NUMERICAL INVESTIGATION OF INDOOR ENVIRONMENTAL QUALITY AND VENTILATION PERFORMANCE IN A UNIVERSITY LECTURE THEATRE

By

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A dissertation submitted to the Department of Mechanical and Material Engineering, Lee Kong Chian Faculty of Engineering, Universiti Tunku Abdul Rahman, in partial fulfillment of the requirements for the degree of Master of Engineering (Mechanical)

MAY 2018

ABSTRACT

NUMERICAL INVESTIGATION OF INDOOR ENVIRONMENTAL QUALITY AND VENTILATION PERFORMANCE IN A UNIVERSITY LECTURE THEATRE

Chin Sze Jing

The indoor ventilation act as an important role in maintaining a good indoor environmental quality (IEQ). In this study, the elaborate performance were studied using a CFD software. The number of participants, discharge angle and temperature from an air conditioner were set as the manipulated variable to study the performance of ventilation. The results showed that discharge angle of 60 ^{o} with 16 ^{o}C has a better performance in maintaining the environmental quality. Besides, the outdoor temperature and number of students will affect the indoor temperature as the indoor temperature increased with the increasing of outdoor temperature and number of students. Lastly, the concentration of carbon dioxide will increase with the increasing of participants.

DECLARATION

I hereby declare that this project report is based on my original work expect for citations and quotations which have been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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ACKNOWLEDGEMENT

First of all, I would like to express my sincere thanks to my thesis supervisor Dr. Lai Soon Onn. He always guide me in the right direction during the research and writing of the thesis.

Besides my supervisor, I would like to thank my coursemate for their encouragement and helpful suggestions.

Last but not least, I would like to thank my family, for supporting me.

FACULTY OF ENGINEERING AND SCIENCE

UNIVERSITI TUNKU ABDUL RAHMAN

Date: 17th May 2018

SUBMISSION OF FINAL YEAR PROJECT /DISSERTATION/THESIS

It is hereby certified that ***Chin Sze Jing*** (***16UEM05483***) has completed this thesis entitled "*Numerical Investigation of Indoor Environmental Quality and Ventilation Performance in a University Lecture Theatre*" under the supervision of Dr. Lai Soon Oon from the Department of Chemical Engineering, Faculty of Engineering and Science.

I hereby give permission to the University to upload softcopy of my thesis in pdf format into UTAR Institutional Repository, which may be made accessible to UTAR community and public.

Yours truly

____

(*Chin Sze Jing*)

APPROVAL SHEET

This dissertation entitled "**NUMERICAL INVESTIGATION OF INDOOR ENVIRONMENTAL QUALITY AND VENTILATION PERFORMANCE IN A UNIVERSITY LECTURE THEATRE**" was prepared by CHIN SZE JING and submitted as partial fulfillment of the requirements for the degree of Master of Engineering (Mechanical) at Universiti Tunku Abdul Rahman.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled "**NUMERICAL INVESTIGATION OF INDOOR ENVIRONMENTAL QUALITY AND VENTILATION PERFORMANCE IN A UNIVERSITY LECTURE THEATRE**" was prepared by **CHIN SZE JING** has met the required standard for submission in partial of the requirements for the award of Master of Engineering (Mechanical) (Structure C) at Universiti Tunku Abdul Rahman.

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Date : ______________________________

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LIST OF ABBREVIATIONS

CFD	Computational Fluid Dynamics
COPD	Chronic Obstructive Pulmonary Disease
DOSH	Department of Occupational Safety and Health Malaysia
HVAC	Heating, Ventilation and Air-Conditioning
SBS	Sick Building Syndrome
IAQ	Indoor Air Quality
PD	Population Dissatisfied
RNG	Re-Normalisation Group
WHO	World Health Organization

CHAPTER 1

INTRODUCTION

1.1 Overview

A conditioning enclosed space is to supply comfortable indoor condition for human being. More and more people spend their time indoors, at home, shopping malls, restaurants, vehicles, theatres and so on. The studies of Europe and U.S. stated that most of the people spent more than 90% of their time indoor (Teodosiu, Ilie and Teodosiu, 2014).

However, some building systems' design or technical flaw may affect the human health or lead to sickness due to the ventilation (Vilčeková et al., 2017). Besides affecting the health, indoor ventilation will influence the working and study productivity.

In this research, the indoor air quality (IAQ) of a university is evaluated. In a ventilated space, the air quality can be studied based on modern computational techniques. (Teodosiu, Ilie and Teodosiu, 2014).

Therefore, computational fluid dynamics (CFD) simulation software (ANSYS Fluent) will be used to predict the air movement in university building.

1.2 Problem Statement

The use of university lecture rooms has increased significantly in recent years due to the increase of students. However, inadequate ventilation is always observed in the university buildings. This will affect the performance of students and staff.

1.3 Objectives

- To simulate the percentage of CO_2 at different scenarios such as number of participants and opened and closed of door.
- To simulate temperature of lecture theatre which affected by outside temperature and discharged temperature of 4 way ceiling cassette.
- To simulate air speed in a university theatre at different discharge angle of 4 way ceiling cassette.

CHAPTER 2

LITERATURE REVIEW

2.1 Indoor Air Pollution

Contaminations of indoor air in terms of chemical, biological and physical are considered as indoor air pollution (QECD, 2003). It is generated normally by poorly ventilated stoves burning biomass fuels, for examples wood, crop waste and dung, or coal (Bruce, Perez-Padilla and Albalak, 2018). Suspended particulate matter (PM), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO), formaldehyde and polycyclic aromatic hydrocarbons (PAHs) are the main sources of indoor air pollution (QECD, 2003).

The indoor concentration of CO_2, CO, O_3, TVOCs, HCHO, humidity, temperature, PM_{10} and $PM_{2.5}$, bacteria and fungi is higher than outdoor and the pollutions will varies by the season. The pollution level of summer will be slightly higher than that of winter due to the increase of temperature and humidity and the level will also be influenced by the human occupancy (Zhou et al., 2017). Besides that, the university may contains some pollution sources such as lab chemicals, cleaning agents, and mold.

According to Kamaruzzaman and Razak (2011), the number of occupants per square foot of schools were four times higher than office and the indoor air was 10 times as polluted as the outdoor air. It means that the amount of polluted air inhaled by students is very high.

2.1.1 General IAQ Health Issues

According to World Health Organization (WHO), there are 4.3 million people die a year due to household air pollution which results in pneumonia, stroke, ischaemic heart disease, chronic obstructive pulmonary disease (COPD) and lung cancer. Besides, some health effects may appear such as irritation of the eyes, nose, and throat, headaches, dizziness, fatigue and asthma (US Environmental Protection Agency, 2017)

The sick building syndrome (SBS) symptoms among the peoples are observed when the air quality is poor. A survey from Vilcekova et al. (2017) stated that the common SBS symptoms among the students were fatigue, feeling heavy-headed, headache, difficulties in concentration, eyes irritation, and nasal symptom, as shown in Figure 2.1.

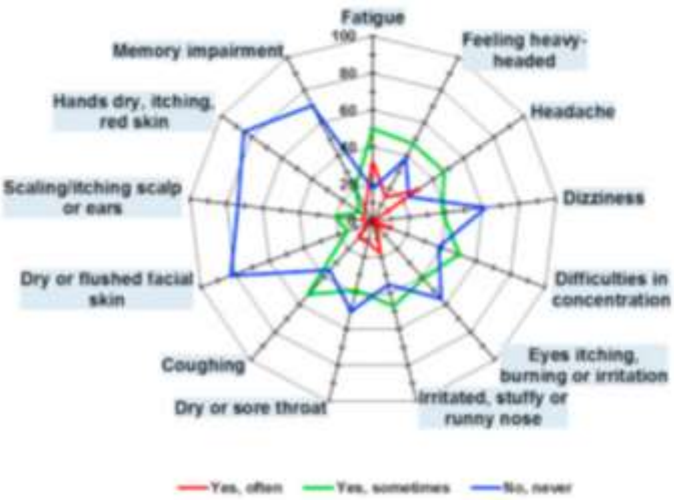


Figure 2.1: Prevalence of SBS Symptoms among students (Vilcekova et al., 2017).

2.2 Indoor Air Quality Guideline

According to the Department of Occupational Safety and Health Malaysia (DOSH), the acceptable range of temperature is 23-26 ^{o}C and concentration of carbon dioxide should not exceed 1000 ppm, as shown in Table 2.1 and Table 2.2.

Table 2.1: Acceptable range for specific physical parameters (DOSH, 2017).

Parameter	Acceptable Range
Air temperature	23-26 ^{o}C
Relative humidity	40-70%
Air movement	0.15-0.50 m/s

Table 2.2: List of indoor air contaminants and the acceptable limits (DOSH, 2017).

