NUMERICAL ANALYSIS OF THE DUCTED VENTILATION AND JET FANS SYSTEMS IN AN ENCLOSED CAR PARK

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NUMERICAL ANALYSIS OF THE DUCTED VENTILATION AND JET FANS SYSTEMS IN AN ENCLOSED CAR PARK

By

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DEDICATION

This project is specially dedicated to my beloved grandmother, parents, family members, supervisor, and friends for their unconditional supports throughout my master’s degree studies.

ABSTRACT

NUMERICAL ANALYSIS OF THE DUCTED VENTILATION AND JET FANS SYSTEMS IN AN ENCLOSED CAR PARK

TNEH XUAN

In recent years, the ductless impulse jet fans ventilation system has been increasingly preferred over the traditional ducted ventilation system for car park ventilation applications. Aside from ventilation, the jet fans system offers several additional advantages such as low design complexity, cost-saving, space-saving, and low maintenance which make it to supersede the ducted system. Despite all the advantages, ventilation performance remains the primary concern for every car park ventilation system. The complex geometry of car parks can contribute to a highly unpredictable airflow behaviour when jet fans are used. Therefore, an experimental approach like CFD modelling is required for an accurate evaluation of the ventilation performance. In this project, an impulse jet fans system was designed in strict accordance with the authorities' requirements for the existing block KB basement car park at UTAR Sungai Long campus. A detailed CFD modelling was carried out to compare the ventilation performance between the existing ducted ventilation system and the jet fans system in the enclosed car park during a fire. The results have shown that the ducted ventilation system can provide a better ventilation during a fire. Although the jet fans system is not as efficient as the ducted model, it managed to fulfil most of the ventilation criteria required by the local authorities.

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APPROVAL SHEET

This thesis entitled **"Numerical Analysis of the Ducted Ventilation System and Jet Fans Systems in an Enclosed Car Park"** was prepared by **TNEH XUAN** 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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SUBMISSION SHEET

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Date: 13^{TH} APRIL 2023

SUBMISSION OF FINAL YEAR PROJECT

It is hereby certified that ***TNEH XUAN*** (ID No: ***22UEM02577***) has completed this final year project entitled **"Numerical Analysis of the Ducted Ventilation System and Jet Fans Systems in an Enclosed Car Park"** under the supervision of ***Ir. Ts. Dr. BERNARD SAW LIP HUAT*** (Supervisor) from the Department of ***Mechanical and Materials Engineering***, ***Lee Kong Chian Faculty of Engineering and Science.***

I understand that University will upload softcopy of my final year project in pdf format into UTAR Institutional Repository, which may be made accessible to UTAR community and public.

Yours truly,

(*TNEH XUAN*)

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UTAR or other institutions.

Name: TNEH XUAN

Date: 13TH APRIL 2023

TABLE OF CONTENTS

CHAPTERS

APPENDICES

LIST OF TABLES

LIST OF FIGURES

Figures **Page**

LIST OF ABBREVIATIONS

ACH	Air changes per hour
AS	Australian Standards
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
BOMBA	Fire and Rescue Department of Malaysia
BRE	Building Research Establishment
BS	British Standards
CAD	Computer-aided drawing
CFD	Computational fluid dynamics
CFM	Cubic feet per minute
CMH	Cubic metre per hour
CO	Carbon monoxide
CO_2	Carbon dioxide
EAG	Exhaust air grille
EV	Electric vehicle
FAG	Fresh air grille
FDS	Fire dynamics simulator
HC	Hydrocarbon
HCI	Hydrogen chloride
HCN	Hydrogen cyanide
HF	Hydrogen fluoride
HRR	Heat release rate
HSE	Health and Safety Executives
ICE	Internal combustion engine
ICEV	Internal combustion engine vehicle
JF	Jet fan
LPG	Liquefied petroleum gas
NFPA	National Fire Protection Association
NIST	National Institute
NO	Nitrogen oxide
NO_2	Nitrogen dioxide

PPM	Parts per million
SCDF	Singapore Civil Defence Force
SFPE	Society of Fire Protection Engineers
SST	Shear stress transport
UBBL	Uniform Building By-Law
UTAR	Universiti Tunku Abdul Rahman

CHAPTER 1

INTRODUCTION

1.1 Background

The increasing number of automotive vehicles is a common issue in many urban cities of developing countries around the world, this has in turn resulted in an excessively high demand for car park space in the city. However, due to the land scarcity in most urban cities, car parks are being built vertically underground and usually consist of multiple levels to maximize the total parking space available. Underground car parks are regarded as enclosed space which have very limited permanent opening to the outdoor environment that eventually gives rise to poor air ventilation within the enclosure. Thus, mechanical ventilation system is essentially important to provide adequate ventilation in these enclosed spaces. Exhaust emissions like carbon monoxide (CO) and nitrogen oxide (NO) from the motor vehicles are extremely harmful to human health where having subjected to a high concentration of these pollutants in such enclosures with poor ventilation will cause significant damage to human health (Demir, 2015).

The absence of adequate ventilation in the enclosed car park can increase the difficulty for efficient evacuation and fire service intervention during a fire event due to the presence of untenable conditions like high smoke density, low visibility, and high temperature. Therefore, the local authorities have mandated the requirement for the installation of mechanical ventilation systems in such building spaces to ensure that adequate ventilation can be provided during both day-to-day and fire-mode operations. Mechanical ventilation system in car park can be classified into ducted and ductless systems. The ducted ventilation system is the conventional method that relies on extensive ductwork for the supply of fresh air and extraction of smoke. Recently, the ductless impulse jet fans ventilation system has been claimed to be more advantageous and efficient than the traditional ducted system in many aspects, including low maintenance, space-saving, and a good level of air circulation throughout the car park space (Gomaa et al., 2015).

There are two different methods that can be used to validate the ventilation performance, namely the traditional experimental approach and the CFD modelling technique. However, the heat and mass transfer of combustion products can be very volatile and exhibit unpredictable characteristics that are extremely difficult to be analysed using the traditional experimental approach. To solve this, the application of CFD modelling could help to deliver a better and more accurate prediction of fire development by solving the fundamental equations to describe the fluid flow characteristics and heat transfer associated with the development of fire.

1.2 Problem statement

Mechanical ventilation system in an enclosed car park plays a very important part in delivering good air quality during day-to-day operation and providing tenable conditions for the evacuees and firefighters during a fire. Traditionally, the mechanical ventilation system in the car park is supported by a bulky network of ducting for smoke and heat extraction as well as the supply of replacement air. However, this method has been claimed to pose several disadvantages, for instance, complex duct sizing, expensive duct fabrication, high static pressure losses in the ductwork, high ceiling clearance requirement, high maintenance requirement, and high construction cost. In recent years, the jet fans ventilation system which has been long used for longitudinal ventilation in many tunnel applications has gained popularity among fire safety designers to be adopted for car park ventilation, mainly because of its lower construction cost and aesthetic reason. However, there are not many comparative studies being done on the ventilation performance between the two systems that run on completely different ventilation approaches. The selection of a suitable ventilation system for the car park should not be based solely on cost and aesthetic reasons. Instead, the ventilation performance in the car park is always the primary consideration that must be carefully thought out by the designers as it involves the safety of evacuees and firefighters during a fire as well as the health of occupants during day-to-day operation. With the increasing usage of jet fans system for car park ventilation, a detailed experimental-based analysis must be carried out to support and validate the ventilation performance of this modern technique which employs an unconventional ventilation method that involves open mixing of combustion products in the car park.

1.3 Objectives

This project aims to develop a better understanding on the ventilation performance between the conventional ducted ventilation system and ductless impulse jet fans ventilation system for car park applications. The three core objectives of this project are as listed below:

1. To construct 3D CAD models of a single-storey enclosed car park.
2. To design an impulse jet-fan ventilation system for a single-storey enclosed car park.
3. To analyse the ventilation performance between the ducted ventilation system and jet fans ventilation system in an enclosed car park in the event of fire using computational fluid dynamics (CFD) technique.

1.4 Scope of studies

This project will mainly focus on the comparative analysis of the ventilation performance between the traditional ducted ventilation system and the modern ductless impulse jet fans ventilation system using CFD modelling approach. The ventilation system in the car park is generally designed to provide adequate ventilation during both day-to-day operation as well as fire mode operation. In this project, the ventilation performance will be evaluated based on a vehicle fire scenario where a virtual fire will be simulated in both ventilation system models using the CFD modelling. The key parameters that will be evaluated include temperature distribution, concentration of combustion products, and smoke and airflow behaviour. These few parameters are extremely important for the evaluation of the adequacy and performance of the ventilation system during a fire in the car park and are also the key criteria that will be thoughtfully evaluated by the local authorities during their inspection activities. The ventilation performance during the normal day-to-day operation will not be studied in this project.

1.5 Justification of studies

In recent years, the increasing usage of jet fans in car park ventilation has gradually replaced the traditional ducted ventilation system mainly due to cost-saving and aesthetic reasons. However, there are not many comparative analyses being done on the ventilation performance between the two ventilation systems except for the cost-benefit analysis as it is the primary concern to most building owners. Understanding the ventilation performance of each system is extremely important for the designer to make an informed decision when selecting a suitable type of ventilation system for the car park. Different car park geometry designs may require different ventilation systems to deliver adequate ventilation. It is extremely important to understand that the ventilation performance of the jet fans system is highly dependent on the geometry of the car park where the presence of structural elements like beams and columns may obstruct the air flow and affect the overall ventilation performance.

Jet fans are traditionally used in tunnel applications to provide longitudinal ventilation throughout the long underground passage which consists of only two openings on both ends. Since the cross-section of most tunnel designs is symmetrical with almost equal height and width except for the length which can stretch up to a few kilometres, the ventilation flow path is mostly designed as unidirectional where critical velocity is the most important consideration in the design process. Critical velocity is defined as the minimum airflow velocity required to keep the smoke in the downstream direction and ensure that there is no back-layering effect. However, when jet fans are being used for car park ventilation, multi-directional ventilation will occur due to the open geometry design of the car park that increases the possibility of complex fluid flow patterns, such as stagnation and recirculation flow. Therefore, there are certainly more considerations needed to be thought out while designing the jet fans ventilation system for the car park as sole reliance on the critical velocity is certainly insufficient for the validation. The additional design considerations include temperature distribution, the concentration of combustion products, and airflow velocity. With the increased design considerations to be evaluated, the CFD technique is undoubtedly the most suitable approach than the traditional full-scale experimental method in terms of reliability, better accuracy, time-efficiency, and cost-efficiency for the evaluation of the ventilation performance for both ventilation systems, Owing to the complex and unpredictable ventilation characteristic of jet fans system in car parks, most of the local authorities in Malaysia, Singapore, the United Kingdom, and the United Arab Emirates require fire safety designers to validate the performance of the jet fans ventilation system by using CFD modelling prior to obtaining official approval for commissioning of system. This requirement is essential to ensure that the jet fans system is properly designed and is capable to provide adequate ventilation for the car park during a fire.

1.6 Significance of studies

Many research studies have claimed that the jet fans system is more beneficial than the traditional ducted ventilation system for several reasons in terms of installation costs, design complexity, maintenance requirement, and aesthetic aspect. However, certainly, these aspects are not the primary considerations for car park ventilation system as they are completely irrelevant to the ventilation performance. This experimental project is intentionally made with a primary objective to provide a better insight into the difference in ventilation performance between the ducted ventilation system and impulse jet fans system during a car park fire.

The experimental findings of this project will be of great contributes to the following stakeholders:

Fire safety designer:

The findings of this experimental project can help the designers to develop a better insight into the comparison of ventilation performance between the ducted ventilation system and impulse jet fans system which had not been widely studied in the industry. Having a good understanding of this subject is beneficial for the designers to make an informed decision while selecting the most appropriate ventilation system for a car park. Furthermore, the well-explained methodology of this project could be used as a useful guideline for the designers to perform the full-scale CFD simulation of the car park ventilation system in future design works. In addition, the design methodology of the jet fans ventilation system of this project could be used as a design reference for the designers in their future projects.

Future research and development:

The experimental project aims to initiate a discourse and research trend in the fire safety industry on the analysis of the ventilation performance of impulse jet fans system for car park application which is an important topic but had not been widely studied in the industry.

CHAPTER 2

LITERATURE REVIEW

2.1 Car park design

In this research, a “car” is defined as a motor vehicle with at least four wheels and has a maximum of nine seating including the driver’s seating, primarily used to transport passengers (New Zealand Transport Agency, 2022). Whereas the term “car park” is defined as a designated area for temporary storage of motor vehicles that accommodates only cars, motorcycles, and light good vehicles that weigh no more than 1200 kilograms gross (Alimzhanova, Spearpoint and Jomaas, 2022). Similar to the report by (Spearpoint and Hopkin, 2019), the term “car park” in the paper does not include any automotive repair or service facilities which is typically regarded as a workshop and possesses a completely different hazard commodity than a general car park which is used solely for the temporary storage of passenger vehicles.

Car park can either be a standalone building structure or built vertically attaching to the structure of the main building. The construction of a car park can come in different ways of design, single-story or multi-storey construction, located either underground or above ground. The design configuration of car park is dependent on several factors. First, the minimum provision of parking lots for a particular facility served by the building. In Malaysia, the local state authority requires strata developers to provide at least two parking lots for each residential unit and 20% of total parking lots to be reserved for visitors' parking (Tay, 2022). Buildings with higher occupancy rates like high-rise residential towers, office towers, and shopping malls will usually have multi-storey car parks to fulfil the authorities' requirement for the sufficient provision of parking lots. It is essentially important to provide sufficient parking lots for all kinds of building types due to the increasing private vehicle ownership in the country. Next is the availability of usable land within the project site and most importantly the project budget. Land scarcity has always been a major issue in metropolitan cities like Kuala Lumpur. To solve this, building architects will usually integrate the main building and the car park as a single building structure where the car park will be either built underground or above-ground, attaching to the main building structure. Oftentimes, building developers will opt for the above-ground car park design due to its lower construction cost. However, the underground car park design solution is sometimes preferred for high-end building types like hotels and shopping malls to maintain the aesthetically pleasing architectural appearance of the buildings. The layout design features of a car park are slightly different from the other building spaces, it usually comes with a relatively low ceiling clearance of around 3 m or lower which is merely sufficient for the typical passenger vehicles to move through and is mostly open throughout the floor with only a little compartment reserved for lift lobbies and staircases in order to maximise the space to make way for more parking lots (Merci and Shipp, 2013; Alimzhanova, Spearpoint and Jomaas, 2022).

Car parks can be classified into two main categories in terms of their structural design, namely open or enclosed car parks. According to the tenth schedule of Uniform Building By-Law (UBBL) 2021 by (Malaysia International Law Book Services, 2021), an open structure is where the total surface area of the permanent openings is to be at least 40% of the total perimeter wall area enclosing the building compartment at which the opening shall be designed in such that the total length of the opening greater than 50% of the perimeter of the compartment. Figure 2.1 and Table 2.1 show the example for the design requirement of open structures.

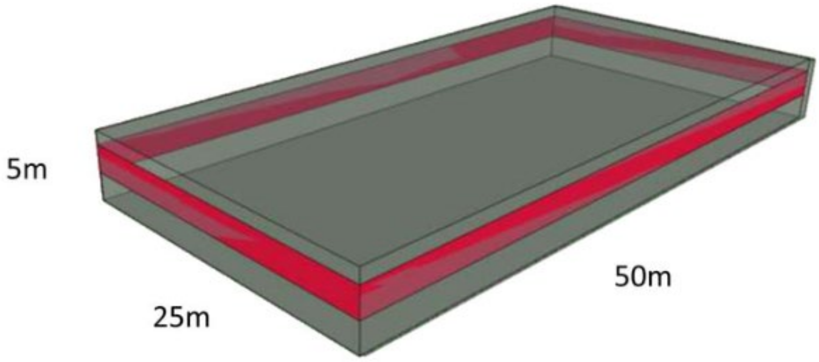


Figure 2.1: Design requirement of open structures (David Yek, 2021)

Table 2.1: Design requirement of open structures (David Yek, 2021)

Total perimeter length	50+50+25+25	150 m
Minimum length of opening	50% × 150	75 m
Total perimeter wall area	150 × 5	750 m^2
Minimum opening area	40% × 750	300 m^2

Building structures that fail to satisfy the above design requirements of open structures will be regarded as closed structures, for instance, a basement car park. Very often, enclosed building spaces have insufficient natural ventilation and require the assistance of mechanical ventilation system to provide adequate ventilation for the spaces. The provision of mechanical ventilation system in an enclosed car park is a legal building requirement by the local authorities in many countries including the Fire and Rescue Department of Malaysia (BOMBA) and Singapore Civil Defence Force (SCDF) as per mentioned in (Dato' Hamzah Bin Abu Bakar, 2006; Singapore Civil Defence Force, 2023).

Owing to the presence of motor vehicles in the car park, adequate ventilation is essential to maintain the air quality in the car park within the safety limit that will not pose deleterious effects on human health. Besides, the storage of vehicles is creating additional fuel load in the car park which can promote vigorous growth and propagation of fire in the event of a car park fire. All in all, fire in car parks especially in the underground ones is an extremely serious issue where the mechanical ventilation system must be appropriately provided to facilitate smoke ventilation by removing the harmful combustion products from the car park and thus creating a tenable condition for efficient evacuation and fire service intervention during a fire. In recent years, many underground car parks are being built underneath commercial or residential buildings due to land scarcity in urban cities. The enclosed design of the underground car park which has a poor leakage ability can pose a significant threat to the evacuees and firefighters during a car park fire as a large amount of combustion products will build up and accumulate in the car park if insufficient ventilation is being provided (Zhang et al., 2007; Santoso, Bey and Nugroho, 2015).

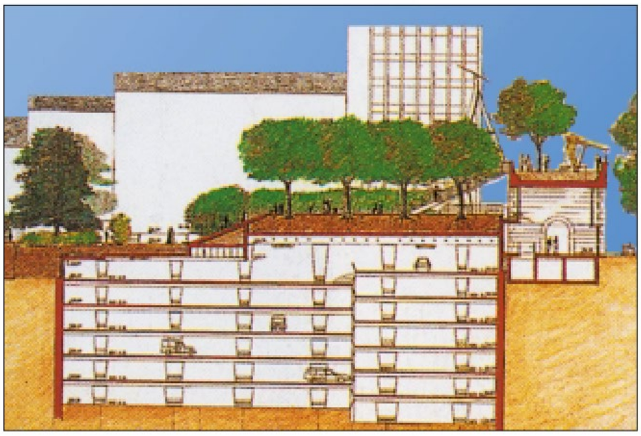


Figure 2.2: Underground enclosed car park (The Institution of Structural Engineers, 2002)

2.2 Emerging fire risks in car park

(Building Research Establishment, 2010) stated that there are very limited regulations being enforced on the fire safety aspects in car designs. Motor Vehicles Approval Regulations 2001 is the only main regulatory body that requires the fuel storage and electrical systems of a vehicle to be designed in such a way as to reduce vehicle fire risk. Over the years, due to the global initiative towards recyclable design and lower manufacturing costs, there has been a substantial increase in plastic quantities being used in modern car components, such as plastic fuel tanks and plastic engine covers. In the report of (Manser and Pentony, 2002, cited in Building Research Establishment, 2010), it was mentioned that the increasing plastic content in modern car designs has contributed to a significant increase in total fuel load represented by each car in the car park.

Alternative power option in modern car design is another conformance to the carbon-neutral trend which aims to reduce the overall carbon emissions associated with the automotive industry. Unlike the conventional vehicle designs which rely entirely on internal combustion engines (ICE) to produce mechanical energy to move the car from the burning of petrol fuel or diesel; Alternative solutions such as liquefied petroleum gas (LPG), natural gas, electric vehicles (EVs), and hybrid systems are being applied in many modern car configurations to replace the ICE which are deemed to be harmful to the environment due to high carbon emissions. It is essentially important to note that these new alternative power solutions are creating new and unprecedented fire risks to the car parks. However, majority of the fire safety guidelines for car park designs being used today were drafted based upon the previous fire experiments done on the traditional ICE vehicles and are deemed to be no longer suitable for existing car parks that contain modern vehicle designs. The guidelines have somewhat become obsolete and may not be safely applicable to those modern cars with alternative power options whose risks have not been comprehensibly studied and identified (Alimzhanova, Spearpoint and Jomaas, 2022).

Today, electric vehicles (EVs) are by far the most popular alternative-powered vehicles seen on-road in our everyday lives. According to the report by (International Energy Agency, 2021), in 2017, China recorded the highest number of EVs being registered which accounts for around 40% of total registered electric passenger vehicles in the world in 2017. European Union was ranked after China, with around 870,000 EVs registered in 2017, which was slightly higher than the United States (US) which has around 760,000 EVs registered.

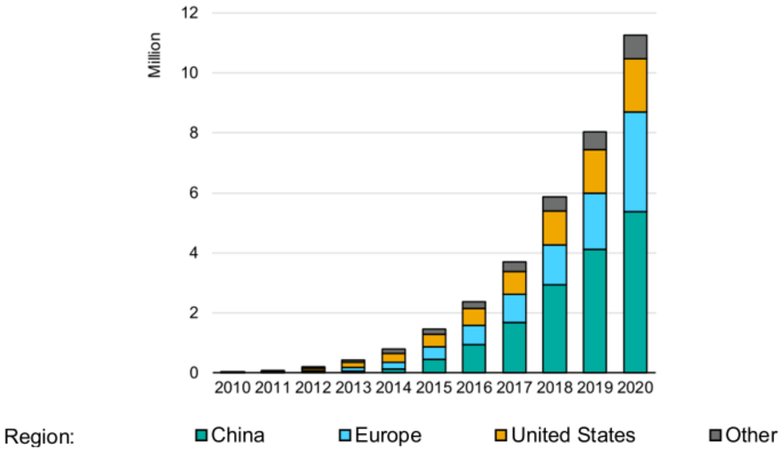


Figure 2.3: Statistical chart of global electric vehicles (International Energy Agency, 2021)

Unlike those traditional vehicles with ICEs, EVs typically come with a huge traction battery installed at the chassis which serve as the main energy storage for the vehicles instead of the fuel tank. There are several types of traction batteries commonly used for EVs, such as lithium-ion (Li-ion), nickel-metal hydride (Ni-MH), molten salt (Na-NiCl2), and lithium sulphur (Li-S) (Iclodean et al., 2017). High energy Li-ion battery is the most popular electric storage systems adopted by modern EVs due to its high energy density (Lecocq et al., 2012). However, the high reactivity of materials and high energy density of Li-ion batteries may prone to failures such as thermal runaway which will lead to leakage, gas venting, fire, and even explosion in the worst-case (Bitsche and Gutmann, 2004). Traction batteries are the main source of fire danger resulting from the invention of EVs that could contribute to unprecedented fire risks due to the uncertainties of the design of mechanical, thermal, and electrical impacts that could possibly lead to spontaneous combustion and fire development. When these batteries are subjected to a high temperature that exceeds the threshold thermal runaway temperature range (130 to 200 °C), the high exothermic reaction will drive the thermal runaways to occur. Thermal runaway is one of the primary risks associated with Li-ion batteries, it is a phenomenon in which the Li-ion cells enter an uncontrollable and self-heating state which would lead to a significant increase in heat release rate hat will eventually result in the development of fire or even explosion (Brandt and Glansberg, 2020; Dorsz and Lewandowski, 2021).

