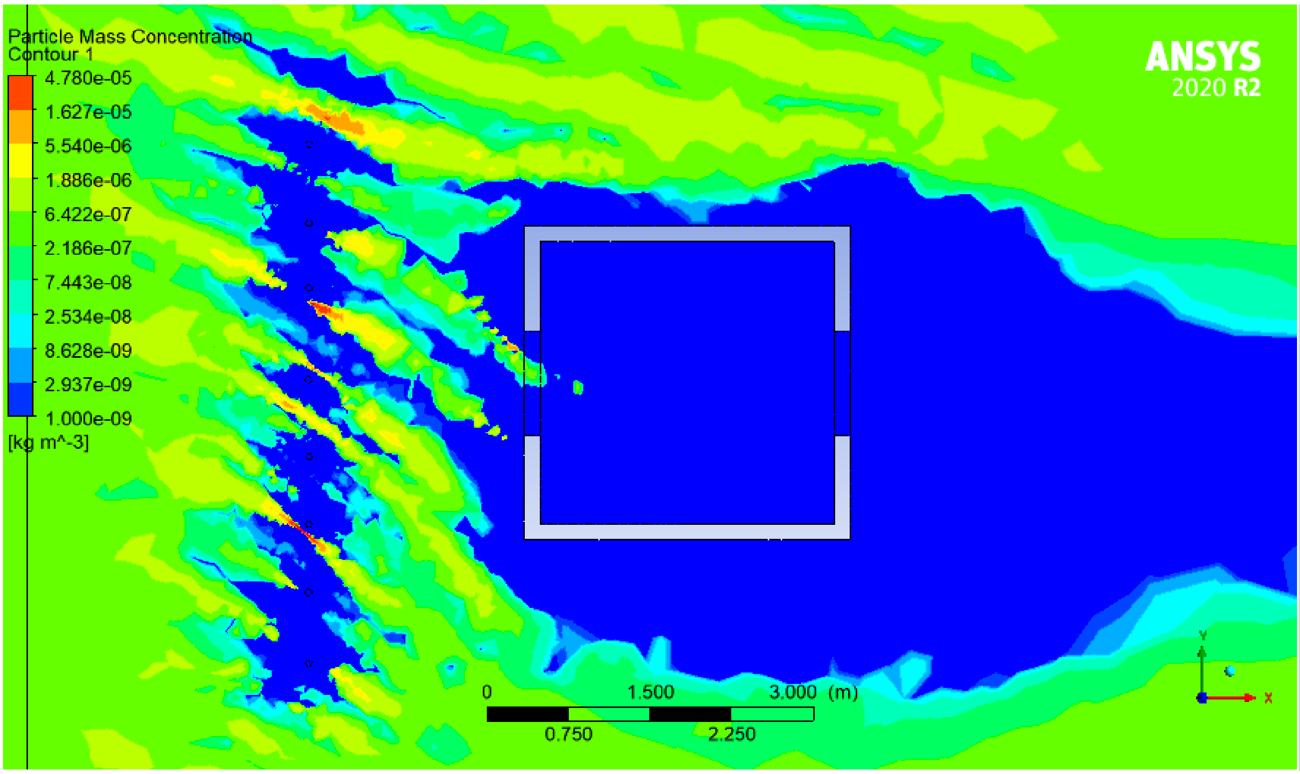


Figure 60 PM_{10} concentration contour inside the room

The highest values of PM_{10} concentration inside the room with respect to various wind angles are shown below.

Angle Variation	PM_{10} Concentration Variation (kg/m^3) 3 m/s
0 Degree	2.44×10^{-08}
5 Degree	1.99×10^{-08}
10 Degree	1.13×10^{-08}
15 Degree	1.07×10^{-08}
20 Degree	1.00×10^{-09}
25 Degree	6.83×10^{-09}
30 Degree	3.85×10^{-09}

Table 8 PM_{10} Concentration Variation when windows are in opposite side at 3m/s (With green belt)

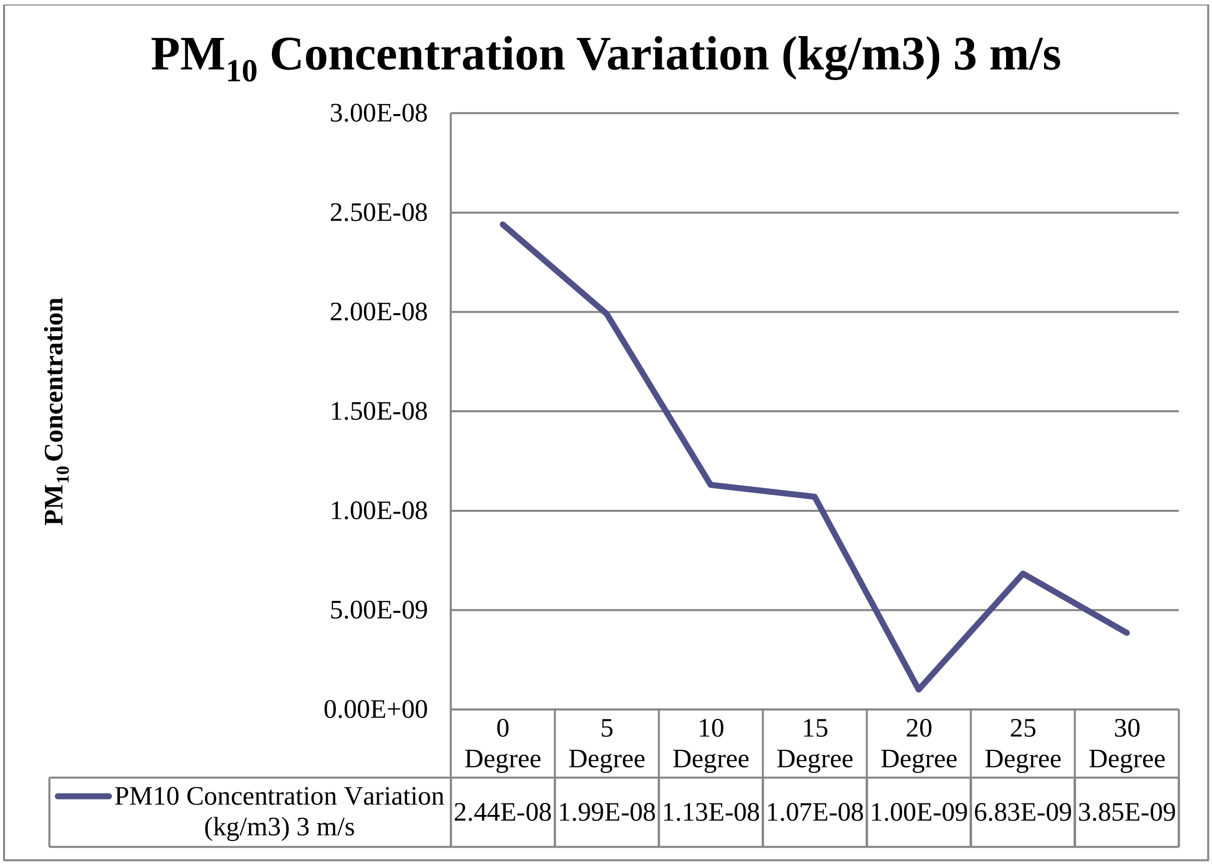


Figure 61 PM_{10} Concentration Variation (kg/m3) at 3 m/s

Wind Speed-5 m/s-

The applied 'West Wind' speed is considered as 5 m/s. PM_{10} concentration contour with the respect of various wind angle inside the room are shown below.