Indoor Air Contaminants	**Acceptable Limits**		
	ppm	**mg/m^3**	**cfu/m^3**
Chemical contaminants			
Carbon monoxide	10	-	-
Formaldehyde	0.1	-	-
Ozone	0.05	-	-
Respirable particulates	-	0.15	-
Total volatile organic compounds (TVOC)	3	-	-
Biological contaminants			
Total bacterial counts	-	-	500*
Total fungal counts	-	-	1000*
Ventilation performance indicator			
Carbon dioxide	C1000	-	-

Notes:

- For chemical contaminants, the limits are eight-hour time-weighted average airborne concentrations.
- C is the maximum limit that shall not be exceeded at any time.
- *excess of bacterial counts does not necessarily imply health risk but serve as an indicator for further investigation.

2.3 Carbon Dioxide

The concentrations of indoor CO_2 are higher than the concentrations of outdoor CO_2. As shown in Table 2.3, most of the indoor CO_2 concentrations were exceed the acceptable limit (1000 ppm). However, the indoor CO_2 concentrations of Egypt and Malaysia were lower than the acceptable limit (ranging from 497 ppm to 507 ppm). Besides, the concentrations of CO_2 in natural ventilation were lower than the concentrations in air-conditioned and heating system. Lastly, the volume of the classroom and the number of participates will affect the CO_2 concentration. A small size of classroom with a lot of participates will have a very high CO_2 concentration, as compared to a large volume of classroom with a few of participates.

Table 2.3: Indoor CO_2 concentration in school from difference countries.

School Name	Floor Area or Volume	Location	Indoor Temperature (°C)	Average Indoor Co_2 Concentration (Ppm)	Mode of Ventilation	References
New Assiut City Primary School and El-Nahda Primary School	-	Egypt	24- 38	497	Natural ventilation and air-conditioned	Hassan Abdallah (2017)
	41-82 m^2	Cassino, Italy	12 - 22	2206.6	Natural ventilation	Stabile et al. (2017)
SCH2 and SCH5	196.5 m^3	Zaječar, Serbian	-	1256.5	Heating system	Turanjanin et al. (2014)
SCH1	216 m^3	Grljan village, Serbian	-	1498	-	Turanjanin et al. (2014)
SCH3	210 m^3	Bor town, Serbian	-	1140.67	Heating system	Turanjanin et al. (2014)

SCH4	282.67 m^3	Belgrade, Serbian	-	1172	-	Turanjanin et al. (2014)
-	112.84 m^3	Kosice, Slovak Republic	7.5 - 13.5	1164.32	Natural ventilation	Vilcekova et al. (2017)
-	171 m^3	Porto, Portugal	20.5	1669	-	Madureira et al. (2015)
Precinct 14 Secondary School	56.3 m^2	Putrajaya, Malaysia	31	502	Natural ventilation	Yang Razali et al. (2015)
JalanReko Secondary School	53.1 m^2	Bandar BaruBangi, Malaysia	31	507	Natural ventilation	Yang Razali et al. (2015)
Section Four Secondary School	74.7 m^2	Bandar BaruBangi, Malaysia	31	498	Natural ventilation	Yang Razali et al. (2015)

2.3.1 CO_2 Health Issues

Carbon dioxide is not a toxic gas but it will affect human body if the concentration exceed the standard. According to Yu, He and Feng (2015), the concentration of fresh air CO_2 was roughly 0.03%. The concentration of CO_2 in the public should not more than 0.07-0.10% (long-stay) and 0.15% (short stay). Based on Table 2.4, human still can tolerate the concentration of CO_2 where population dissatisfied (PD) rate at 20%-30%.

Table 2.4: Human health effects of concentration level of indoor CO_2 (Yu, He and Feng, 2015).

Indoor CO2 Concentration Level (ppm)	**Population Dissatisfied (PD) Rate**	**Health Effect**
Based on non-self-adaptive crowd		
485-1015	5.8%-20%	General ideal range
485-615	5.8%-10%	Ideal range of sensitive crowd
616-1015	10%-20%	General permission range
1016-1570	20%-30%	Continuing bearable range (SBS occurrence range)
1571-5000	>30%	Temporary bearable range

5001-15000	100%	Unbearable range
>15000	100%	
Based on self-self-adaptive crowd		
485-2420	5.8%-20%	General ideal range
485-1225	5.8%-10%	Ideal range of sensitive crowd
1226-2420	10%-20%	General permission range
2421-4095	20%-30%	Continuing bearable range (SBS occurrence range)
4096-5000	>30%	Temporary bearable range
5001-15000	100%	Unbearable range
>15000	100%	

The main health issue of carbon dioxide is the stimulation of respiratory center, which will cause difficulty in breathing, increasing the volume of smoke inhaled. Besides, it will also cause headaches, confusion and other signs.

2.4 Human

Our human body is a very complex structure. The age, gender, height and lifestyle will affect the parameters in Chapter 3.

2.4.1 Respiratory System

The maximum exhalation speed for nasal breathing is 1.4 m/s while mouth breathing is 1.3 m/s. Besides, the velocity of sneezing 4.5 m/s (Tang et al., 2013). According to Noh, Han and Oh (2007), the CO_2 emitted from the participants' mouth was 0.014 m^3/hr (4 %). Furthermore, men will emit more CO_2 compare to women as men have larger lungs compared to women. (McClaran et al. 1998; Wall et al. 2002).

According to Shaw and Messer (1930), human skin will also emit carbon dioxide depend upon the surrounding condition such as temperature, humidity, individual characteristics, seasonal changes and gas tensions.

2.4.2 Thermal Properties of Human

According to (Cohen, 1977), the thermal conductivity of human skin varies from 0.29 W/mK to 3.1 W/mK. The heat exchange coefficient of a human is 2.3 to 2.7 W/m^2K (Thermopedia, 2011). Therefore, in this simulation, the heat exchange coefficient of a human was set as 2.5 W/m^2K. Lastly, the thickness of human skin was 15–20 μm ((Dąbrowska et al., 2016)

2.5 Air Conditioning Cycle

Air conditioner is a close loop system. It is work by the circulating a refrigerant with the principle of second law of thermodynamics and ideal gas law (Heaton, 2017). The liquids will absorb heat when turn into gases and the gases release heat when turn into liquids. As shown in Figure 2.2, the warmer indoor air transfer heat to the refrigerator through evaporator and release the heat to outside through condenser. In the compressor, the low–pressure gas will be compressed to high-pressure gas, then will release heat to the outside and condense to high-pressure liquid in the condenser (SWTC, n.d.). The expansion valve decreases the pressure of refrigerant to form low-pressure liquid (SWTC, n.d.).

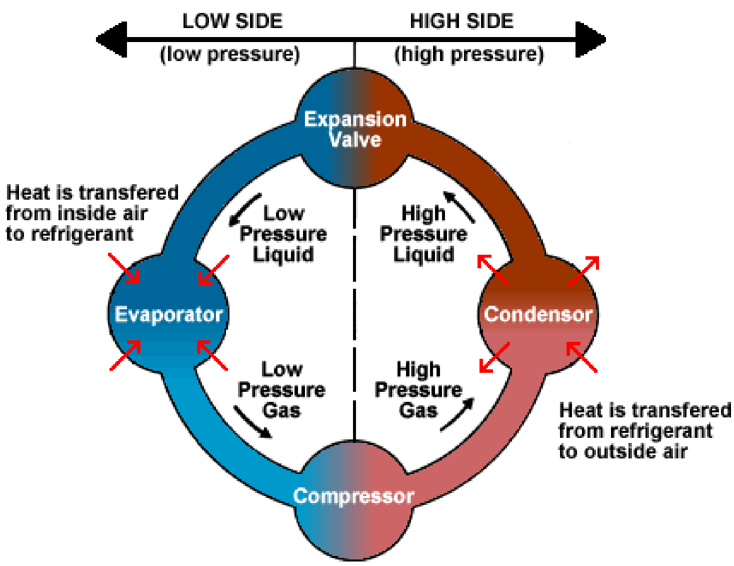


Figure 2.2: Refrigeration cycle (SWTC, n.d.).

2.6 Ventilation

In the research of Yu, He and Feng (2015), the ventilation in a room would affect the CO_2 concentration. There were 4 scenarios taken: door and window were all opened, opened door and closed window, opened window and closed door and both window and door were closed. From the result, we know that at the scenario of door and window were opened, the carbon dioxide concentration was still remain at low level when the people increased while when all the window and door closed, the concentration increase spontaneously even there were only 3 persons in the room, as shown in Table 2.5.

Table 2.5: Peak concentration of carbon dioxide at different scenarios (Yu, He and Feng, 2015).

Scenario	**Peak Indoor CO_2 Concentration (ppm)**
Door and window were all opened	480
Opened window and closed door	2580
Opened door and closed window	600
Window and door were all closed	30000

Besides, the ventilation rate (CFM) can be measured using many ways such as velocity measurement and carbon dioxide measurement. Carbon dioxide measurement is a more simple way to measure the ventilation rate and air quality. The recommended ventilation rate for a person is 20 cfm.