Li-ion batteries will produce a significantly high amount of toxic gaseous products when subjected to thermal runaway. They can also vent toxic gases even without undergoing thermal runaway. The gaseous product of Li-ion batteries produced when it is not burning have been claimed to be more toxic. These gases can accumulate and experience a delayed ignition and finally result in a massive gas explosion if it was placed in a confined space like an enclosed car park. The composition of these gaseous products highly depends on several factors, such as the chemical composition of the battery, the state of charge, temperature, pressure, and surrounding atmospheric conditions (Pfrang and Ruiz, 2018; Bisschop et al., 2019). The common gaseous products produced by the burning of Li-ion batteries include hydrogen fluoride (HF), hydrogen chloride (HCI), carbon monoxide (CO), nitrogen oxide (NO), and carbon dioxide (CO_2). Experimental data from (Lecocq et al., 2012; Truchot, Fouillen and Collet, 2018) have found that the gaseous products emitted from the burning of Li-ion batteries in EVs are of a higher toxic level than the burning of ICE vehicles.

Hydrogen fluorine (HF) is the most toxic gaseous product among other gaseous emissions resulting from a vehicle fire. HF is a toxic, corrosive, and light weight gas that can penetrate through certain types of protective gears and can cause severe irritation to human eyes and skin even at a low level of concentration. (Lecocq et al., 2012) found that the concentration of HF measured in the smoke plume during their experimental vehicles fire tests was above the safety threshold limit of 600 ppm for both EVs and ICEVs which will compromise the safety of firefighters during their intervention. HF is a common gaseous emission contained in all kinds of vehicle fires including EVs as well as ICEVs. The fluorine compound is usually produced from the burning of electrolytes and the binder or separator in Li-ion batteries but is also found in the burning of flame retarded materials like plastic and the air-conditioning refrigerant. Therefore, both EVs and ICEVs will produce highly toxic HF in the case of vehicle fires but at different mass fractions (Bisschop et al., 2019). In the experimental finding of (Truchot, Fouillen and Collet, 2018), the average quantity of HF produced by the burning of EVs is two times greater than that of a similar size medium class familial ICE vehicle as shown in Table 2.2 and Figure 2.4.

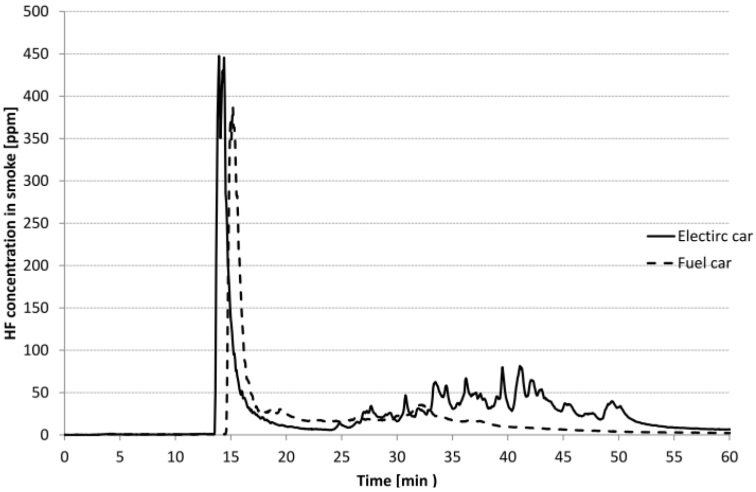


Figure 2.4: HF emission factor of fuel car and electric car (Truchot, Fouillen and Collet, 2018)

Table 2.2: Gaseous emission data in vehicle fires (Truchot, Fouillen and Collet, 2018)

	Car 1	Car 2
Vehicle type	Fuel	Electric
Category	Medium class familial vehicle	
Hydrogen chlorine (HC)	0.29%	0.30%
Hydrogen fluorine (HF)	0.11%	0.23%
Carbon dioxide (CO_2)	96.95%	96.98%
Carbon monoxide (CO)	2.11%	1.83%
Nitrogen oxide (NO)	0.1%	0.12%

Figure 2.5: Electric vehicle charger installation in car park (Brandt and Glansberg, 2020)

Apart from the battery component, EVs are also susceptible to higher risk and may give more intense damages during their charging process due to the high reactivity of electron charges that could result in a high HRR in the case of fire. This risk is significant and should not be neglected as the charging process is normally performed in a car park without being monitored. Problems associated with the charging process of EVs such as external short circuits, cell damage, and faulty charger issues have caused a self-ignited fire incident in 2020 (Qi et al., 2017). The increasing ownership of EVs also leads to increasing demands and provisions of recharging points in the car park which will contribute to new and unprecedented fire risks to the car park and must be taken into serious consideration (Building Research Establishment, 2010).

Figure 2.6: Plugged-in electric vehicle caught on fire during charging (The Nation, 2018)

2.3 Past car park fire incidents

Owing to the purpose of the car park, it has a relatively low occupancy rate as compared to other building spaces as the occupants will only be present for a short period during parking or collecting their vehicles. Therefore, the fatalities and injuries rate associated with car park fires is rather insignificant as compared to those normally occupied building spaces like shopping complexes, convention halls, residential units, etc. Despite of that, car park fire can still pose a significant danger to the firefighters during their intervention, the level of danger can be further intensified when there is structural damage caused by the high-temperature heat or fire explosion resulting from car fires. In a car park fire in Gretzenbach, Switzerland in 2004, seven Swiss firefighters were killed in the collapse of a concrete ceiling that trapped them inside during their fire intervention in a basement car park. The structural failure of the concrete slab was mainly because of the long exposure of approximately 90 minutes and direct contact to the high-temperature plume (Haavard, Klassen and Olenick, 2020).

Fire propagation to the adjacent building structure is also another fire hazard that will cause potential loss of human lives. A similar incident happened in Monica Wills House in Bristol, where fire spread from the car park to the residential building above and killed one occupant in that building. These incidents have proven that apart from property losses, car park fires can also lead to the loss of human lives. Although the possibility of a car park fire is lower than that of other building spaces, the potential risk and hazard should not be compromised as it involves the life safety of humans (Alimzhanova, Spearpoint and Jomaas, 2022).

Many experimental studies on car park fires done in the mid of the twentieth century claimed that car parks do not pose significant fire hazards due to the low fire load available and low chances of fire spread between vehicles. In reference to the experimental studies done by (Butcher et al., 1968 cited in Alimzhanova, Spearpoint and Jomaas, 2022), who concluded that the likelihood of fire spread between cars is nearly impossible as most motor vehicles contain a considerably low fire load. Also, (Marchant E., 1990 cited in Alimzhanova, Spearpoint and Jomaas, 2022) mentioned that the standard spacing of cars in a normal car park can reduce the chances of fire spreading between adjacent cars. However, as mentioned by the National Fire Protection Association (NFPA), these experiments were done based on the car design of that time and should no longer be used as the grounds for modern car parks that accommodate modern cars with higher combustible content (Haavard, Klassen and Olenick, 2020).

According to the most recent major car park fire experiment done by the Building Research Establishment (BRE) in the United Kingdom where modern car designs were tested, it was found that fire could spread from one vehicle to another if no additional fire suppression system like automatic fire sprinkler was provided at the instant. King’s Dock car park fire in Liverpool in 2017 is a great example to support the statement mentioned by the BRE, it was reported that the fire spread from one vehicle to another every 30 seconds due to the absence of an automatic fire suppression system which eventually gave rise to around 1150 cars being destroyed by the fire (Building Research Establishment, 2010). More recently, a total of six vehicles were damaged in a car park fire incident due to the spread of fire between adjacent vehicles at a condominium in Kuala Lumpur, Malaysia in 2022 (Justin Zack, 2022). Although the findings of the statistical analyses done by (Building Research Establishment, 2010) on car park fires in the United Kingdom between 1994 to 2005 showed that fires in car parks represented only a very small percentage of the total fire incidents in the country (with only 0.1% in 2006) and has a low occurrence of fire spread to nearby vehicles and additional compartments, however, substantial structural damage and property losses have been witnessed when fires occurred. One of the investigations done by (Building Research Establishment, 2010) found that a fire that originated from the first vehicle eventually spread to over 20 nearby vehicles and resulted in a severe structural damage in an underground car park. The fire safety of a car park should not rely solely on the statistical records as fires are highly unpredictable and will happen at anywhere and anytime in a vigorous manner without giving any early signs.

Figure 2.7: Aftermath of King’s Dock car park fire (British Broadcasting Corporation, 2018)

Figure 2.8: King’s Dock car park fire (Merseyside Fire and Rescue Service, 2018)

The recent disastrous car park fire incidents have refuted the previous findings which claimed that car parks possess a low fire risk and have a low chance of fire propagation between vehicles. The obsolete experimental findings are no longer valid in this modern era where vehicles have changed tremendously in terms of design, size, and power transmission. As a result, the likelihood of fire incidents caused by modern cars in the modern car park is becoming higher than ever. Therefore, better fire safety measures and fire protection systems, for example, smoke ventilation systems and other fire suppression systems must be designed and implemented with due diligence to enhance the safety of the evacuees and fire-fighters during a car park fire.

2.4 Normal mode ventilation

Exhaust emissions produced by motor vehicles can give persistent and harmful effects on both human health and the environment. These effects are further aggravated in enclosed building spaces with inadequate natural ventilation like enclosed car parks. The harmful exhaust emissions produced by motor vehicles include carbon monoxide (CO), hydrocarbon (HC), and nitrogen oxide (NO) gases. These gases will give deleterious effects on human health and long exposure to these gases will damage the entire system of the human body (Demir, 2015). Therefore, sufficient ventilation must be provided at the car park space to maintain good air quality throughout the spaces. Ventilation can be provided either by natural means if the car parks have sufficient permanent openings to the atmosphere or by mechanical means when the car parks have insufficient openings to the atmosphere, for example, an underground car park. The primary function of car park ventilation system during normal operation is to remove harmful exhaust contaminants from the car park and replenish the space with fresh outdoor air so as to maintain a healthy and sustainable indoor environment. Having adequate ventilation in either open or enclosed car parks is a mandatory legal requirement by the local authorities in many countries as well as in Malaysia which is stated in the UBBL-2021 (Malaysia International Law Book Services, 2021). In the case of an enclosed car park, the mechanical ventilation system shall be able to deliver a minimum ventilation rate of 6 ACH throughout the car park space to ensure good air circulation (Dato' Hamzah Bin Abu Bakar, 2006). Experimental studies done by (Demir, 2015) concluded that in the case where adequate ventilation is not provided in either underground or above-ground multilevel car parks, the harmful exhaust emission can reach a more dangerous level which can put the health of the occupants at a higher risk.

During the normal mode operation, the mechanical ventilation system will be activated based on the concentration level of CO level in the car park, the ventilation system will only be activated when the CO level exceeds the pre-determined safety limit. The CO concentration will be continually monitored and measured by the CO sensors located in the car park (Demir, 2015). The concentration of CO can be used to predict the occupancy rate in the car park. This design approach can help to achieve significant energy savings by avoiding the continuous running of the system which is deemed to be unnecessary during non-peak hours when the occupancy rate is low. Keeping the CO concentration level low is a necessary approach in all occupied spaces to fulfil the indoor air quality acceptance requirement as well as to provide a safe environment for the occupants. Constant removal of harmful exhaust emissions from the car park and replenishment of fresh outdoor air into the car park are essential measures to provide a safe and healthy indoor environment (Papakonstantinou et al., 2003).

Carbon monoxide (CO) is a common contaminant found in the car park, it is a by-product of the incomplete burning of hydrocarbon fuel in the internal combustion engines of automotive vehicles (Chow, 1996). According to the findings of (The Institution of Structural Engineers, 2002), a 5-passenger car could reach a maximum CO emission rate of 1.47 m^3/h, while a 7-passenger car could reach a maximum CO emission rate of 2.52 m^3/h. To maintain safe and healthy indoor air quality, the CO level in the car park should not exceed 50 ppm during normal traffic and 100 ppm during peak traffic. At the entrance or exit tunnels, which are usually of high traffic flow, the CO level should not exceed 150 ppm (The Institution of Structural Engineers, 2002).

Table 2.3: CO emission rate of vehicles (The Institution of Structural Engineers, 2002)

Type of vehicle	Rate of emission of Carbon Monoxide
5-passenger car	1.47 m^3/h
7-passenger car	2.52 m^3/h

Table 2.4: Maximum allowable CO levels (The Institution of Structural Engineers, 2002)

Location	Traffic Flow	Maximum allowable CO level (ppm)
General parking area	Normal	50
	Peak	100
Entrance and exit tunnels	Transient occupation	150

2.5 Fire mode ventilation

Apart from vehicle emissions, car park fire is another significant phenomenon that will pose a more disastrous effect to both evacuees and firefighters. Other than the primary fire extinguishing systems, an adequate mechanical ventilation system is essentially important, especially in an enclosed car park where it is required to work synchronously with other fire extinguishing system to extinguish and control the fire. Meanwhile, to provide a tenable condition for safe evacuation and fire service intervention (Khalil and Gomaa, 2017). During a fire in an enclosed car park, the fire extinguishing systems, such as automatic sprinkler and hydrant systems are responsible for putting out the fire; While the mechanical ventilation system is responsible to remove the high-temperature smoke and harmful combustion products from the car park so as to create a tenable condition in the car park with toxicity, visibility, and temperature of the indoor air that will not endanger the safety of human beings (Weng, 2011). Untenable conditions were defined as where the environmental conditions associated with a fire event is not safe for human which simply refers to a condition that can cause injuries or even fatalities (Ramsay et al., 2005). Maintaining a tenable condition in the enclosed car park or any other building space is crucially important to ensure a safe and efficient evacuation process and fire service intervention during a fire.

Although the smoke ventilation system plays a less significant role in extinguishing the fire as compared to the fire extinguishing system like automatic sprinkler, it does help in creating a tenable condition for efficient evacuation and fire service intervention by removing the toxic and high-temperature combustion products from the enclosed car parks that have poor natural ventilation. Heat is one of the three main elements in the fire triangle which must be eliminated or reduced to prevent further growth of the fire. Thus, heat removal from the fire can also give a significant contribution to the extinguishment of the fire. Furthermore, the fresh air supply system which is an integral part of the mechanical ventilation system will constantly replenish the car park space with fresh outdoor air to prevent a low oxygen level near the fire source which can result in a catastrophic and dangerous phenomenon called the backdraft effect. The backdraft effect is an abrupt explosion that can happen when oxygen is suddenly reintroduced into a quiet and smoky fire with oxygen deprivation but contains a high amount of unburnt fuel like carbon. In the event of a fire in an enclosed car park, the smoke ventilation system and fire suppression system must work synchronously to extinguish the fire to minimize the impact on both the life safety of evacuees and fire fighters as well as reducing property damages.

Unlike the longitudinal ventilation found in tunnels at which the smoke back-layering must be prevented during a fire for a safe evacuation, some back-layering effect caused by the mechanical ventilation is usually allowed in the car parks for up to a certain safety length (typically around 10 to 15 m). The main reason behind this relaxed restriction is because of the primary objective for smoke and heat ventilation in car parks is typically not for the evacuation of occupants, but to create a tenable and safe environment that allows the firefighters to approach the fire and extinguish it from within a certain distance that deemed as safe. The safe distance for firefighters to approach the fire is commonly derived from the maximum allowable smoke back-layering distance resulting from the fire (Tilley, Deckers and Merci, 2012). Smoke back-layering distance is defined as the distance covered by the smoke in the upstream direction of the ventilation flow path with respect to the initial fire source as illustrated in Figure 2.9. To prevent the smoke back-layering effect, the upstream velocity of the ventilation provided must exceed the critical velocity so that it has sufficient momentum to push the smoke in downstream towards the exhaust points (Zhang et al., 2021). According to the findings by (Deckers et al., 2013), the ventilation velocity must be around 1.1 m/s to limit or limit a smoke back-layering to a distance of 15 m for a 4 MW fire in a flat ceiling car park. A higher ventilation velocity will be required when beams are present, particularly for longitudinal beams as it has a higher chance of having a recirculation of trapped smoke within the gaps.

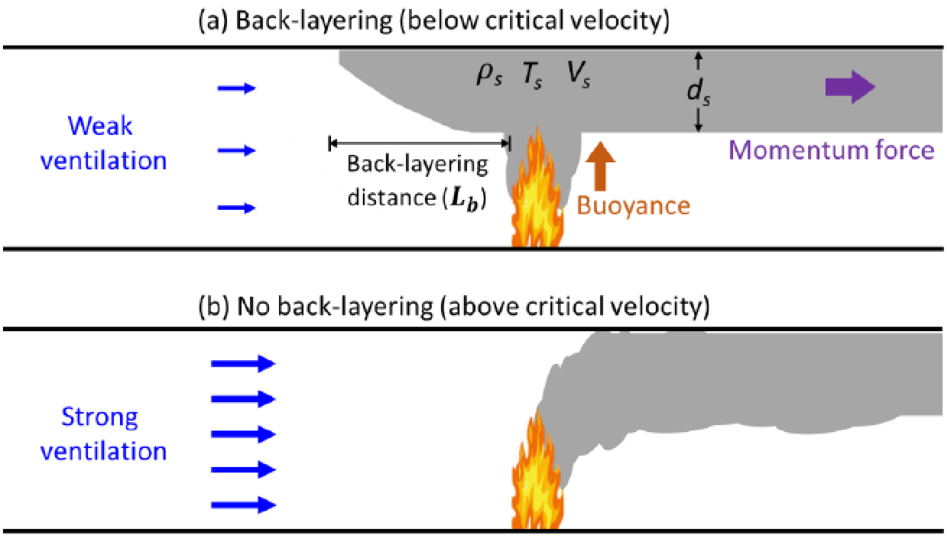


Figure 2.9: Schematic diagrams of the influence of ventilation for smoke back-layering; (a) Back-layering occurs under weak ventilation, and (b) No back-layering under strong ventilation (Zhang et al., 2021)

2.5.1 Tenability criteria during a fire

During a fire, a large amount of smoke will be produced and can spread rapidly throughout the car park space. Fire smoke usually contains a high concentration of carbon monoxide (CO), which is a by-product of incomplete combustion. CO is a harmful substance that will affect the respiratory system of humans, if being inhaled at high concentration. Statistical evidence has shown that the major cause of fatalities in fire incidents is not caused by direct contact with fire, but by smoke inhalation. Inhalation of smoke with high content of CO will cause oxygen asphyxiation in the human body, which is the major cause of fatalities in any fire incident (Weng, 2011).

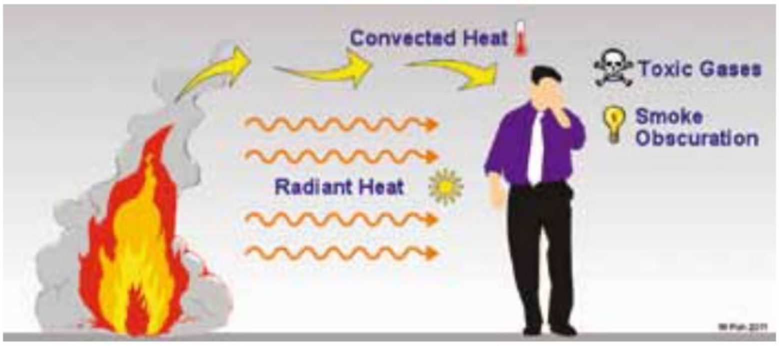


Figure 2.10: Hazards of fire smoke (Weng, 2011)

The most common by-product resulting from building fires is CO, followed by the more toxic hydrogen cyanide (HCN). The safety exposure limits depend on the type of gas, concentration, and duration of exposure. Figure 2.11 below shows the results obtained from the exposure limit tests conducted on primates by exposing them to different concentrations of CO and HCN. The experiment has found that HCN is more toxic than CO with a shorter time to incapacitation, even at lower concentration. It was assumed that humans will react similarly to primates under those conditions (Weng, 2011).

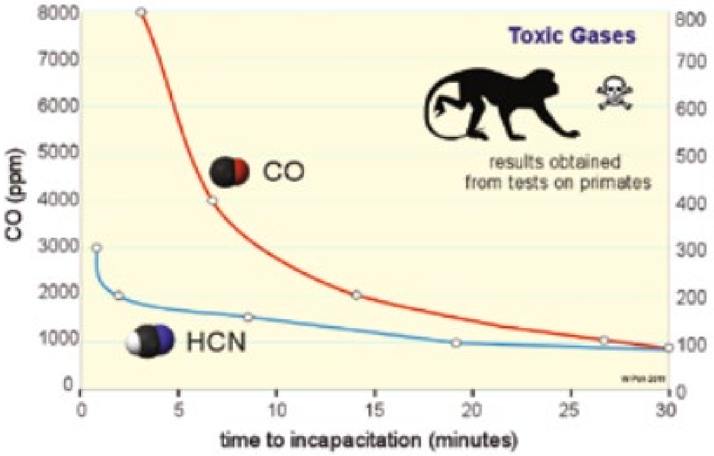


Figure 2.11: Exposure limits to CO and HCN (Weng, 2011)

The quantities of CO emitted from the burning of vehicle differs from one vehicle to another, the emission rate is dependent on several factors such as the age of the car, engine power, and the car's condition. According to the experimental findings by (Truchot, Fouillen and Collet, 2018), the average emission rate of CO generated by the burning of EVs and traditional ICE vehicles over 60 minutes of burning time could reach twice higher than the reference French standard emission rate of CO (around 38 mg/s) as shown in Figure 2.12 (CETU, 2003). (Truchot, Fouillen and Collet, 2018) has identified that the average CO emission factors of different types and sizes of vehicles are around 1.80% to 2.30% of the total smoke emission resulting from vehicle fires.