1) <u>0 Degree Angle Variation-</u>

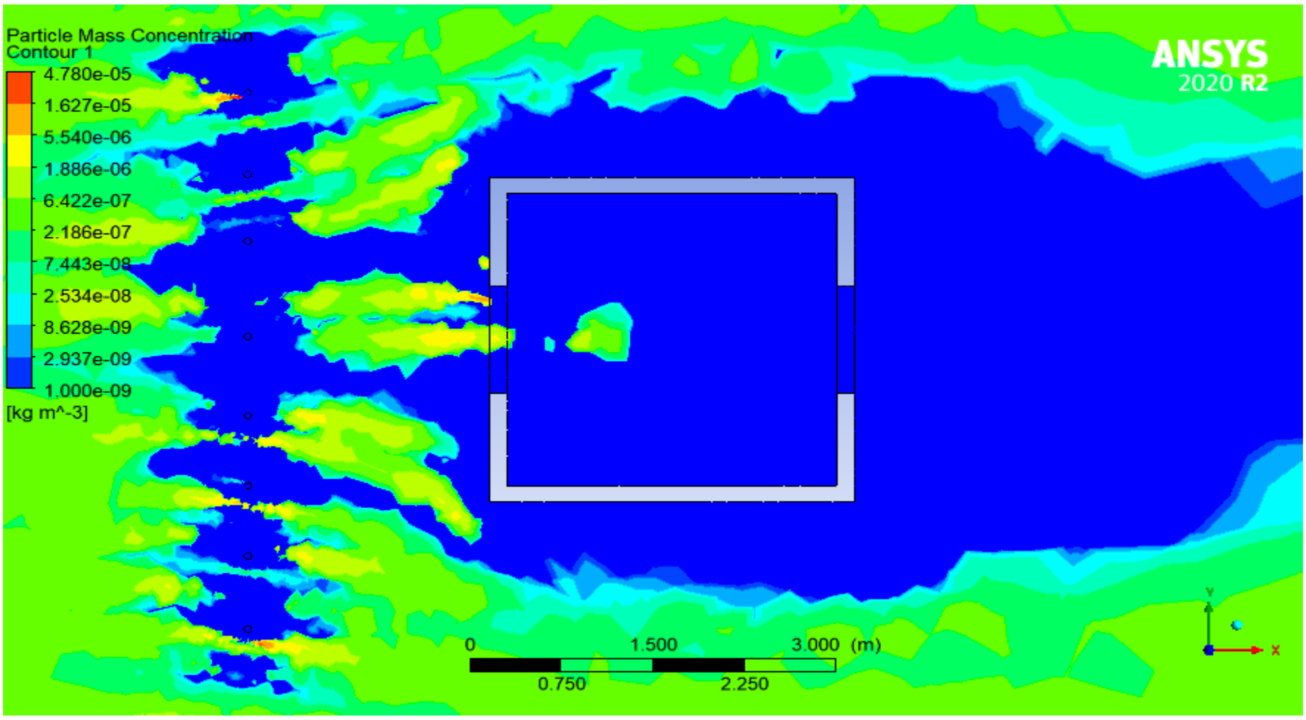


Figure 62 PM10 concentration contour inside the room

2) <u>5 Degree Angle Variation-</u>

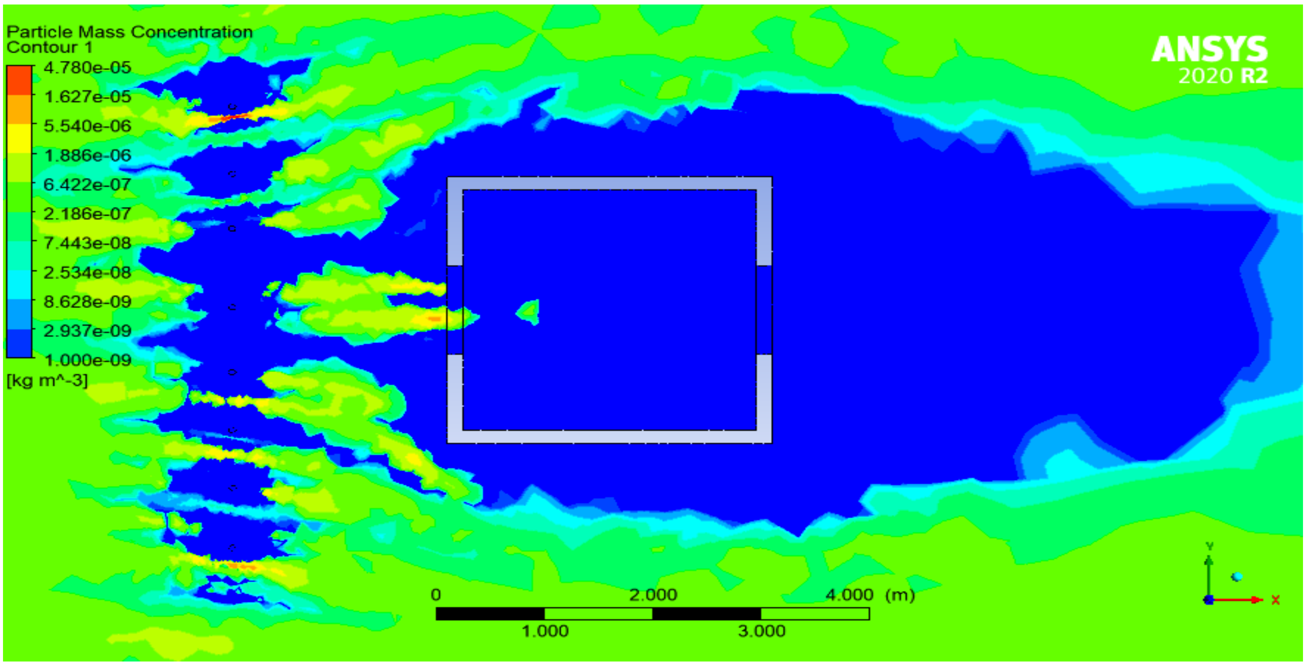


Figure 63 PM10 concentration contour inside the room

3) <u>10 Degree Angle Variation-</u>

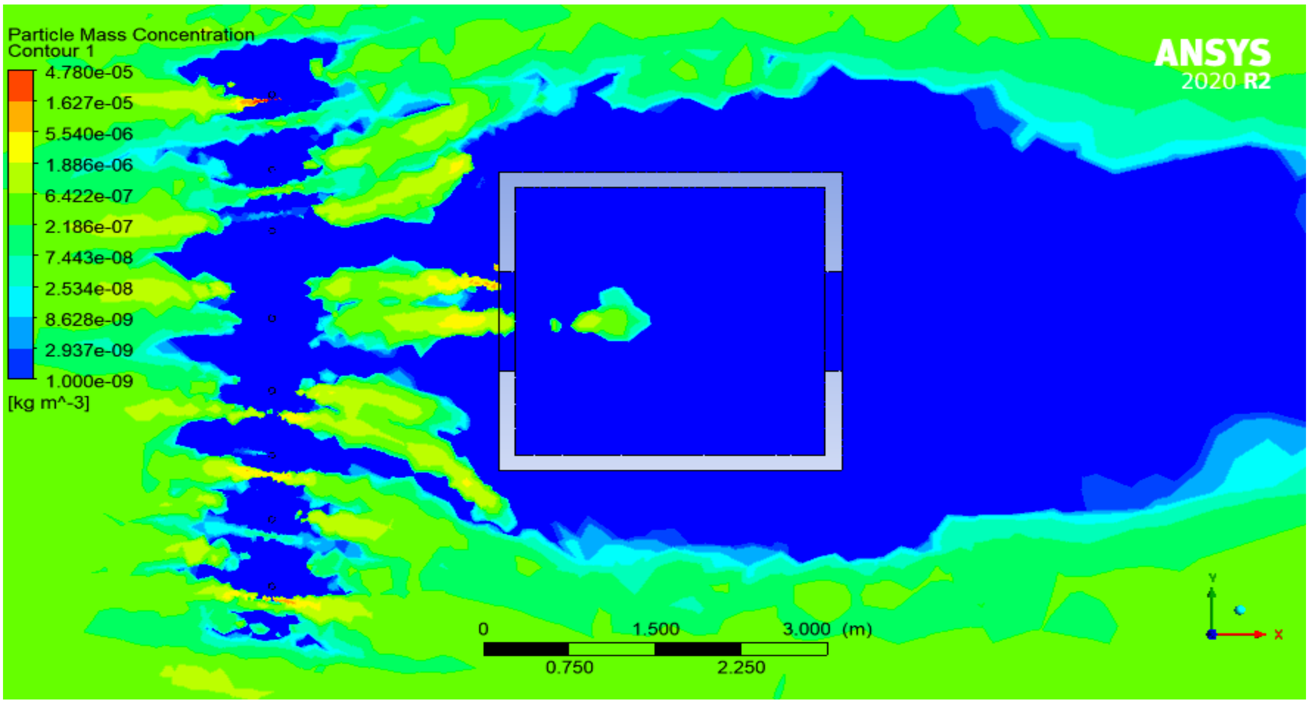


Figure 64 PM_{10} concentration contour inside the room

4) <u>15 Degree Angle Variation-</u>

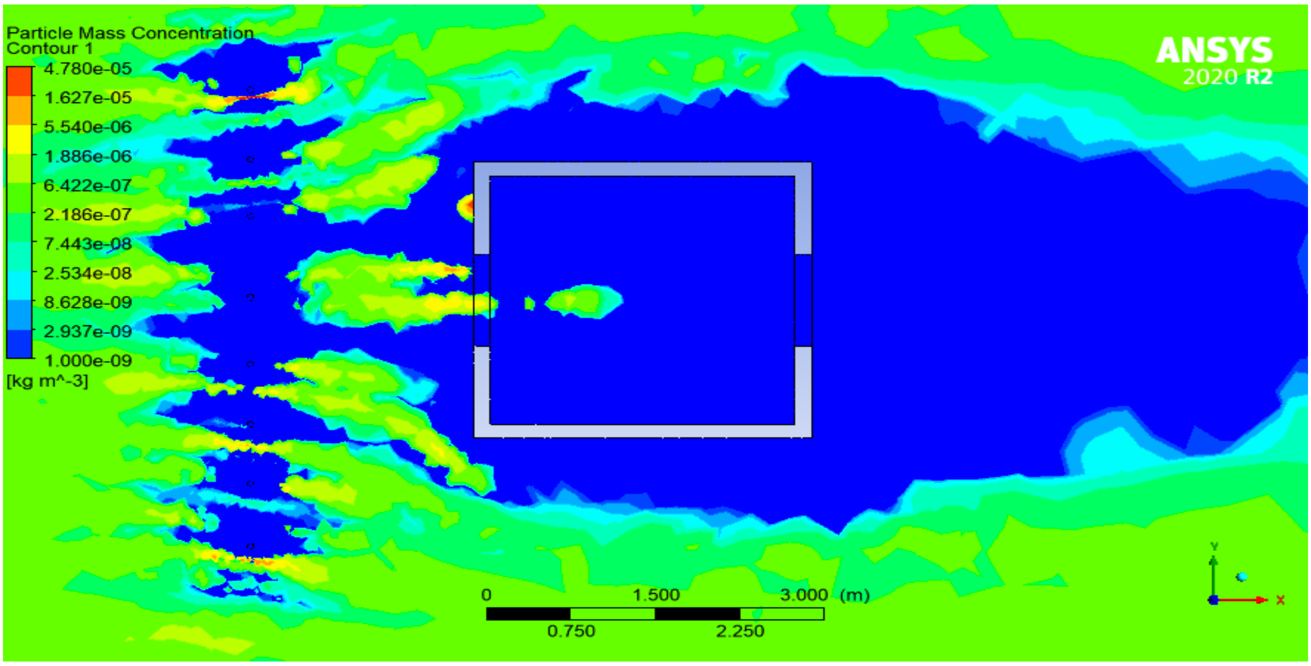


Figure 65 PM_{10} concentration contour inside the room

5) 20 Degree Angle Variation-

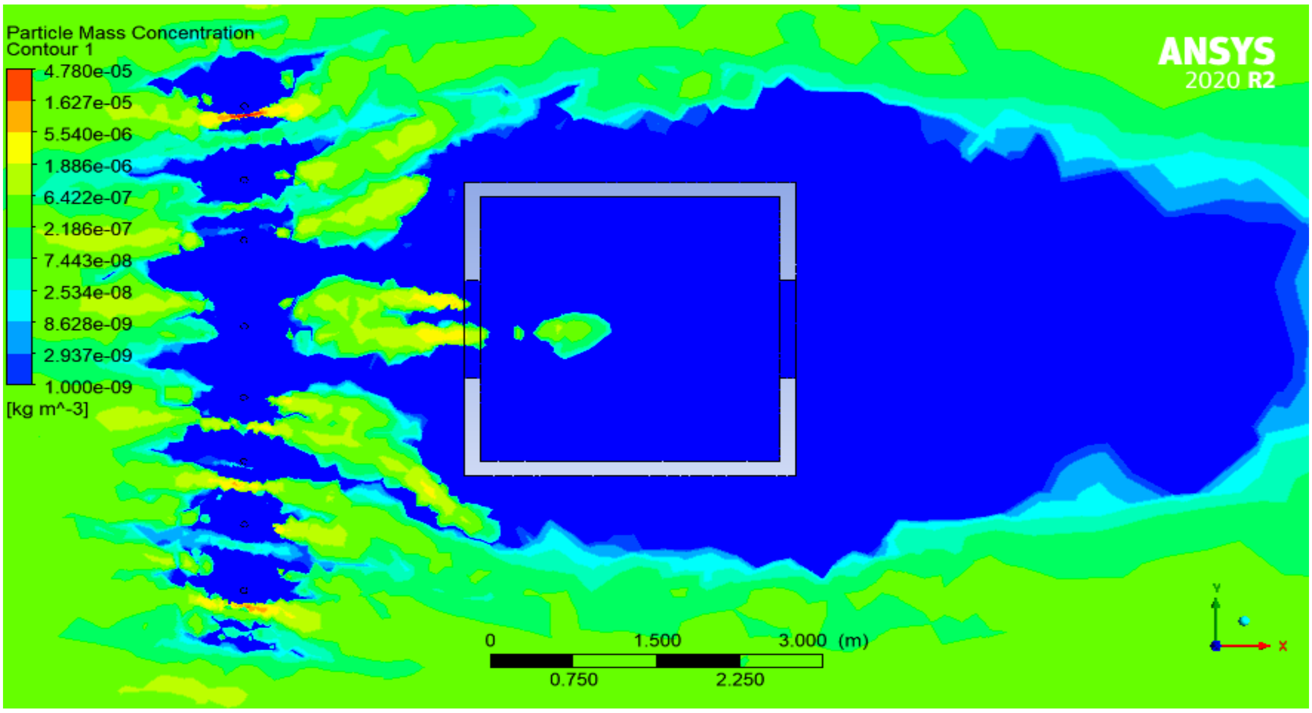


Figure 66 PM_{10} concentration contour inside the room

6) 25 Degree Angle Variation-

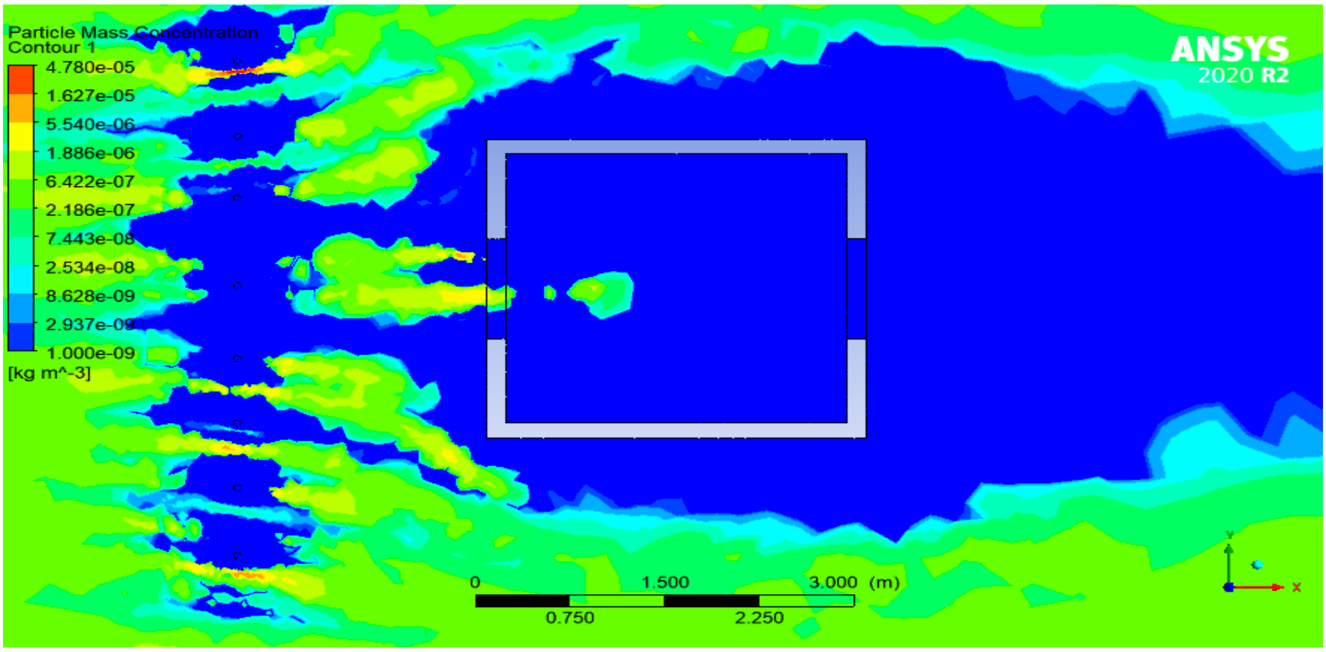


Figure 67 PM_{10} concentration contour inside the room

7) 30 Degree Angle Variation-

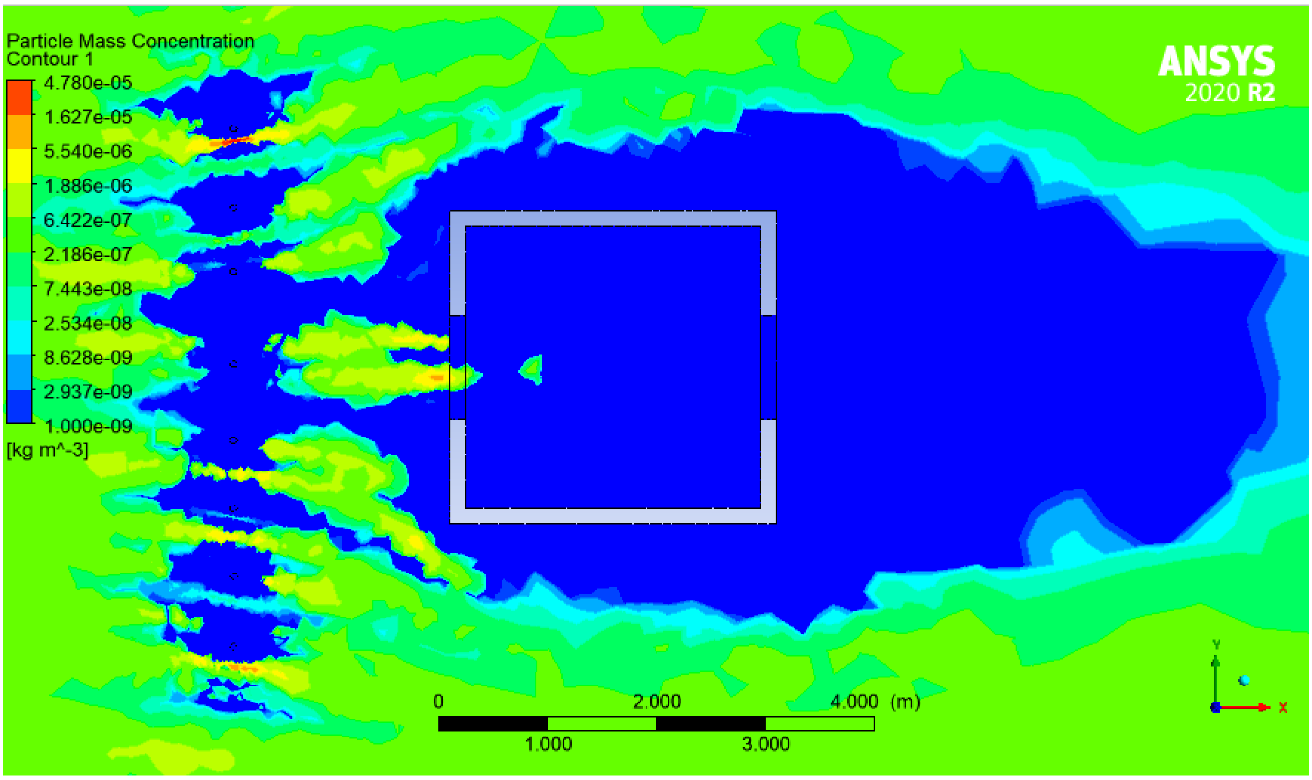
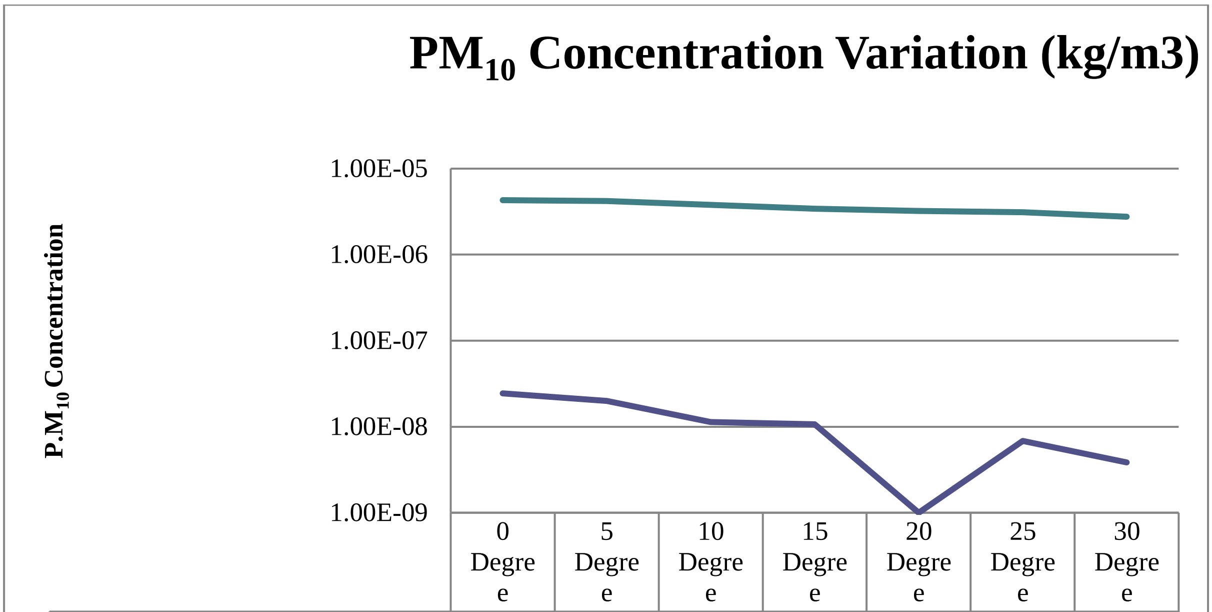


Figure 68 PM_{10} concentration contour inside the room

The highest values of PM_{10} concentration inside the room with respect to various wind angles are shown below.

Angle Variation	PM_{10} Concentration Variation (kg/m^3) 3 m/s	PM_{10} Concentration Variation (kg/m^3) 5 m/s
0 Degree	2.44×10^{-08}	4.30×10^{-06}
5 Degree	1.99×10^{-08}	4.21×10^{-06}
10 Degree	1.13×10^{-08}	3.78×10^{-06}
15 Degree	1.07×10^{-08}	3.41×10-06
20 Degree	1.00×10^{-09}	3.21×10^{-06}
25 Degree	6.83×10^{-09}	3.11×10^{-06}
30 Degree	3.85×10^{-09}	2.69×10^{-06}

Table 9 PM_{10} Concentration Variation when windows are in opposite side at 3m/s & 5m/s (With green belt)



	0 Degree	5 Degree	10 Degree	15 Degree	20 Degree	25 Degree	30 Degree
PM10 Concentration Variation (kg/m3) 3 m/s	2.44E-08	1.99E-08	1.13E-08	1.07E-08	1.00E-09	6.83E-09	3.85E-09
PM10 Concentration Variation (kg/m3) 5 m/s	4.30E-06	4.21E-06	3.78E-06	3.41E-06	3.21E-06	3.11E-06	2.76E-06

Figure 69 PM_{10} Concentration Variation (kg/m3) at 3 m/s & 5 m/s

- It is clearly observed that if green belt is applied between the road and the guard room, the PM_{10} concentration inside the guard room is less. The green belt acts as an obstruction. So, the PM_{10} particles are stuck in the green belt.
- It is also observed that, the PM_{10} concentration level inside the guard room for wind speed 5 m/s is more. So, when the wind speed is increased the PM_{10} concentration inside the room is also increased.

CASE-2 –

In this case, windows are located in adjacent side wall of the guard room. A green belt following the above mentioned dimension is applied.