Table 2.6: Comparison of ventilation rate at different CO_2 concentration levels (Northern Arizona University, n.d.).

Concentration (ppm)	Approximate Ventilation Rate (cfm/ person)
380	
800	20
1,000	15
1,100	
1,400	10
2,400	5

2.7 Computational Fluid Dynamics (CFD)

CFD can analyse very complex scenario such as heat transfer, mixing of fluids, unsteady flow and compressible flows (Solidworks.com, 2015). It is a simulation using different methods to predict the fluid flows such as:

i. numerical methods (discretization and solution techniques)

ii. mathematical modeling (partial differential equations)

iii. software tools (solvers, pre- and postprocessing utilities).

2.7.1 Applications

In the research of Phonekeo, López-Jiménez and Guillamón (2016), it stated that the position of the room and door would also affect the ventilation and it could be solved using the CFD model simulation technique and also the energy saving. CFD could be used in many conditions such as pedestrian wind comfort and wind safety around buildings, air pollutant dispersion, wind-driven rain, convective heat transfer and natural ventilation of buildings and streets (Blocken, Janssen and van Hooff, 2012).

From the result of Teodosiu, Ilie and Teodosiu (2014), it showed that the k-ω model had the best average overall performance in comparison with the measurements. It means that the k-ω model has a better performance in simulating indoor airflow in ventilated spaces, but it is only limited for low Reynolds number models. Therefore, in this research, a k-ε model will be used, because the flow in this experiment are turbulence flow which is high Reynolds number.

Height of air conditioning can affect the ventilation performance and CO_2 distribution in an environment. Figure 2.3 showed that when the air conditioning system located at 0.8 m above the floor level, the ventilation performance were the best due to more effective in removing exhaled CO_2 (Ning et al., 2016). Therefore, in this research, the discharge angles of the air conditioning systems were one the manipulated variables.

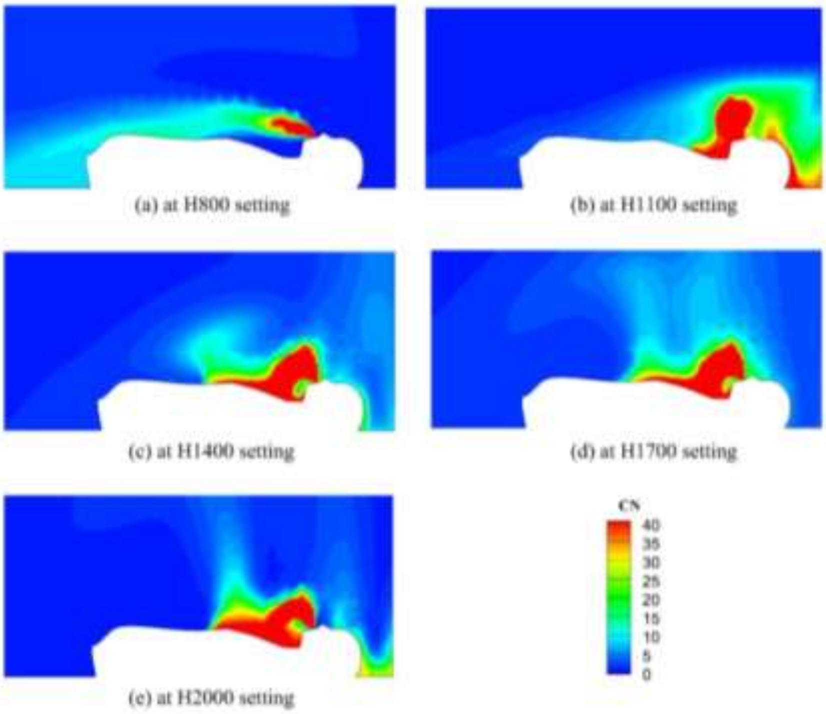


Figure 2.3: Distributions of CO_2 concentration at 5 scenarios (Ning et al., 2016).

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Background of Study Area

A lecture theatre of UTAR Sungai Long (KB block) had been selected as the study area to evaluate the air ventilation. UTAR Sungai Long is located at Kajang (3.0402° N, 101.7944° E) as shown in Figure 3.1. The KB block includes a multipurpose hall which can accommodate 1,000 peoples, 45 laboratories, 32 computer labs, 6 architectural studios, a gym and a student activity centre. Besides, the building is made by environmental-friendly materials such as heat-reflective glass windows, following the criteria of Green Building Index. During the last decade, it has been shown that the number of students in Universiti Tunku Abdul Rahman (UTAR) increase from only 411 students in to more than 26,000 students.

Figure 3.1: Location of Study Area.

The lecture theatre is located at second floor of KB Block (KB 208) as shown in Figure 3.2. The dimensions of this lecture theatre are 16.4 m (L) x 15.575 m (D) x 4.573 m (H). It has 2 doors (1.8 m width and 2.05m tall) and 6 4 way ceiling cassette (air conditioner) with 5 horsepower which located at the front row, 6^{th} row and last row. Besides, it can be occupied by 200 students, distributed roughly 18 people on 11 rows. Each row is 18 cm higher than the previous one.

Figure 3.2: Lecture theatre of KB208.

3.2 CFD Simulations

In this experiment, the discharge temperature from air conditioner, discharge angle (angle of air conditioner blade) and the number of the students were set as the manipulated variables. The discharge temperature was set as 16 ^{o}C, 24 ^{o}C and 27 ^{o}C while the discharge angle was set as 30^{o}, 45^{o} and 60^{o} with the velocity of 3 m/s as shown in Figure 3.3.

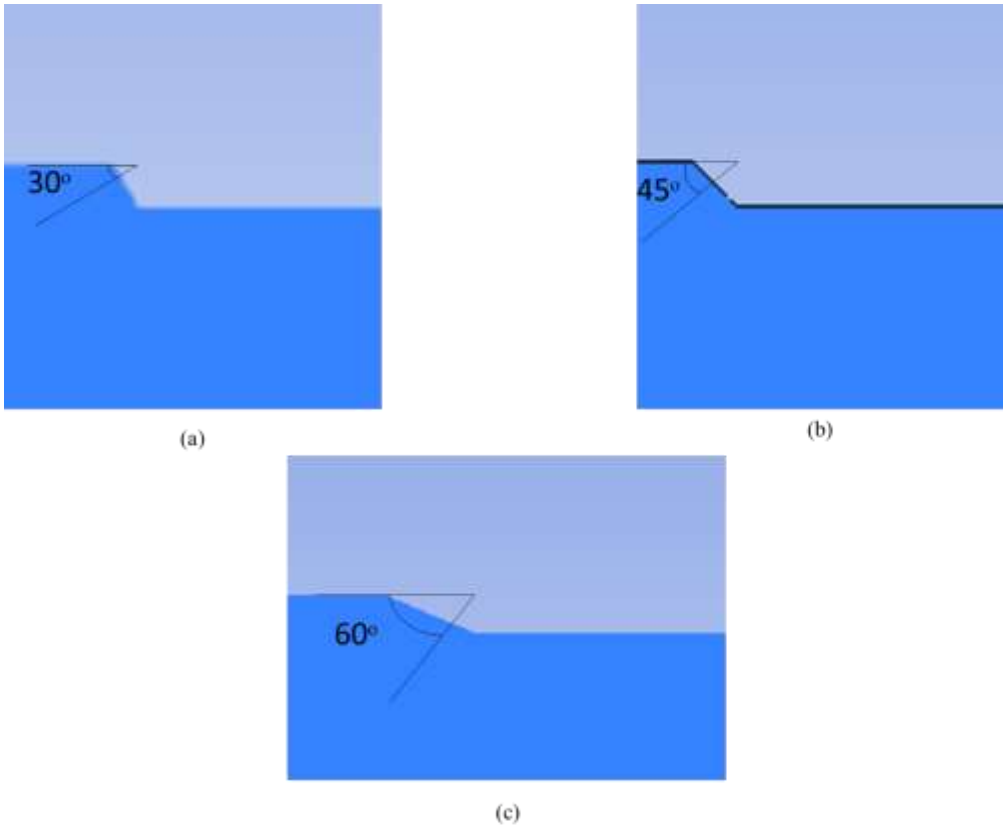
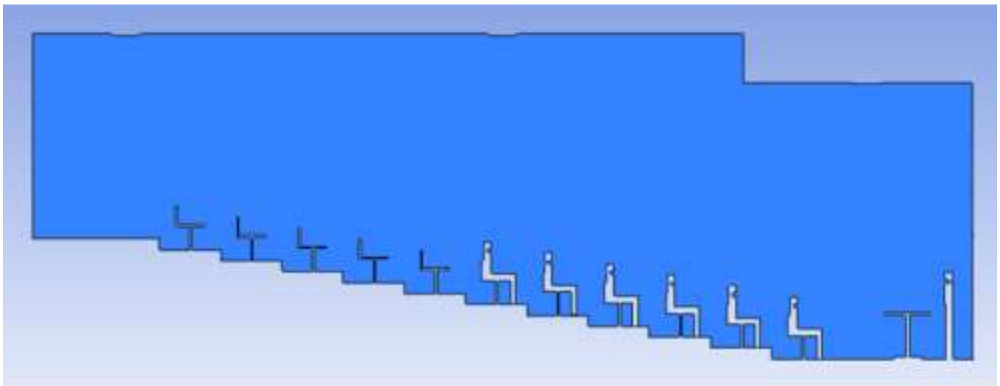