Table 2.5: CO emission factor of 4 different vehicle fires (Truchot, Fouillen and Collet, 2018)

Car type	Urban fuel vehicle	Medium-class fuel vehicle	Upper-class fuel vehicle	Electric vehicles
CO emission factor (%)	2.29	2.11	1.94	1.83

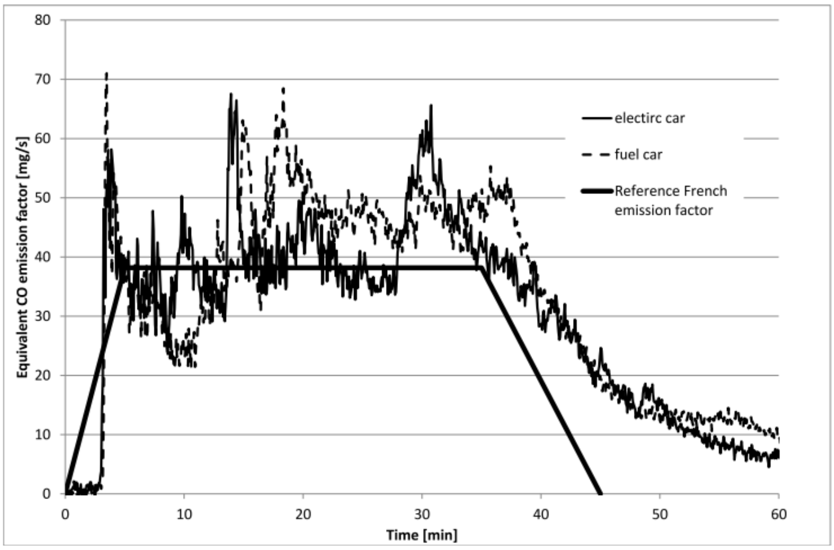


Figure 2.12: Evolution of CO emission rate of fuel and electric vehicle fires (Truchot, Fouillen and Collet, 2018)

Heavy smoke logging is generally known as the major cause of fatality in most fire incidents. The propagation of soot particles is another parameter that is significant in the study of smoke ventilation in an enclosed car park. The soot particles will obscure the light and reduces visibility. The yield of soot is highly dependent on the oxygen level around the ignition source, it is known that inadequate ventilation and oxygen deprivation could lead to higher soot emission due to incomplete combustion (Zhang et al., 2007). Although visibility does not pose a direct life-threatening hazard as those caused by exposure to heat and smoke, it is a large factor that contributes to fatality in most fire incidents. An environment with low visibility can slow down the walking speeds of evacuees which will affect the evacuation and increase the evacuees' exposure time in the fire environment. The presence of smoke products in an occupied building enclosure can obscure the illumination from the emergency light source like the "EXIT" signs which were intended to guide the evacuees during an emergency. Consequently, the evacuees will not be able to locate a safe egress path correctly which can cause them to be trapped in the fire environment. Figure 2.13 shows the walking speed of occupants at different smoke densities and visibility levels when subjected to irritant smoke and non-irritant smoke. The walking speed of occupants, when subjected to irritant smoke, reduces more significantly than that of non-irritant smoke. Acid gases and organic irritant gases contained in the combustion gases will cause irritation to human eyes and further reduce the occupants' walking speed and slow down the overall evacuation process (Zhang et al., 2007; Weng, 2011; Gager III and Dominguez, 2016). The visibility criteria data available in the SFPE Handbook shows that the maximum allowable smoke density and minimum visibility length can be varied by a person's familiarity with the building. According to data, a minimum visibility of 13 m should be provided for occupants or visitors who are not familiar with the building while minimum visibility of 4 m is sufficient for occupants who are familiar with the building (Yamada and Akizuki, 2016). The visibility is also dependent on the size and geometry of the building space which would affect the smoke flow behaviour. According to the studies by (Purser and McAllister, 2016), the recommended visibility tenability criteria for small building enclosures is 5 m while for large building enclosures is 10 m. Visibility in the building space is irrefutably a vital tenability criterion that should not be compromised during a fire to safeguard the life safety of evacuees and fire fighters.

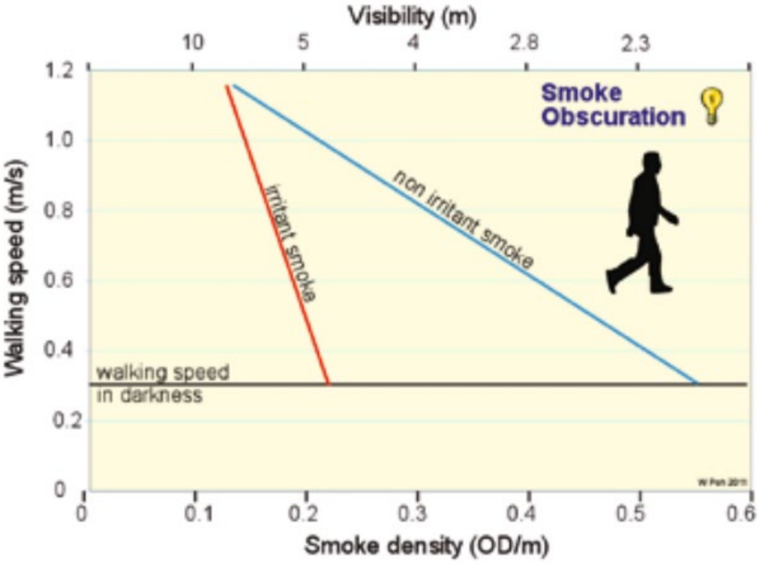


Figure 2.13: Walking speed at different visibility level and smoke density (Weng, 2011)

Sensible heat resulting from the hot smoke is another important element of the tenability criteria. During a fire, the hot smoke heat can be transferred to human skin through convection and radiation. Long exposure of more than 15 minutes to high-temperature environments may cause heat stroke. Whereas short exposure may cause skin inflammation and respiratory tract burns (Weng, 2011). Exposure to high-temperature heat can cause incapacitation or fatality to the casualties in several ways such as heat stroke (hyperthermia), body surface burns, and respiratory tract burns. Heat stroke can occur in the human body after a prolonged exposure of approximately 15 minutes in a heated environment where the surrounding air temperature is equal to around 120 °C for dry air or 80 °C for saturated air. Thermal burns to the respiratory tract can occur upon the inhalation of air with a temperature greater than 60 °C (Gager III and Dominguez, 2016). The SFPE Handbook provides a useful reference on the maximum tolerable temperature as shown in Figure 2.14 which predicts the approximate allowable tolerance times for unclothed subjects at different temperatures under both humid and dry conditions with a low air movement of around 0.5 m/s. At temperatures below 120 °C human tolerance is limited by heat stroke, whereas above this temperature skin burns and burns at the upper respiratory tract become significant. A victim who exposed to high temperature exceeding 120 °C in a fire for more than a few minutes is likely to suffer from burns and die either during or immediately after the exposure due to heat stroke. Victims who survived the heat stroke phase may die in the later stage due to burns of the respiratory tract or secondary degree of skin burns (Purser and McAllister, 2016).

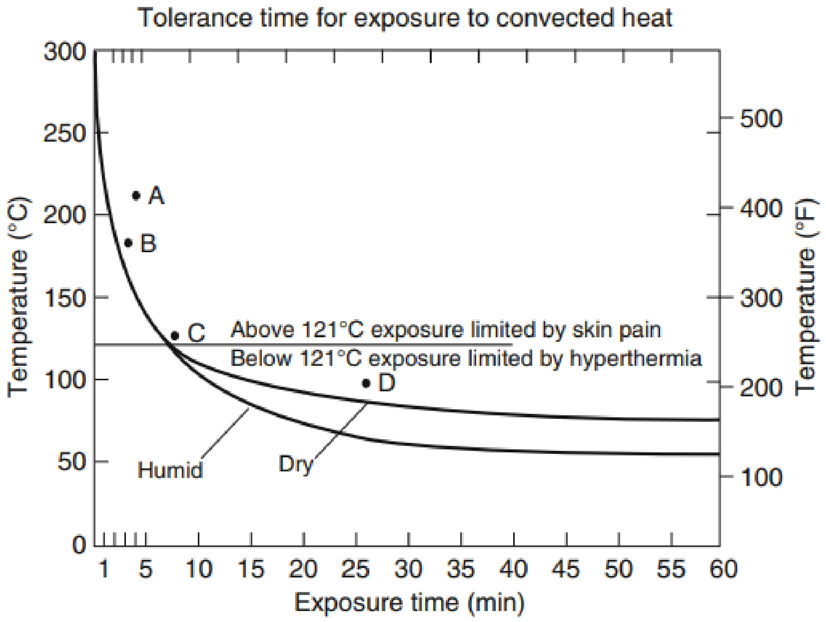


Figure 2.14: Thermal tolerance times for exposure to convected heat (Purser and McAllister, 2016)

Table 2.6 shows the temperature tenability criteria over the incapacitation time provided by NFPA 130 — Standard for Fixed Guideway Transit and Passenger Rail Systems (National Fire Protection Association, 2007) which were derived from the following equation:

$$t_{exp} = (1.125 \times 10^7) T^{-3.4}$$

Where,

t_{exp} = time of exposure (minute)

T = Maximum allowable temperature

Table 2.6: Maximum exposure time before incapacitation (National Fire Protection Association, 2014)

Exposure temperature (°C)	Without incapacitation (minute)
80	3.8
75	4.7
70	6.0
65	7.7
60	10.1
55	13.6
50	18.8
45	26.9
40	40.2

2.6 Design requirements of mechanical ventilation system

The mechanical ventilation system in an enclosed car park shall be able to operate effectively in both normal and fire mode operations. During normal operation, the mechanical ventilation system is responsible to maintain the indoor air quality in the enclosed car park within the safety limit which will not affect the health of occupants. However, during fire mode operation, it must act as a smoke and heat ventilation system to create a tenable condition for a safe and efficient evacuation process and fire service intervention.

According to the design requirements stated by BOMBA and SCDF as in (Dato’ Hamzah Bin Abu Bakar, 2006; Malaysia International Law Book Services, 2021; Singapore Civil Defence Force, 2023), the ventilation rate required for normal and fire mode operation in an enclosed car park shall be at least 6 ACH and 12 ACH respectively. ACH is known as air changes per hour which is the rate of ventilation that refers to the number of times the total volume of air contained in the space being removed and replaced with fresh new air in every hour interval.

ASHRAE Standard 62.1—Ventilation and indoor air quality has recommended that the ventilation rate for an enclosed car park should be at least 1.5 CFM/ft^2 (American Society of Heating Refrigerating and Air-Conditioning Engineers, 2022). The ventilation rate required for an enclosed car park should be determined based on four factors:

1. Acceptable contaminant level in the car park
2. Number of cars in operation during peak traffic
3. Travel distance of vehicles in the car park
4. The emission rate of a typical car under various engine conditions

Different standards organizations from different countries have different recommendations for the CO exposure limits in an enclosed car park, however, a limit of 25 ppm for long-term exposure and 100 ppm for short-term exposure to CO is applicable to most of the requirements listed in Table 2.7.

Table 2.7: International standards for car park ventilation design (Krarti and Ayari, 2001; Health and Safety Executive, 2020)

Standards / Organizations	Exposure time	CO concentration (ppm)	Ventilation Rate
ASHRAE	8 hours	9	1.5 CFM/ft^2
	1 hour	35	
OSHA	8 hours	50	nil
	Ceiling	200	
HSE	8 hours	20-30	6-10 ACH
	15 minutes	100-200	
NFPA	nil	nil	6 ACH
WHO	8 hours	10	nil
	15 minutes	9	

During normal operation, the mechanical ventilation in the enclosed car park is usually controlled by the CO level in the car park rather than running continuously. Doing this can help to achieve significant energy consumption and reduce noise levels during non-peak periods when the CO level is below the safety limit. Continuous monitoring of the CO concentration in the car park is necessary and should be linked to the mechanical ventilation system to activate the fans automatically whenever the CO concentration level exceeds the pre-set value. The pre-set values are usually set as per the threshold limit of CO concentration stipulated in the building codes and may vary from one to another in different countries (Krarti and Ayari, 2001).

In the event of a fire incident, the mechanical ventilation system will act as a smoke and heat ventilation system. Under such mode, the mechanical ventilation system shall be activated either automatically by the fire alarm system serving the car park area or manually by a remote on-off switch located at the fire command centre of the car park (Dato' Hamzah Bin Abu Bakar, 2006). The fire alarm system of a car park is linked to multiple sensors and devices located at the car park including the smoke detectors, heat detectors, emergency break-glass, and fire sprinkler flow switches. For example, during a car park fire, the smoke and heat detectors located near the fire source will first be activated, which then set off the fire alarm and the fire alarm panel will send a signal to activate the mechanical ventilation system to initiate the smoke purging function.

For every smoke ventilation system in an enclosed car park, replacement air must be provided to compensate for the loss of extracted air to create a balanced airflow (Wu et al., 2011). The replacement air will supply fresh outdoor air to replace the smoke which has been removed by the exhaust system to prevent a vacuum effect which will lead to a disastrous fire backdraft effect (Rafinazari and Hadjisophocleous, 2020). A backdraft effect is an extremely dangerous explosion phenomenon that can generate a vast amount of powerful and heavy smoke unexpectedly that will threaten the safety of the occupants and firefighters if happened. The backdraft effect frequently occurs during fires where there is limited ventilation and deprivation of oxygen near the fire source. Although according to the fire triangle principle, fires will subside when the oxygen level drops, however, smouldering fires continue to produce flammable gases like carbon which will accumulate in the closed compartment and remain unburnt due to lack of oxygen. When fresh air is suddenly reintroduced into the oxygen-depleted environment through an open door or broken window, the hot-fuel-rich gases at high temperature can reignite rapidly and usually result in deflagration (Wang, Lin and Yu, 2008).

Replacement air can be introduced through natural ventilation when the car park has a total permanent opening area to the outdoor environment of not be lesser than 2.5% of the total floor area of the car park. For example, a minimum permanent opening area of 25 m^2 will be required at a 1000 m^2 car park for the replacement of fresh outdoor air using the natural ventilation method. However, in the case of enclosed car parks with usually have insufficient permanent openings, the replacement air must be provided by mechanical means at a rate of not more than the total smoke extraction rate. This design requirement is a crucial measure to ensure that the car park will not be over-pressurized than the pre-pressurized fire escapes such as the protected staircases or lift lobbies (Dato' Hamzah Bin Abu Bakar, 2006). This is because the positive pressure at the car park space will force the smoke to enter and compromise the pre-pressurized spaces which can hinder the evacuation process and fire service intervention since the pressure in the car park is now greater and can overcome the air pressure in the pre-pressurized areas.

Different authorities and standard organizations have suggested different design requirements for the supply rate of replacement air for smoke control ventilation systems. BOMBA requires a fresh air supply rate of 50% to 75% of the total extraction rate (Dato' Hamzah Bin Abu Bakar, 2006). ASHRAE recommends a replacement air supply rate of 80% to 95% (Klote et al., 2012). Whereas the Australian Standard AS 1688.2-2012 — Mechanical Ventilation In Buildings recommends a replacement air supply rate of 75% to 90% (Shoket, 2018). The replacement air supply can be provided either using the natural method where there are sufficient permanent openings or by a mechanical fan supply system where natural ventilation is deemed insufficient like in an enclosed car park. The provision of adequate replacement air is essential for an effective smoke ventilation system in the car park.

The Fire and Rescue Department of Malaysia (BOMBA) suggested the mechanical ventilation system in enclosed car park should be designed based on the following requirements (Dato' Hamzah Bin Abu Bakar, 2006):

1. Replacement air must be drawn directly from the outdoor environment and the intake shall be located not less than 5 m from any exhaust discharge openings to prevent smoke recirculation.
2. A smoke ventilation system must be an independent system separated from other building systems i.e., staircase and lift lobby pressurization systems.
3. All ventilation components i.e., fans, ductwork, and electrical cable shall be capable to operate at 250 °C for at least 2 hours.

4. An independent secondary source of power supply shall be provided for every smoke ventilation system in case of primary power source failure.
5. The smoke ventilation system must be fully operated within 60 seconds upon activated by the fire alarm panel.

2.7 Traditional ducted mechanical ventilation system

Traditionally, the mechanical ventilation system in the enclosed car park is supported by an extensive ductwork. This design comprises two separate ductworks, one is the exhaust ductwork which removes the contaminant and smokes out of the car park space, while another one is the supply ductwork which is responsible to deliver fresh replacement air to the car park space to prevent the car park from being over-depressurised which will cause oxygen deprivation to the fire. Very often, the exhaust ductwork in the enclosed car park will be extended to a high-level extraction inlet closed to the ceiling and a low-level extraction inlet closed to the exhaust outlet of the motor vehicles. The high-level ductwork is intended to extract the high-temperature smoke layer which has a smaller density. While the low-level ductwork is designed to remove the heavier toxic contaminants from the exhaust emissions of the vehicles (Colt International, 2015).

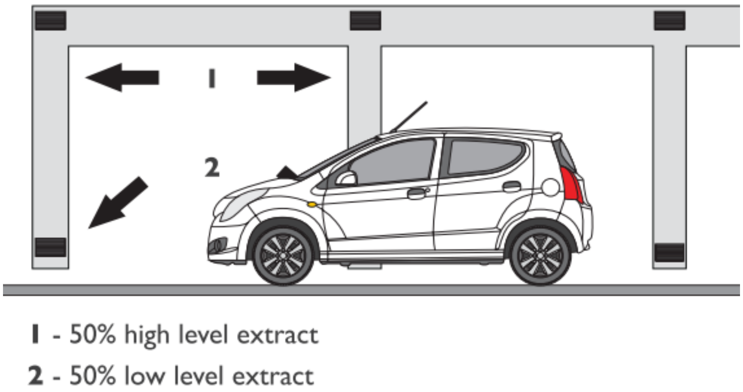


Figure 2.15: Typical ducted ventilation system in car park (British Standards Institution, 2013)

During the installation of high-level ductwork, a minimum height clearance of around 2.1 m is required for vehicles to travel below the ductwork in the car park. Therefore, deeper excavation is required to create a higher ceiling clearance at the car park in order to fit in the ductwork and at the same time meet the minimum height clearance of 2.1 m for the vehicles to pass through. Consequently, it contributes to higher construction costs for the excavation work of the basement car park. Furthermore, the low-level ducting often require barrier protection to prevent the moving vehicles from crashing into them which will take up some parking space available. Other than space issues, the design process of a ducted ventilation system is rather tedious as it involves a lot of complex duct sizing and coordination with other building elements such as the down-stand beams, lighting fixtures, and sprinklers location to avoid airflow obstruction (Colt International, 2015).

Furthermore, the extensive length of ductwork will contribute to significantly high static losses through the extended length of ductwork, duct bending, duct turning, and air grilles. Consequently, a higher magnitude of vibration will occur which in turn increases the noise level of the mechanical system. Besides, the high static losses will cause the mechanical ventilation system to be less efficient than the original design capacity since a certain amount of work will be wasted to overcome the static losses. It also leads to higher energy consumption for the ventilation system. To improve the efficiency, fans with higher flow rate capacity must be provided and this will incur additional cost for construction of the ventilation system.

Another drawback associated with the ducted ventilation system is the poor reliability of ductwork when subjected to direct flame contact with the fire. According to several design standards by (Dato' Hamzah Bin Abu Bakar, 2006; British Standards Institution, 2013; Singapore Civil Defence Force, 2023), the ducting material used for the mechanical ventilation system in the car parks shall have a fire resistance of 250 °C for at least 2 hours. However, the flame temperature can go up to 1200 °C, according to the experimental findings by (Shipp and Spearpoint, 1995). The high flame temperature when in contact with the ductwork can easily damage this section of ductwork and compromise the ventilation performance of the entire affected ductwork due to leakage (Lisa Cherney, 2022).

Figure 2.16: Ducted ventilation system in car park (Colt International Ltd, 2020)

2.8 Impulse jet fans ventilation system

The impulse jet fans ventilation system is a modern ventilation technology that has been widely used in many car park ventilation applications in recent years. Impulse ventilation is a ductless ventilation system that does not require any bulky ductworks. Instead, the jet fans will generate a thrust force at high velocity jet to push and direct the smoke toward the main extraction fan in a ductless manner. The typical thrust force generated by each jet fan during normal operation and fire mode operation is 27 N and 50 N respectively. During normal operation, the impulse jet fans ventilation is constantly controlled by the CO level in the enclosed car park; The jet fans will be activated when these sensors detected a high concentration of CO build-up in the enclosed car park. Similar to ducted ventilation, jet fans ventilation system requires both extraction fans and supply air fans to create a balanced airflow and pressurisation throughout the car park (Nazari et al., 2021).

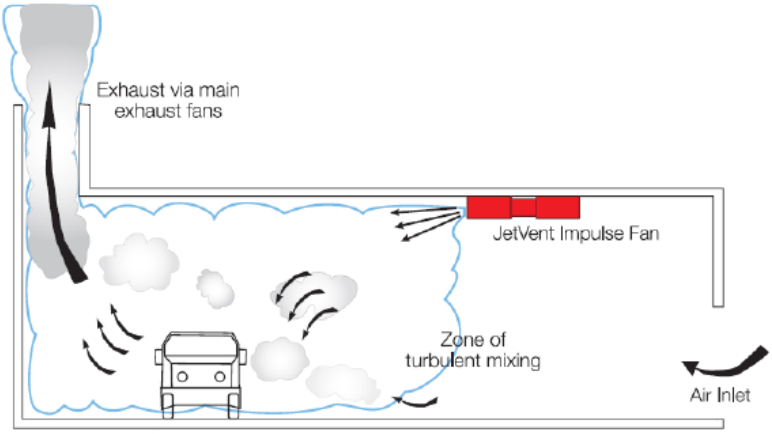


Figure 2.17: Working principle of impulse jet fans ventilation system (Mahesh Patil, 2016)

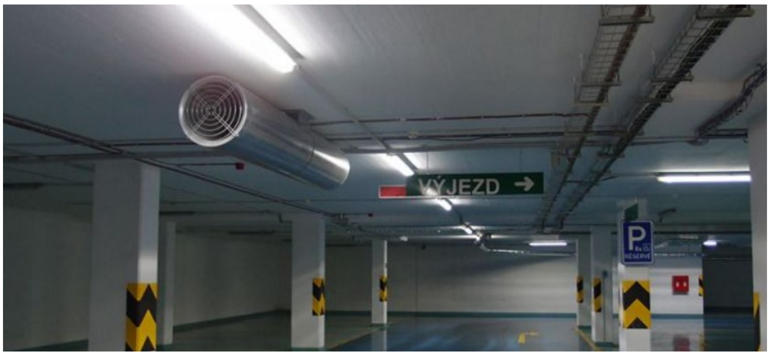


Figure 2.18: Impulse jet fans ventilation system in an underground car park (Colt Singapore, 2022)

Impulse jet fans ventilation system offers a few advantages over the traditional ducted ventilation system for enclosed car parks (Nazari et al., 2021).

1. Eliminate extensively large ductwork which is expensive and requires high maintenance requirements.
2. Smaller ceiling height requirement which contributes to significant saving in excavation and construction cost.
3. Space-saving, flexible installation, and low maintenance requirements.
4. Smaller extraction and supply fan sizes due to the significant reduction in static pressure losses resulting from the absence of ductwork.

According to experimental results obtained by (Colt International, 2015), impulse jet fans ventilation system has a better effectiveness than traditional ducted ventilation system in smoke clearance. It was found that the time taken for impulse jet fans ventilation to achieve smoke clearance in an enclosed car park is 9 minutes faster than that of ducted ventilation system.