MODEL-

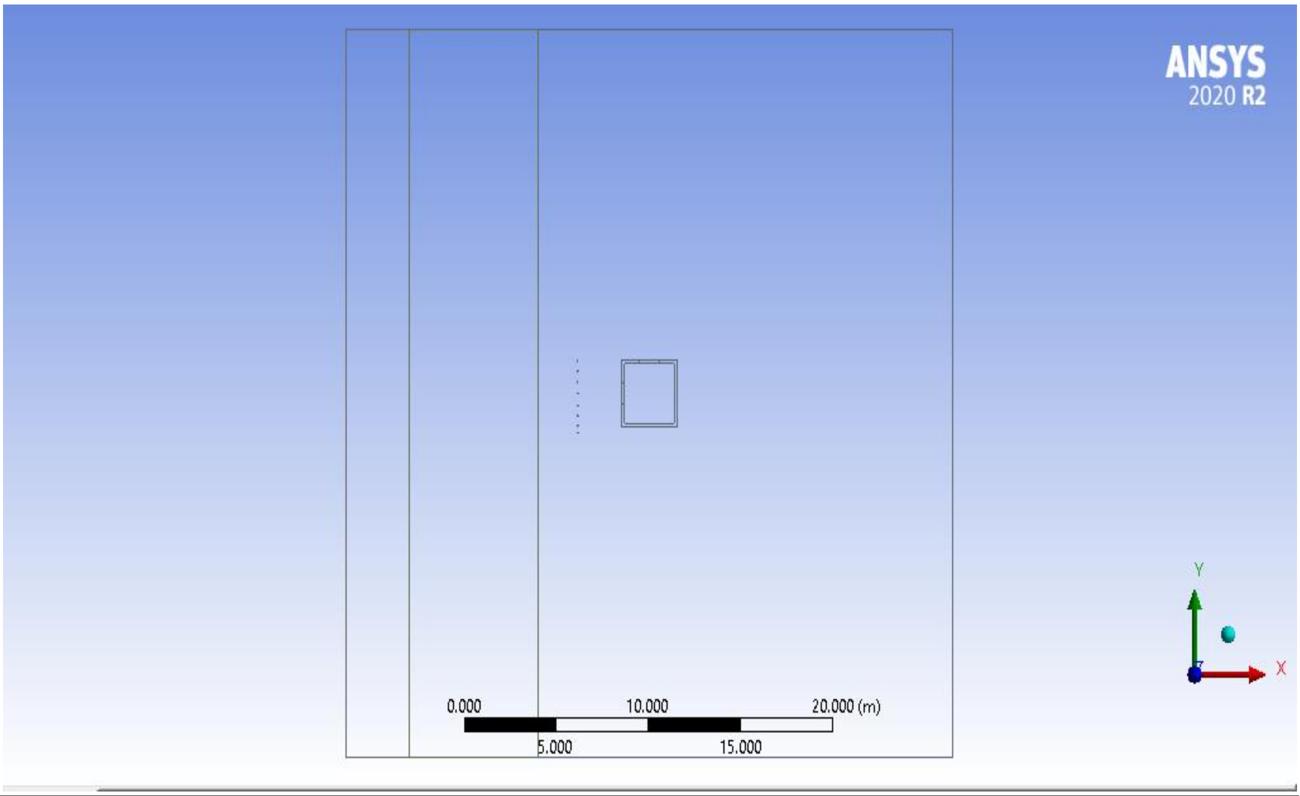


Figure 70 Top view of the model

Meshing-

Here, tetrahedral meshing is considered.

Quality of meshing-

Jacobian Ration of mesh- 1.0041

Skewness- 0.23688

Element Quality- 0.81032

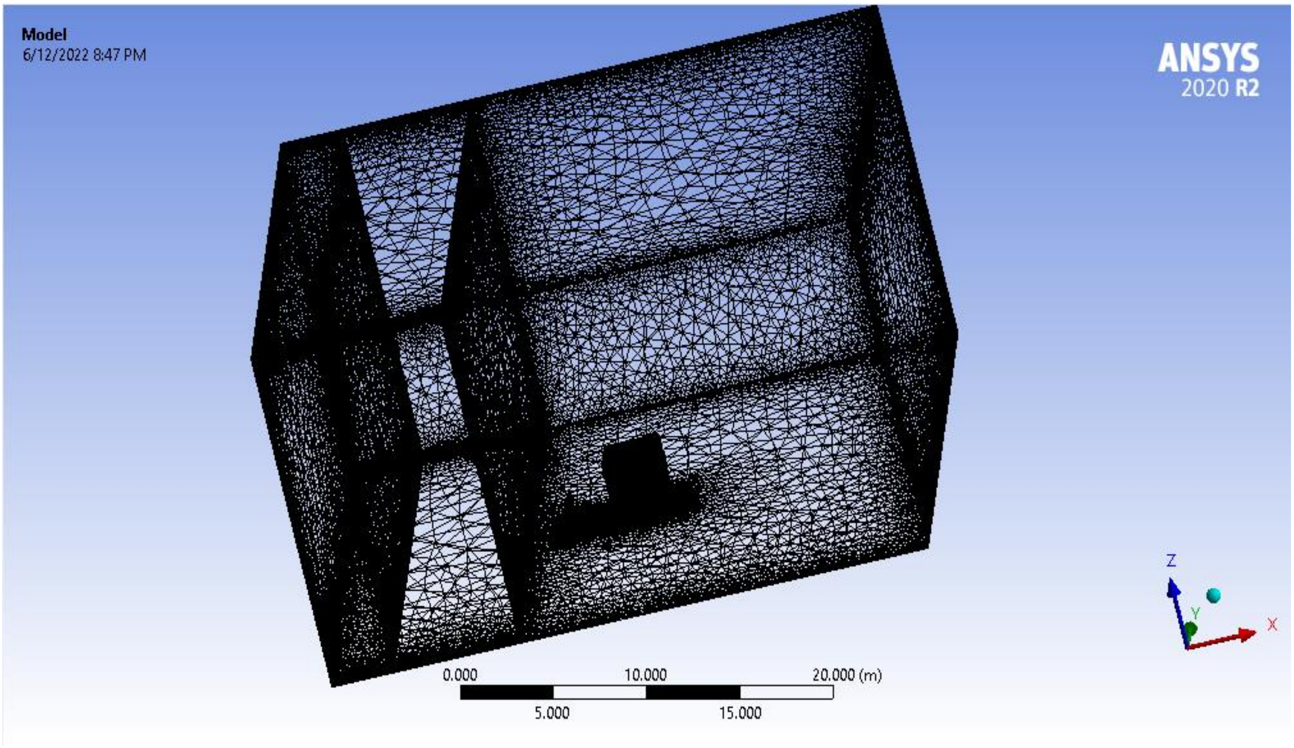


Figure 71 Meshing of the model

Wind Speed- 3 m/s-

The applied 'West Wind' speed is considered as 3 m/s. PM_{10} concentration contour with the respect of various wind angle inside the room are shown below.