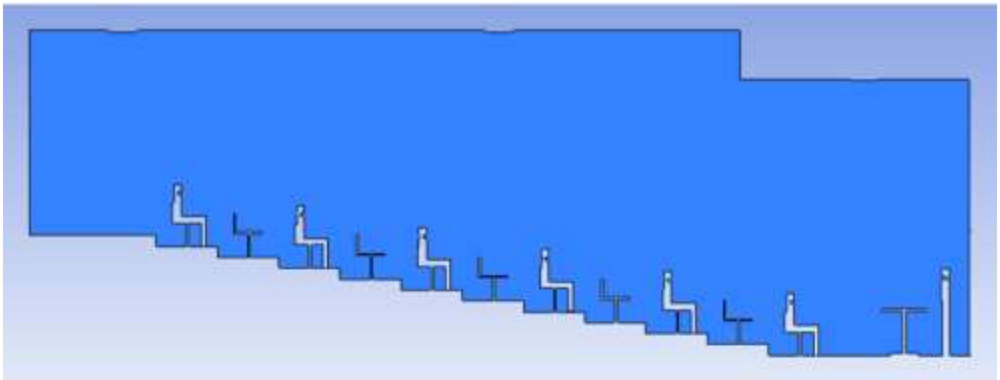
Figure 3.3: Discharge angle (a) 30°, (b) 45° and (c) 60°.

Besides, the numbers and position of students were set as half, random and full as shown in Figure 3.4:

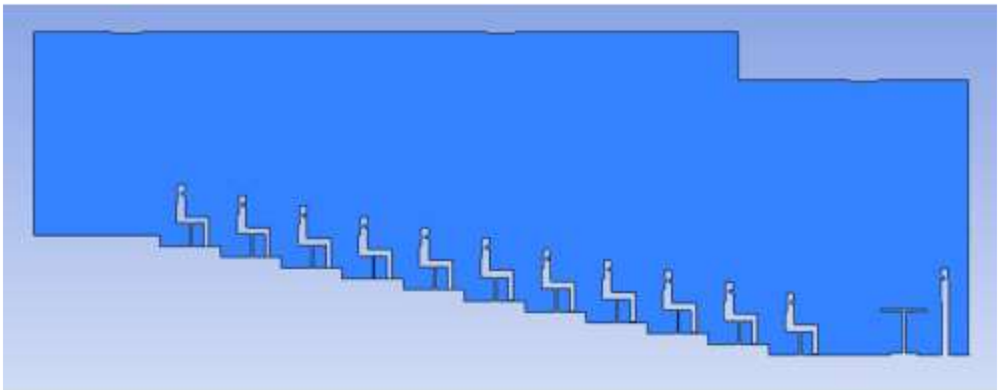
i. Half: half of the students in lecture theatre sit at the front rows.
ii. Random: half of the students in lecture theatre sit randomly.
iii. Full: the lecture theatre was full of students.



Half



Random



Full

Figure 3.4: Number and position of students.

3.2.1 Geometry Model

The geometry model was established according to the lecture theatre as shown in Figure 3.4. Then the ventilation performance such as CO_2 distributions, temperature distribution and air velocity were simulated by using the CFD simulation software (ANSYS Fluent version 19.0).

3.2.2 Mesh Generation

The model was meshed or grid into small size elements. The surface was meshed into 0.5 cm while the rest of domain will be into 2 cm, as shown in Figure 3.5.

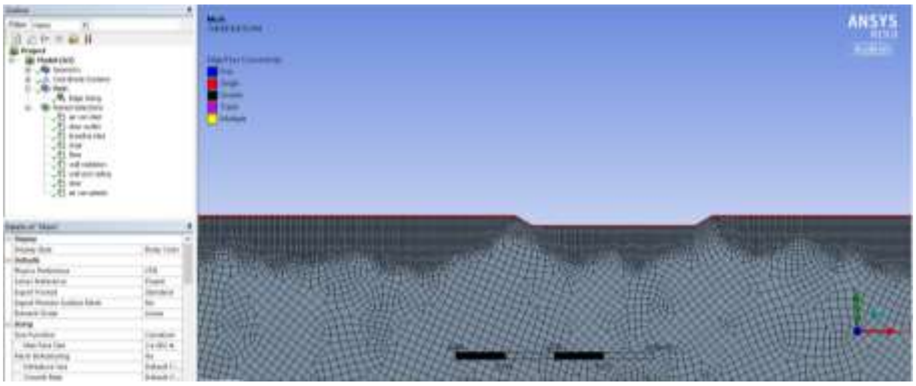


Figure 3.5: Meshing occurred at the air conditioner outlet.

3.2.3 CFD Model

In the simulation, a RNG k-ε turbulence model was used to predict the air flow, temperature and concentration as shown in Figure 3.6. A few equations were used (Ning et al., 2016):

Continuity equation:

$$\frac{\partial p}{\partial t} + \nabla.(\rho\,\vec{v}) = 0 \qquad (Eq\ 1)$$

where

t = time (s)

$\vec{v}$ = air velocity at measurement position (m/s)

ρ = air density (kg/m3)

Momentum equation:

$$\frac{\partial}{\partial t}(\rho\,\vec{v}) + \nabla.(\rho\,\vec{v}\vec{v}) = -\nabla P + \nabla.(\bar{\bar{\tau}}) + \rho\vec{g} \qquad (Eq\ 2)$$

where

P = static pressure (Pa)

$\bar{\bar{\tau}}$ = stress tensor (Pa)

$\rho\vec{g}$ = gravitational body force

Energy equation:

$$\frac{\partial}{\partial t}(\rho E) + \nabla.\left(\vec{v}(\rho E + p)\right) = \nabla\left(\rho k_{eff}\nabla T - h + \left(\overline{\overline{\tau_{eff}}}.\vec{v}\right)\right) \qquad (Eq3)$$

$$E = h - \frac{p}{\rho} + \frac{v^2}{c} \qquad (Eq\ 4)$$

where

E = total energy (J)

h = enthalpy (J)

k_{eff} = effective conductivity (W/m k)

T = air temperature (K)

$\overline{\overline{\tau_{eff}}}$ = deviatoric stress tensor (Pa)

Navier-Stokes equation:

$$div(\rho V\Phi - \Gamma_{eff} grad\Phi) = S_{\Phi} \qquad (Eq\ 5)$$

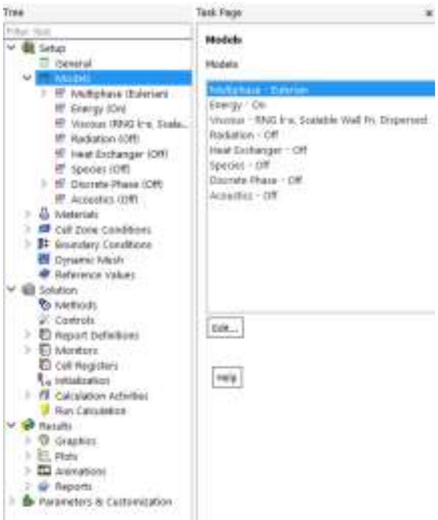


Figure 3.6: Models selected.

3.2.4 Boundary Conditions

The exhaled air was 34 °C and the human body was 24 °C (Bulińska, Popiołek and Buliński, 2014). Others parameters were summarized in Table 3.1.

Table 3.1: Summary of parameters.

Boundary condition	Value
Operating temperature	24 °C
Operating pressure	1 atm
Discharge speed from air conditioner	3 m/s
Exhalation speed	1.4 m/s
Volume fraction of CO_2 from exhalation	0.04
Volume fraction of CO_2 in lecture theatre	0.0004
Wall thickness	0.2 m
Skin thickness	0.001 m
Heat transfer of wall	12 W/m^2K
Heat transfer of human	2.5 W/m^2K
Outdoor temperature	34 °C

3.2.5 Solution

The duration of time was set as 2 hours and the value was recorded in every 30 minutes. The calculation were run until convergence was reached.