Figure 2.19: Smoke clearance system tests at Bristol car park (Colt International, 2015)

Table 2.8: Experimental results of smoke clearance in the car park (Colt International, 2015)

Ventilation system	Time to see end wall	Time to smoke clearance
Traditional ducted	27 minutes	42 minutes
Impulse jet fans	19 minutes	33 minutes

2.8.1 Design guidelines and recommendations

The impulse jet fan ventilation system is an essential part of the fire protection system in the enclosed car park which must be designed with strict conformance to the design guidelines and requirements stipulated by the relevant local authorities to ensure that the system is efficient. Several authorities like BOMBA, SCDF, and British Standards have outlined the design requirements of impulse jet fans ventilation system for car parks application to serve as a guideline for the designers. The design guidelines published by the authorities are practically similar and can only be applied for conventional car parks that contain only light passenger vehicles.

The jet fans unit shall be placed immediately above the driveway instead of being positioned above the parking bays to prevent the ventilation performance of the jet fans system from being compromised during a car fire. This is because the parking bays are intentionally designed for the temporary storage of vehicles. Thus, when a parked vehicle catches fire in the car park, the hot plume resulting from the vehicle fire will come into direct contact with the jet fan that was positioned immediately above the fire which will potentially compromise the overall smoke ventilation performance of the jet fans system. According to the experimental findings of (Shipp and Spearpoint, 1995), the peak plume temperature resulting from the burning of a medium-sized vehicle can reach up to 1200 °C which is way higher than the fire resistance rating of typical jet fans at 350 °C. Therefore, the jet fans are susceptible to failure when subjected to direct contact with the extremely high plume temperature. Positioning the jet fans above the driveway will reduce the chances of jet fans failure caused by direct contact of fire since the driveways normally do not contain parked vehicles and have a lower possibility of vehicle fires as compared to the parking bays.

The design guidelines and requirements for impulse jet fans ventilation system from several local authorities (Singapore Civil Defence Force, 2008; Fire and Rescue Department of Malaysia, 2010; British Standards Institution, 2013) are summarized as below:

1. The position of sprinkler heads and jet fan units shall be arranged in such that the effect on the spray pattern of sprinklers is minimized upon the operation of jet fans that induce a relatively high velocity jet.
2. The jet fans shall be spaced not more than 15 m apart (sideways) and not more than 30m apart (air-throw distance). This also applicable to the distance between jet fans and the main extraction point.
3. The car park space shall be split into smoke control zones with an area of not greater than 2000 m^2 in each zone as stated in (Singapore Civil Defence Force, 2008) or 2600 m^2 in (Fire and Rescue Department of Malaysia, 2010) (excluding fire compartment space) for the intention of smoke containment within the zone boundaries.
4. Each smoke control zone shall consist of its independent jet fans system which includes the replacement air supply, smoke exhaust system, and jet fan units for efficient smoke removal from the affected zone.
5. The smoke exhaust system shall be designed to operate in at least two separate parts with two separate fans, such that the total smoke extraction capacity will not fall below 50% of the total required extraction rate for the affected zones when any one of the parts fail. This design requirement is also required for mechanical fresh air supply system.

6. An independent secondary source of emergency power supply shall be provided through an automatic activation in the event of primary power supply source failure.
7. The activation of the jet fans system shall be limited to the affected smoke control zone and its adjacent zones only.
8. The air velocity throughout the escape paths shall not exceed 5 m/s to prevent the escapees and firefighters from being obstructed by the high air flow velocity.
9. The location of replacement air supply shall be located at the opposite ends of the smoke extraction points to minimize the chances of opposing flow.
10. The face velocity at exhaust air grilles and supply air grilles shall not exceed 5 m/s as per (Dato' Hamzah Bin Abu Bakar, 2006) or 2 m/s as per (Singapore Civil Defence Force, 2008; British Standards Institution, 2013).
11. The car park space shall be provided with a mechanical ventilation system that could deliver at least an air change rate of 12 ACH during a fire.
12. The operation of the jet fans system shall be designed in such that there the total stagnation areas (with air flow below 0.2 m/s) not greater than 10 m^2 where smoke can accumulate.
13. All the jet fans system components including fresh air fans, smoke extraction fans, jet fans, ventilation duct, and electrical wiring shall be capable to operate effectively at 250 ºC for at least 2 hours.

14. The total air movement rate generated by the activation of jet fans shall not exceed the total exhaust capacity in each zone to prevent over-pressurisation in the car park.

The acceptance criteria for the impulse jet fans ventilation system during a car park fire are listed below (Singapore Civil Defence Force, 2008; British Standards Institution, 2013):

1. The total smoke-logged area near the car fire with temperature greater than 250 ºC shall not be greater than 1000 m^2.
2. At least one tenable and viable route shall be provided for firefighters with the following conditions:
    i. Smoke temperature in the affected zone shall not exceed 250 ºC at a height of 1.7 m above the floor level.
    ii. Visibility shall be greater than 5 m at a height of 1.7 m above the floor level.
3. All areas outside the smoke-logged area shall be cleared from smoke with temperature at 1.7 m above the floor level not more than 60 ºC and minimum visibility of 25 m.

2.9 Analysis of ventilation performance using CFD approach

Computational Fluid Dynamics (CFD) is a field of science that employs numerical methods to analyse fluid flow, heat and mass transfer and chemical reactions using computer-based simulation. Computer modelling of fire is a popular technique used for the design, evaluation, and assessment of fire safety systems in buildings, this approach is widely known as the Performance Based Approach in the fire and safety industry. Over the last few decades, the performance of the CFD modelling approach has seen a drastic improvement, thanks to the advancement of the digital computer system. The efficient and economical benefits of the CFD approach have made it to gain popularity in both research and design activities of fire science and technology. Unlike the traditional experimental approach, the CFD approach is more economical, less time-consuming, and more efficient. Besides, CFD is capable to provide a detailed information of the fluid flow field and heat and mass transfer of fluid which are very important for the analysis of fire and smoke behaviours. CFD approach serves as an effective tool for modelling of fire and the associated heat and mass transfer in an enclosure domain. Several areas are involved in the CFD modelling of fire, including fluid dynamics, turbulence flow, heat and mass transfer, combustion chemistry development, and structural behaviours of the building enclosure. Thermal radiation plays a vital role in the random and unpredictable heat transfer process from the fire in CFD modelling. Moreover, the fluid flow in fire modelling is highly dominated by the turbulent buoyancy driven flow generated by the fire. Thus, both the thermal radiation and buoyancy turbulence must be modelled to obtain a higher accuracy. A conjugate heat transfer must also be added to the numerical model to deliver an accurate modelling of fire development (Liu, Moser and Sinai, 2004).

CFD analysis is widely employed by design engineers to optimize and validate the smoke and heat ventilation performance which can be highly unpredictable and complex in nature, such as tunnel ventilation, car park ventilation and atrium ventilation. It is a cost-effective technique that can deliver an accurate output result in lieu of having a full-scale actual testing which is time-consuming and will incur high experimental cost (Mahesh Patil, 2016). (Fire and Rescue Department of Malaysia, 2010) has stated that the jet fans system design for any car parks with a total floor area exceeding 2600 m^2 shall be demonstrated with CFD modelling during the design submission stage. CFD modelling is an effective technique to model the distribution of heat and smoke in complex geometries like car park that consists of plenty of structural obstructions like column, beam, and wall. An appropriate CFD modelling of the jet fans system can help the designers to validate the ventilation performance.

The performance of the jet fans ventilation system for the car park should be analysed based on several key parameters like smoke distribution, visibility, temperature, airflow, and concentration of toxic combustion products. The CFD results should, as a minimum, show in the horizontal place at 1700 mm from the finished floor level which represents the average humans breathing height (British Standards Institution, 2013).

There are several reliable CFD software packages available in the market, some of them are uniquely designed for fire modelling purposes, such as the Fire Dynamics Simulator (FDS) developed by the National Institute of Standard and Technology (NIST) and Smartfire developed by Greenwich University. Some general purpose CFD software packages like ANSYS CFX developed by ANSYS, FLUENT developed by Fluent Limited, and PHOENICS developed by CHAM are also good CFD software for fire modelling applications (Liu, Moser and Sinai, 2004).

2.9.1 Governing equations

In fire dynamic simulation, turbulence flow is highly recommended over laminar flows due to the high inertial terms in the modelling of smoke and fire that contains multi-species flow. Turbulence flow consists of several eddies with different dimensions which can be broken down into smaller eddies and transfer energy to nearby eddies. For accurate modelling of the fluid flow field, reliable turbulence models must be employed to model the buoyancy-generated turbulence. The two turbulence models commonly used for indoor environment simulations are turbulence averaged Navier-Stokes (RANS) and Large Eddy Simulation (LES). The concept of the LES model is being adopted in the building of the Fire Dynamics Simulator (FDS) software (Liu, Moser and Sinai, 2004).

The two commonly used turbulence models in enclosed environment fluid simulation are denoted as k—ε and k—ω which are closely related to the two-equation Eddy-Viscosity models. k—ε is well-known in turbulence models that are very convenient to use (Barsim et al., 2020). (Chow, 1998) revealed that the k—ε is capable to provide accurate results for fire and smoke simulation equivalent to those complex turbulence models in a more convenient way. (Zhang et al., 2007; Wu et al., 2011) have demonstrated in their studies that k—ε is capable to predict the fire-induced turbulent flow in their fire and smoke modelling.

Experimental findings have demonstrated that both the k—ε model and the Shear Stress Transport (SST) hybrid turbulence model are capable to give an accurate prediction of the turbulent flow and heat and mass transfer associated with the fire. SST is a hybrid turbulence model was developed by the ANSYS-CFX company where k—ε and k—ω models were employed to resolve the complicated turbulent buoyant flow. The laminar sublayer which is a low-level turbulence model that can be found near the wall surface is modelled by the k—ω model for better accuracy. Whereas k—ε model is employed for the modelling of fully-developed turbulent flow that locates in the region far from the surface of the solid wall. Both the SST model and the k—ε model have been found to be capable to predict the temperature field in the gas fluid domain with a small deviation of only around 20 °C when compared with the experimentally measured smoke temperature in the hot layer. The general-purpose CFD software package ANSYS-CFX has been claimed as a useful CFD modelling tool that can deliver accurate results through numerical analysis for fire modelling purposes (Liu, Moser and Sinai, 2004).

The Menter's k-ω SST turbulence model comprises two governing equations for both k and ω which are known as specific turbulent kinetic energy and specific turbulent dissipation rate respectively.

k, specific turbulent kinetic energy (m^2s^{-2}):

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(U_i \rho k) = \frac{\partial}{\partial x_j}(\mu_k \frac{\partial}{\partial x_j} k) + \check{P}_k - \beta^* \rho \omega k$$

ω, specific turbulent dissipation rate (s^{-1}):

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(U_i \rho \omega) = \frac{\partial}{\partial x_j}\left(\mu_\omega \frac{\partial}{\partial x_j} \omega\right) + P_\omega - \beta \rho \omega^2$$

$$+2\rho(1 - F_1)\frac{1}{\omega}\frac{1}{\sigma_{\omega,2}}\frac{\partial}{\partial x_j} k \frac{\partial}{\partial x_j} \omega$$

Where,

$\rho = \text{ density (kg m}^{-3})$

$\check{P}_k = \text{Effective rate of production of k (kg m}^{-1}\text{s}^{-3})$

$P_\omega = \text{ Rate of production of } \omega \text{ (kg m}^{-3}\text{s}^{-2})$

$\beta^* \text{or } \beta = \text{ Turbulence modeling constant}$

$U = \text{ Incident free} - \text{stream airflow (m s}^{-1})$

$\mu = \text{Eddy viscosity (kg m}^{-1}\text{s}^{-1})$

$\sigma_\omega = \text{Turbulence modeling constant}$

Reference: (Rocha et al., 2014)

2.9.2 Modelling of vehicle fire

The vehicle fire in the car park is usually a developing fire that typically starts in the engine compartment or the passenger compartment due to several causes like fuel leakage, electrical system failure, etc. Unlike the vehicle fire resulting from violent crashes, typical vehicle fire in a car park starts at a relatively slower rate until the fire environment becomes well-ventilated. The fuel load contained in a vehicle includes fuel storage, upholstery seating, and plastic material that are highly combustible and will burn vigorously. An appropriate modelling of design fire is an essential step in the CFD modelling of the ventilation system in the car park. The design fire can be assigned by using two different approaches, either steady-state design fire or time-dependent design fire. A steady-state design fire ignores the growth phase of the fire development. Instead, it assumes that the output of the design fire like the heat release rate (HRR) to be constant throughout the simulation which is not possible in the actual scenario as fire will go through several stages from growth, steady burning to decay. Applying the steady-state approach in design fire can ensure a significant margin of safety to the reliability and performance of the ventilation system during the CFD modelling. (British Standards Institution, 2013) has suggested the HRR of steady-state design fire for passenger vehicles under two different scenarios as shown in Table 2.9. On the other hand, (Morgan, Vanhove and De Smedet, 2004) suggested a design fire with an HRR of 3 MW and 12 m perimeter in the case of passenger vehicle fires. (Singapore Civil Defence Force, 2008) suggested a design fire with an HRR of 4 MW and 10 MW for passenger vehicles and goods vehicles respectively.

Table 2.9: Steady-state design fire parameters (British Standards Institution, 2013)

Fire parameters	Unsprinklered indoor car park	Sprinklered indoor car park
Dimensions	$5\ \mathrm{m} \times 5\ \mathrm{m}$	$2\ \mathrm{m} \times 5\ \mathrm{m}$
Fire perimeter	20 m	14 m
Heat release rate (HRR)	8 MW	4 MW

The convective portion of the total heat release rate is a more accurate parameter to identify the thermal properties of the smoke layer as most of the heat is transferred to the surrounding air fluid by means of convection, it can be obtained using the atrium smoke control model published by (John H. Klote, 2014) as per below:

$$\text{Convective heat release rate}, Q_C = \lambda \times \mathrm{HRR}$$

λ is the convective fraction that is usually set at 0.7 in most of the design applications and is suggested by NFPA 92 Standard for Smoke Control Systems Book in section 5.5.1.3 (National Fire Protection Association, 2015).

The mass flow rate and temperature of the hot smoky gas reaching the ceiling can be calculated using the large fire plume model by (Morgan, Vanhove and De Smedet, 2004):

$$\text{Mass flow rate of smoke}, \mathrm{m_s} = \mathrm{C_e P H_p}^{1.5}$$

$$\text{Temperature of smoke layer}, \theta_s = \frac{\mathrm{Q_C}}{\mathrm{m_s.C_p}} + \theta_{\mathrm{amb}}$$

H_p is the height of the smoke plume which can be assumed as the distance between the fire layer and the ceiling in the case of car park fires. P is the fire perimeter and C_e is the dimensioned entrainment constant in the large fire plume model. The value C_e is dependent on the pattern of the fire; C_e can be taken at 0.19 where the fire plume rises vertically upwards to a high smoke layer base which is usually used in the smoke atrium; or at 0.21 where the smoke layer base is close to the fire which is suitable for car park fire where the ceiling clearance is relatively low; or 0.34 where the air approaches the fire from one side and push the fire plume to another side. C_p refers to the specific heat capacity of surrounding ambient air (Morgan, Vanhove and De Smedet, 2004).

The design car park fire is generally similar to that of the design fires in large atrium space which can be analysed as an axisymmetric plume as shown in Figure 2.20. In this case, the mass flow rate of the plume can be obtained using the ASHRAE atrium plume model (John H. Klote, 2014).

$$\text{Mass flow rate of plume}, m_s = 0.071{Q_c}^{1/3}z^{5/3} + 0.0018Q_c$$

Where Q_c is the convective heat transfer rate associated with the fire and z is the height of smoke layer measured from the base of fire.

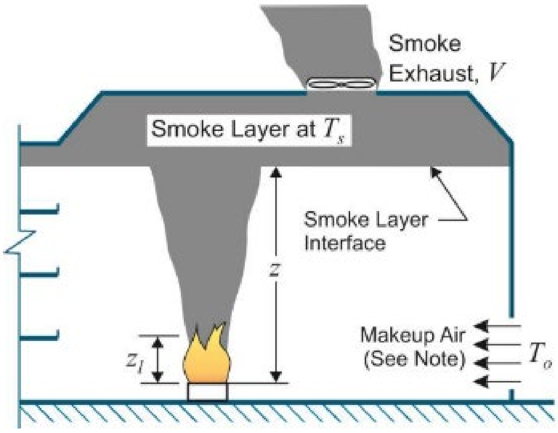


Figure 2.20: Axisymmetric plume in smoke atrium model (John H. Klote, 2014)

According to (Singapore Civil Defence Force, 2008), the design fire in the CFD modelling shall be located furthest away from the smoke extraction point and across the boundaries of two adjacent smoke control zoning to demonstrate the worst-case scenario for a better validation of the ventilation performance of impulse jet fans system in car parks. The CFD simulation should be done in a transient state for at least 20 minutes in order to observe and analyse the distribution of smoke and temperature throughout the burning process.

2.10 Summary

Temporary storage of vehicles is the primary function of car parks which causes these building spaces to be extremely hazardous due to the enormous amount of fuel load available. Mechanical ventilation system in the enclosed car park plays a vital role in safeguarding the life safety of humans by creating a safe and tenable environment during both day-to-day operation and fire event. Enclosed car parks which usually have very limited permanent openings to the outdoor environment is unable to provide the enclosure with sufficient ventilation by natural means. Thus, a mechanical ventilation system must be provided to deliver adequate ventilation in such building spaces. Recently, jet fans have been widely preferred over the traditional ducted ventilation by many fire safety designers for car park ventilation applications, mainly due to the cost saving and low design complexity advantages. However, not many experimental studies have been carried out to compare the ventilation performance between the two different ventilation systems. During a car park fire, several parameters must be critically analysed to evaluate and validate the ventilation performance, such as the concentration of poisonous combustion products, distribution of temperature, visibility, and airflow velocity. A full-scale experimental approach is traditionally used to evaluate the ventilation performance. However, this approach is extremely expensive and time consuming to perform. CFD modelling is a modern computational approach that can be used to validate the ventilation performance with significant cost reduction and time saving.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Project flow chart

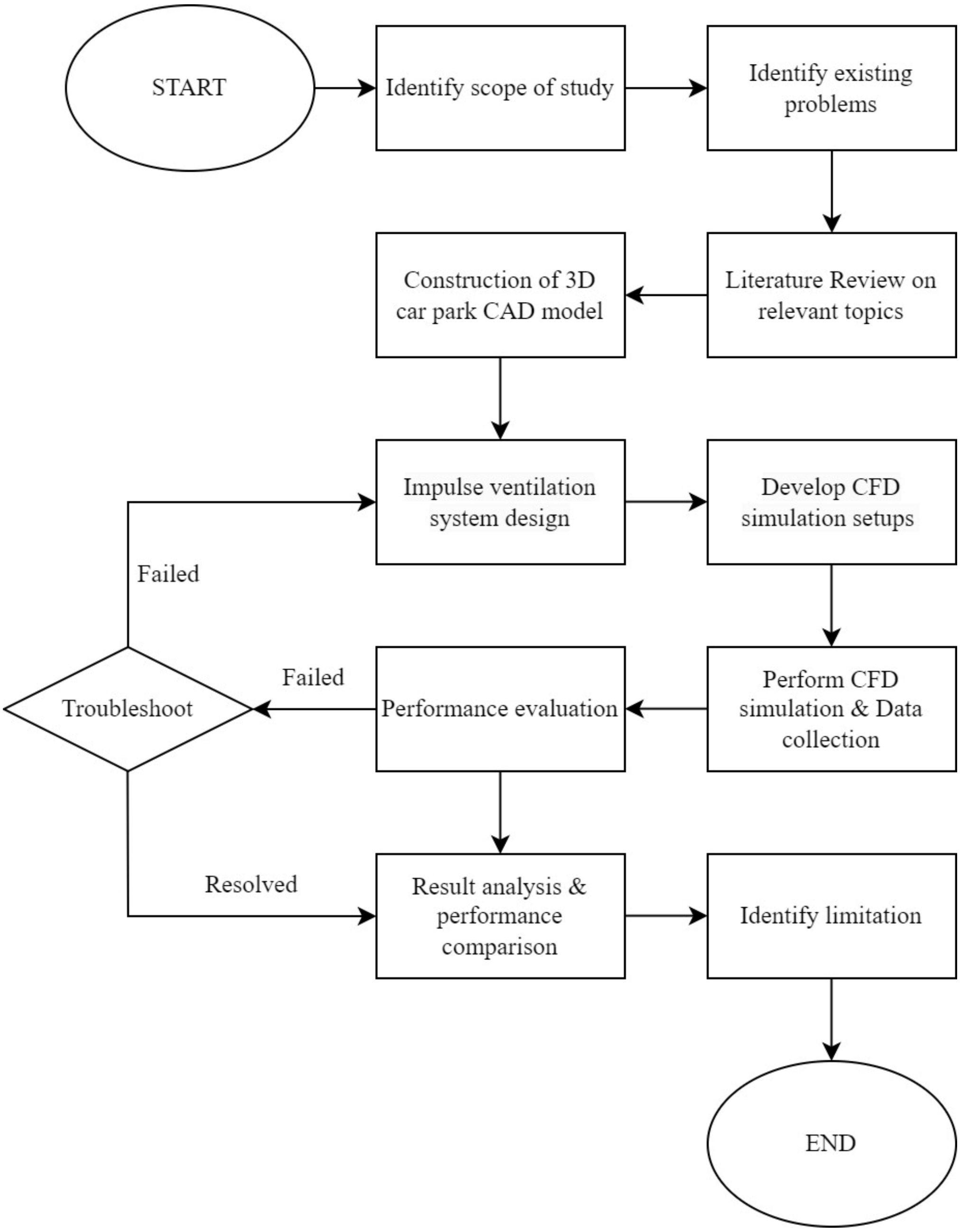


Figure 3.1: Project flow Chart

The scopes of the study were identified at the beginning of the project to set a focal point and narrow down the areas that need to be covered and studied in this project. Next, research studies were carried out to identify the existing problems associated with the traditional ducted mechanical ventilation system used in car parks. Literature review on various topics related to car park ventilation such as fire risk in the car park, past car park fire incidents, and design requirements of car park ventilation system have also been covered in this project.

Prior to the simulation stage, a 3D CAD model of a single-story enclosed car park was constructed using Solidworks software. Meanwhile, an impulse jet-fan ventilation system was designed from scratch for the existing basement car park at UTAR Sungai Long with strict accordance with the local authorities' requirements. The design works included jet fan placement, jet fan selection, jet fan zoning arrangement, and the sizing calculation of supply and extraction fans.

After the preliminary design was completed, the 3D CAD model of the car park model was imported to ANSYS CFX software using the Parasolid format. The boundary condition settings were then applied in the simulation setup stage using ANSYS-Pre for both the ducted ventilation system and the impulse jet fans ventilation system.