1) 0 Degree Angle Variation-

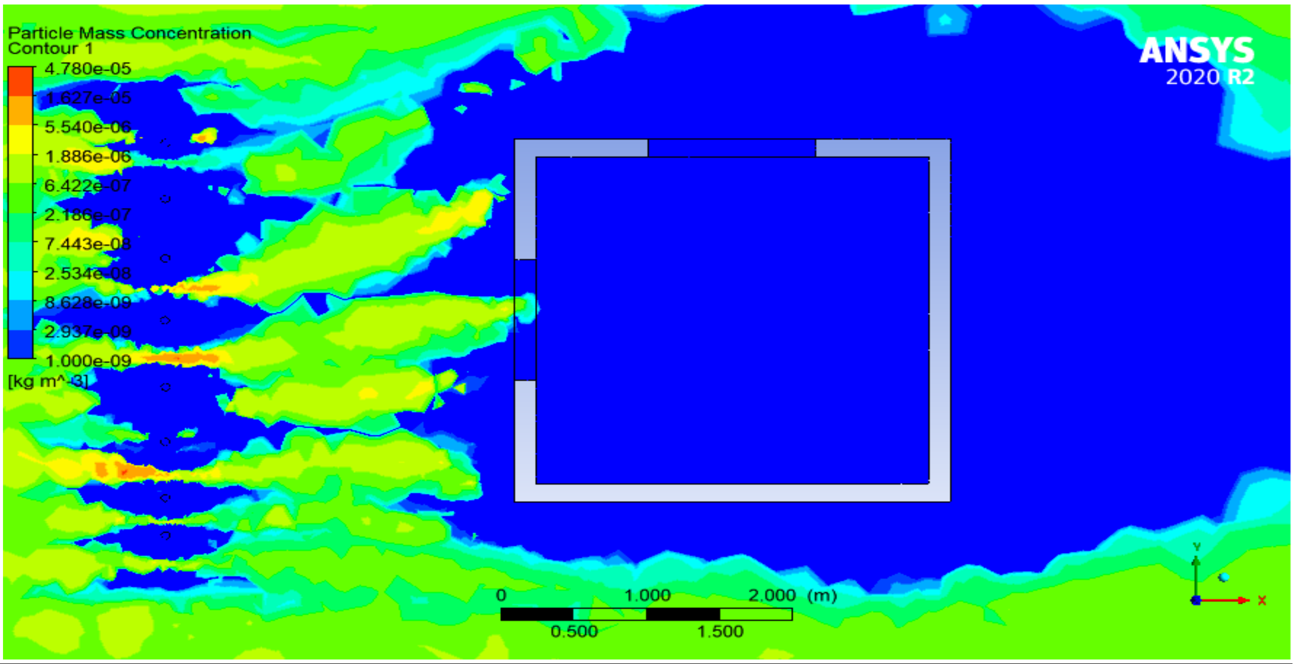


Figure 72 PM_{10} concentration contour inside the room

2) 5 Degree Angle Variation-

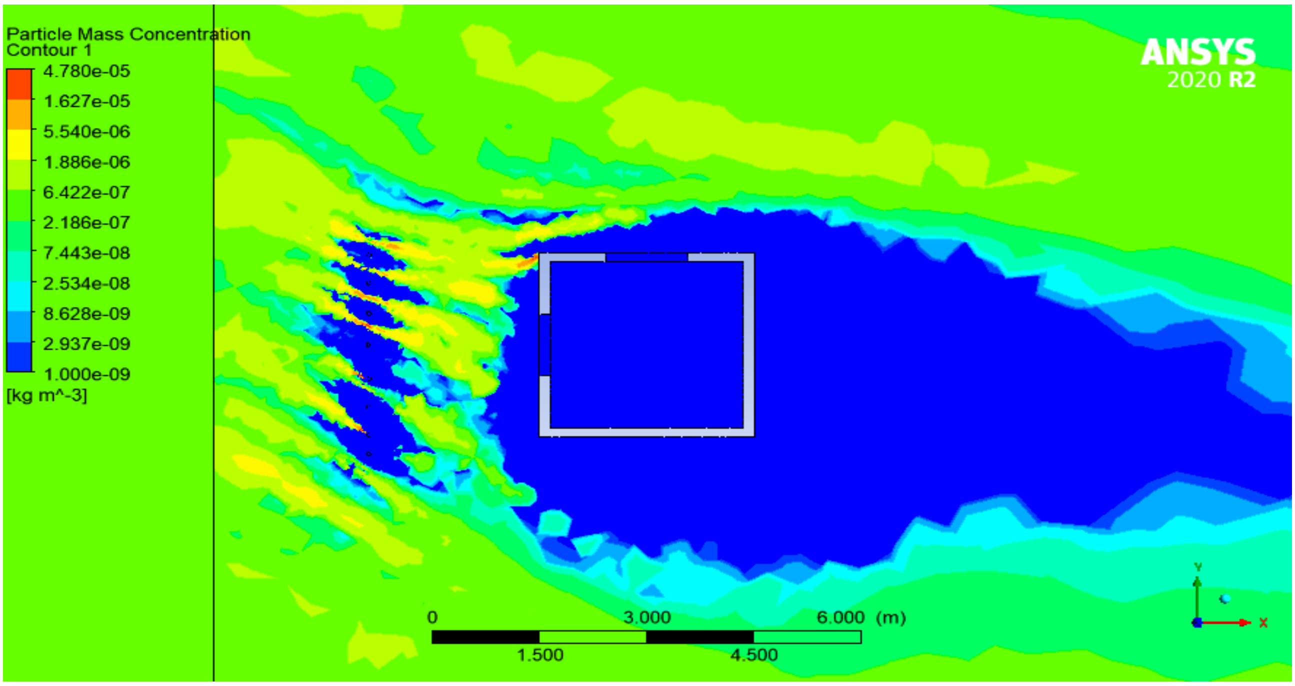


Figure 73 PM_{10} concentration contour inside the room

3) <u>10 Degree Angle Variation-</u>

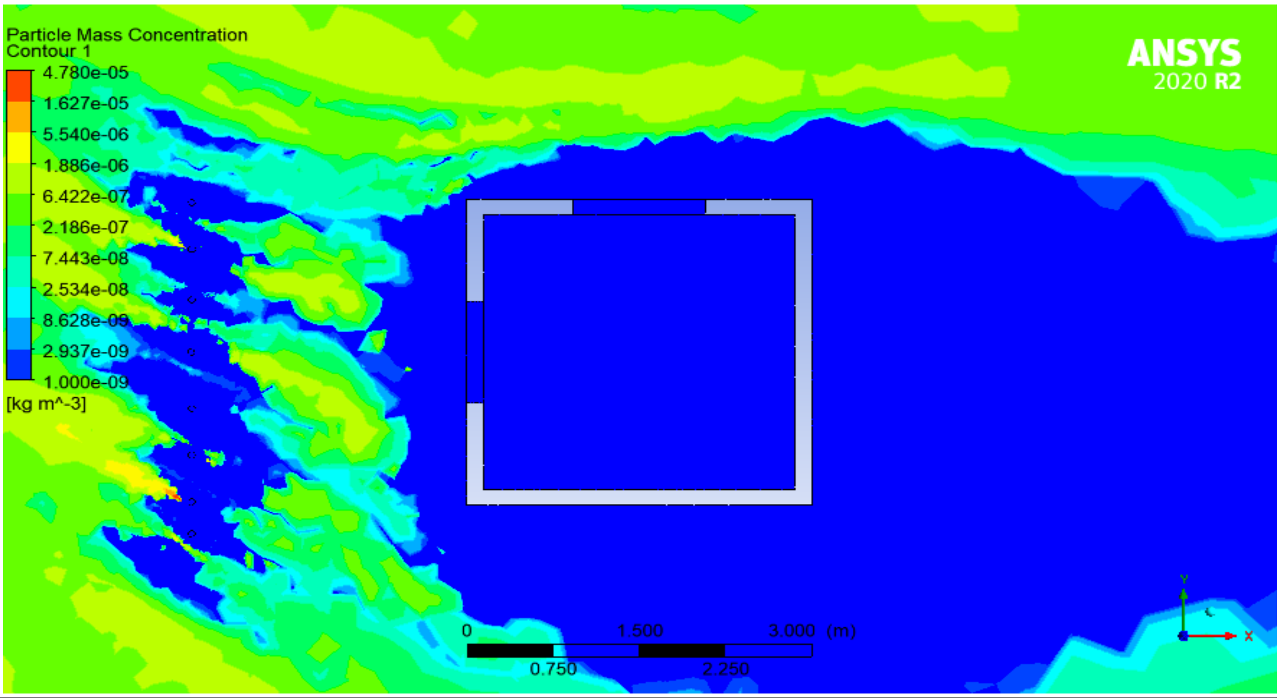


Figure 74 PM_{10} concentration contour inside the room

4) <u>15 Degree Angle Variation-</u>

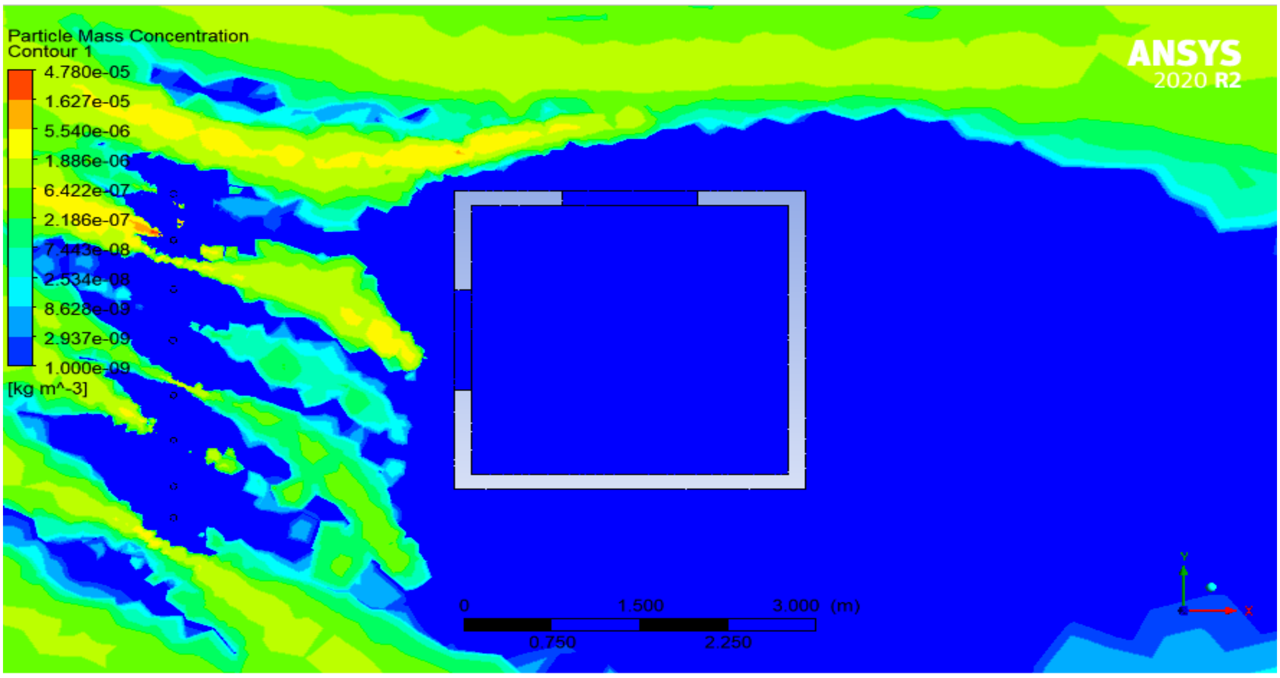


Figure 75 PM_{10} concentration contour inside the room

5) 20 Degree Angle Variation-

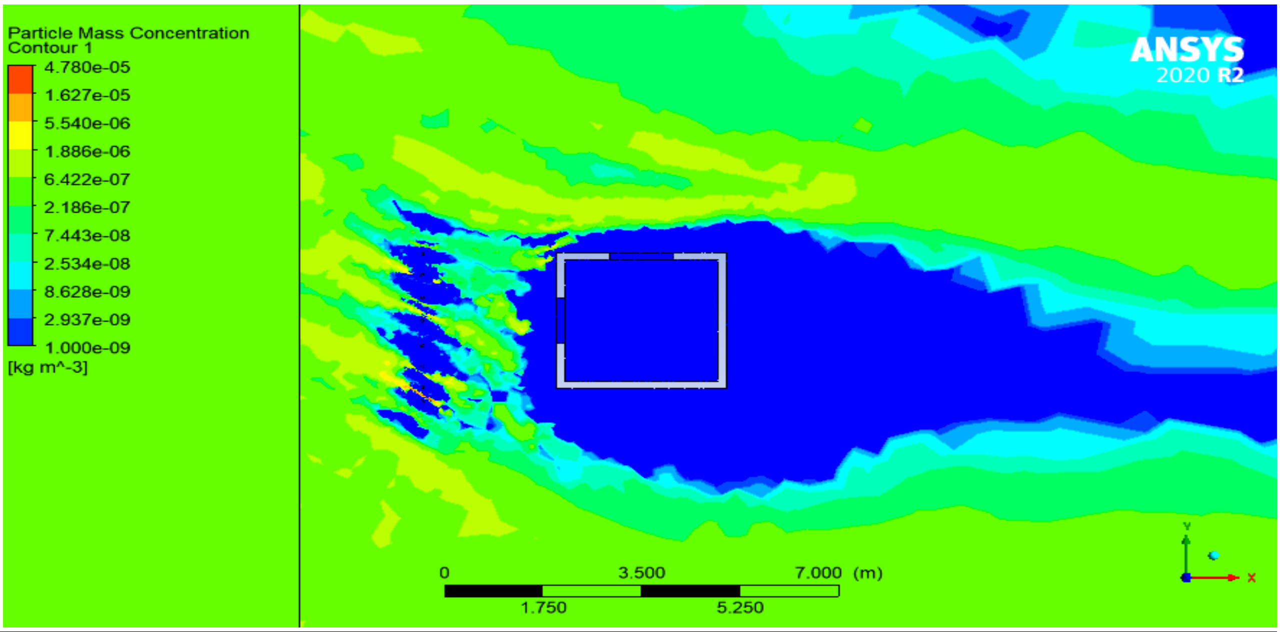


Figure 76 PM_{10} concentration contour inside the room

6) 25 Degree Angle Variation-

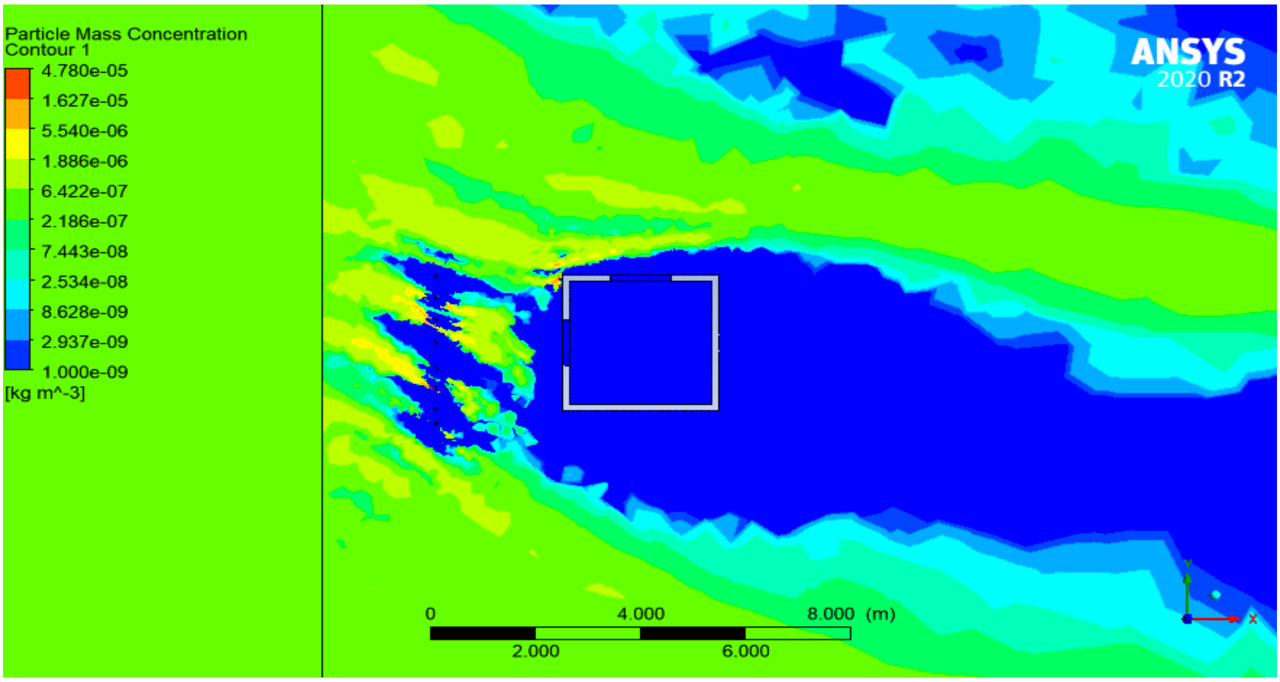


Figure 77 PM_{10} concentration contour inside the room

7) 30 Degree Angle Variation-

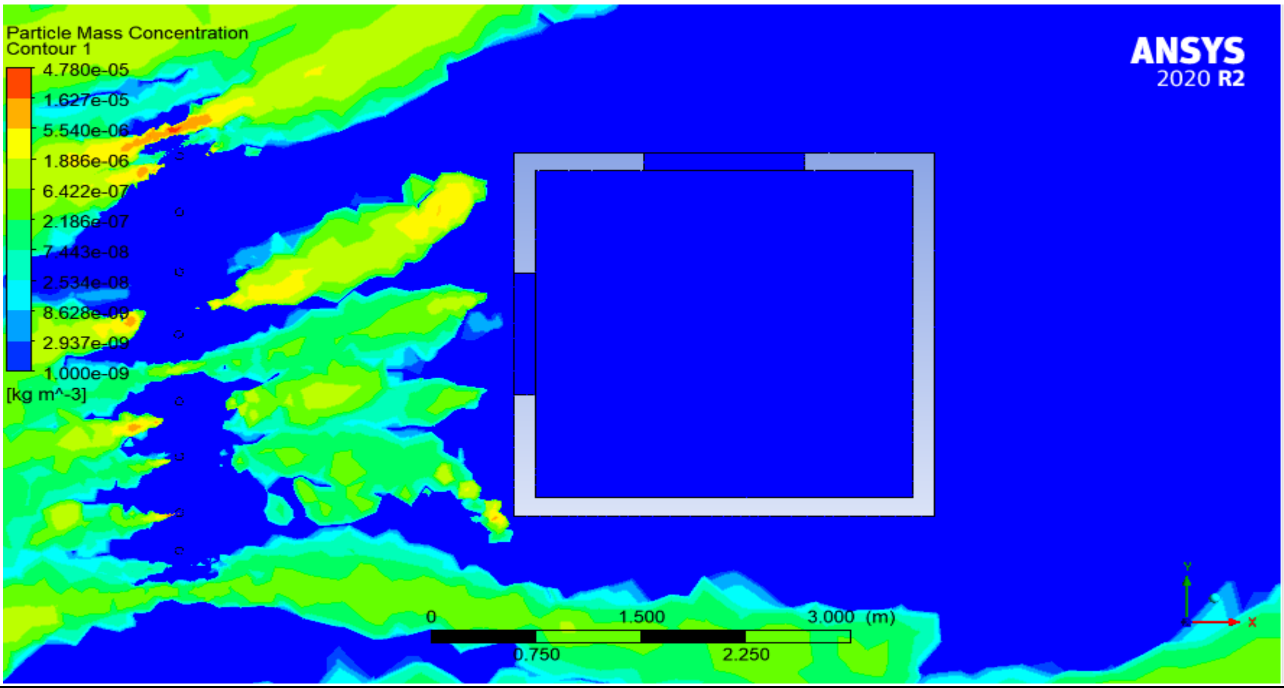


Figure 78 PM_{10} concentration contour inside the room

The highest values of PM_{10} concentration inside the room with respect to various wind angles are shown below.

Angle Variation	PM_{10} Concentration Variation (kg/m^3) 3 m/s
0 Degree	2.50×10^{-08}
5 Degree	1.00×10^{-09}
10 Degree	1.00×10^{-09}
15 Degree	1.00×10^{-09}
20 Degree	1.00×10^{-09}
25 Degree	1.00×10^{-09}
30 Degree	1.00×10^{-09}

Table 10 PM_{10} Concentration Variation when windows are in adjacent side at 3m/s (With green belt)

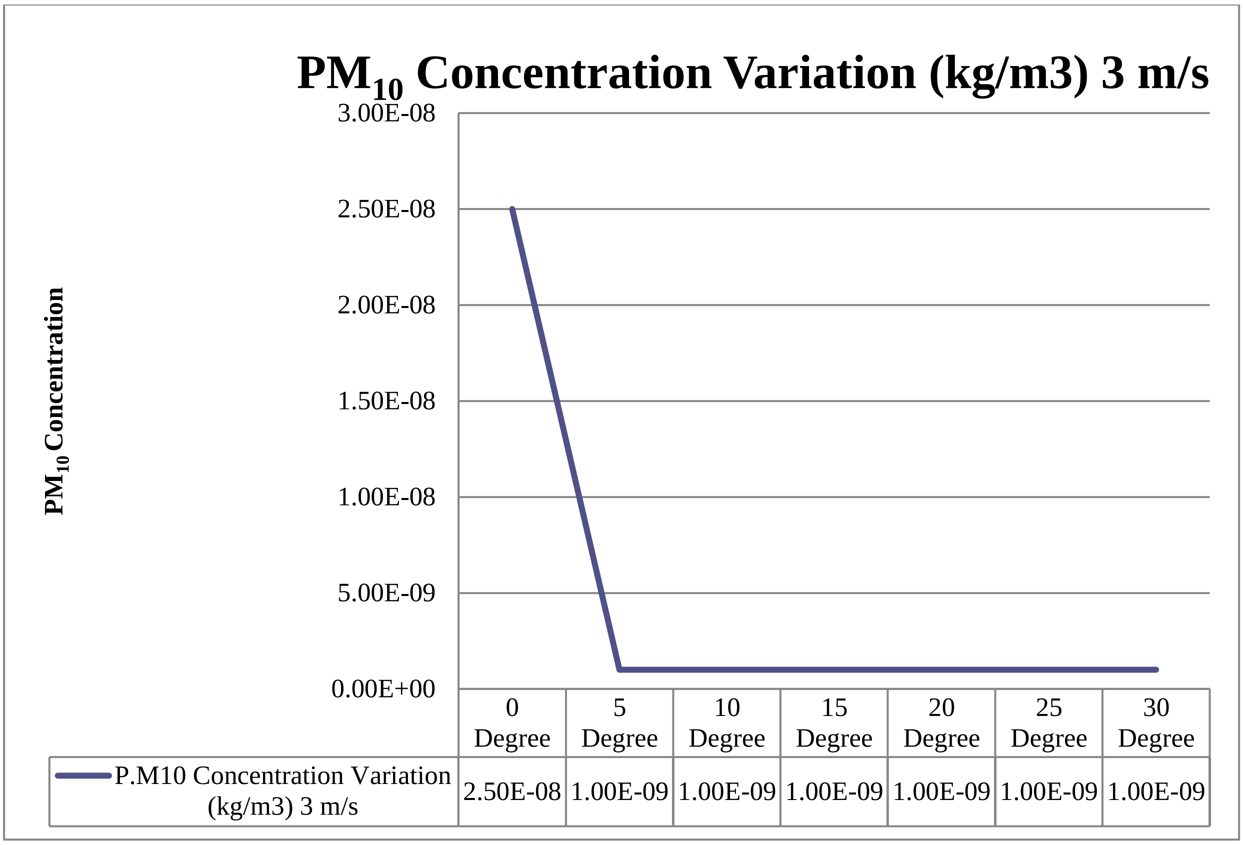


Figure 79 PM_{10} Concentration Variation (kg/m3) at 3 m/s

It is observed that when windows positions are in adjacent side and a green belt is applied between the road and guard room, the PM_{10} concentration inside the room is very less.

Wind Speed- 5 m/s-

Here, the applied 'West Wind' speed is considered as 5 m/s. PM_{10} concentration contour with the respect of various wind angle inside the room are shown below.