3.3 Methodology Procedures

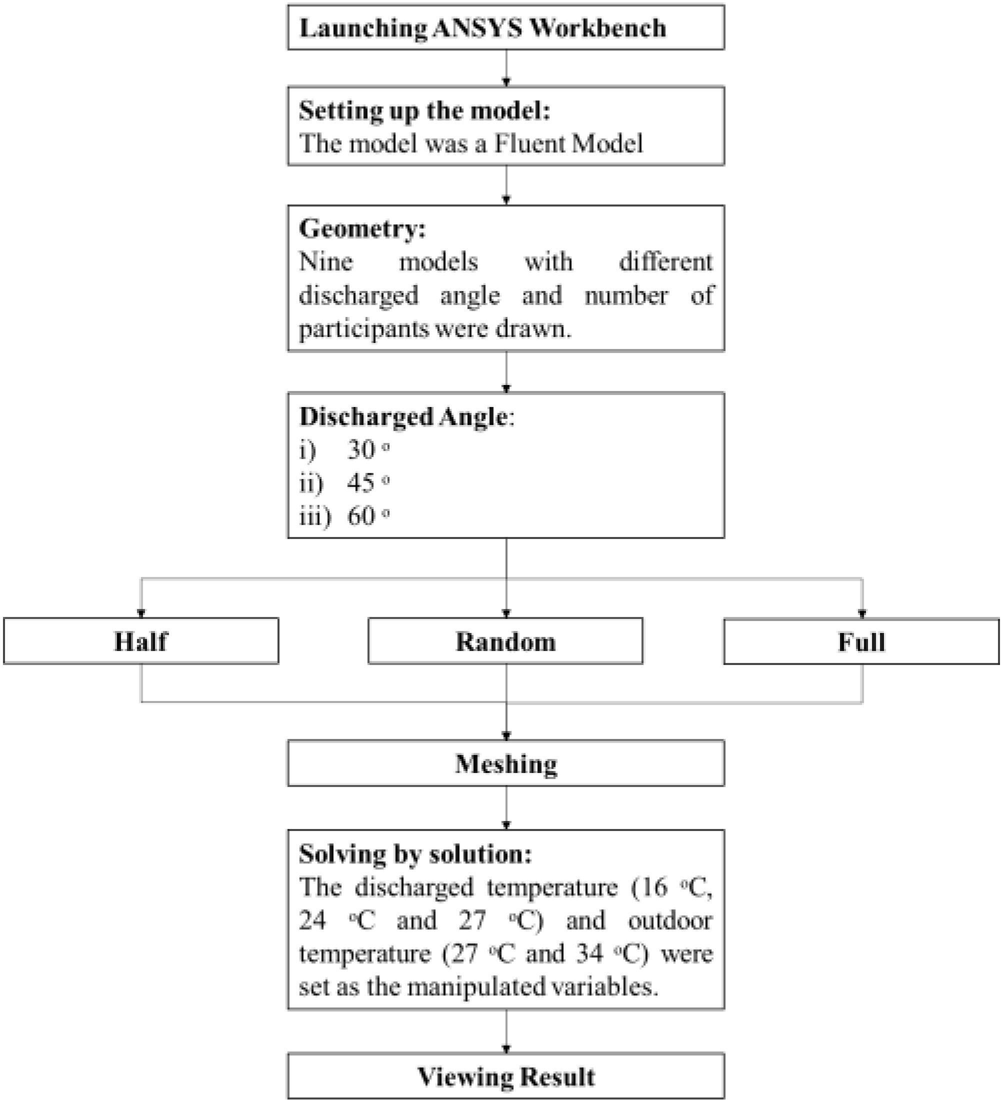


Figure 3.7: Simulation methodology.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Discharge Angle

The air movement in the lecture theatre can be affected by the discharge angle of air conditioner. The required air speed set by DOSH 0.15-0.50 m/s. Table 4.1 shows the air speed at different discharged angle. All the average air speeds from the simulation were under the requirement.

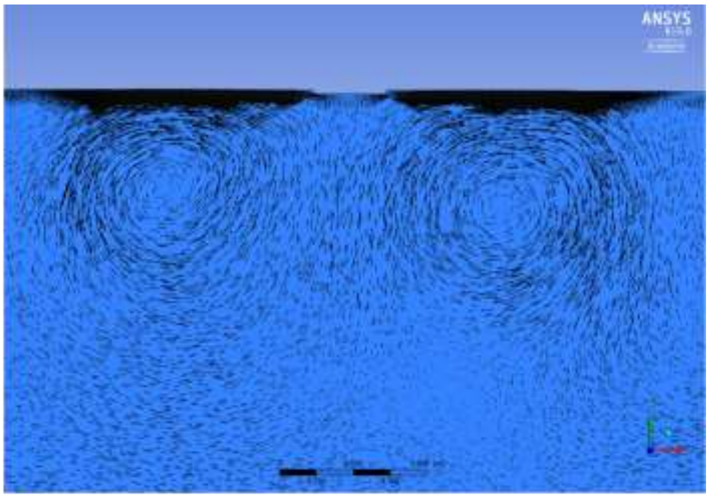
Table 4.1: Average air speed in lecture theatre with different discharge angle**.**

Discharged angle	Position of Students	Air Speed (m/s)
30^{o}	Half	0.255465
	Random	0.271581
	Full	0.276810
45^{o}	Half	0.225246
	Random	0.233763
	Full	0.222157
60^{o}	Half	0.217295
	Random	0.231251
	Full	0.256327

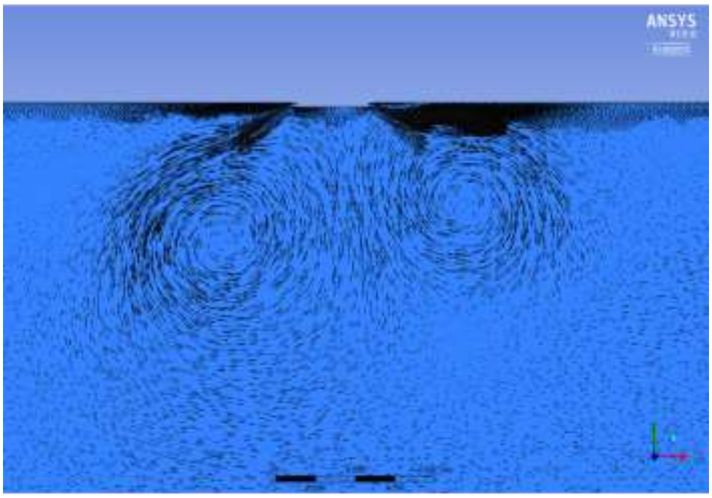
4.1.1 Air Flow Pattern

Figure 4.1 shows the air flow pattern at the air conditioner outlet located above the 6th row with different discharge angle. Primary vortex was formed at the outlet of air conditioner due to the velocity emitted from air conditioner. A speed of 3 m/s is sufficient to induce a primary vortex and corner vortices (Park et al., 2012).

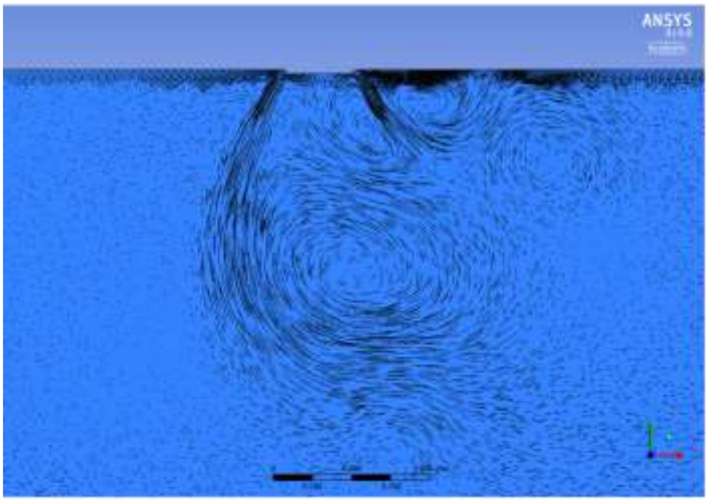
As can see from Figure 4.1, the air emitted from 30^{o} discharge angle accumulated more at the ceiling compared to others. Besides, the pattern of vortex from 60^{o} discharge angle was slightly partial to the direction of door due to the influence by the air flow that emitted from the air conditioner (located at the last row).