After all simulation set-ups and appropriate mesh sizing were completed, steady-state CFD simulations were executed in two different ventilation system models to simulate and compare the ventilation performance between the ducted ventilation system and the impulse jet-fan ventilation system in the event of a fire. The ventilation performance was evaluated based on several parameters which include temperature distribution, CO concentration, CO_2 concentration, smoke flow pattern, and airflow velocity. However, if the experimental findings failed to achieve a satisfactory outcome, for example, unsatisfactory convergence of residual values, the experimental simulation will first be troubleshot to identify the possible source of error. If the findings remained unsatisfactory, the process will be reverted to the initial preliminary design stage.

Finally, limitations that could possibly influence the overall project outcomes were discussed to interpret the validity of experimental findings and recommendations were proposed for future projects to further improve the accuracy of the experimental outcomes.

3.2 Enclosed car park model geometry and introduction

A single-storey basement car park situated at the block KB of UTAR Sungai Long campus was selected as the enclosed car park model for the simulation analysis of this project. This car park accommodates parking lots for both general vehicles and motorcycles which has an approximate total floor area of 5800 m^2 with a ceiling height of 3 m as shown in Figure 3.2. This basement car park consists of three protected staircases and two protected lift lobbies for emergency evacuation and fire service intervention purposes. It consists of a two-way ramp structure connected to the ground floor that is assumed to be permanently opened to the outdoor environment.

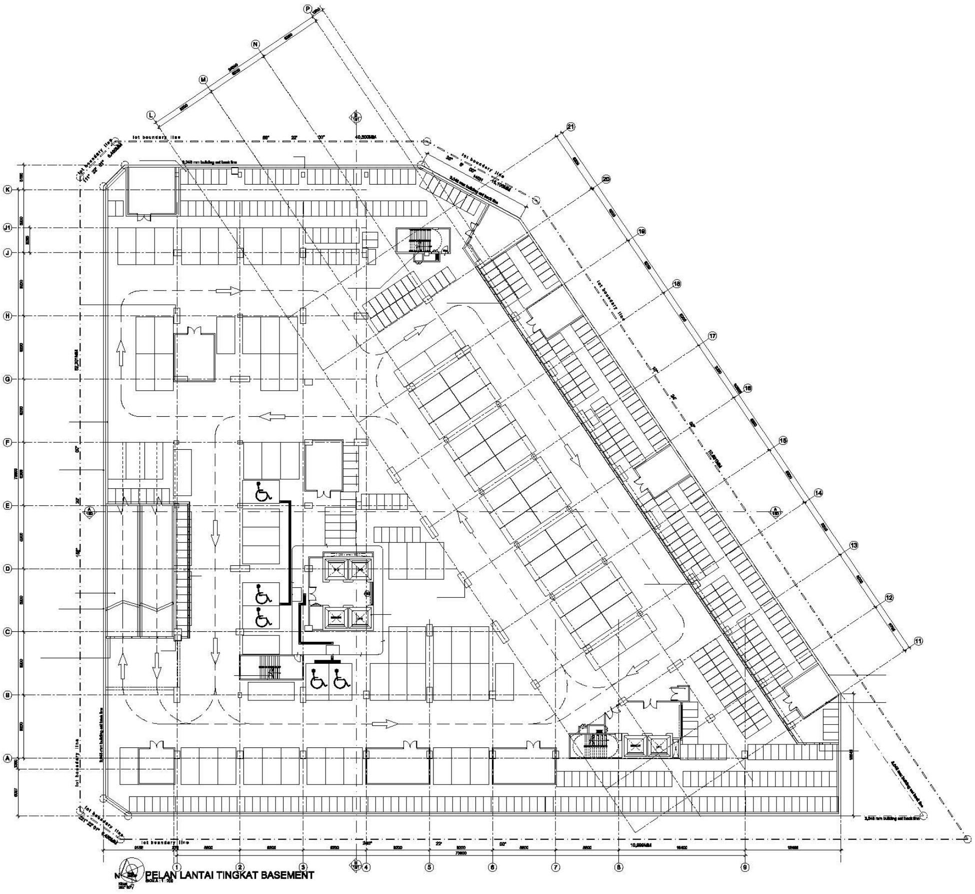


Figure 3.2: Layout drawing of the basement car park at UTAR block KB

A 3D CAD model of the enclosed car park with a drawing scale of 1:1 was constructed using Solidworks software as shown in Figure 3.3. All the original structural elements like columns, walls, floor, and ceiling were presented in the 3D CAD model. The ceiling was assumed as a flat slab structure without any down-stand beam to reduce the complexity of the geometry model.

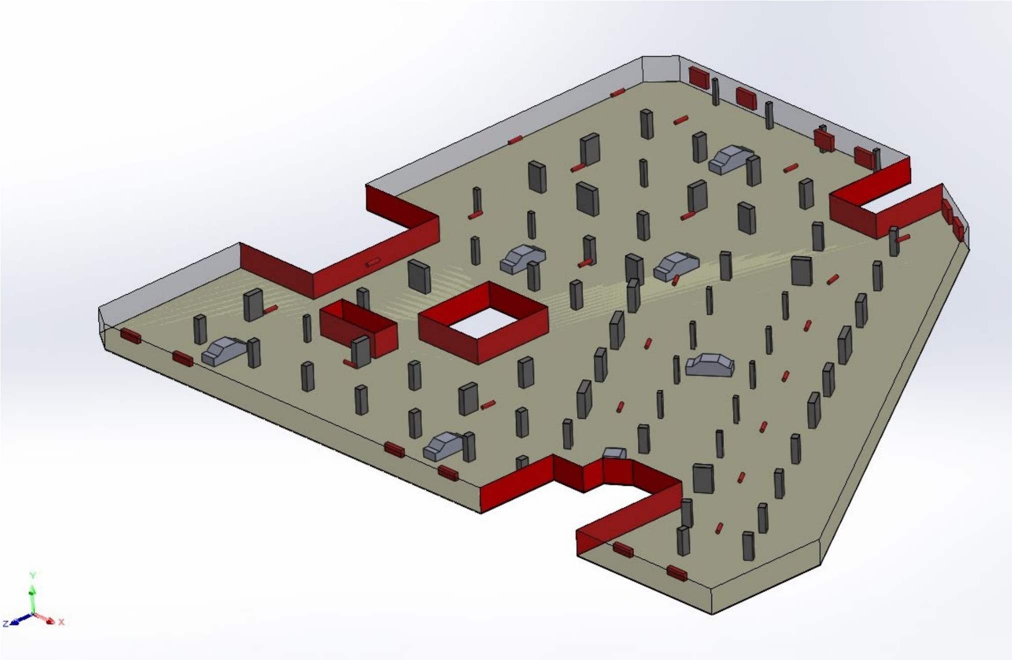


Figure 3.3: 3D CAD model of the basement car park

This enclosed car park was originally designed with a conventional ducted ventilation system with a total extraction rate of 91.34 kg/s and fresh air supply rate of 43.22 kg/s delivered through 101 points of exhaust grille and 62 points of fresh air grille distributed in the car park. In this project, impulse jet fans ventilation was designed for the same enclosed car park to compare the ventilation performance between the two ventilation systems in the event of a car fire. The design procedures of the jet fans system will be discussed in Chapter 3.3. In the jet fans model, the fan rooms were relocated to be closer to the main supply air grilles and extraction air grilles as shown in Figure 3.4.

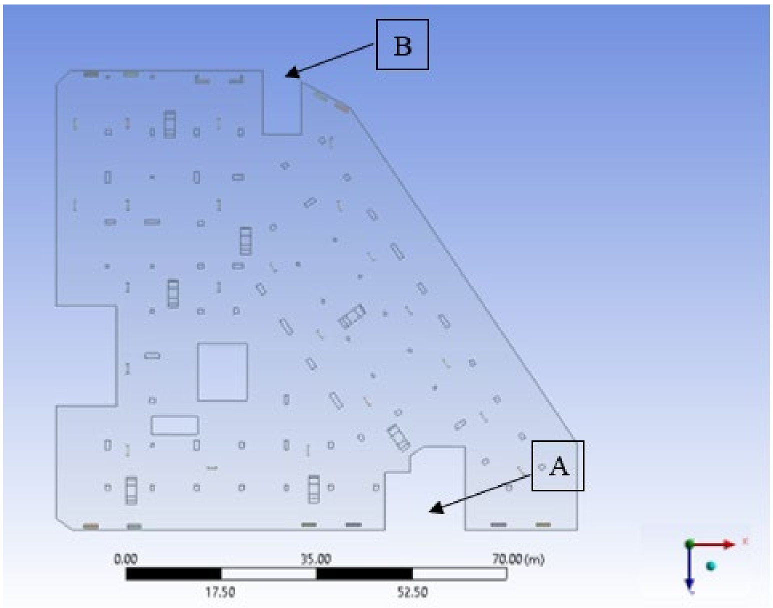


Figure 3.4: Location of fan rooms in jet fans system; (A) Fresh air fan room, and (B) Exhaust fan room

3.3 Impulse jet-fan ventilation system design methodology

The impulse jet-fan ventilation system was designed in accordance with the car park ventilation design requirements gazetted by several authorities including BOMBA, SCDF, and British Standard BS 7346 — Components for smoke and heat control systems (Singapore Civil Defence Force, 2008; Fire and Rescue Department of Malaysia, 2010; British Standards Institution, 2013).

3.3.1 Smoke control zoning

The car park was divided into three different smoke control zones with a total area of not more than 2000 m^2 (excluding staircases, fan rooms, and lift lobbies) in each zoning as shown in Figure 3.5. The floor area occupied by the ramp was excluded from the zoning area and was assumed as a permanent opening. Each of the smoke control zones will serve as an individual jet-fan system which comprised individual sets of fresh air supply fans, smoke exhaust fans, and jet fans to provide a balanced ventilation. The exhaust fan system was designed to run in two separate parts with two exhaust fans serving one smoke control zone to provide redundancy so that the total extraction capacity will not fall below 50% of the total required smoke extraction rate when any one of the parts fail. The fresh air fan systems were also designed in a similar manner. In this design, the fresh air grilles (FAG) were located at the opposite end of the exhaust air grilles (EAG) as shown in Figure 3.5 to create a cross-ventilation flow path to ensure that the air flows in a single direction towards the extraction points with minimal opposing flow or recirculation flow.

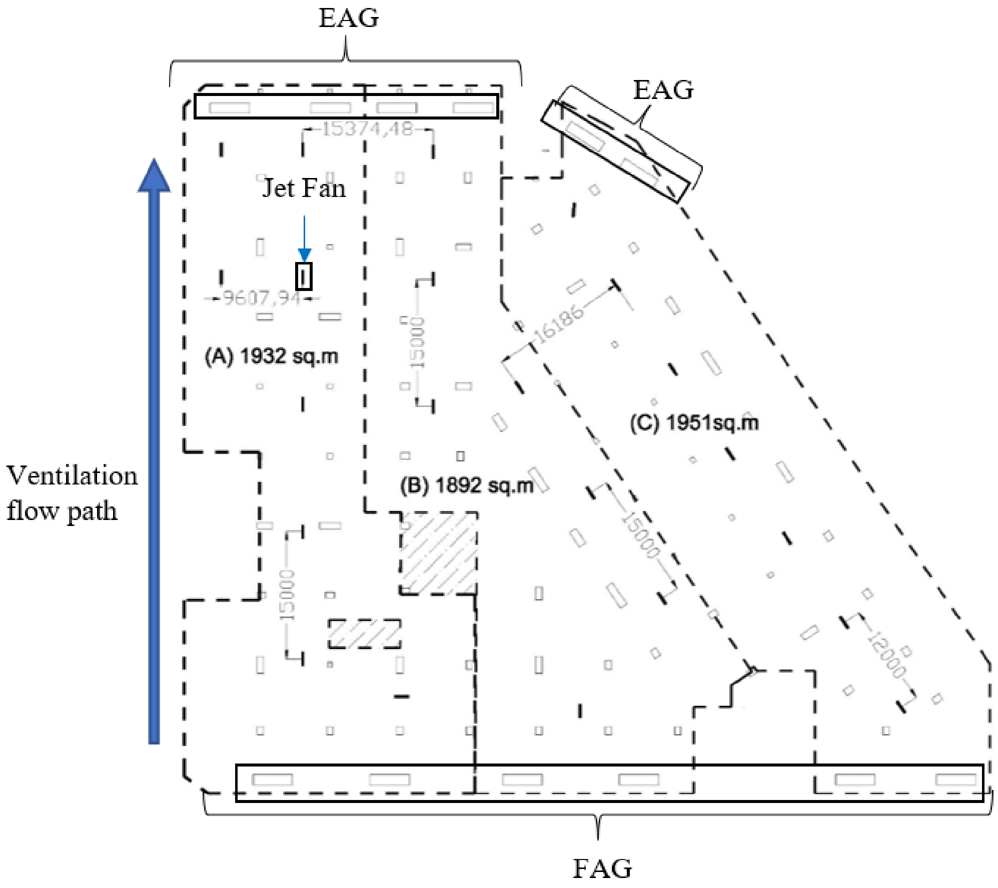


Figure 3.5: Smoke control zoning of impulse jet fans system

Table 3.1: Floor area of smoke control zoning

Smoke Control Zone	Total Floor Area (m^2)
A	1932
B	1892
C	1951

3.3.2 Smoke exhaust and fresh air supply systems

According to the local authorities' requirements, the exhaust system shall be designed to provide at least 12 ACH during the fire mode operation while the replacement air supply shall be at least 50% and not more than 75% of the exhaust fan capacity (Dato' Hamzah Bin Abu Bakar, 2006; Malaysia International Law Book Services, 2021). In the Handbook of Smoke Control Engineering, the ASHRAE standard recommends a replacement air supply rate of between 85% to 95% of the total smoke extraction rate (Klote et al., 2012). Whereas the Australian Standard AS 1668 — Mechanical Ventilation In Buildings recommends a makeup air supply rate of between 75% to 90% of the total smoke extraction rate (Shoket, 2018).

In this project, the impulse jet fans ventilation system was designed at 12 ACH which conforms with the minimum requirement by BOMBA as stated in (Dato' Hamzah Bin Abu Bakar, 2006). The replacement air will be provided at a rate of 75% of the total smoke extraction capacity which satisfies most of the authorities' requirements as well as the recommendations by ASHRAE. In addition, the smoke exhaust system and fresh air supply system in all smoke control zones were designed to run in two separate parts with two exhaust fans and two supply air fans serving each zone separately as shown in Figure 3.9.

This design approach was part of the conformance to the local authority design requirement to provide redundancy for the ventilation system so that the effective capacity of the smoke exhaust system or fresh air supply system will not fall below 50% of the total required capacity when any of the parts encounters failure. Therefore, the total required exhaust capacity and supply air capacity were split into two fans as shown in fan sizing calculation below:

The exhaust fan capacity (CMH) was calculated using the formula below:

$$\text{Exhaust capacity per fan} = \frac{\text{Area} \times \text{Height} \times \text{ACH}}{2\ \text{Fans}}$$

The supply fan capacity (CMH) was taken at 75% of the exhaust fan capacity:

$$\text{Supply air capacity per fan} = 0.75 \times \text{Exhaust capacity per f}an$$

The sizing calculation of the exhaust fan and supply fan in each smoke control zones were shown in Table 3.2.

Table 3.2: Sizing calculation of exhaust fan and supply fan system at 12 ACH

Zone	Area (sq.m)	Height (m)	Volume (m^3)	ACH	Total extraction rate required (CMH)	Qty.	Extraction capacity required per fan (CMH)	Smoke spill fan capacity (CMH)	Supply air fan capacity (CMH)
A	**1,932**	**3**	5796	12	69552	**2**	34776	40000	30000
B	**1,892**	**3**	5676	12	68112	**2**	34056	40000	30000
C	**1,951**	**3**	5853	12	70236	**2**	35118	40000	30000

Based on the calculation as shown in Table 3.2, the extraction capacity per fan required in the respective zone was 34776 m^3/h in zone A, 34056 m^3/h in zone B, and 35118 m^3/h in zone C. During the operation of fans, a certain amount of static pressure losses will certainly be encountered by the fans which will affect flow rates as well as the ventilation performance. Therefore, by taking the static losses into consideration, the extraction capacity of all six smoke spill fans was rounded up to 40000 m^3/h with an approximate 10% safety factor to provide redundancy for the efficiency of smoke extraction. As mentioned earlier, the airflow rate of the supply air fans was designed at 75% of the total extraction capacity. Thus, the required capacity for each supply air fan was calculated at 30000 m^3/h.

Axial fan (AXC—F) with 2 hours temperature resistance of 350 ºC from System Air was selected for both the smoke spill fans and supply air fans in order to fulfil the temperature resistance requirement from the authority as stated in (Dato' Hamzah Bin Abu Bakar, 2006).

Figure 3.6: Axial fan (AXC—F) for exhaust fan and supply air fan (System air, 2009)

3.3.3 Selection and placement of jet fans

Jet fans help to move and direct the airflow by pushing and sweeping the airflow towards the extraction points with the help of the high momentum thrust created by the propeller in the jet fan units. The selection of jet fans is commonly based on the thrust value which could range from as low as 20 N to 100 N. The required thrust value for the selection of jet fans is highly dependent on the architectural design of the car park layout as well as the placement and spacing of jet fans. With the assistance of CFD simulation, the designer can accurately determine the most suitable thrust value required to ensure a good ventilation performance with minimal air stagnation in the car park.

In this project, jet fans with a thrust value of 66 N from System Air were selected to be used for the impulse jet fans ventilation system. The following are the manufacturer's specifications of the selected jet fan:

Table 3.3: Jet fan specification (System air, 2013)

Model	AJR (B)-400-2/4 (B)-TR-L
Power (kW)	1.7 (High) / 0.37 (Low)
Thrust (N)	66 (High) / 17 (Low)
Fan impeller speed (rpm)	2886 (High) / 1443 (Low)
Maximum airflow (m^3/s)	2.62 (High) / 1.32 (Low)
Weight (kg)	85
Outer dimension (mm)	1875 (Length) x 516 (Diameter)
Temperature resistance	2 hours at 350 °C

Figure 3.7: 66 N AJR-TR Jet Fan from System Air (System air, 2013)

The placements of the jet fans were done with reference to the fan spacing recommendations by (Venco, 2020) and (Fire and Rescue Department of Malaysia, 2010) which recommended a parallel distance of 15 m and a serial distance of 30 to 35 m. Parallel distance refers to the distance between the two horizontally adjacent jet fans. Whereas the serial distance refers to the longitudinal distance between the two jet fans in the direction of induced airflow.

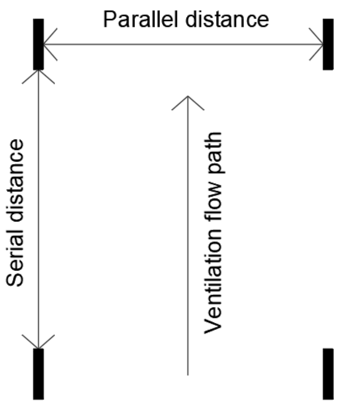


Figure 3.8: Spacing of jet fans

Table 3.4: Recommended jet fan spacing (Venco, 2020)

Thrust Value (N)	Parallel Distance (m)	Serial Distance (m)
30	8-10	20
50	15	35
80	15-17	50
100	15-20	70

According to (British Standards Institution, 2013), the total combined air flow rate created during the jet fans operation shall not exceed the total designed extraction rate in each smoke control zone to ensure a smooth and efficient extraction of smoke. This was also taken into consideration in the design of the impulse jet fans ventilation for this project as shown in Table 3.5.

Table 3.5: Combined air flow rate of jet fans and designed extraction rate

Zone	Number of jet fans	Combined air flow rate of jet fans (CMH)	Total designed extraction rate (CMH)
A	8	75456	80000
B	7	66024	80000
C	7	66024	80000

All the jet fan units were placed at a height of 2.5 m which measured between the finished floor level to the centre point of the jet fans. The exact location of the jet fans in respective smoke control zones were shown in Table 3.6.

Table 3.6: Locations of jet fans

Smoke control zone	Jet fan	Location (x, y)
Zone A	JF A1	(25632, 11397)
	JF A2	(13990, 15835)
	JF A3	(13990, 30835)
	JF A4	(13990, 45835)
	JF A5	(13990, 60835)
	JF A6	(13990, 75835)
	JF A7	(4377, 60835)
	JF A8	(4377, 75835)
Zone B	JF B1	(46631, 9727)
	JF B2	(56289, 22966)
	JF B3	(47981, 35395)
	JF B4	(39508, 47824)
	JF B5	(29359, 45835)
	JF B6	(29359, 60835)
	JF B7	(29359, 75835)
Zone C	JF C1	(84482, 10169)
	JF C2	(77778, 20112)
	JF C3	(71034, 30055)
	JF C4	(64315, 39998)
	JF C5	(57612, 49940)
	JF C6	(50894, 59884)
	JF C7	(45927, 68728)

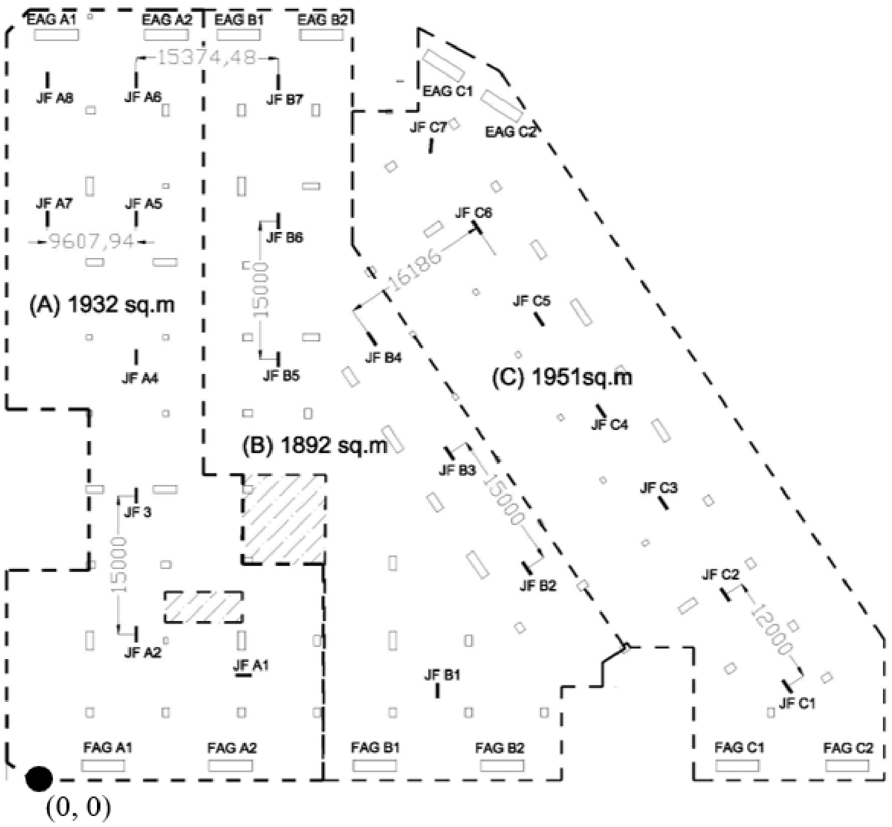


Figure 3.9: Layout diagram of impulse jet fans ventilation system

In this design, the jet fans were arranged as illustrated in Figure 3.9 with a serial distance of not more than 15 m and a parallel distance of not more than 20 m. The jet fans were arranged in such a way to optimise the ventilation performance by reducing the chances of stagnation airflow. Smoke control zone A has a total of 8 units of jet fans and 7 units of jet fans in zone B and C respectively. All the jet fans selected are capable to deliver a maximum thrust value of 66 N with 2 hours fire resistance rating of up to 350 ºC.