1) <u>0 Degree Angle Variation-</u>

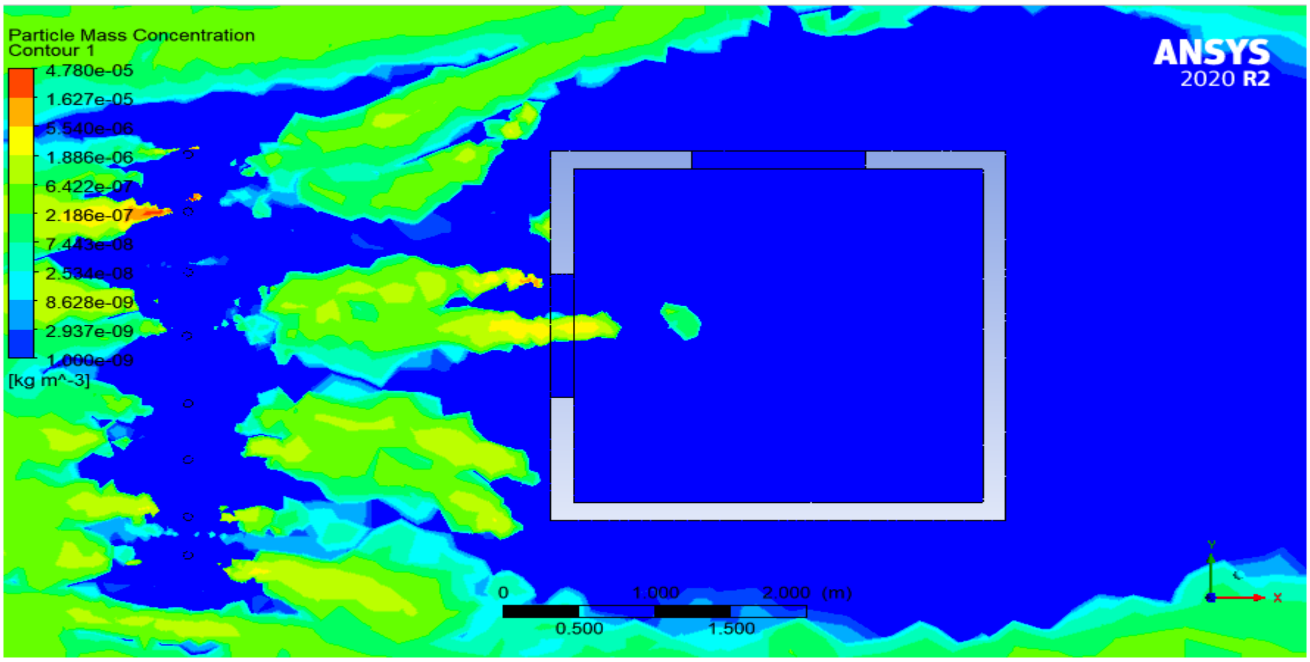


Figure 80 PM_{10} concentration contour inside the room

2) <u>5 Degree Angle Variation-</u>

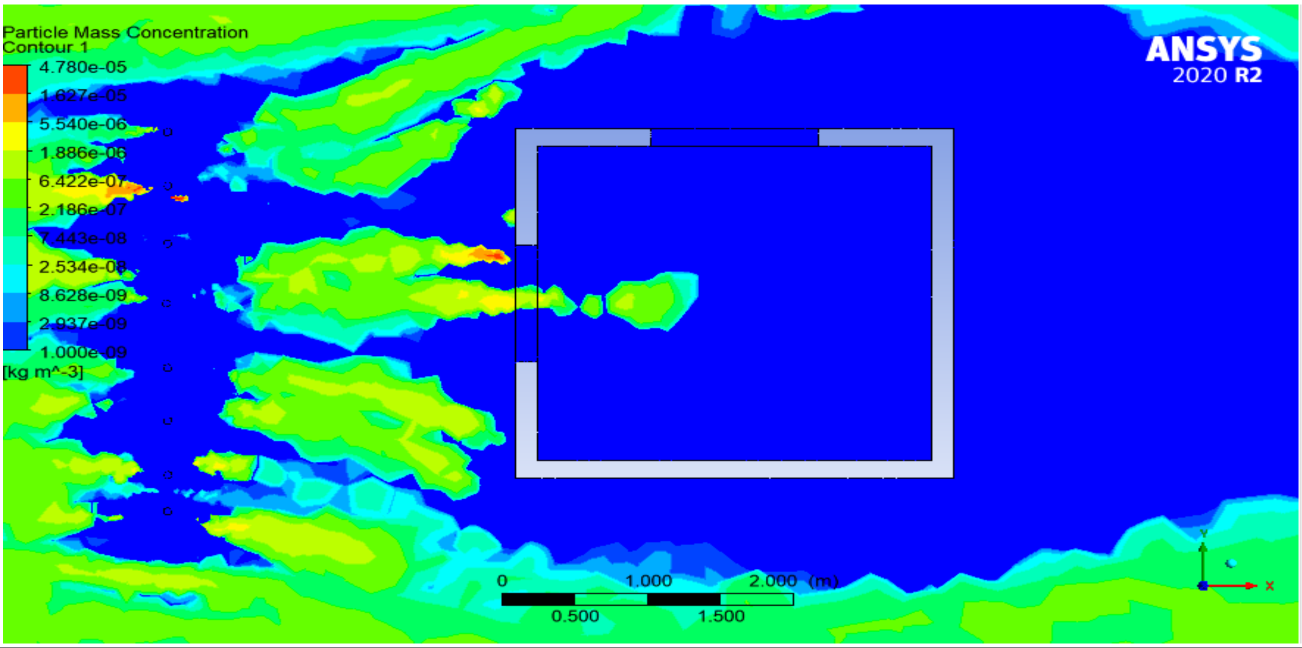


Figure 81 PM_{10} concentration contour inside the room

3) 10 Degree Angle Variation-

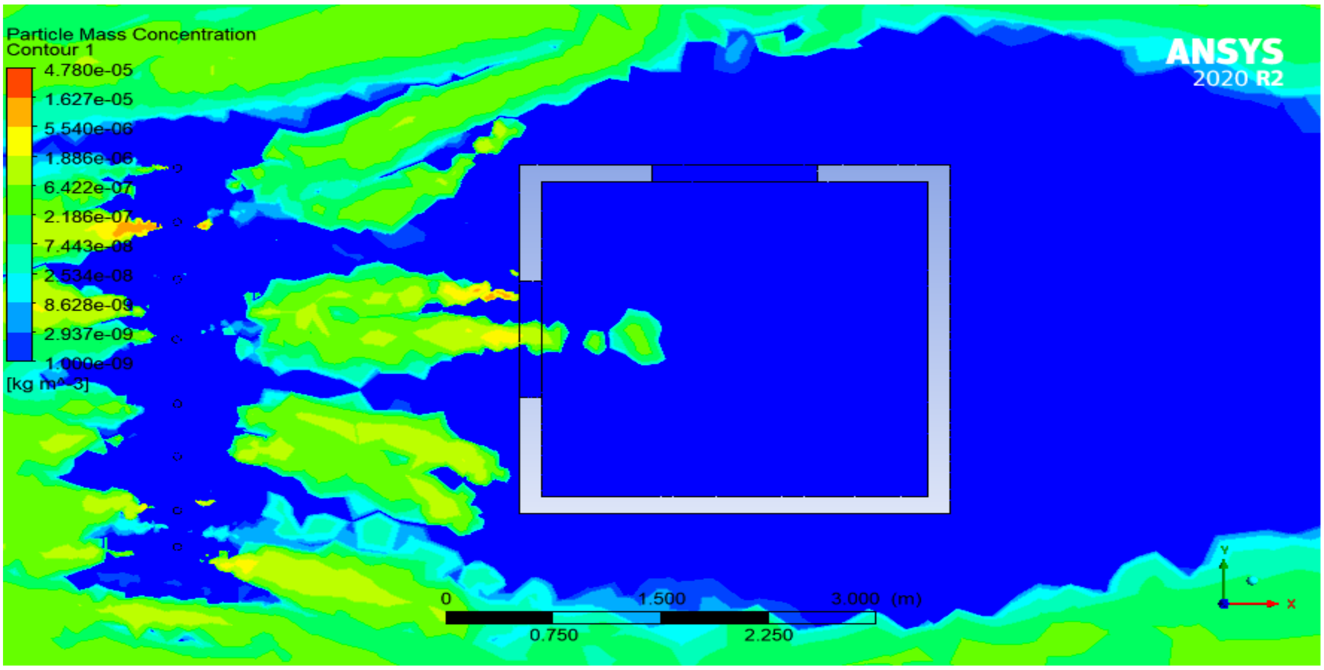


Figure 82 PM_{10} concentration contour inside the room

4) 15 Degree Angle Variation-

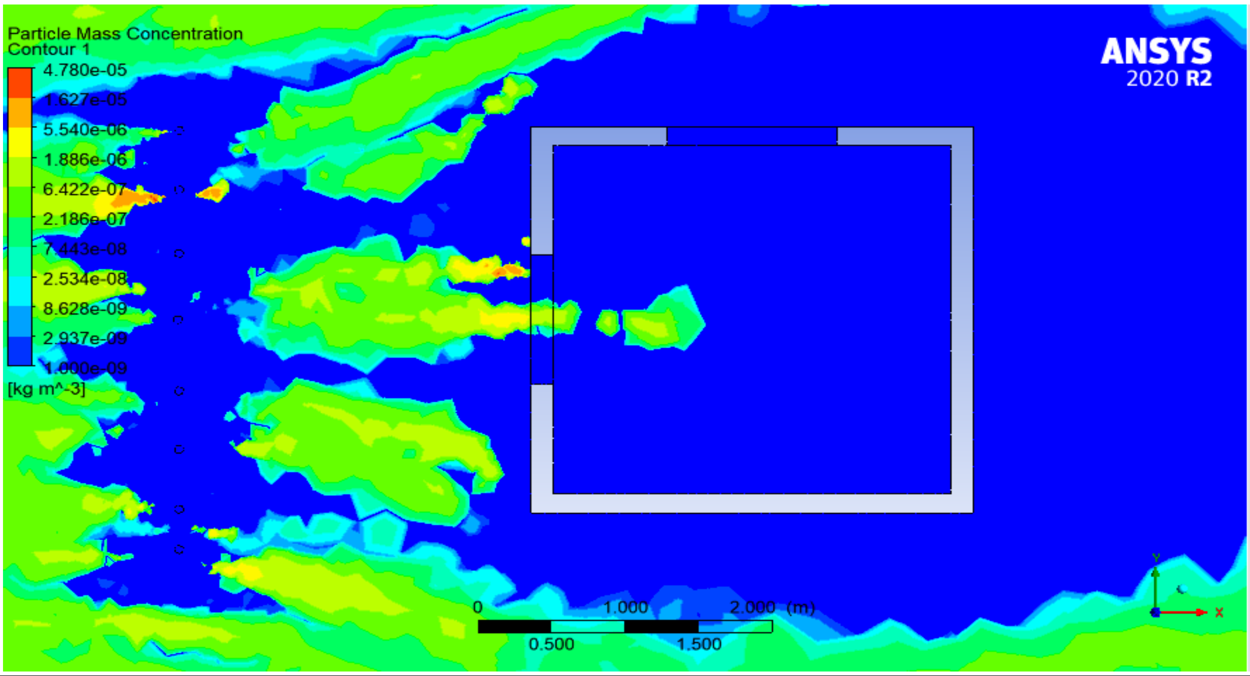


Figure 83 PM_{10} concentration contour inside the room

5) <u>20 Degree Angle Variation-</u>

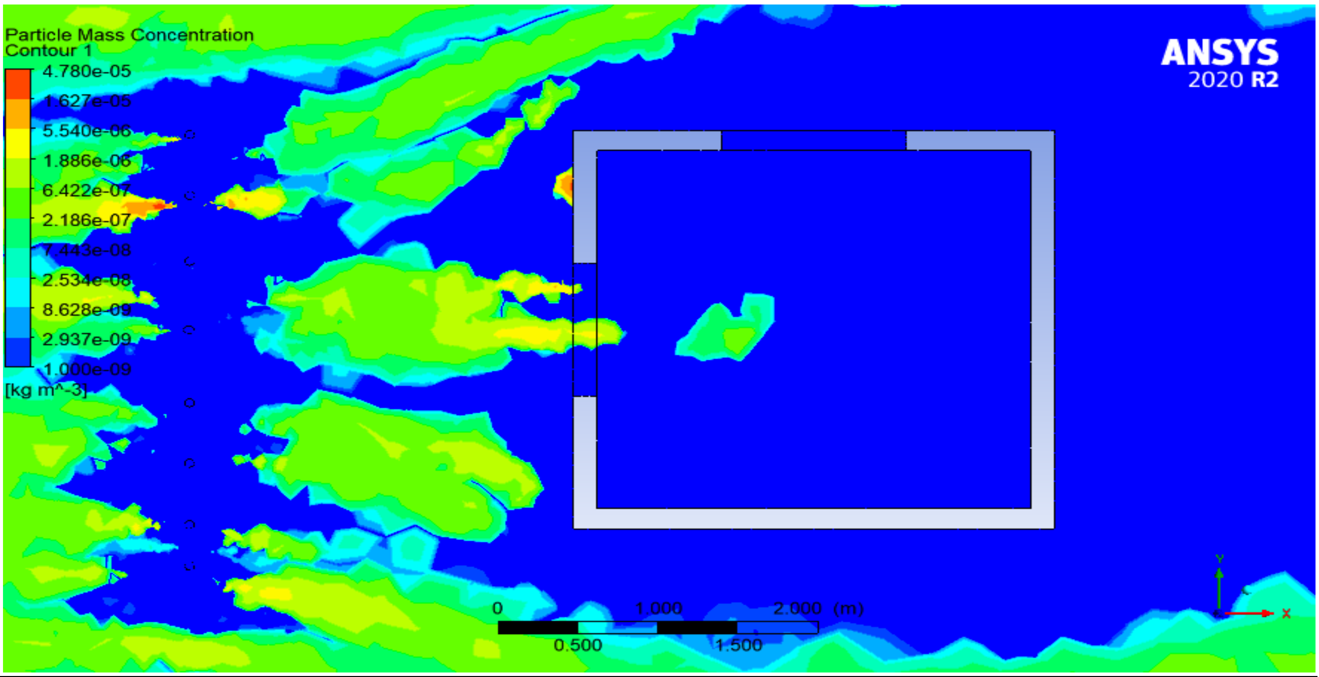


Figure 84 PM_{10} concentration contour inside the room

6) <u>25 Degree Angle Variation-</u>

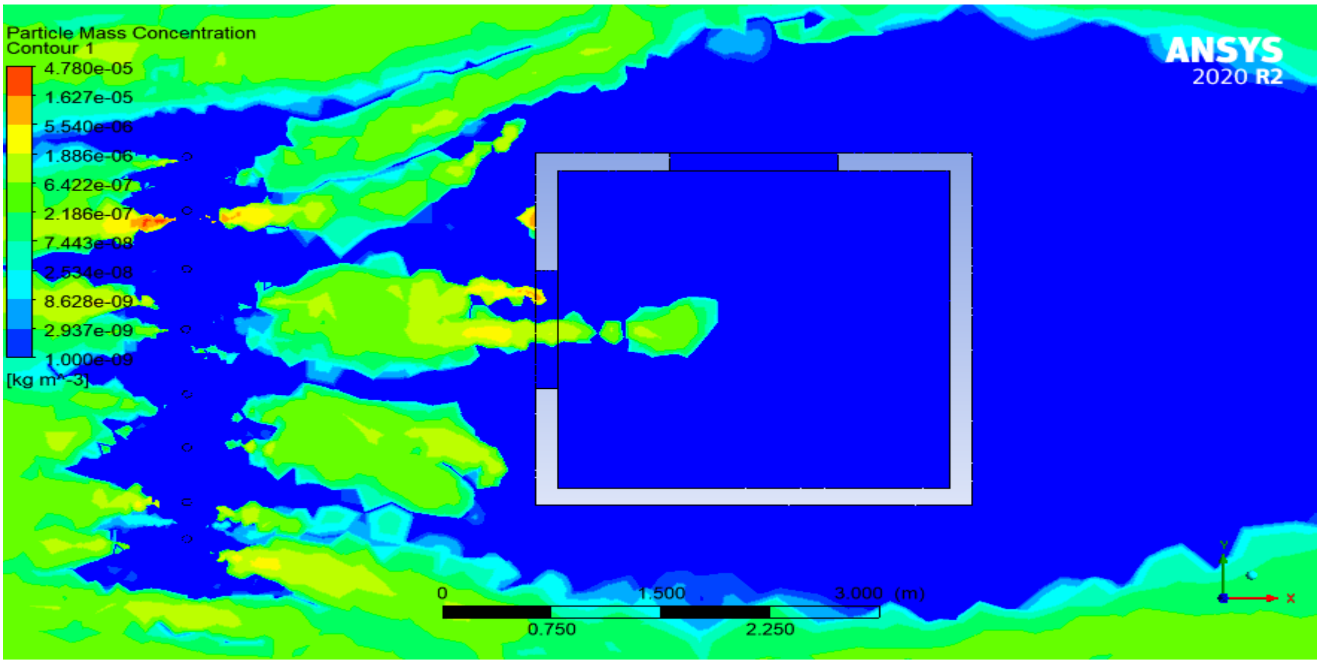


Figure 85 PM_{10} concentration contour inside the room

7) 30 Degree Angle Variation-

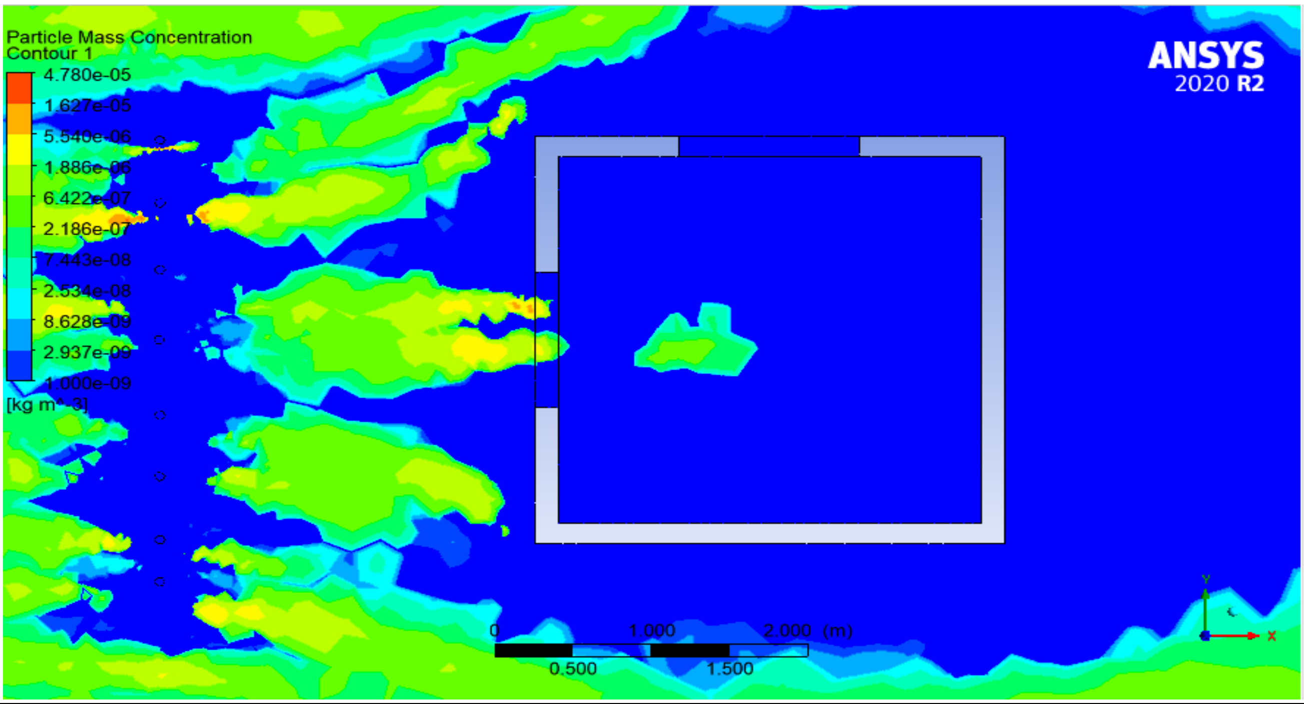
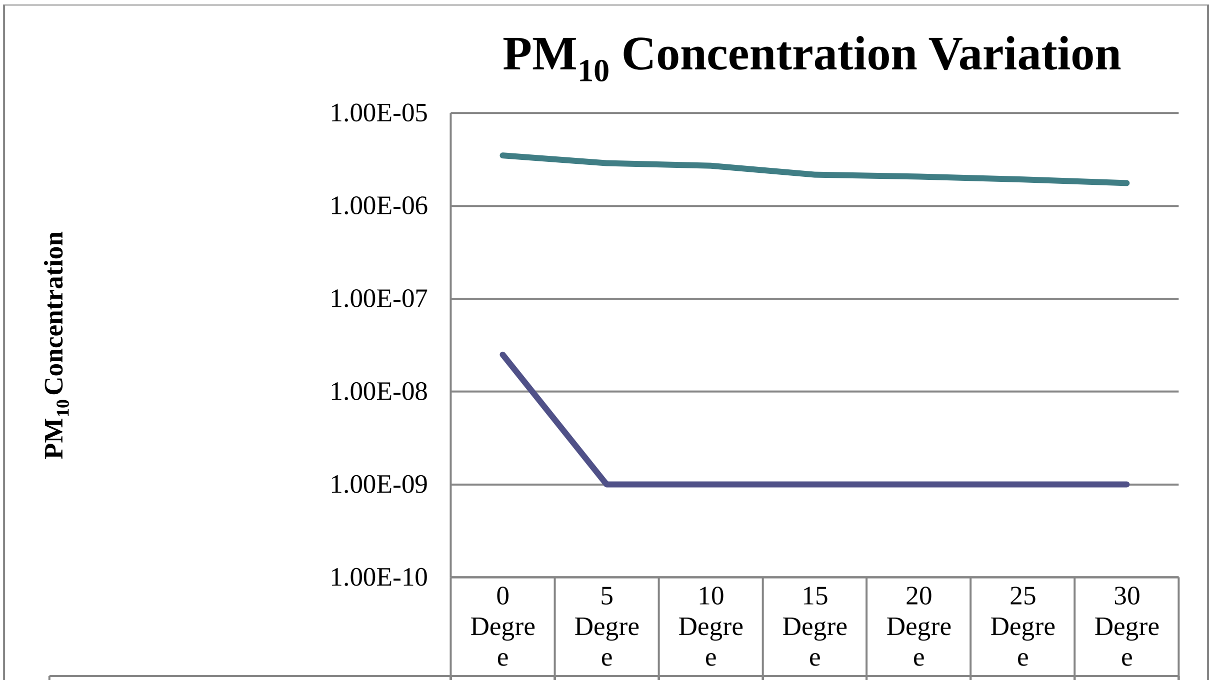


Figure 86 PM_{10} concentration contour inside the room

The highest values of PM_{10} concentration inside the room with respect to various wind angles are shown below.

Angle Variation	PM_{10} Concentration Variation (kg/m^3) 3 m/s	PM_{10} Concentration Variation (kg/m^3) 5 m/s
0 Degree	2.50×10^{-08}	3.49×10^{-06}
5 Degree	1.00×10^{-09}	2.89×10^{-06}
10 Degree	1.00×10^{-09}	2.70×10^{-06}
15 Degree	1.00×10^{-09}	2.16×10^{-06}
20 Degree	1.00×10^{-09}	2.06×10^{-06}
25 Degree	1.00×10^{-09}	1.93×10^{-06}
30 Degree	1.00×10^{-09}	1.76×10^{-06}

Table 11 PM_{10} Concentration Variation when windows are in adjacent side at 3m/s & 5m/s (With green belt)



	0 Degree	5 Degree	10 Degree	15 Degree	20 Degree	25 Degree	30 Degree
PM10 Concentration Variation (kg/m3) 3 m/s	2.50E-08	1.00E-09	1.00E-09	1.00E-09	1.00E-09	1.00E-09	1.00E-09
PM10 Concentration Variation (kg/m3) 5 m/s	3.49E-06	2.89E-06	2.70E-06	2.16E-06	2.06E-06	1.93E-06	1.76E-06

Figure 87 PM_{10} Concentration Variation (kg/m3) at 3 m/s & 5 m/s

- It is observed that when the wind speed is increased from 3 m/s to 5 m/s, the PM_{10} concentration level inside the room is increased.
- Besides that, when the variation of wind angle is increased, the PM_{10} concentration level inside the room is slightly deceased.
- It is clearly observed that if the green belt is applied in-front of the guard room, the PM_{10} concentration inside the room is very less.

7.3. PM_{10} Concentration Level Comparison between Different Windows' Positions-

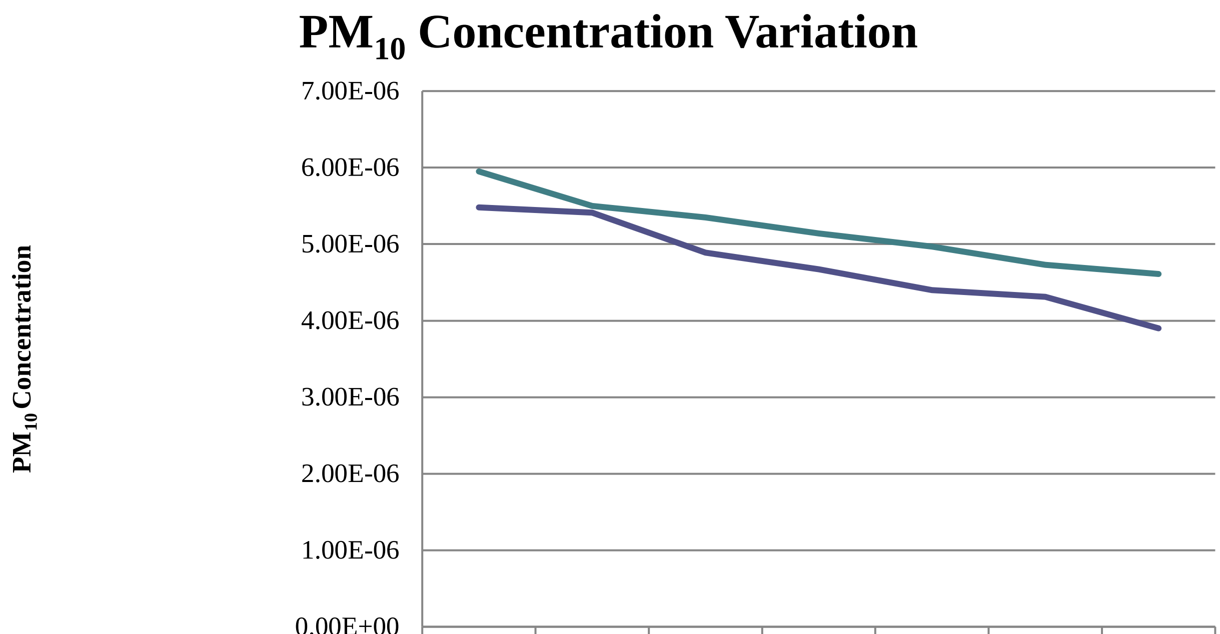
Two different types of window positions are considered, one is opposite side window position and another one is adjacent side window position. Also there is no green belt.

Comparison table and graph are given below-

For Wind Speed 3 m/s-