(a)



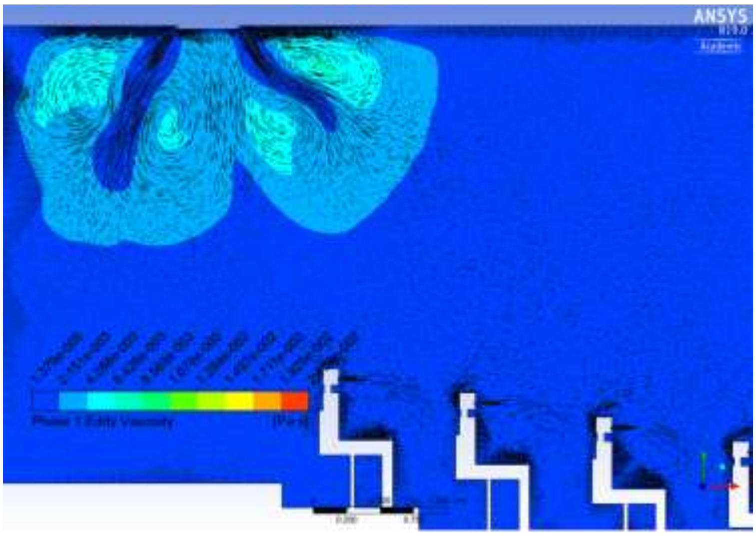
(b)



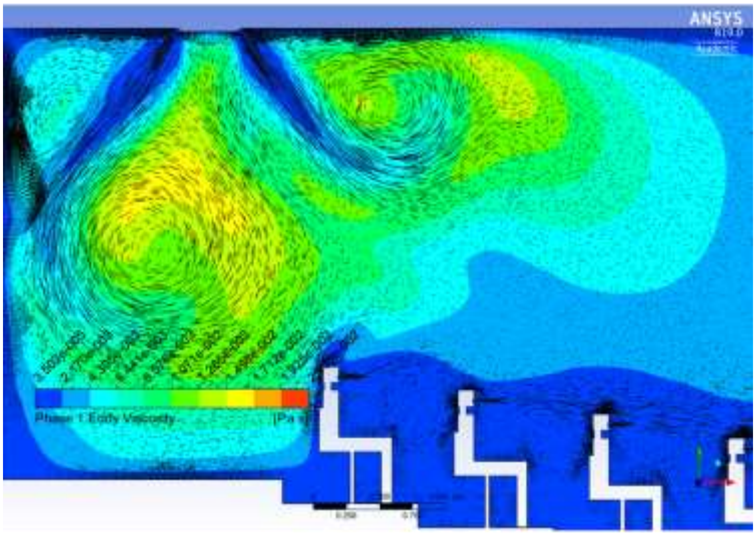
(c)

Figure 4.1: Air flow pattern at the air conditioner inlet located above the 6th row - (a) 30^{o}, (b) 60^{o} and (c) 45^{o}

Furthermore, when there is a difference in temperature, the primary vortex will expand toward the hotter fluid, the turbulence structure will be changed and turbulence eddies will be generated due to the shear instability as shown in Figure 4.2.



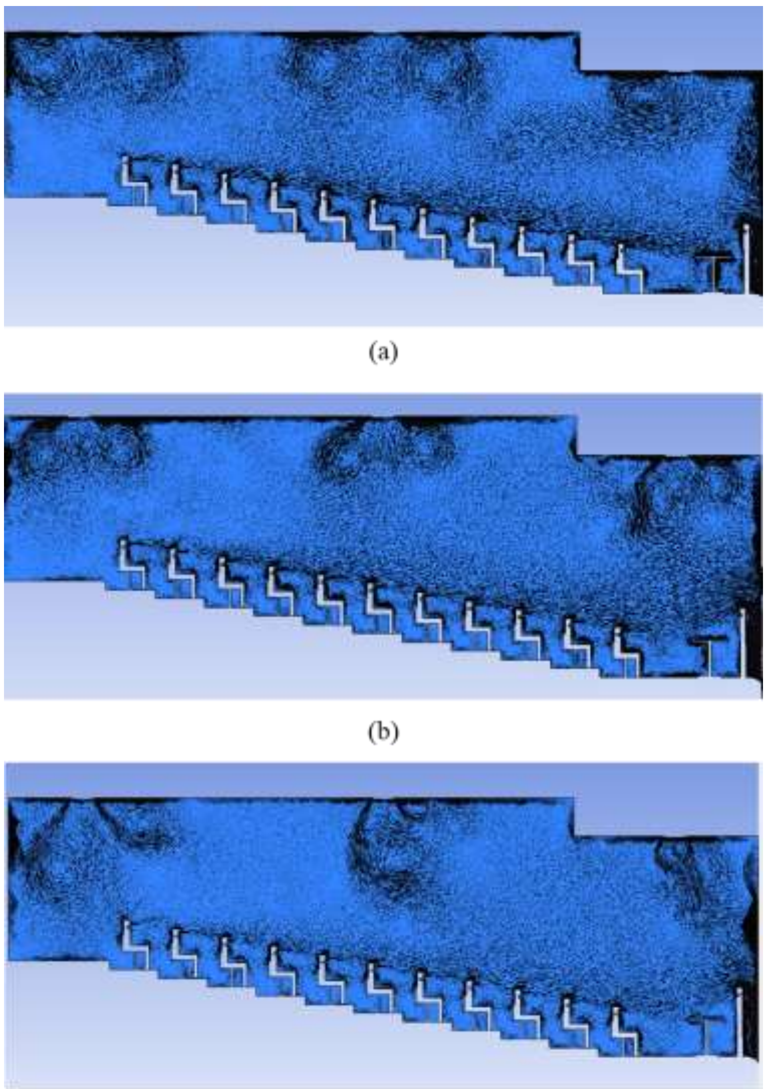
30 min



2 hours

Figure 4.2: Formation of turbulence eddies at outlet of air conditioner which located at the last row.

Although the air speeds were under the requirement stated in Section 4.1, the air flow of discharge angle of 45^{o} was steadier compared to discharge angle of 30^{o} and 60^{o} as shown in Figure 4.3. However, the maximum value of velocity of these three scenarios were far away from the occupants, so it did not affect much on the occupants. It means that the occupants still under the comfort zone.



(a)

(b)

(c)

Figure 4.3: Vector plot for discharged angle of (a) 30^{o}, (b) 45^{o} and (c) 60^{o} in lecture theatre with a discharge temperature of 16 ^{o}C.

From Figure 4.4, the temperature at the last row was much cooler compared to others row and the temperature at the first row was the hottest. It is because the discharged air will accumulate at the ceiling once emitted from the air conditioner. Then, the air will flow toward the ground due to the density difference, cold air is denser than hot air. The cold air will contact with the occupants at the last row first and the occupants at the first row was the person that last contact with the cold air.

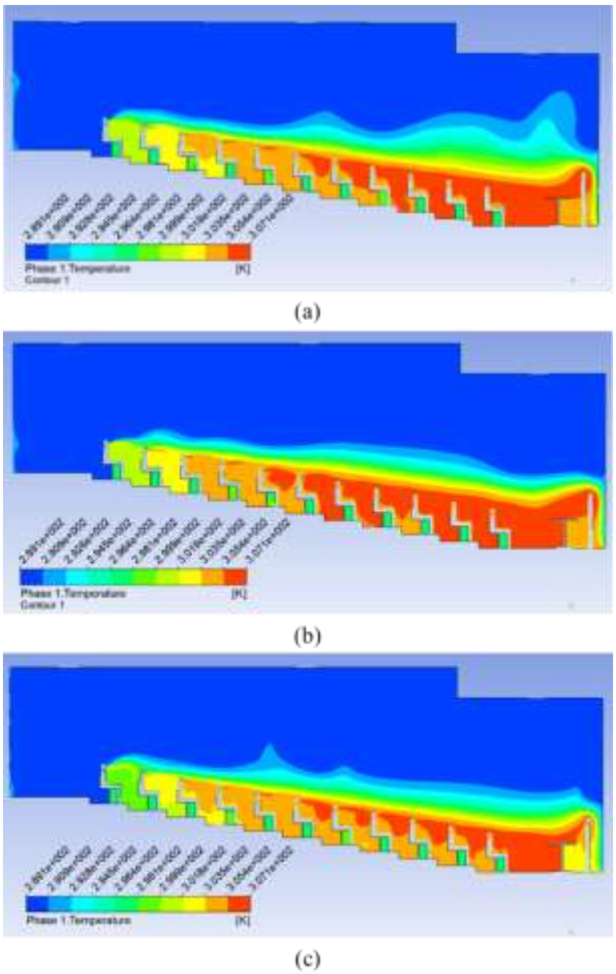


Figure 4.4: Temperature of theatre at different discharge angle (a) 30^{o} (b) 45^{o} and (c) 60^{o} with the fixed discharge temperature of 16 ^{o}C.

Besides, the region below the chairs has very small velocity magnitude and 'dead zone' is formed, as can be seen in Figure 4.5.

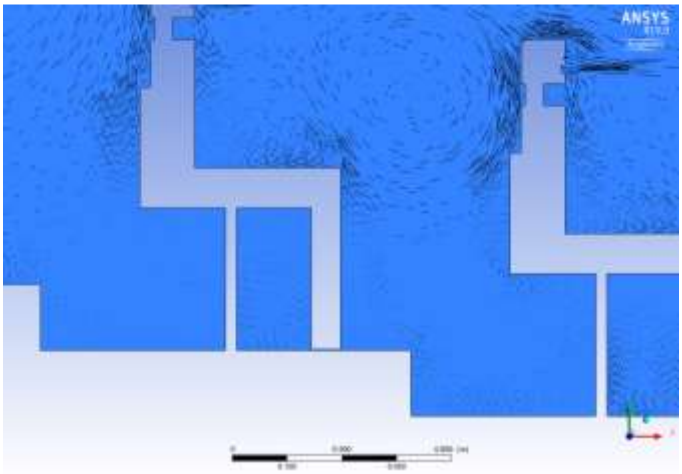


Figure 4.5: Dead zone under the chairs.