3.4 Car fire simulation

The car park was assumed as a general parking space that contains only general passenger vehicles. A fire source was simulated on the bonnet of a vehicle as shown in Figure 3.10 at 1 m above ground level at (61165, 15000). The simulated fire source was placed at a location furthest away from the exhaust grilles and along the boundary line across the two adjacent smoke control zones of the impulse jet fans ventilation system (as shown in Figure 3.10) to simulate the worst-case scenario for the location of the car fire as required by (Singapore Civil Defence Force, 2008). According to (Singapore Civil Defence Force, 2008; British Standards Institution, 2013), the heat release rate of the steady-state design fire for the CFD fire modelling shall be at least 4 MW in the case of passenger vehicle fire assuming that the car park is protected by sprinklers. Steady-state fire refers to when the fire has achieved a steady state condition in which vigorous fire growth like an explosion or flashover is not likely to happen.

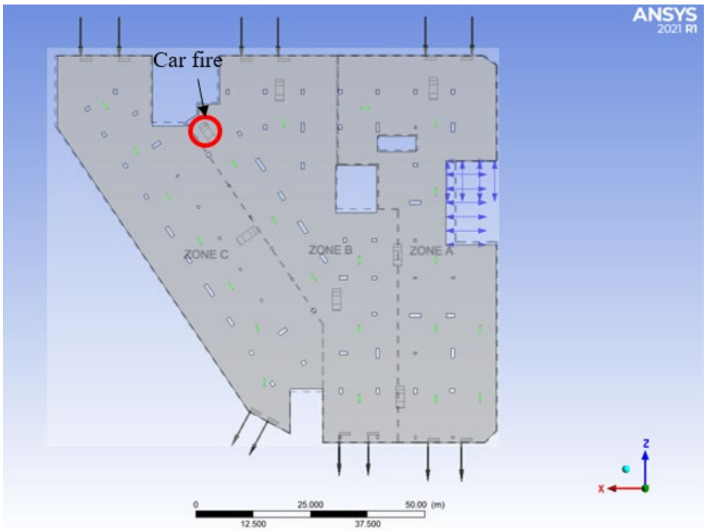


Figure 3.10: Location of car fire

In this project, the mass flow rate and temperature of smoke used for the simulation were obtained from the experimental results of a full-scale car fire test of a 4-door sedan passenger car carried out by (Li et al., 2017). According to the experimental findings, the maximum smoke production rate of a car fire was 1.76 m^3/s while the peak smoke temperatures were measured at a range of 89 to 285 °C at various locations close to the burning vehicle. The design car fire in this simulation project was simulated as a mass and momentum inlet with an initial temperature of 300 °C which was slightly higher than the peak smoke temperature of 285 °C for a conservative approach. The volumetric flow rate of the smoke was converted into a mass flow rate using the formula as shown below:

$$\text{Smoke density at 300 °C}$$

$$= 1.22 \times \left[\frac{290}{\text{Smoke Temperature} + 273}\right]$$

$$= 1.22 \times \left[\frac{290}{300 + 273}\right]$$

$$= 0.6175\ \mathrm{kg/m^3}$$

$$\text{Mass flow rate of smoke, } \mathrm{m_s}$$

$$= \text{Volumetric flow rate } \times \text{Smoke Density}_{@300\ °\mathrm{C}}$$

$$= 1.76\,\frac{\mathrm{m^3}}{\mathrm{s}} \times 0.6175\,\frac{\mathrm{kg}}{\mathrm{m^3}}$$

$$= 1.09\ \mathrm{kg/s}$$

Formula reference: (V. K. Jain, 2006)

Other than emitting high-temperature smoke, the combustion products were also modelled as a multi-species mixture that contained CO and CO_2 with a mass fraction of 0.0299 and 0.9654 respectively with reference to the vehicle fire emission results of several gaseous products obtained by (Truchot, Fouillen and Collet, 2018). The remaining combustion product like NO and NO_2 was ignored due to extremely small and negligible values.

3.5 Boundary conditions

All the important information and relevant details related to boundary condition settings of both simulation models will be elaborated in this chapter.

3.5.1 Air domain

In this simulation, an enclosure volume was created to model the air medium contained within the car park model. All the structural elements like walls, columns, floor, and ceiling were removed from the enclosure leaving only the air domain for CFD simulation. The ambient air domain in the car park was modelled as a multi-species mixture that contained gaseous components like O_2 and N_2 with respective mass fraction values. Other gas components like CO_2 and H_2O were ignored due to negligible mass fraction at ambient conditions. The boundary condition settings of the ambient air domain are shown in Table 3.7.

Table 3.7: Boundary condition of ambient air domain

Parameters	Boundary condition
Multi-species mixture	O_2: 0.23 N_2: 0.77
Air temperature at ambient condition	30 °C
Air density	1.195 kg/m^3
Pressure	1 atm
Walls	Adiabatic and non-slip surface

3.5.2 Car fire source

The design fire source was simulated as per the experimental findings of the full-scale vehicle fire test conducted by (Li et al., 2017). The boundary settings of the car fire are shown in Table 3.8.

Table 3.8: Boundary condition of design car fire

Parameters	Settings
Mass & Momentum domain	Inlet
Multi-species mixture of smoke (Truchot, Fouillen and Collet, 2018)	CO_2: 0.9654 CO: 0.0229
Smoke layer temperature	300 °C
Mass flow rate of smoke	1.09 kg/s
Location (x, y)	61165, 15000
Flow direction	Normal to boundary condition
Car surface	Adiabatic and non-slip wall

3.5.3 Ducted mechanical ventilation system

The boundary settings of the ducted mechanical ventilation system were set in accordance with the existing design of the block KB basement car park at UTAR Sungai Long campus. The existing ducted ventilation system at the car park comprises both the fresh air supply and smoke exhaust system delivered through the conventional ductwork system. The 3D CAD model of the ducted system was simplified by removing the ductwork and leaving only the fresh air grilles and exhaust grilles. The fresh air grilles were set as inlets while the exhaust air grilles were set as outlets with respective mass flow rates as shown in Table 3.9. The fresh air supply through the inlets and openings were set as a multi-species mixture with O_2 and N_2 at 0.23 and 0.73 respectively at 30 ºC which were similar to the atmospheric conditions.

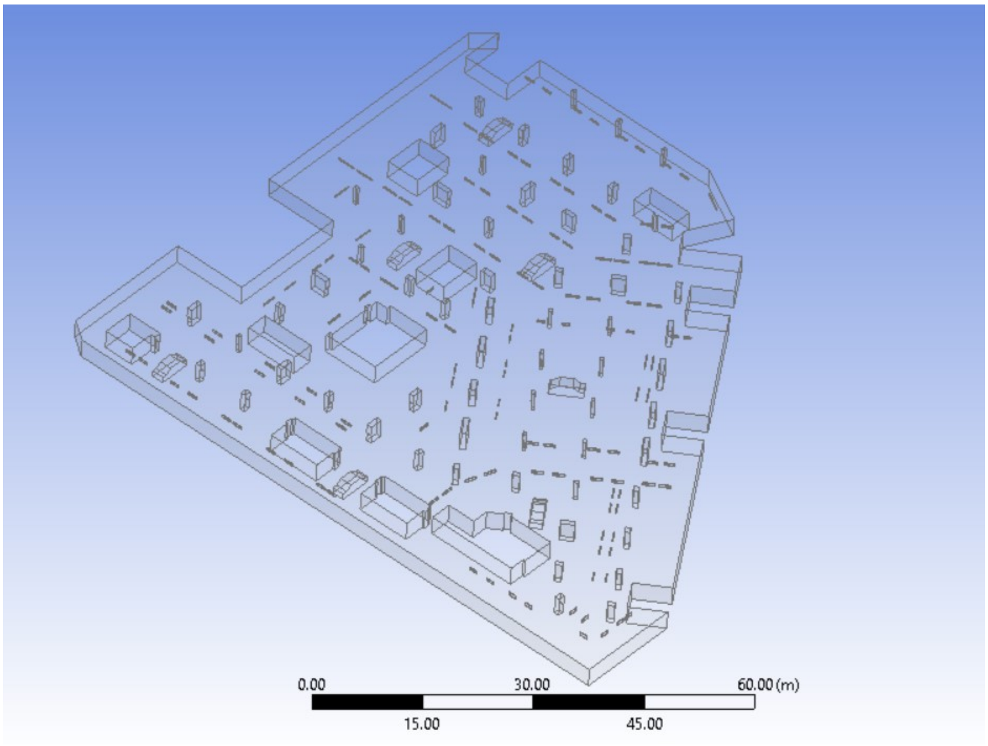


Figure 3.11: 3D CAD model of ducted ventilation model

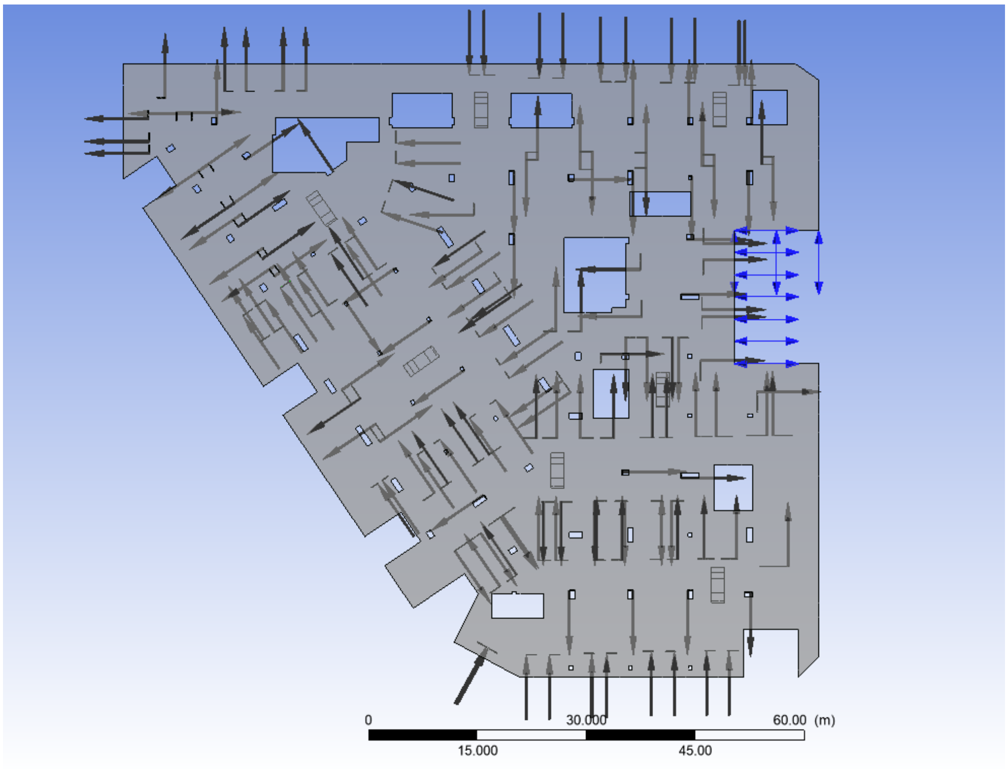


Figure 3.12: Boundary settings of ducted ventilation system

Figure 3.12 is the as-built drawing of the existing ducted ventilation system at block KB basement car park at UTAR Sungai Long campus. As can be seen from the existing design, there are six smoke control zones in total with each zone comprising a pair of fresh air duct and exhaust air duct serving the respective zones individually. The mass flow rate of the respective fresh air grilles and exhaust air grilles are shown in Table 3.9.

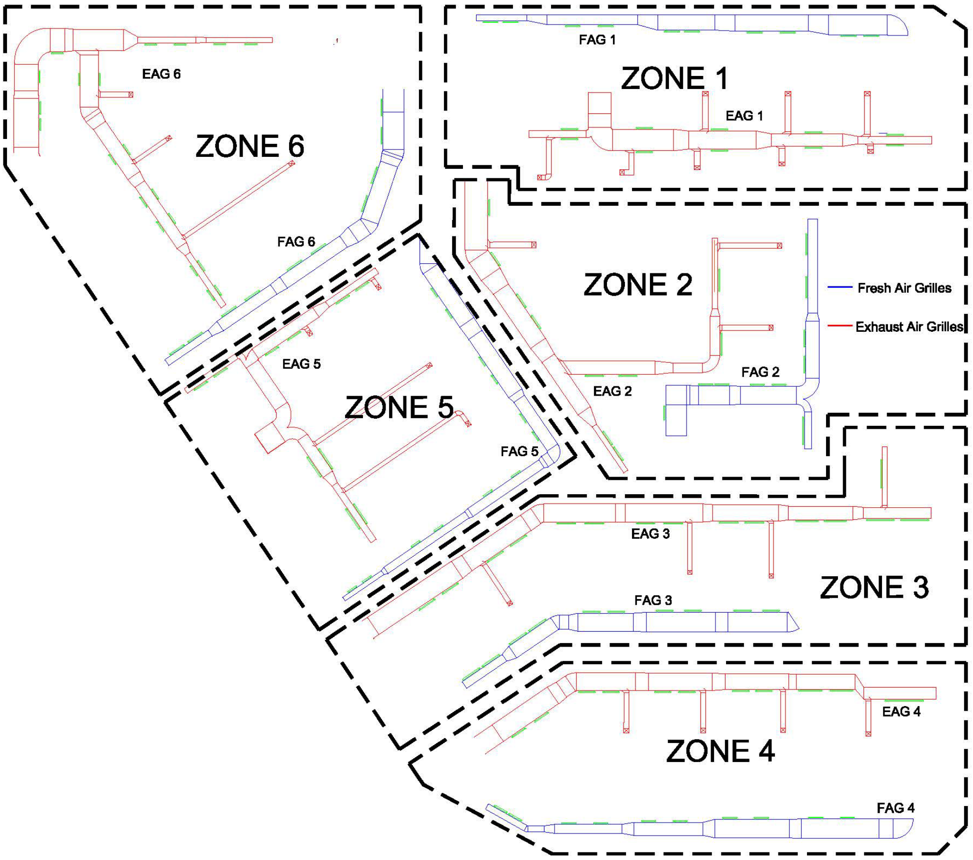


Figure 3.13: Existing layout design of ducted mechanical ventilation system

Table 3.9: Mass flow rates of respective fresh air grilles and exhaust air grilles

Fresh air grilles	Boundary Condition	Mass Flow Rate (kg/s)	Quantity
FAG 1	Inlet	0.8555	10
FAG 2		0.6111	10
FAG 3		0.7333	10
FAG 4		0.6321	10
FAG 5		0.5285	12
FAG 6		0.8555	10
Exhaust air grilles	Boundary Condition	Mass Flow Rate (kg/s)	Quantity
EAG 1	Outlet	0.9510	18
EAG 2		0.9405	13
EAG 3		0.8148	18
EAG 4		0.8416	15
EAG 5		0.9068	14
EAG 6		0.9568	23

3.5.4 Impulse jet fans ventilation system

The boundary settings of the impulse jet fans ventilation system were set in accordance with the design as discussed in Chapter 3.3 which comprises three main components, namely the fresh air supply, exhaust system, and jet fans. Similarly, the six fresh air grilles and six exhaust air grilles were set as inlets and outlets with the respective mass flow rates as shown in Table 3.11. The fresh air supply through the inlets and openings was set as a multi-species mixture with O_2 and N_2 at 0.23 and 0.73 respectively at 30 ºC which were similar to the atmospheric conditions.

The jet fan units were simulated as a cylindrical object with a radius of 0.258 m and length of 0.1535 m located at 2 m above the ground level and modelled as subdomains with momentum source coefficient calculated from the thrust value of the jet fans using the formula below:

$$\text{Momentum coefficient}$$

$$= \frac{\text{Thrust (N)}}{\text{Volume of Jet Fan } (\text{m}^3)}$$

$$= \frac{66}{\pi R^2 L}$$

$$= \frac{66}{\pi (0.258)^2 (1.535)}$$

$$\text{Momentum coefficient of each jet fan} = 169\ \text{N/m}^3$$

The replacement air supply grilles and exhaust grilles were simulated as rectangle openings located at two opposite ends of the enclosed car park. The grilles were assumed to have 50% area of openings and the dimensions were sized in such a way as to ensure that the air velocity near the grilles will not exceed 5 m/s as per the design requirement by (Dato' Hamzah Bin Abu Bakar, 2006) using the formula below by (Building Calculator, 2023).

$$\text{Grille Free Area } (m^2) = \frac{\text{Air Flow Rate}}{\text{Face Velocity } \times 3600}$$

$$\text{Total Grille Area } (m^2) = \frac{\text{Grille Free Area}}{\text{Grille Free Area Percentage}} \times 100\%$$

$$\text{Grille Height (m)} = \frac{\text{Total Grille Area}}{\text{Grille Width}}$$

Table 3.10: Grille sizing for exhaust air grille and fresh air grille

	Exhaust Air Grille	Fresh Air Grille
Air Flow Rate (m^3/h)	40000	30000
Face Velocity (m/s)	5	
Grille Free Area (m^2)	2.222	1.667
Grille Free Area Percentage	50%	
Total Grille Area (m^2)	4.444	3.334
Grille Width (m)	2.5	
Grille Height (m)	1.8	1.4
Grille Dimension (m)	2.5 (W) x 1.8 (L)	2.5 (W) x 1.4 (L)

With reference to the location of the design car fire highlighted in Figure 3.14 below which was located across the boundaries the smoke control zone B and C in order to simulate the worst-case scenario. In view of the design requirement by (Singapore Civil Defence Force, 2008; British Standards Institution, 2013), the jet fans system in the affected fire zone and adjacent zones must be activated to contain the smoke particulate within the affected zone.

Therefore, since the design fire was located across the boundaries of zone B and C, the jet fans system in zone B and C (affected zones) as well as the adjacent zone (zone A) will be activated in the CFD simulation.

Table 3.11: Boundary settings of jet fans ventilation system

Fresh air grilles	Boundary condition	Mass flow rate (kg/s)
FAG A1 & A2	Inlet	9.7
FAG B1 & B2		
FAG C1 & C2		
Exhaust air grilles	Outlet	12.93
EAG A1 & A2		
EAG B1 & B2		
EAG C1 & C2		
Jet fans	Momentum coefficient	Momentum source (N/m^3)
JF A1		-140 (X-axis)
JF A2-A8		-140 (Z-axis)
JF B1-B7		
JF C1-C7		
All surfaces of jet fans	Adiabatic and non-slip surface	

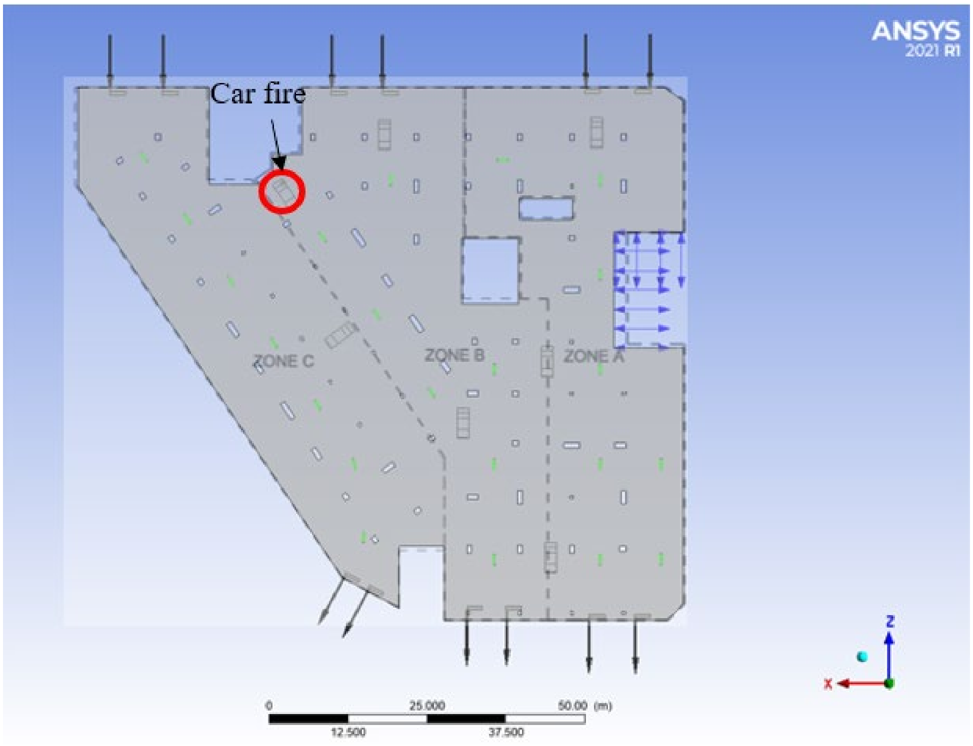


Figure 3.14: Boundary settings of jet fans ventilation system

3.6 Simulation Model

ANSYS CFX software was selected as the software for the CFD simulation of this project. Owing to the limitation of computer systems and project time constraints, the CFD simulation was run in a steady state instead of transient simulation. The shear stress transport governing equation was selected to solve the highly turbulent fluid flow which involved the simulation of smoke and heat and mass transfer in a large enclosure. The convergence criteria for the residual value were set as 1×10^{-4}. All the relevant details of the simulation and computer hardware configuration are as shown in Table 3.12 and 3.13.

Table 3.12: Simulation model details

Simulation software	ANSYS CFX 2021 R2
Analysis type	Steady state
Governing equation	Shear stress transport
Fluid model	Turbulence
Turbulence numeric	First order
Timescale control	Auto timescale
Length scale option	Aggressive
Convergence criteria	
Residual type	RMS
Residual target	1×10^{-4}
Convergence control	
Minimum Iteration	1
Maximum Iteration	300

Table 3.13: Specifications of computer system

Processor	Intel(R) Core (TM) i7-6800 K CPU @ 3.40 GHz (12 CPUs)
RAM	128 GB
System type processor	64-bit OS
Graphic Memory	NVIDIA GeForce GTX 1060 6 GB

3.7 Meshing

In this project, three different mesh sizing ranging from coarse, medium to fine were performed on the CFD simulation for both the ducted ventilation model as well as the jet fan model for mesh independence study to verify the accuracy of the simulation results. The following as shown in Table 3.14 are the meshing details of the simulations.