Angle Variation	PM_{10} Concentration Variation (kg/m^3) when windows are in opposite side	PM_{10} Concentration Variation (kg/m^3) when windows are in adjacent side
0 Degree	5.48×10^{-06}	5.95×10^{-06}
5 Degree	5.41×10^{-06}	5.50×10^{-06}
10 Degree	4.89×10^{-06}	5.35×10^{-06}
15 Degree	4.67×10^{-06}	5.14×10^{-06}
20 Degree	4.40×10^{-06}	4.97×10^{-06}
25 Degree	4.31×10^{-06}	4.73×10^{-06}
30 Degree	3.90×10^{-06}	4.61×10^{-06}

Table 12 Comparison of PM_{10} Concentration Variation when windows are in adjacent and opposite side at 3m/s



	0 Degree	5 Degree	10 Degree	15 Degree	20 Degree	25 Degree	30 Degree
PM10 Concentration Variation (kg/m3) when windows are in opposite side and wind speed 3 m/s	5.48E-06	5.41E-06	4.89E-06	4.67E-06	4.40E-06	4.31E-06	3.90E-06
PM10 Concentration Variation (kg/m3) when windows are in adjacent side and wind speed 3 m/s	5.95E-06	5.50E-06	5.35E-06	5.14E-06	4.97E-06	4.73E-06	4.61E-06

Figure 88 PM_{10} Concentration Variation (kg/m3) at 3 m/s (Different window position Opposite & Adjacent Side)

- So, it is observed that the PM_{10} concentration is less when windows' position of guard room is in opposite side.

For Wind Speed 5 m/s-

Angle Variation	PM_{10} Concentration Variation (kg/m^3) when windows are in opposite side	PM_{10} Concentration Variation (kg/m^3) when windows are in adjacent side
0 Degree	5.52×10^{-06}	2.06×10^{-05}
5 Degree	5.49×10^{-06}	1.69×10^{-05}
10 Degree	5.30×10^{-06}	1.47×10^{-05}
15 Degree	5.25×10^{-06}	1.30×10^{-05}
20 Degree	5.05×10^{-06}	1.07×10^{-05}
25 Degree	4.58×10^{-06}	6.93×10^{-06}
30 Degree	4.36×10^{-06}	6.70×10^{-06}

Table 13 Comparison of PM_{10} Concentration Variation when windows are in adjacent and opposite side at 5m/s

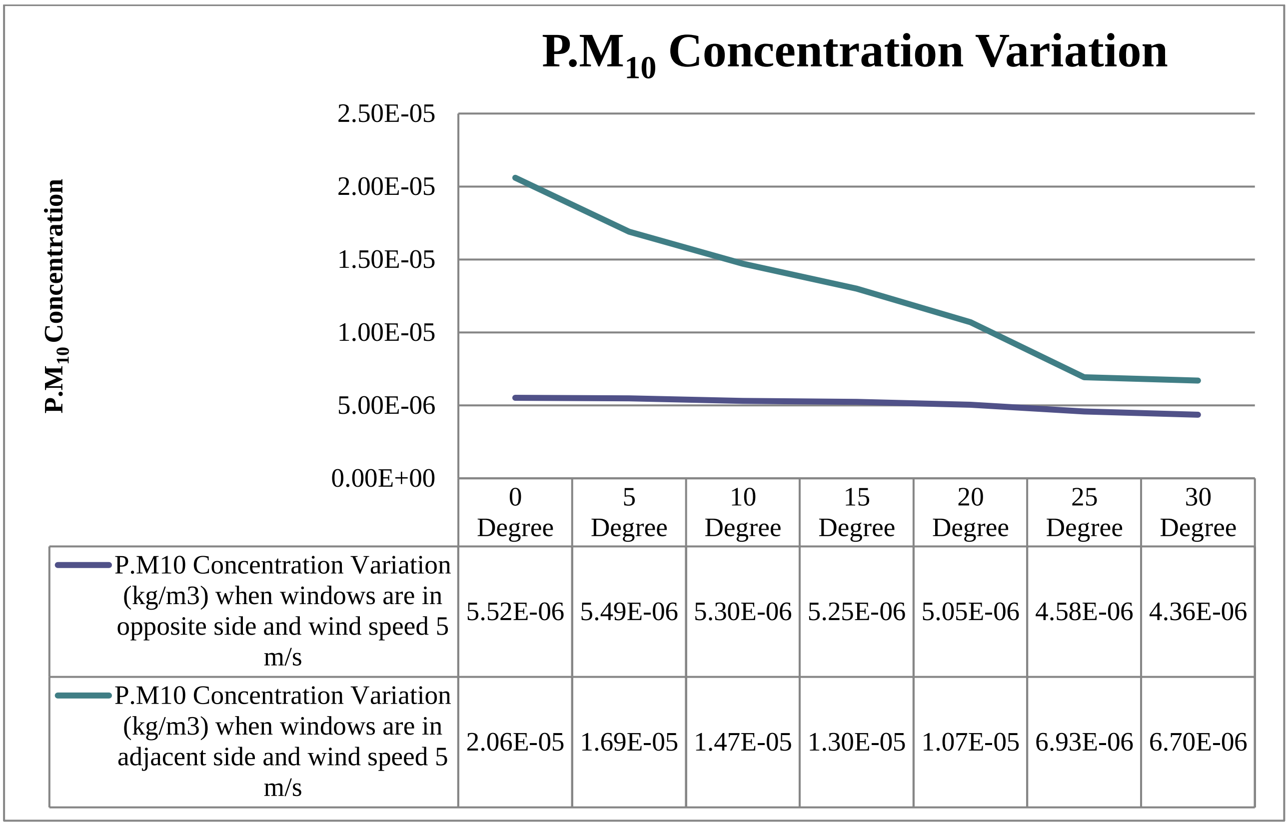


Figure 89 PM_{10} Concentration Variation (kg/m3) at 5 m/s (Different window position Opposite & Adjacent Side)

- If window position is considered then it is observed that, the room which has opposite side windows, PM_{10} concentration level inside the room is less.

7.4. PM_{10} Concentration Level Affected by Green Belt-

Here a green belt is applied in between road and the guard room. So, the effect of green belt is shown by tabular form and graphical form.

When Wind Speed 3 m/s-

	Without Green Belt	With Green Belt
	PM_{10} Concentration Variation (kg/m^3) when windows are in opposite side	PM_{10} Concentration Variation (kg/m^3) when windows are in opposite side
0 Degree	5.48×10^{-06}	2.44×10^{-08}
5 Degree	5.41×10^{-06}	1.99×10^{-08}
10 Degree	4.89×10^{-06}	1.13×10^{-08}
15 Degree	4.67×10^{-06}	1.07×10^{-08}
20 Degree	4.40×10^{-06}	1.00×10^{-09}
25 Degree	4.31×10^{-06}	9.99×10^{-09}
30 Degree	3.90×10^{-06}	3.85×10^{-09}

Table 14 Comparison of PM_{10} Concentration Variation when windows are in opposite side at 3m/s (With & without green belt)