4.2 Discharge Temperature

With the outside temperature of 34 ^{o}C, the average temperature inside the lecture theatre was much higher than the discharge temperature of air conditioner as shown in Table 4.2. It is because the different value of temperature in the air (temperature from the air conditioner, exhalation, radiation, convection and temperature of corridor) will interact and come to equilibrium according to the second law of thermodynamics (Heaton, 2017). Therefore, the heat energy outside will flow naturally into the lecture theatre.

Besides, the lecture theatre with full of students has the highest average temperature compared to others. Discharge temperature of 16 ^{o}C is needed in this scenario according to the requirement of DOSH, which the acceptable range of indoor temperature is 23 °C - 26 °C. For the lecture theatre with fewer occupants, a higher discharge temperature is needed, otherwise the average temperature will under the requirement. Discharge temperature within 16 to 24 °C is recommended if there are fewer occupants in the theatre. Additionally, the discharge angle of 60° is the most efficient in decreasing the average temperature of lecture theatre at all scenarios.

Lastly, the discharge temperature of 27 °C is not recommended for all the scenarios because the average temperature in lecture theatre will exceed the acceptable range.

Table 4.2: Temperature of lecture theatre affected by the discharge temperature and number of occupants.

Discharge angle	Position of students	Discharge Temperature (°C)		
		16	24	27
30°	Half	20.22	26.01	28.18
	Random	21.52	26.60	28.58
	Full	23.57	27.71	29.26
45°	Half	19.96	25.90	28.12
	Random	21.84	26.82	28.65
	Full	23.02	27.55	29.16
60°	Half	20.08	25.94	28.14
	Random	21.95	26.95	28.89
	Full	22.50	27.41	29.12

4.3 Radiation

In this situation, the discharge temperature from the air conditioner is fixed at 16 ^{o}C and the temperature in lecture theatre is examined by decreasing the outside temperature from 34 to 27 ^{o}C. As shown in Table 4.3, the temperature inside theatre was decreased. However, there is no much difference at the temperature even the outside temperature is changed.

It can be explained by the fixed corridor temperature (24 ^{o}C). In real life, there will be a difference in the theatre temperature when the outdoor temperature deceases. It is because more heat can be absorbed by the refrigerant when the outside temperature is low (refer to Section 2.5). Thus, the temperature of corridor and lecture theatre will decrease and a higher discharge temperature is needed to reach the thermal comfort.

Table 4.3: Temperature in lecture theatre affected by the outside temperature.

Discharge angle	Seat of students	Outdoor temperature	
		34 ^{o}C	27 ^{o}C
30^{o}	Half	20.22	20.17
	Random	21.52	21.28
	Full	23.57	23.54
45^{o}	Half	19.96	19.93
	Random	21.84	21.80
	Full	23.24	23.02
60^{o}	Half	20.08	20.07
	Random	21.95	21.80
	Full	23.01	22.99

4.4 Number of Participants

The number of participants will affect the concentration of indoor CO_2 and temperature in lecture theatre as when the number of participants increase, the concentration of indoor CO_2 and temperature will also increase.

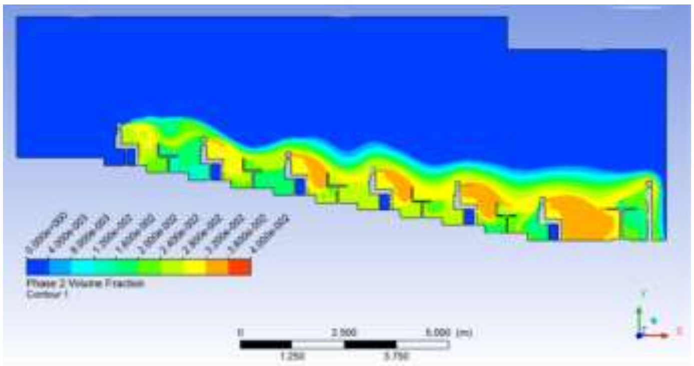
4.4.1 Concentration of Carbon Dioxide

Table 4.4 shows the average concentration of carbon dioxide increase when the number of students increase. The concentration of carbon dioxide under these 3 scenarios are under the acceptable range which is below 1,000 ppm. There are some leakage of carbon dioxide from the lecture theatre to the corridor through the 1 cm door gap. As can see in Table 4.4, the lecture theatre with full of students has a concentration of carbon dioxide approximately 2 times higher than the theatre with half of students seat at the front row.

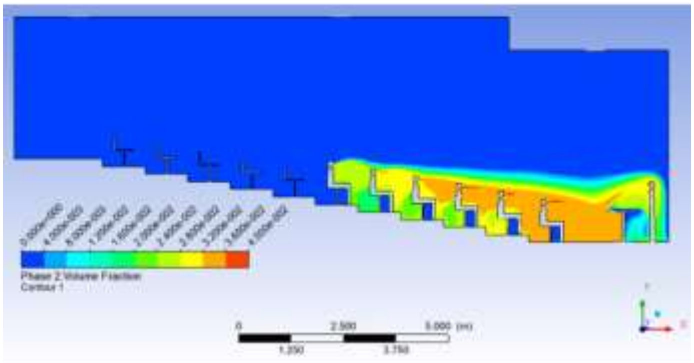
However, the lecture theatre with random seating of students has a 140.91 ppm concentration of carbon dioxide higher than theatre with half of students seating at the front rows, although the number of students were the same. It can be explained from Figure 4.6, there are no accumulation of carbon dioxide at the last few row when half of the students seated at the front rows but all the carbon dioxide will accumulate in front of the theatre. For the randomly seated scenario, some of the carbon dioxide will be trapped at dead end zone which under the chair as stated in Section 4.1.1 due to the higher density of carbon dioxide compared to air.

Table 4.4: Average concentration of carbon dioxide affected by the number of students.

Position of students	Average Concentration of Carbon Dioxide in 2 hours (ppm)
Half	439.49
Random	580.40
Full	868.77



Random



Half

Figure 4.6: Distribution of carbon dioxide at different position of students at the discharge temperature of 16 °C.

4.4.2 Temperature

The number of participants affected the temperature of lecture theatre as shown in Table 4.2. It is because the human body will emit heat to the environment from skin and respiration as stated in Section 2.4. From Figure 4.7, it shows that the temperature around the human body is the highest compared to others part of the lecture theatre.

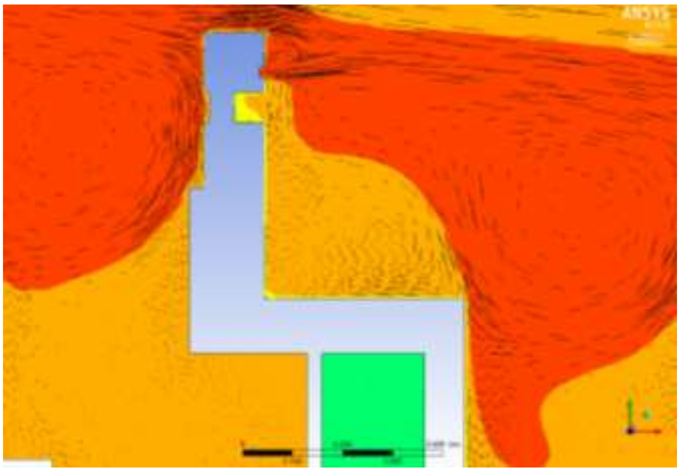


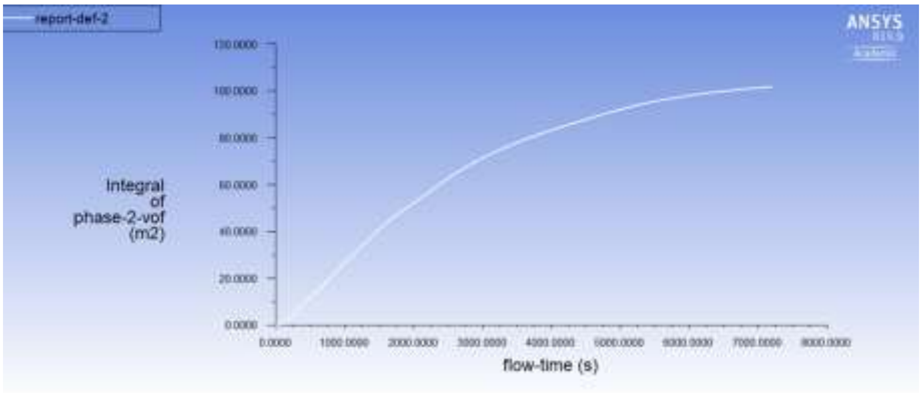
Figure 4.7: Temperature around human body.