Table 3.14: Mesh size and number of elements

Model	Mesh size (mm)		Number of elements	Number of nodes
Ducted ventilation system	Fine	100	49026114	9067972
	Medium	200	16446848	3081892
	Coarse	400	10931059	2037652
Impulse jet fans system	Fine	100	39374813	12598266
	Medium	200	8759053	3176826
	Coarse	400	3167591	646810

Figures 3.15 and 3.16 illustrate the mesh generation of both ducted ventilation system model and impulse jet fans ventilation system model at an element size of 100mm. Finer meshing were done at critical areas such as the grilles and jet fans to provide a more accurate simulation result.

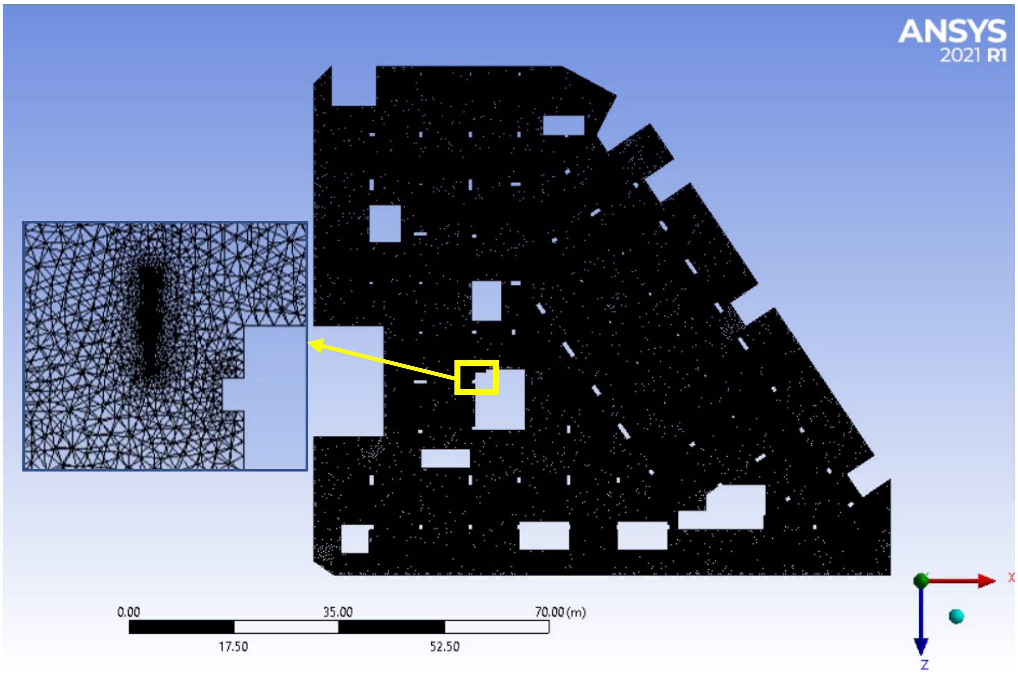


Figure 3.15: Mesh generation of ducted ventilation system model

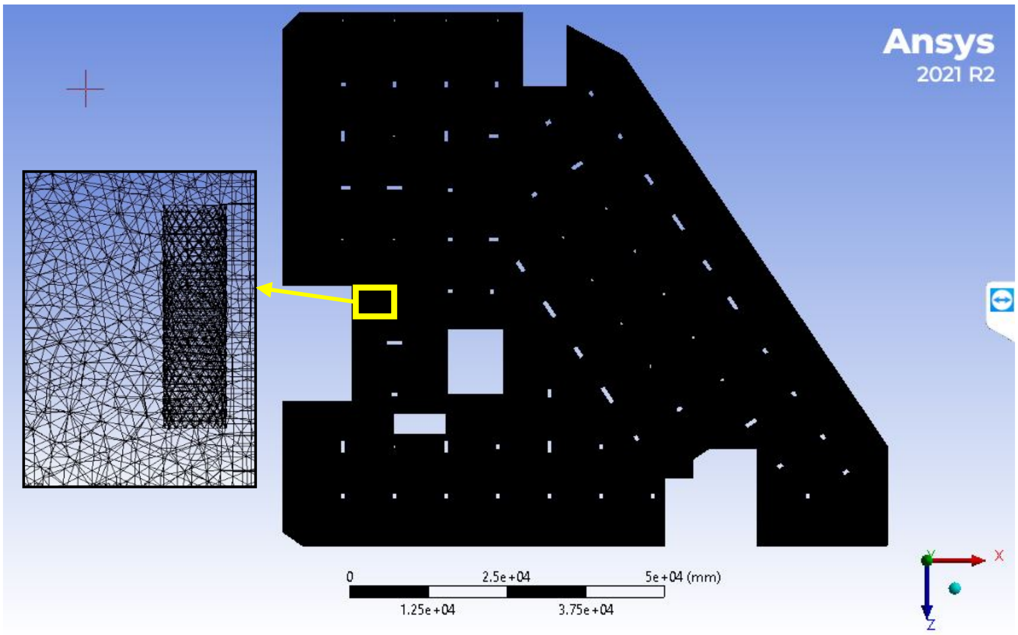


Figure 3.16: Mesh generation of impulse jet fans ventilation system

3.8 Summary

In this project, ANSYS CFX software was employed to perform CFD numerical simulation using shear stress transport as the governing equation to solve the highly turbulent fluid flow that involved heat and mass transfer. Meanwhile, the 3D CAD models of ducted ventilation system and jet fans system were constructed using Solidworks CAD software. The boundary settings for the CFD simulation of the ducted ventilation system were applied in accordance with the existing ventilation design available at the UTAR KB block basement car park. The impulse jet fans system was designed for the existing UTAR KB block basement car park with strict compliance with the authorities' design guidelines and requirements in terms of ventilation rate, jet fans placement, zoning area, etc. A total of 3 smoke control zones were designed for the jet fans system, with each zone equipped with exhaust outlets, fresh air inlets, and jet fan units that are capable to deliver 12 ACH of ventilation rate. 66 N jet fan model from System Air with a momentum source of 140 N/m^3 was selected for the jet fan system design. The virtual vehicle fire was simulated based upon the worst-case scenario in terms of fire size and location required by (Singapore Civil Defence Force, 2008). The virtual fire was modelled on the engine bonnet of a vehicle located between zone B and C with a smoke mass flow rate of 1.04 kg/s at 300 °C. The smoke contained 96.54% of CO_2 and 2.29% of CO. Three different mesh sizing from coarse, medium to fine (400 mm, 200 mm, and 100 mm) were created for each simulation model to perform mesh independence analysis to validate the accuracy of simulation results.

CHAPTER 4

RESULTS AND DISCUSSION

All the simulations were run in a steady-state due to computational limitations and time-constraint reasons. Therefore, in the following analysis, simulation results were presented as in a steady-state condition. This chapter will discuss and analyse the five parameters that are crucial for the evaluation of ventilation performance in the event of fire which include temperature distribution, airflow velocity, smoke flow pattern, CO concentration, and CO_2 concentration across a virtual horizontal plane at $y = 1.7$ m. The horizontal plane height of $y = 1.7$ m considers the average humans breathing height which permits a better analysis of the tenability criteria for the safety of evacuees and firefighters (Singapore Civil Defence Force, 2008; British Standards Institution, 2013). A 2-dimensional horizontal plane also provides a better illustration for the propagation of combustion products (CO and CO_2), heat transfer behaviour, and the airflow velocity facilitated by the ventilation system.

The following criteria were evaluated in both cases at $y = 1.7$ m above ground level to compare the performance of smoke and heat ventilation in the car park between the ducted ventilation model and jet fans ventilation model.

1. The smoke temperature shall not be higher than 60 °C in the car park. Therefore, the contour distribution in the temperature contour was clipped within the range of 300 K (27 °C) to 330 K (57 °C), where the transparent areas indicate temperature higher than 57 °C and deemed as an unsafe area (Singapore Civil Defence Force, 2008; British Standards Institution, 2013).
2. The velocity shall be greater than 0.2 m/s to avoid stagnation of airflow and less than 5 m/s for safe evacuation. Therefore, the velocity contours show the air movement between $v = 0.2$ to 5 m/s, where the transparent areas indicate velocities lower 0.2 m/s or higher than 5 m/s (Singapore Civil Defence Force, 2008; British Standards Institution, 2013).
3. The concentration of carbon monoxide (CO) shall not be higher than 100 ppm to satisfy the maximum safe exposure limit for short-term exposure of 15 minutes as stated by (Health and Safety Executive, 2020), assuming that the evacuation will be completed within 15 minutes at the early stage of fire incident. The colour mapping of the contour diagram was clipped within the range of 0 to 0.000115 kg/m^3 (equivalent to 0 to 100 ppm), where transparent areas indicate high concentrations of CO (greater than 100 ppm) and deemed unsafe.
4. The concentration of carbon dioxide (CO_2) shall not be higher than 10000 ppm to satisfy the maximum safe exposure limit for short-term exposure of 15 minutes as stated by (Health and Safety Executive, 2020) assuming that the evacuation will be completed within 15 minutes at the early stage of fire incident. The colour mapping of the contour diagram was clipped within the range of 0 to 0.018 kg/m^3 (equivalent to 0 to

10000 ppm), where the transparent areas indicate high concentrations of CO_2 (greater than 10000 ppm) and deemed unsafe.

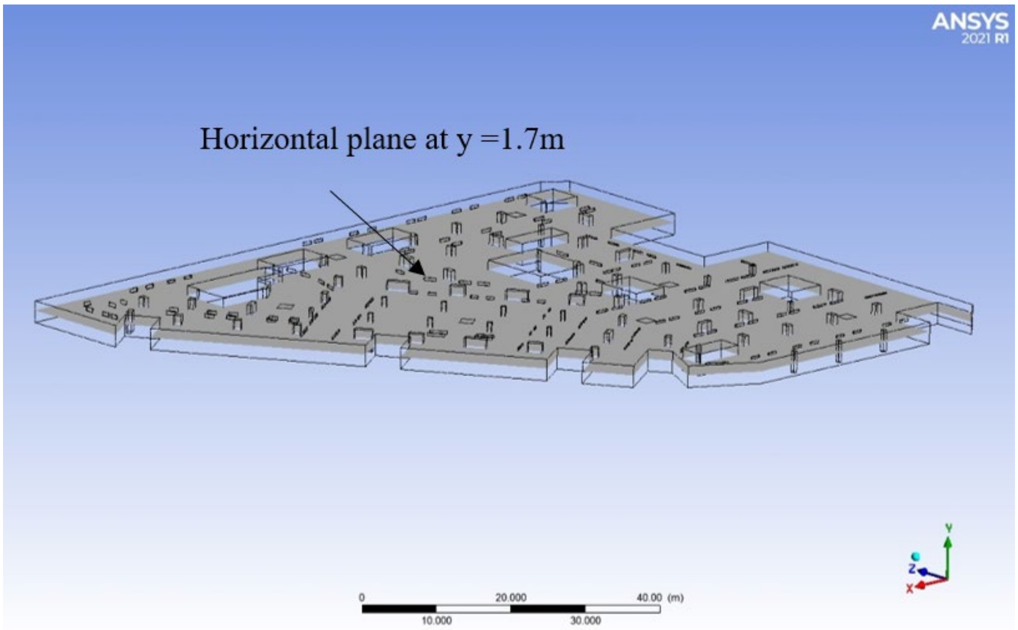


Figure 4.1: Location of virtual horizontal plane at y = 1.7 m

A well-converged simulation is essential to produce a reliable and accurate simulation result. Convergence of an iterative numerical solution like CFD simulation can be determined based on the root mean square (RMS) residual values obtained across the iterations. In this project, the convergence criteria were set at RMS residual level of $1x10^{-4}$ for the mass and momentum, heat transfer, and turbulence model. The information of the CFD simulation is shown in Table 4.1.

Table 4.1: Simulation time and convergence results

Model	Mesh size (mm)	Iterations	Time taken for solution
Ducted ventilation system	100	250	21 hours 18 minutes
	200	250	5 hours 47 minutes
	400	250	3 hours 38 minutes
Jet fans system	100	250	19 hours 55 minutes
	200	300	4 hours 12 minutes
	400	300	3 hours 20 minutes

4.1 Mesh independence study

In this project, a mesh independence study was carried out to analyse the deviation of simulation results across three different mesh sizes of 100 mm, 200 mm, and 400 mm. Four important parameters at the virtual plane y = 1.7 m including the maximum temperature, maximum pressure, maximum CO concentration, and maximum CO_2 concentration were monitored. Table 4.2 shows the simulation results of both the ducted ventilation model and jet fans model obtained from three CFD simulations of different mesh sizing. All the initial boundary condition settings were fixed as the controlled variables which remained unchanged across the three simulations except for the mesh sizing which were manipulated for the purpose of mesh independence study.

Table 4.2: Simulation results at different mesh size

Ducted ventilation system			
Mesh size	Fine	Medium	Coarse
	100 mm	200 mm	400 mm
Maximum Temperature (°C)	570.88	569.15	564.45
Deviation (%)	nil	-0.303%	-0.8258%
Maximum Pressure (Pa)	0.1463	0.1416	0.1378
Deviation (%)	nil	-3.21%	-2.69%
Maximum CO concentration (kg/m^3)	0.02083	0.02068	0.02030
Deviation (%)	nil	-0.72%	-1.838%
Maximum CO_2 concentration (kg/m^3)	0.8779	0.8719	0.8557
Deviation (%)	nil	-0.683%	-1.858%
Impulse jet fans system			
Mesh size	Fine	Medium	Coarse
	100 mm	200 mm	400 mm
Maximum Temperature (°C)	571.84	567.01	569.67
Deviation (%)	nil	-0.845%	+0.469%
Maximum Pressure (Pa)	10.94	11.41	11.92
Deviation (%)	nil	+4.3%	+4.47%
Maximum CO concentration (kg/m^3)	0.02090	0.02051	0.02073
Deviation (%)	nil	-1.87%	+1.07%
Maximum CO_2 concentration (kg/m^3)	0.8813	0.8645	0.8737
Deviation (%)	nil	-1.91%	+1.06%

The variation of results obtained from the simulation across three different mesh sizing in the ducted ventilation model and jet fans model were plotted as shown in Figure 4.2 to 4.5.

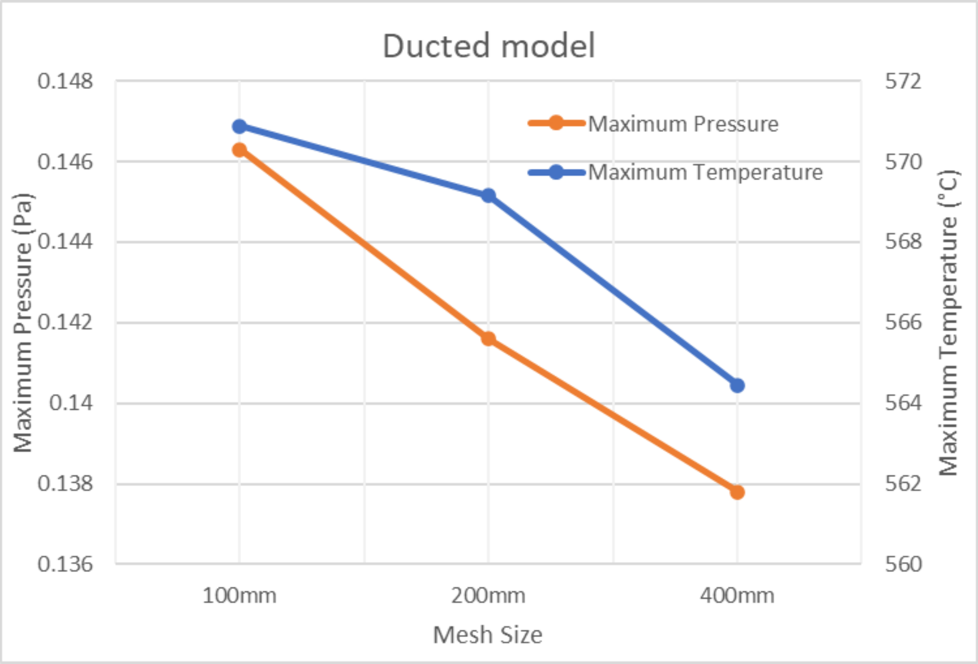


Figure 4.2: Grid independence study of ducted model simulation; Maximum pressure and maximum temperature

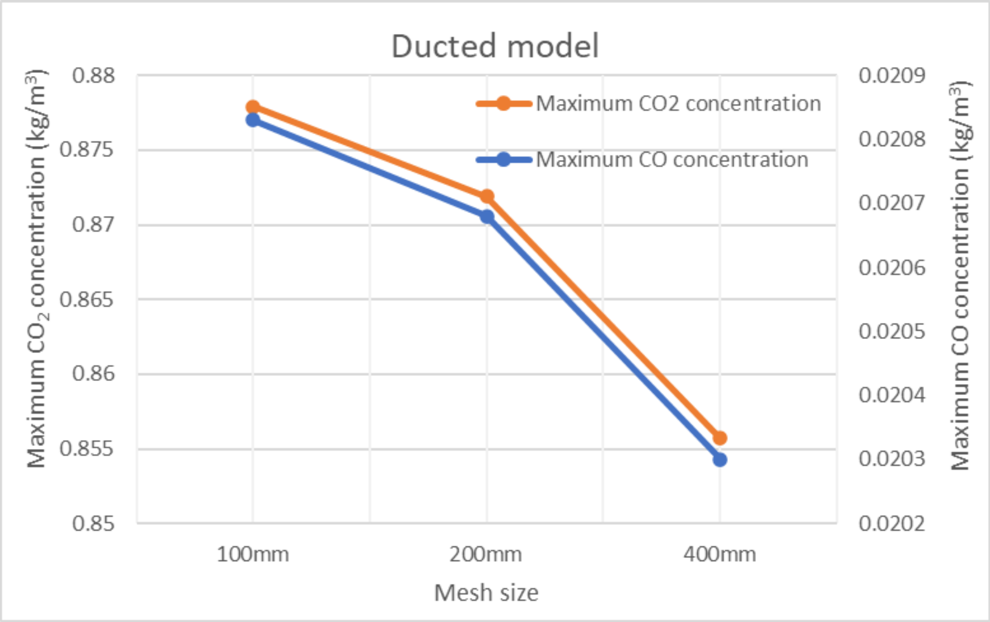


Figure 4.3: Grid independence study of ducted model simulation; Maximum concentration of CO_2 and CO

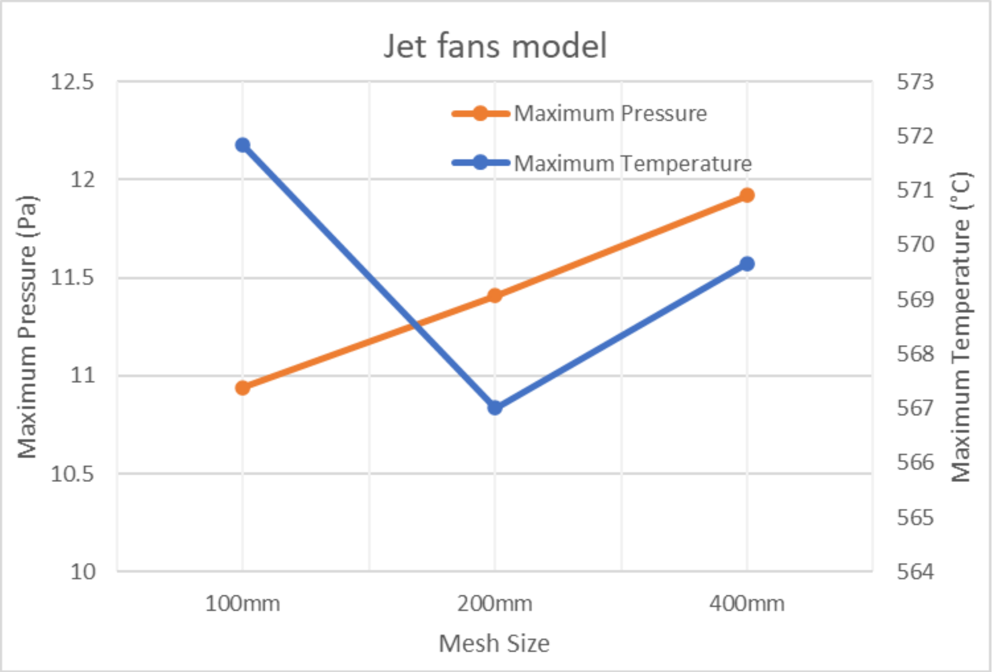


Figure 4.4: Grid independence study of jet fans model simulation; Maximum pressure and maximum temperature

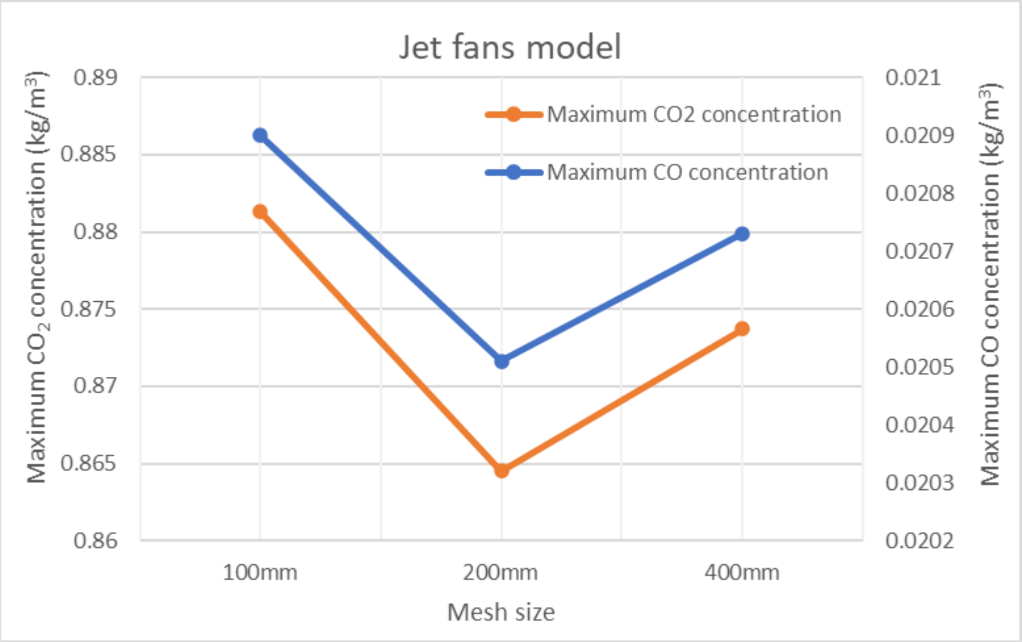


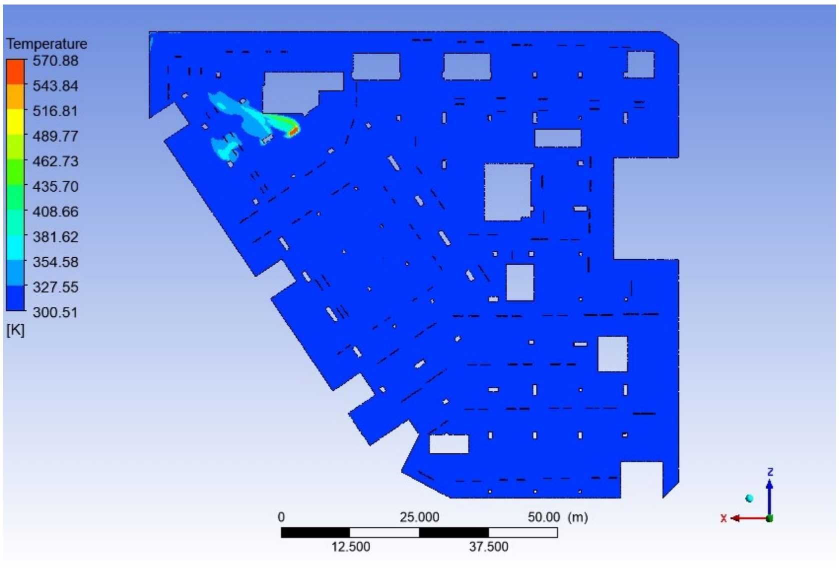
Figure 4.5: Grid independence study of jet fans model simulation; Maximum concentration of CO$_2$ and CO

Based on Table 4.2, the deviation in simulation results obtained across three different mesh sizing for both the ducted model and jet fans model were well below 5% which satisfied the general satisfactory criteria of a typical mesh independence study for CFD simulation. Among all the experimental data, maximum pressure has the highest deviation of results in both simulation models with 3.21% and 4.47% in the ducted and jet fan models respectively.