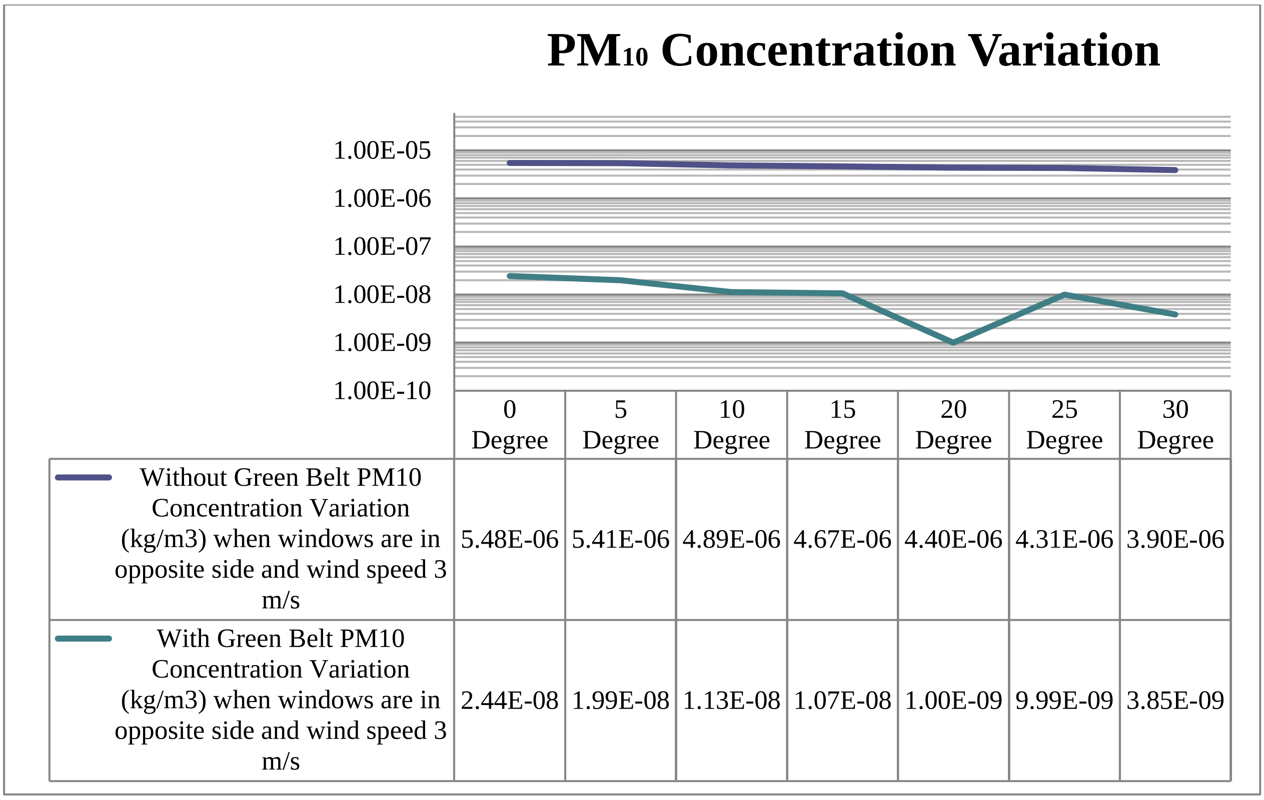
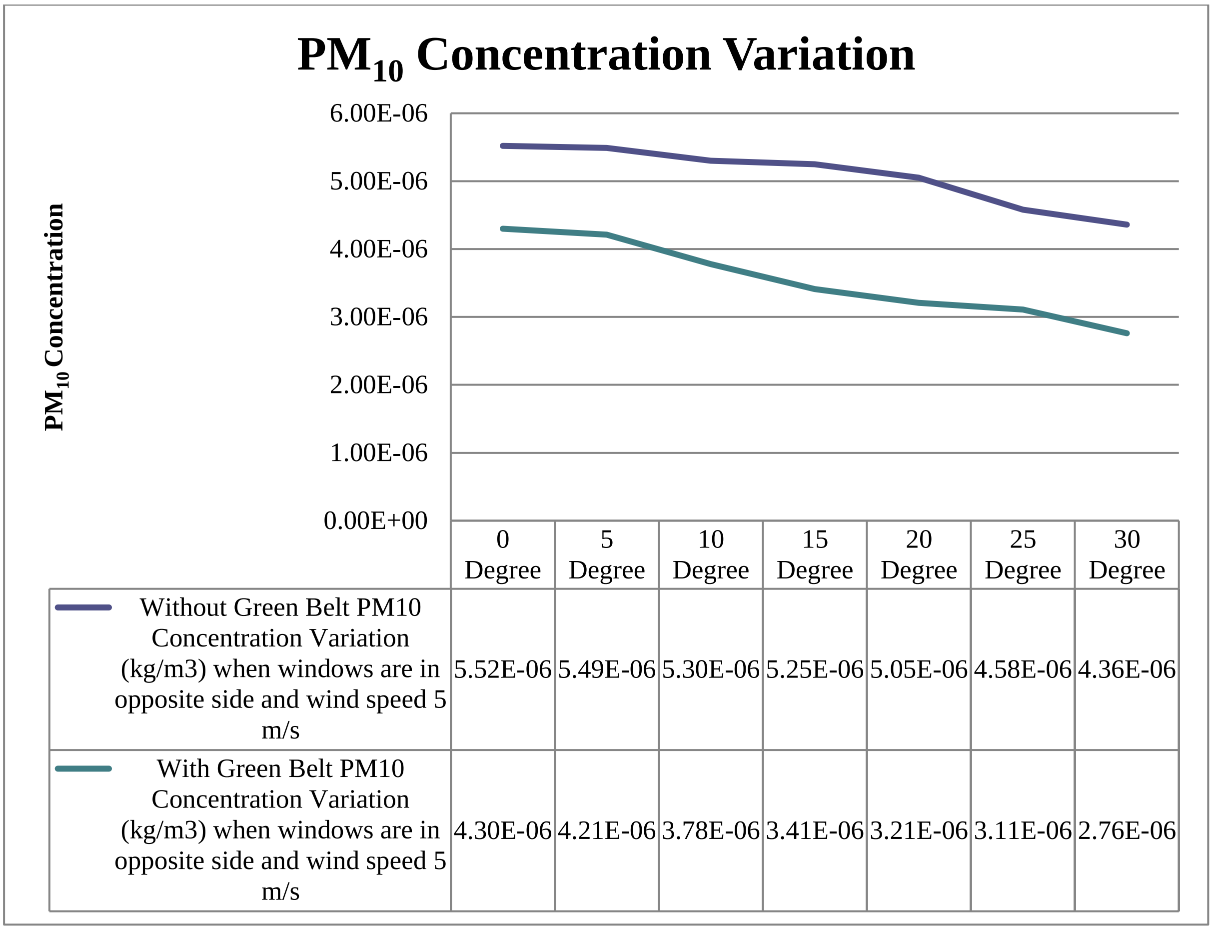


Figure 90 PM_{10} Concentration Variation (kg/m3) at 3 m/s (With & Without Green Belt)

For Wind Speed 5 m/s-

	Without Green Belt	With Green Belt
	PM_{10} Concentration Variation (kg/m^3) when windows are in opposite side	PM_{10} Concentration Variation (kg/m^3) when windows are in opposite side
0 Degree	5.52×10^{-06}	4.30×10^{-06}
5 Degree	5.49×10^{-06}	4.21×10^{-06}
10 Degree	5.30×10^{-06}	3.78×10^{-06}
15 Degree	5.25×10^{-06}	3.41×10^{-06}
20 Degree	5.05×10^{-06}	3.21×10^{-06}
25 Degree	4.58×10^{-06}	3.11×10^{-06}
30 Degree	4.36×10^{-06}	2.76×10^{-06}

Table 15 Comparison of PM_{10} Concentration Variation when windows are in opposite side at 5m/s (With & without green belt)



	0 Degree	5 Degree	10 Degree	15 Degree	20 Degree	25 Degree	30 Degree
Without Green Belt PM10 Concentration Variation (kg/m3) when windows are in opposite side and wind speed 5 m/s	5.52E-06	5.49E-06	5.30E-06	5.25E-06	5.05E-06	4.58E-06	4.36E-06
With Green Belt PM10 Concentration Variation (kg/m3) when windows are in opposite side and wind speed 5 m/s	4.30E-06	4.21E-06	3.78E-06	3.41E-06	3.21E-06	3.11E-06	2.76E-06

Figure 91 PM_{10} Concentration Variation (kg/m3) at 5 m/s (With & Without Green Belt)

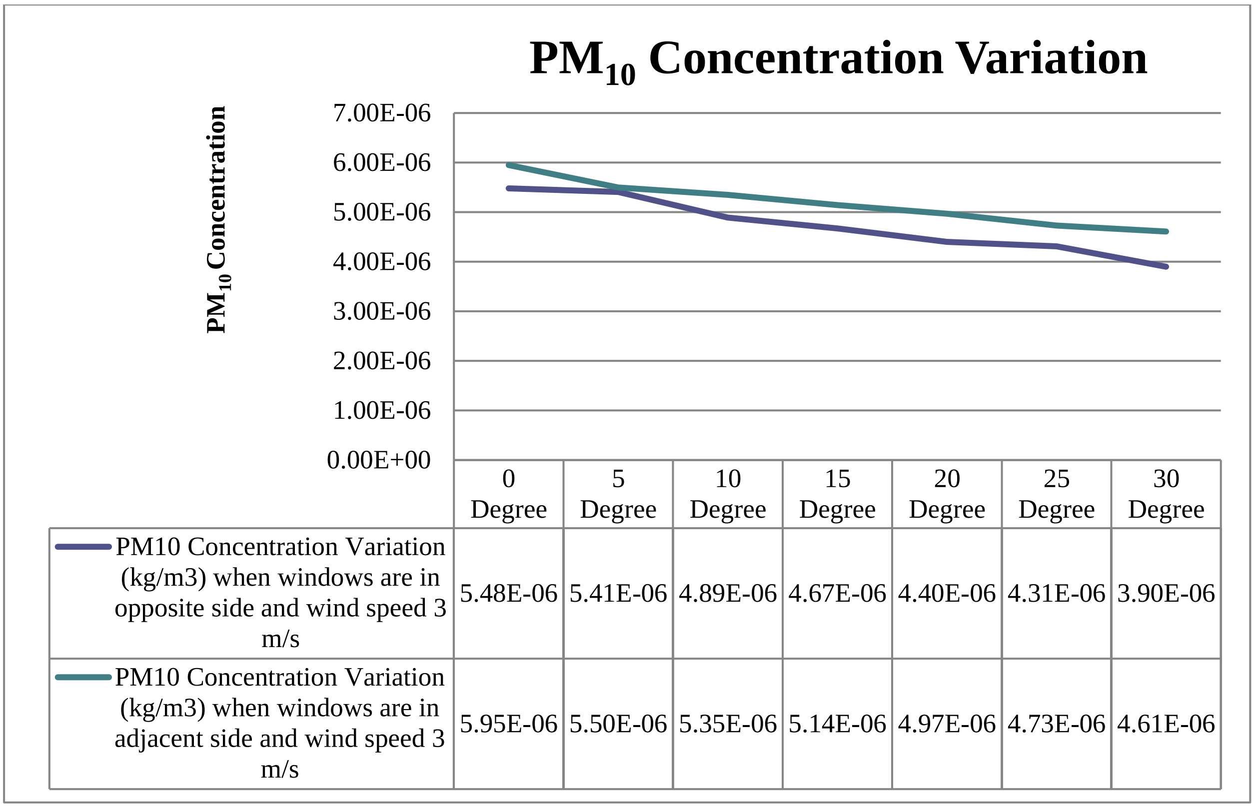
- It is clearly observed that, if green belt is applied in between the road and guard room, PM_{10} concentration is going to less. The green belt acts as an obstruction. So, the PM_{10} particles are stuck in the green belt.

Chapter 8: Conclusion:-

Measurements are always better than prediction. Measurements tell us what the concentrations are at a particular location. But, they cannot tell us what the concentration is going to be in future or what it is now at locations where no measurements are being made. Air Pollution models help us to understand the way air pollutants behave in the environment.

In this study, **ANSYS FLUENT 2020** software is used for modeling and simulation purpose. It is CFD (Computational Fluid Dynamics) based software. Rapid advancements in the CFD bring nowadays interest of many researchers to apply numerical modeling for prediction of indoor environment quality.

A road survey was conducted on 16th March, 2022, in front of Jadavpur University Gate No-3 **(Raja Subodh Chandra Mullick Road, Kolkata-700032)**. It was founded that the PM load is **2.5644×10^{-6} kg/s (calculated based on CPCB emission factor).** PM_{10} concentration level inside the Guard Room of Gate No-3 was measured on that date. **Portable Air Quality Monitor Pollution Meter** was used for PM_{10} concentration measurement. The observed concentration level was **45 $\mu g/m^3$ (4.5×10^{-8} kg/m^3).** The measured wind speed was **3 m/s** and wind direction was **North-West (NW Wind) (45º Angle variation).**
Now, **ANSYS FLUENT 2020** software has been used for modeling of passive control techniques based on the Guard Room. Two types of passive control techniques are used **(Window position variation, Green belt)**. Also wind angle variation **(0º, 5º, 10º, 15º, 20º, 25º, 30º)** is considered. 0º is the most critical wind angle variation because in this case wind can enter in the room directly. There are 2 windows considered in the Guard Room for convenience. It is considered that windows' positions are in **opposite side and adjacent side**.



	0 Degree	5 Degree	10 Degree	15 Degree	20 Degree	25 Degree	30 Degree
PM10 Concentration Variation (kg/m3) when windows are in opposite side and wind speed 3 m/s	5.48E-06	5.41E-06	4.89E-06	4.67E-06	4.40E-06	4.31E-06	3.90E-06
PM10 Concentration Variation (kg/m3) when windows are in adjacent side and wind speed 3 m/s	5.95E-06	5.50E-06	5.35E-06	5.14E-06	4.97E-06	4.73E-06	4.61E-06

Figure 92 PM_{10} Concentration Variation (kg/m^3) at 3 m/s (Different window position Opposite & Adjacent Side)

It is observed that when windows' positions are in adjacent side the PM_{10} concentration is more. Because when windows' positions are in opposite side, wind can directly passes through one window to another window but in adjacent side case wind can't directly passes.

It is also observed that the PM_{10} concentration inside the room is decreasing when wind angle variation is increased. When wind angle variation is 0°, wind can enter in the room directly. That's why in 0° wind angle variation the PM_{10} concentration inside the room is more.

Also in this study two wind speeds are considered **(3m/s, 5m/s). When wind speed is increased the PM_{10} concentration is also increased.**

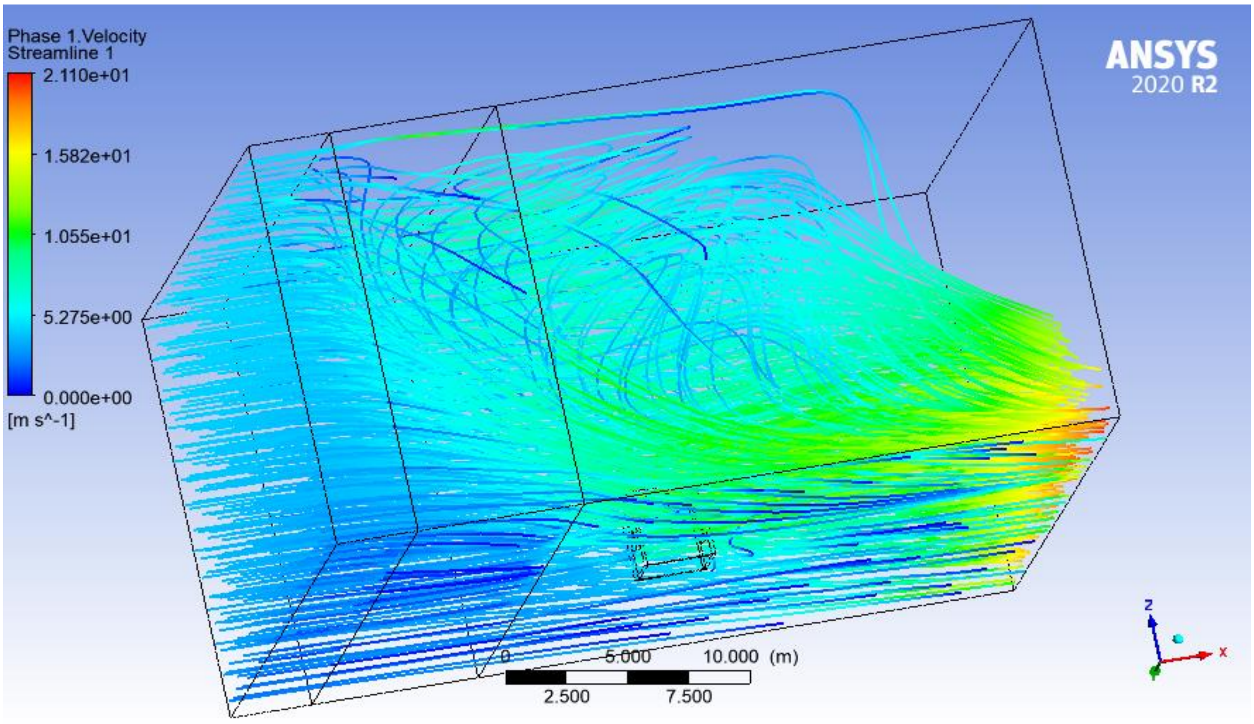
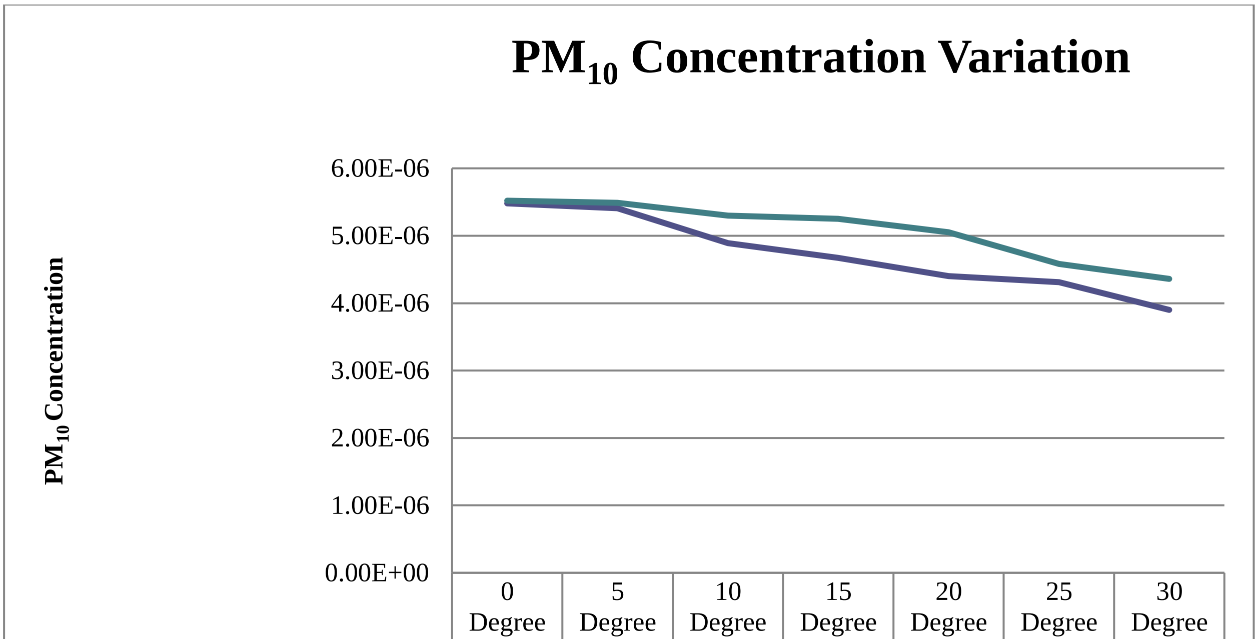