4.5 Scenario of Door

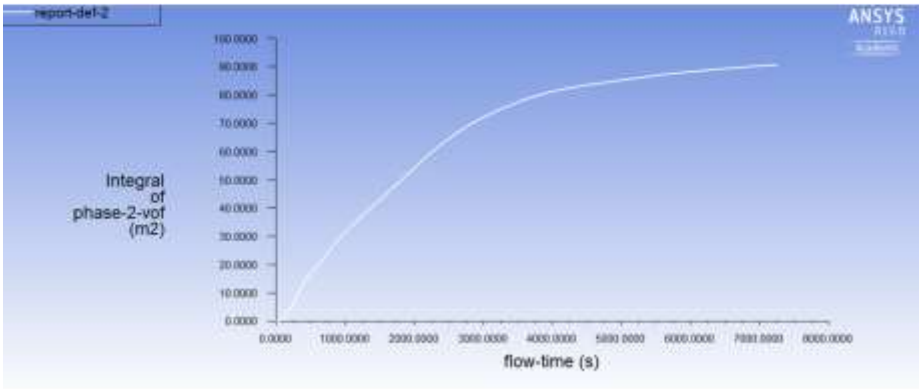
There were 2 scenarios taken in this section: door is opened and door is closed, the number of students are fixed as “Full”, the temperature is set as 16 ^{o}C and the duration time was 2 hours. From Table 4.5, the concentration of carbon dioxide with opened door has lower ppm compare to closed door. Although there is no much difference in the concentration which is only 6.425 % difference, the concentration of CO_2 in the scenario of closed door was keep increasing as shown in Figure 4.8, while the concentration of CO_2 in the scenario of closed door is almost reached steady state at approximately 90 min. Therefore, the difference in the concentration of CO_2 will increase along with the time.

Table 4.5: Average value of temperature and carbon dioxide at scenario of door opened and closed.

Parameter	Scenario		Percentage Difference (%)
	Opened	Closed	
Temperature (^{o}C)	24.26	23.03	0.994
Concentration of CO_2 (ppm)	814.69	868.77	6.425



Door closed



Door opened

Figure 4.8: Average volume integral of carbon dioxide versus time at discharge angle of 30^{o}.

Figure 4.9 shows the distribution of carbon dioxide along the time with discharge angle of 30^{o} and discharge temperature of 16 ^{o}C. The carbon dioxide will accumulate at in front of the students first then only flow to the door.

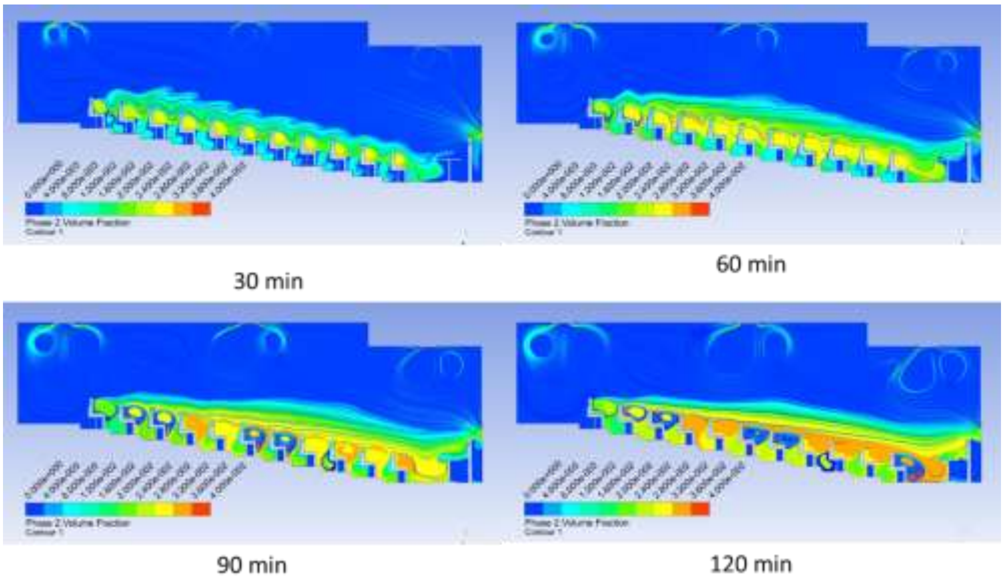


Figure 4.9: Distribution of carbon dioxide along time with 30 ° discharge angle.

Opening the door during the lecture is the easiest way to reduce the concentration of CO_2, but it will increase the temperature inside the lecture theatre as shown in Table 4.5. Therefore, a few suggestions will be discussed in Section 4.6 to improve the ventilation of theatre.

4.6 Ventilation

Ventilation is a very important engineering controls in improving the indoor air quality. Therefore, it is necessary to provide a sufficient fresh air for the occupants.

4.6.1 Side Effect of Poor Ventilation

The study of Vilčeková et al. (2017) stated that environmental factors such as temperature, quality of indoor air, aural and visual environments would affect the acceptability, productivity and work performance of human. Besides, contaminated environment can cause health problems such as worsen acute respiratory infections, allergies and trigger asthma attacks, headaches, fatigue, shortness of breath, coughing, sneezing, eye and nose irritation and dizziness (Kalimeri et al., 2016). Therefore, the ventilation of indoor is very important to enhance the indoor air quality.

4.6.2 Ways to Improve Ventilation

There are several ways to improve the ventilation of lecture theatre such as HVAC system, exhaust fan, mixing ventilation system and displacement ventilation system:

i. Heating, Ventilation and Air-Conditioning (HVAC)

   It is a system that bring the fresh air from outside into the indoor and release the air from indoor to outdoor through filter and ducts as shown in Figure 4.10. According to Matela (2006), the filter inside a HVAC system can reduce the percentage of carbon dioxide at the range of 4 % to 9 %.

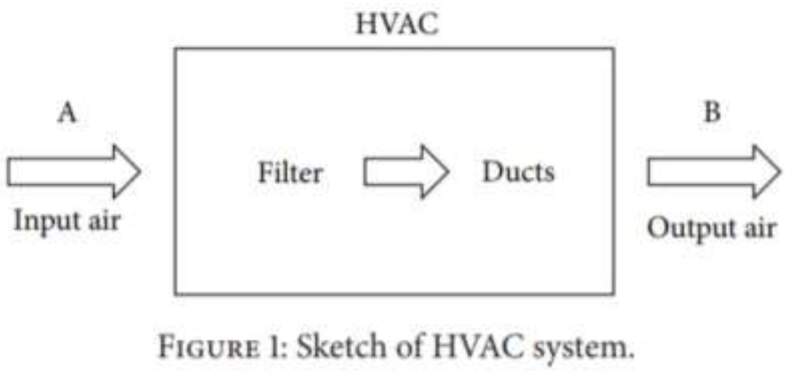


Figure 4.10: Sketch of HVAC system (Basile et al., 2016).

ii. Exhaust Fan

Exhaust fan will exhaust the indoor air to the outdoor environment. According to Gao, Wargocki and Wang (2014), the installation of an exhaust fan could achieved a ventilation rate of 5.6 L/s per person compared to the classroom with non-exhaust fan (ventilation rate of 4.3 L/s per person). The exhaust fan have a significant performance in reducing the indoor contaminants concentration (12% to 53 %) without affecting the indoor air exchanging rate (Mallach et al., 2016).

iii. Mixing Ventilation System

The function of this system is to bring in the fresh outdoor air and mix with the contaminated indoor air. The purpose of this system is to dilute the concentration of contaminant. It mostly located at the ceiling and side wall (Cao et al., 2014).

iv. Displacement Ventilation System

In the displacement ventilation, there will have an inlet which is ocated near the floor and an outlet near the ceiling. This will create a vertical gradients of air velocity, temperature and contaminant concentration (Cao et al., 2014). Thus increasing the ventilation rate. In the research of Norbäck et al. (2011), the displacement ventilation system had a better performance in reducing the concnetration of indoor carbon dioxide compared to mixing ventilation system. The result showed that the concentration of carbon dioxide for displacement ventilation system were 655 and 867 ppm for mixing ventilation system.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

From this report, it shows that all the indoor environmental quality parameters of lecture theatre were within the acceptable range set by DOSH. The average air speeds at different scenarios were under the acceptable range. Besides, concentration of carbon dioxide will increase when the number of participants increase. When the door is opened, the concentration of carbon dioxide will decrease. The temperature in lecture theatre increased with the number of participants and outdoor temperature.

The recommended discharged angle from the air conditioner is 60^{o} with 16 ^{o}C when the lecture theatre is full of occupants and 16 ^{o}C to 24 ^{o}C when the number of occupants decreases.

5.2 Recommendations

As this project is all about the simulation, the result may different with the actual experimental result due to the different in the human being and changes on the environment. Therefore, an experiment is suggested to be conducted to verify this numerical simulation. Lastly, a 3D simulation is recommended to have a more accurate result.

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