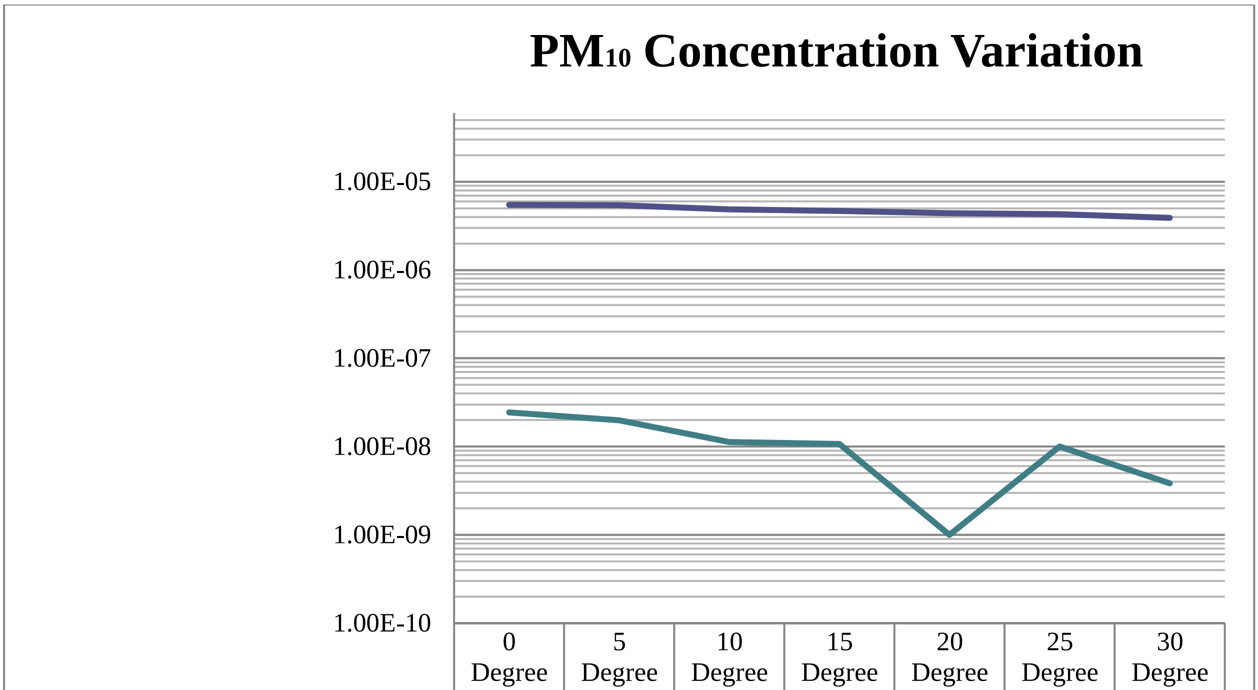
Figure 93 Streamline and velocity along +Z axis (wind speed-3m/s)



	0 Degree	5 Degree	10 Degree	15 Degree	20 Degree	25 Degree	30 Degree
PM10 Concentration Variation (kg/m3) 3 m/s	5.48E-06	5.41E-06	4.89E-06	4.67E-06	4.40E-06	4.31E-06	3.90E-06
PM10 Concentration Variation (kg/m3) 5 m/s	5.52E-06	5.49E-06	5.30E-06	5.25E-06	5.05E-06	4.58E-06	4.36E-06

Figure 94 PM_{10} Concentration Variation (kg/m^3) at 3 m/s & 5 m/s

When green belt is applied in between the main road and the Guard Room, the PM_{10} concentration inside the room is very less (Janhall, 2015).



	0 Degree	5 Degree	10 Degree	15 Degree	20 Degree	25 Degree	30 Degree
Without Green Belt PM10 Concentration Variation (kg/m3) when windows are in opposite side and wind speed 3 m/s	5.48E-06	5.41E-06	4.89E-06	4.67E-06	4.40E-06	4.31E-06	3.90E-06
With Green Belt PM10 Concentration Variation (kg/m3) when windows are in opposite side and wind speed 3 m/s	2.44E-08	1.99E-08	1.13E-08	1.07E-08	1.00E-09	9.99E-09	3.85E-09

Figure 95 PM_{10} Concentration Variation (kg/m^3) at 3 m/s (With & Without Green Belt)

So, according to **ANSYS FLUENT 2020**, if the windows' **positions are in opposite side and green belt are applied in between the road and guard room, PM_{10} concentration in the room is minimum** (Janhall, 2015) (M. Tallis, 2011)**.**

Chapter 9: Future Scope of Study:-

1) In this thesis work **steady state method** is used for modeling and simulation purpose. **Transition method** can also be used in for this work.
2) Windows' sizes are unchanged here. So, **windows' sizes can be changed**. We can study the effect of different sizes' windows on PM_{10} concentration level inside the room.
3) Different types of ventilation systems like **displacement ventilation, mixing ventilation, under floor air distribution systems UFAD** (Mateus N. M., 2017)**;** **impinging jet ventilation** by (Ye X. , 2016) and (Ye X. , 2019) and their effect on PM_{10} concentration level inside the Guard room can be studied.
4) There are various types of passive control techniques like **noise barrier, low boundary wall, parked car** (Janhall, 2015) (Nowak, 2006) etc. These techniques can be used for further study.
5) In **ANSYS FLUENT 2020** modeling work **Tetrahedral meshing** is used. **Hexahedral or Polyhedral meshing** (Sosnowski, 2018) can be used for further study. These types of meshing are very advance and tough, but it can give better result.
6) The main objective of this thesis work is to mitigate the PM_{10} concentration inside the room with the help of various passive control techniques. There is a scope of **thermal satisfaction study** (Zhenlei Chen, Air quality and thermal comfort analysis of kitchen environment with CFD, 2020) inside the room.
7) There is lot of air pollutants in environment like **PM_{10}, $PM_{2.5}$, NO_X, SO_2, CO, O_3** etc. In this thesis work, main focus is about **PM_{10}**. So, other pollutants and their effect inside the room can be considered for future study (BONDREA, 2015).

Chapter 10: References:-

(2021). Retrieved from https://www.simscale.com/docs/simulation-setup/global-settings/k-epsilon/.

Akoua. (2003). Experimental and numerical VOC concentration field analysis from flooring material in a ventilated room.

Alzaid, A. M. (2019). Experimental and numerical investigation of air distribution in a large air-conditioned space building. Brunel University London.

Amorim, J. V. (2013). Pedestrian Exposure to Air Pollution in Cities. *Advances in Urban Biometeorology Vol 2013*.

Awbi. (2003). *Ventilation of buildings: Second edition.* London: Taylor and Francis Group.

Bjerg, B. (2011, January). CFD analyses of methods to improve air quality and efficiency of air cleaning in pig production.

BONDREA, D. A. (2015). Numerical simulation of the air pollutants dispersion emitted by CPH using ANSYS. *World Amademy of Science, Engineering and Technology.*

Boonthanom, J. (2019). *A CFD STUDY OF POLLUTION DISPERSION IN STREET CANYON AND EFFECTS.*

Brohus. (1997). *Personal exposure to contaminant source in ventilated room.*

Fathollahzadeh. (2016, August). Producing a better performance for the under floor air distribution system in a dense occupancy space.

Gallagher. (2012). Numerical modelling of the passive control of air pollution in asymmetrical urban. *Building and Environment vol 56*, 232-240.

Hangan. (2001). Case study: Numerical simulations for comfort assessment and optimization of the ventilation design for complex atriums. *Journal of Wind Engineering and Industrial Aerodynamics Vol-89*, 1031-1045.

Heikki Setäläa, V. V.-L.-P. (2013). Does urban vegetation mitigate air pollution in northern conditions? *Environmental Pollution Vol 183*, 104-112.

Hollworth, B. R. (1992). Impingement Cooling of Electronics. *Journal of Heat Transfer, Vol 114*, 607-6013.

IEA. (1998). *International Energy Agency.*

Ioannis K. Panagopoulos1*, A. N. (2011). A CFD Simulation Study of VOC and Formaldehyde Indoor Air Pollution. *Aerosol and Air Quality Research vol 11(6)*.

Janhall. (2015). Review on urban vegetation and particle air pollution – Deposition and dispersion. *Atmospheric Environment Vol 105*, 130-137.

Jeanjean, A. (2017, march 27). Modelling the Impact of Trees on Vehicular Emissions in the Urban Environment Using Computational Fluid Dynamics. Leicester.

John Gallagher, R. B. (2015). Passive methods for improving air quality in the built environment. *Passive methods for improving air quality in the built environment: A review of porous and solid barriers*.

Karimipanah, A. M. (2008). The Air Distribution Index as an Indicator for Energy Consumption and Performance of Ventilation Systems. *Journal of the Human-Environmental System, 11 (2)*, 77-84.

Kathuria. (2002, September). Vehicular pollution control in Delhi. pp. 373-387.

Larraona. (2013). Computational parametric study of an impinging jet in a cross-flow configuration for electronics cooling applications. *Applied Thermal Engineering vol 52*, 428-438.

Li. (2010, January). EXPERIMENTAL INVESTIGATION OF SUBMERGED IMPINGING JET USING CUWATER NANOFLUID.

Li. (2019). Hood performance and capture efficiency of kitchens: A review. *Building and Environment Vol 161*, 106-221.

Lin. (2005). Comparison of performances of displacement and mixing ventilations. Part II: Indoor air quality. *International Journal of Refrigeration 28(2)*, 288-305.

Lin, C. (2006). Modeling particle deposition and distribution in a chamber with a two-equation Reynolds-averaged Navier–Stokes model. *Journal of Aerosol Science Vol 37(12)*, 1770-1780.

Livchak. (2005). The Effect of Supply Air Systems on kitchen thermal environment.

M. Tallis, G. T.-S. (2011). Estimating the removal of atmospheric particulate pollution by the urban tree canopy of london, under current and future environments. *Landscape and Urban Planning Vol 103*, 129-138.

Macía, Y. M. (2012). Experimental study of the turbulent flow around a single wall-mounted cube exposed to a cross-flow and an impinging jet. *International Journal of Heat and Fluid Flow 38*, 50-71.

Madsen, S. K. (2019). CFD modelling of pollutant transport. Use of ANSYS Workbench® simulating emissions to air from vessel at Port of Breivika. *International Conference of Multiphysics, Dubai, UAE, 14-15* (p. 62). International Society of Multiphysics.

Mateus, C. d. (2017). Simulated and measured performance of displacement ventilation systems in large rooms. *Building and Environment vol 114*, 470-482.

Mateus, N. M. (2017). Simulated and measured performance of displacement ventilation systems in large rooms. *Building and Environment vol 114*, 470-482.

McNabola. (2009). Reducing pedestrian exposure to environmental pollutants: A combined noise exposure and air quality analysis approach. *Transportation Research Part D: Transport and Environment Vol 14*, 309-316.

McNabola. (2010). New Directions: passive control of personal air pollution exposure from traffic emissions in urban street canyons. *Atmospheric environment 44(24)*, 2940-2941.

Mr. Rahul Kumar, M. D. (2016). CFD ANALYSIS OF POLLUTION DISPERSION IN COMPLEX DOMAIN. *International Journal Of Advance Research And Innovative Ideas In Education Volume 2 Issue 1 2016*, 1515.

Muhieldeen, A. S. (2015). Experimental and numerical studies of reducing cooling load of lecture hall. *Energy and Buildings Vol-89*, 163-169.

Nielsen. (2011). Lung Cancer Incidence and Long-Term Exposure to Air Pollution from Traffic. *Environ Health Perspect 119(6)*, 860-865.

Nowak, D. J. (2006). Air Pollution Removal by Urban Trees and Shrubs in the United States. *Urban Forestry & Urban Greening Vol-4*, 115-123.

OECD. (1997). Retrieved from https://stats.oecd.org/glossary/detail.asp?ID=86#:~:text=Air%20pollution%20is%20the%20presence,produce%20other%20harmful%20environmental%20effects.

P.E. Vos, B. M. (2013). Improving local air quality in cities: to tree or not to tree? *Environmental Pollution Vol 183*, 113-122.

Persily. (1997). Evaluating Building IAQ and Ventilation with Indoor Carbon Dioxide. *Indoor Air Quality in Sustainable, Energy vol 103(2)*, 193-204.

Revuz, J. (2012). On the domain size for the steady-state CFD modelling of a tall building. *Wind and Structures vol 15*, 313-329.

Rundström, D. (2008). Journal of Heat Transfer 130(12)Investigation of Heat Transfer and Pressure Drop of an Impinging Jet in a Cross-Flow for Cooling of a Heated Cube. *Investigation of HeatJournal of Heat Transfer Vol-130(12)*, 121401 (13 pages).

S, R. (2005). Performance Evaluation of CFD Model PANAIR for Air Pollution Dispersion of Industrial Stack Emissions. *Americal Meterological society*.

Sandberg. (1981). The use of moments for assessing air quality in ventilated rooms. *Building and Environment vol 18*, 181-197.

Sheng-Yi, C.-Y. T.-T.-D.-S.-S. (2011). Microalgal biomass production and on-site bioremediation of carbon dioxide, nitrogen oxide and sulfur dioxide from flue gas using Chlorella sp. cultures. *Bioresource Technology vol-102*, 9135-9142.

Skistad. (2002). *Displacement Ventilation in Non-Industrial Premises.*

Sosnowski, M. (2018). Polyhedral meshing in numerical analysis of conjugate heat transfer. *EPJ Web of Conferences 180, 02096 (2018).* EDP Sciences.

Teodosiu, C. (2015). Appropriate CFD Turbulence Model for Improving Indoor Air Quality of Ventilated Spaces. *Mathematical Modelling in Civil Engineering 10(4)*, 28-42.

Tham. (2016). Indoor air quality and its effects on humans—A review of challenges and developments in the last 30 years. *Energy and Buildings Vol 130*, 637-650.

W. King, E. P. (2009). An experimental study of sound generated by flows around cylinders of different cross-section. *Journal of Sound and Vibration Vol 328*, 318-337.

WHO. (2021). Retrieved from https://www.who.int/thailand/health-topics/air-pollution#tab=tab_1.

Wikipedia. (n.d.). Retrieved from https://en.wikipedia.org/wiki/Air_pollution_episode#:~:text=An%20air%20pollution%20episode%20is,1939%20Saint%20Louis%20Episode.

Ye, X. (2016). Heating energy consumption of impinging jet ventilation and mixing ventilation in large-height spaces: A comparison study. *Energy and Buildings Vol 130*, 697-708.

Ye, X. (2019). Comparison study of contaminant distribution and indoor air quality in large-height spaces between impinging jet and mixing ventilation systems in heating mode. *Building and Environment vol 160*, 106-159.

Yuting Ma, Y. J. (2015). *Numerical Simulation of PM2.5 Distribution in Indoor Air*.

Zhen, P. (2020). An integrated low-energy ventilation system to improve indoor air quality and thermal comfort of primary school buildings in the cold climate zone of China. *Building and Environment vol 182*, 107-153.

Zhenlei Chen, J. X. (2020). Air quality and thermal comfort analysis of kitchen environment with CFD. *Building and Environment Vol 172*, 106-691.

Zhenlei Chen, J. X. (2020). Air quality and thermal comfort analysis of kitchen environment with CFD. *Building and Environment vol 172*, 106-691.

Zhenlei Chen, J. X. (2020). Air quality and thermal comfort analysis of kitchen environment with CFD simulation and experimental calibration. *Building and Environment Vol 172*, 106-691.