The simulation with the finest mesh size of 100 mm which fulfilled the satisfactory convergence criteria can be claimed to have obtained the most accurate results among the three simulations of different mesh sizing. Therefore, the simulation results used in the following analysis and discussion were based on the simulation with the finest mesh size of 100 mm for both simulation models.

4.2 Temperature distribution

The contour diagrams as shown in Figure 4.6 illustrate the distribution of temperature across the virtual horizontal plane at $y = 1.7$ m. The range of the colour mapping in the contour diagrams was set as local range with the maximum temperature set as the upper limit and the minimum temperature set as the lower limit.



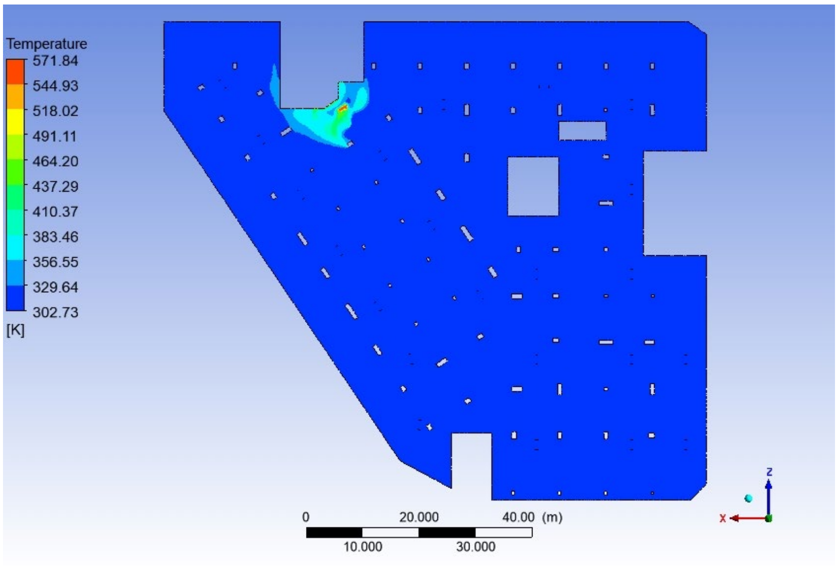


Figure 4.6: Temperature distribution (local range) at y = 1.7 m of ducted ventilation system (top) and jet fans system (bottom)

Table 4.3: Maximum temperature at 1.7m above ground level

Model	Maximum temperature
Ducted ventilation system	570.88 K
Jet fans system	571.84 K

Based on the contour diagrams in Figure 4.6, the area close to the car fire was found to have a higher range of temperature than the remaining areas in the car park. The maximum temperature found on the virtual plane was 570.88 K and 571.84 K in the ducted ventilation system and jet fans system respectively. Whereas the region outside the car fire showed a lower temperature range with blue colour mapping. These contour diagrams shown in Figure 4.6 could not provide a good illustration of the overall temperature distribution because of the wide colour mapping range between 303 K to 570 K that neglects the maximum safe temperature limit of 333 K.

Therefore, in the contour diagrams as shown in Figure 4.7, the colour mapping range was further narrowed to allow a better illustration of the temperature distribution for analysis. The lower limit was set at 303 K (30 °C) which refers to the ambient temperature of Malaysia weather at atmospheric conditions, while the upper limit was set as 333 K (60 °C) which is the maximum allowable temperature at 1.7 m above ground level for safe evacuation and firefighting intervention during a car park fire as required by (Singapore Civil Defence Force, 2008). Therefore, any area on this plane in the car park with a temperature greater than 333 K will be regarded as a dangerous area. The colour mapping of the contour diagrams in Figure 4.7 was clipped at a temperature range of 303 K to 333 K where any area with a temperature greater than 333 K will be illustrated as a transparent region for quick and easy identification.

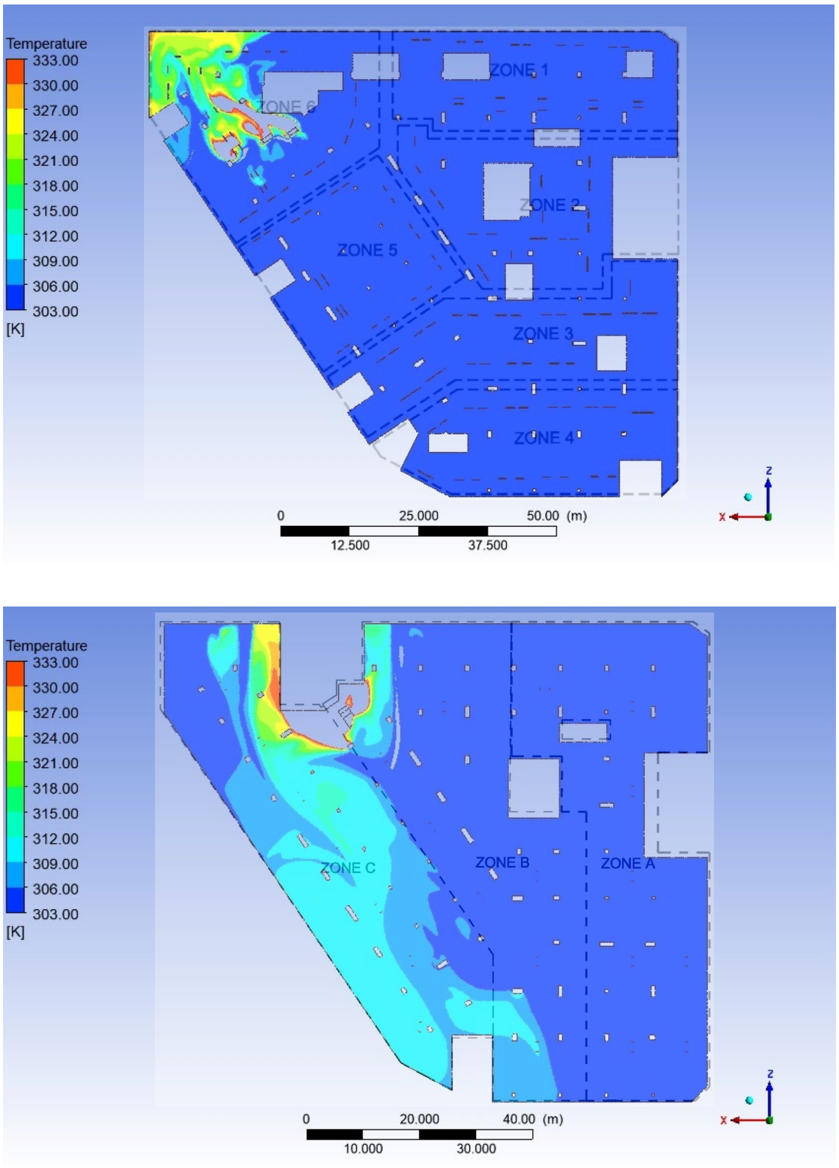


Figure 4.7: Temperature distribution at y = 1.7 m of ducted ventilation system (top) and jet fans system (bottom)

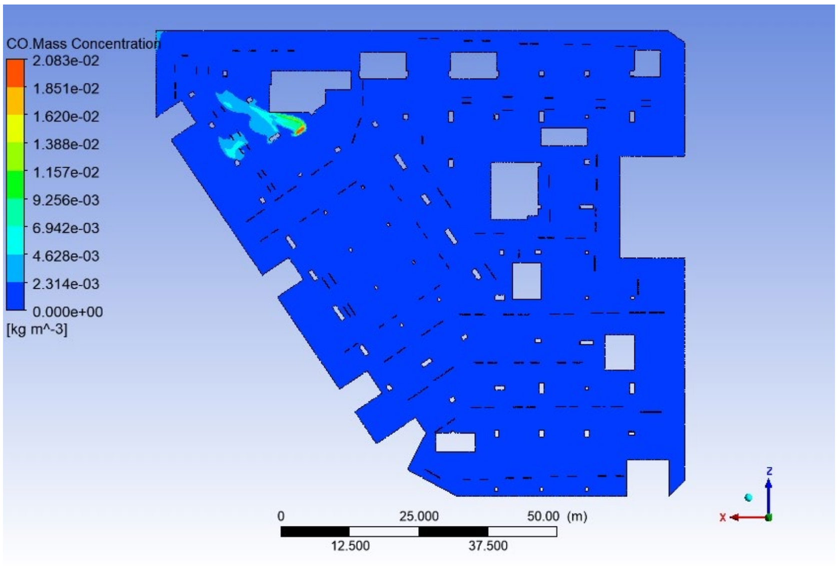
Based on the contour diagram in Figure 4.7 (top), the ducted ventilation system was found to have a better containment of high-temperature air within the area close to the car fire. As can be observed in Figure 4.7 (top), the region with higher air temperature was located at the top left corner in zone 6 of the basement car park which consists of 23 exhaust air grilles that are responsible to remove the high-temperature smoke from the car park before it dispersed to a wider area. A relatively small portion of the region in zone 6 was mapped as transparent since the temperature in this region was greater than the safe temperature limit of 333 K and deemed as dangerous. As can be seen, the transparent mapping extended from the car fire towards several exhaust grilles in zone 6 where the heat was extracted from the car park. The temperature at the remaining region outside the car fire and zone 6 was maintained at a relatively low temperature which was close to the initial ambient temperature of 303 K as can be observed from the wide area of blue colour mapping outside the affected zone.

On the other hand, in the jet fans ventilation system, the high temperature smoke of the car fire propagated to a much wider area outside the car fire location as can be observed from the light blue and green colour mapping that extended through the entire area of zone C in Figure 4.7 (bottom). The main reason that led to this phenomenon was because of the ventilation characteristic of jet fans that involves open mixing of high-temperature smoke and air without the use of ducting. The open mixing process was facilitated by the induced bulk airflow created by the thrust of jet fans that helped to push and direct the high-temperature air and smoke toward the smoke exhaust grilles. As a result, the ventilation flow path in the affected smoke control zone (Zone C) was filled with relatively high temperature smoke originated from the car fire and extended toward the exhaust grilles as can be observed from the light blue colour mapping. In zone B, the temperature distribution along the ventilation flow path remained relatively low except for a small section of the transparent area near the car fire which contained the combustion products from the burning of vehicle with temperature greater than 333 K. In zone A, the temperature distribution was unaffected by the car fire which remained close to the initial ambient temperature of 303 K as can be observed from the uniform blue colour mapping in Figure 4.7 (bottom).

Although the overall performance of the temperature distribution in the jet fans system was not as good as that of the ducted ventilation system, it was still capable to provide a tenable temperature distribution in most of the areas at below the maximum safe temperature limit of 333 K as required by (Singapore Civil Defence Force, 2008), since no transparent mapping was observed in the affected zones along the ventilation path except for a small area close to the car fire. Moreover, the jet fans ventilation system has successfully contained the high air temperature within the affected smoke control zones in zone C with slight dispersion to zone B without spreading to the adjacent zone A. Successful containment of high-temperature air within the affected zones is an important criterion required by the authorities for the validation of effective jet fans ventilation system in car park.

4.3 Concentration of carbon monoxide

The contour diagrams as shown in Figure 4.8 illustrate the concentration level of carbon monoxide (CO) across the virtual horizontal plane at y = 1.7 m. The range of the colour mapping in the contour diagrams of CO concentration was set as local range with the maximum concentration set as the upper limit and the minimum concentration set as the lower limit.



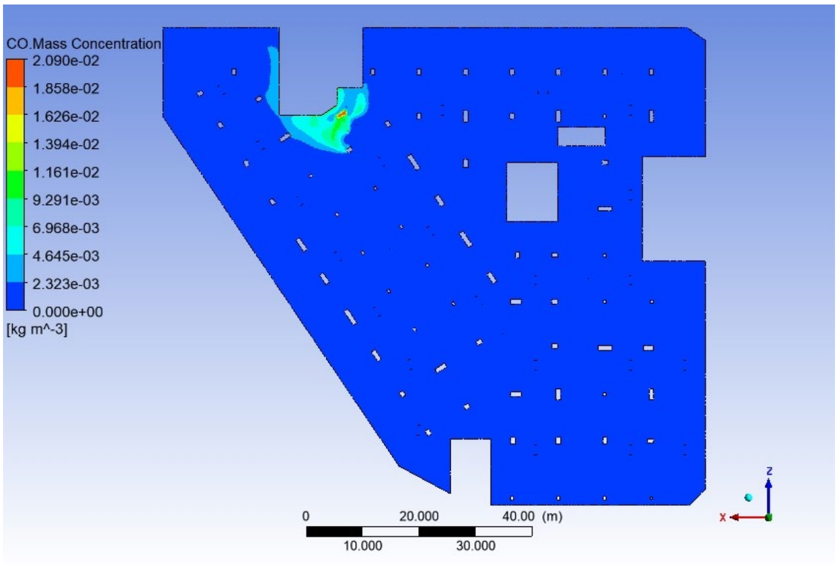


Figure 4.8: CO concentration (local range) at y = 1.7 m of ducted ventilation system (top) and jet fans system (bottom)

Table 4.4: Maximum CO concentration at y = 1.7 m

Model	Maximum CO concentration
Ducted ventilation system	0.02083 kg/m^3
Jet fans system	0.02090 kg/m^3

Based on the contour diagrams in Figure 4.8, the area near the car fire was found to have a higher concentration of CO in both the ducted ventilation system and the jet fans system. The maximum concentration of CO found on the plane y = 1.7 m was 0.02083 kg/m^3 and 0.2090 kg/m^3 in the ducted system and jet fans system respectively. The contour diagrams in Figure 4.8 could not deliver a good illustration of the overall CO concentration in other regions outside the car fire because of the wide colour mapping range.

Therefore, the mapping range of the contour diagrams in Figure 4.9 was narrowed down to a smaller range with the upper limit of the CO concentration level fixed at 0.000115 kg/m^3 (equivalent to 100 ppm) which is the maximum allowable exposure limit of CO concentration as recommended by HSE in the United Kingdom for short-term exposure (Health and Safety Executive, 2020). Maintaining the CO concentration level below the recommended value is a necessary approach for effective ventilation in the car park during a fire since it is an extremely poisonous and deadly gas. Inhalation of high concentration of CO will cause asphyxiation as it can reduce the oxygen level transported to critical organs like the brain and heart. The range of the colour mapping for the contour diagrams in Figure 4.9 was clipped between 0 to 0.000115 kg/m^3. Thus, areas with CO concentration greater than the upper limit will be shown as a transparent region for quicker and easier identification of dangerous areas with CO concentration levels exceeding the safety limit.

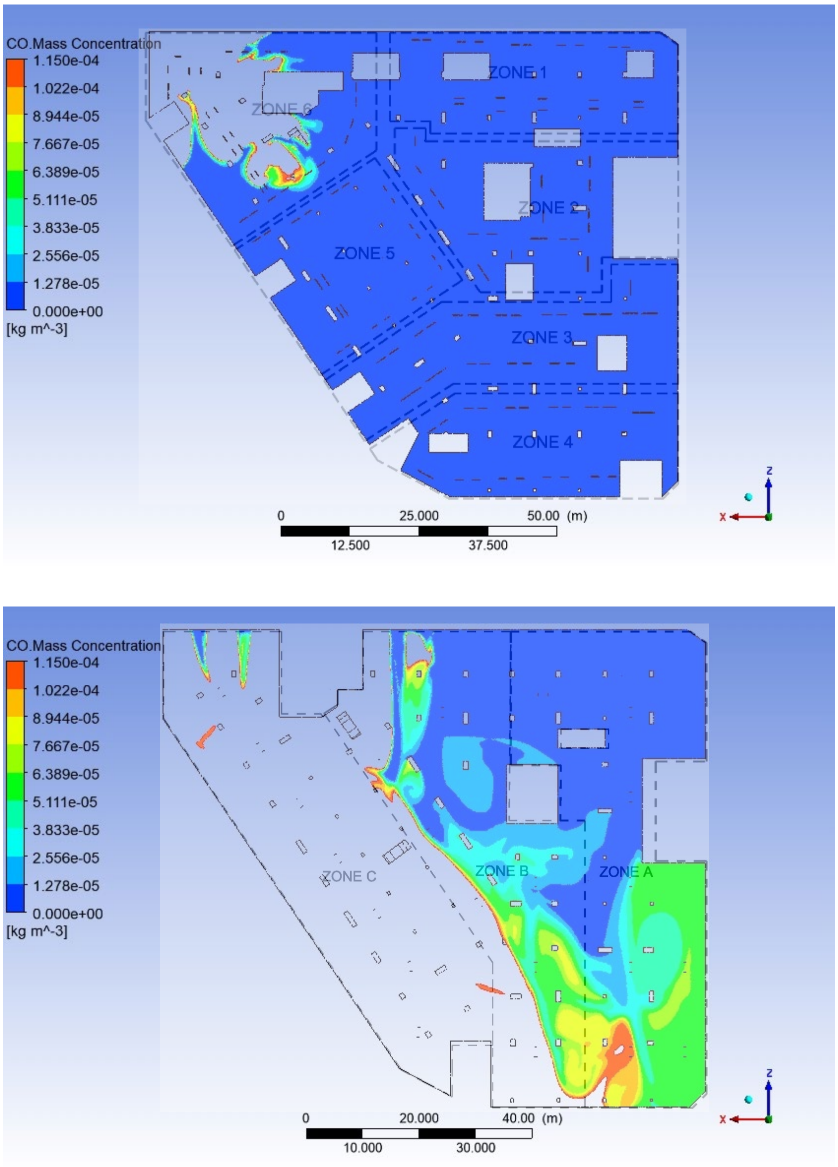


Figure 4.9: CO concentration y = 1.7 m of ducted ventilation system (top) and jet fans system (bottom)

Based on Figure 4.9 (top), a fraction of the transparent area was found at the top left corner in zone 6 of the car park near the location of the car fire. This area contained a high concentration level of CO at above 0.000115 kg/m^3 and was deemed as dangerous. The main reason that led to the dense accumulation of highly concentrated CO in this zone was mainly due to the 23 points of exhaust grilles in zone 6 that helped to extract the combustion products including the deadly CO gases out from the car park before they dispersed to a wider area outside the affected zone. As a result, the remaining areas outside the location of the car fire were found to have a significantly lower concentration of CO as plotted in blue colour mapping since most of the smoke products had been contained within the affected zone and removed through the exhaust grilles in zone 6. In overall, the ducted ventilation system showed an excellent containment of CO level within the affected zone by maintaining the CO concentration in most of the areas outside the car fire location at a level below the safety concentration limit of 0.000115 kg/m^3 (100 ppm), which in turn creating a safe and tenable environment for the evacuees and firefighter during a car park fire.

On the other hand, the jet fans system was found to have a greater area of transparent mapping as shown in Figure 4.9 (bottom) which indicated that there were more areas in the car park containing a high concentration level of CO that exceeded the safety limit of 0.000115 kg/m^3 (around 100 ppm). In other words, there were generally more dangerous areas with an excessively high concentration level of CO in the car park with jet fans system as compared with the ducted ventilation system. In the jet fans ventilation system, the CO originated from the fire source propagated along the ventilation path in the affected smoke control zones (zone B & C) towards the exhaust grilles located at the opposite end (negative z-axis). Zone C was particularly found to be more dangerous than the remaining zones as most of the areas in zone C were plotted as transparent which contained a high concentration of CO that was greater than the safety limit of 0.000115 kg/m^3. Whereas in zone B, fewer transparent areas were noticed except for the area located near the car fire and the smoke exhaust grilles in zone B. Some transparent areas were also identified along the boundary line separating zone B and C. Besides, the CO gases have also dispersed into zone A but at a concentration level lower than the safety limit except for a significantly small area located near the extraction grilles in zone A which was mapped as transparent area.

The significant dispersion of high-concentration CO observed in the jet fans system was mainly because of the open mixing of air and combustion products caused by the induced bulk movement of air generated by the thrust of jet fans.

The main function of the jet fans is to generate a thrust force to push and direct the combustion products toward the exhaust points and finally remove to the atmosphere. In the case of jet fans system, the temperature distribution and propagation of CO is highly dependent on the location of car fire. The further the fire location is away from the exhaust points, the greater the propagation distance of combustion products throughout the ventilation path which eventually dispersed to a wider area. For example, in this case, the design fire was simulated as a worst-case fire scenario which located at the furthest point away from the exhaust points. Consequently, the smoke product with high temperature (greater than 333 K) and CO concentration level (greater than 100 ppm) propagated through the entire ventilation flow path in the affected smoke control zones B and C due to the mixing of air and combustion products caused by the thrust of jet fans which was intended to drive the smoke product towards to exhaust points that located at the opposite ends.

In overall, the ducted mechanical ventilation system was found to have a much better performance for the containment of the deadly CO gases within the affected zone than that of the jet fans ventilation system which contained a widespread of CO in most of the car park areas. Despite of that, the jet fans system managed to contain the dangerously high concentration level of CO (above 100 ppm) within the affected smoke control zones (zone B and C) with only a significantly small fraction being dispersed into the adjacent zone A. The containment of high concentration of CO within the affected zones is also one of the stringent criteria required by the local authorities.

4.4 Concentration of carbon dioxide

The contour diagrams as shown in Figure 4.10 illustrate the concentration level of carbon dioxide (CO_2) across the virtual horizontal plane at $y = 1.7$ m. The range of the colour mapping in the contour diagrams was set as local range with the maximum concentration set as the upper limit and the minimum concentration set as the lower limit.

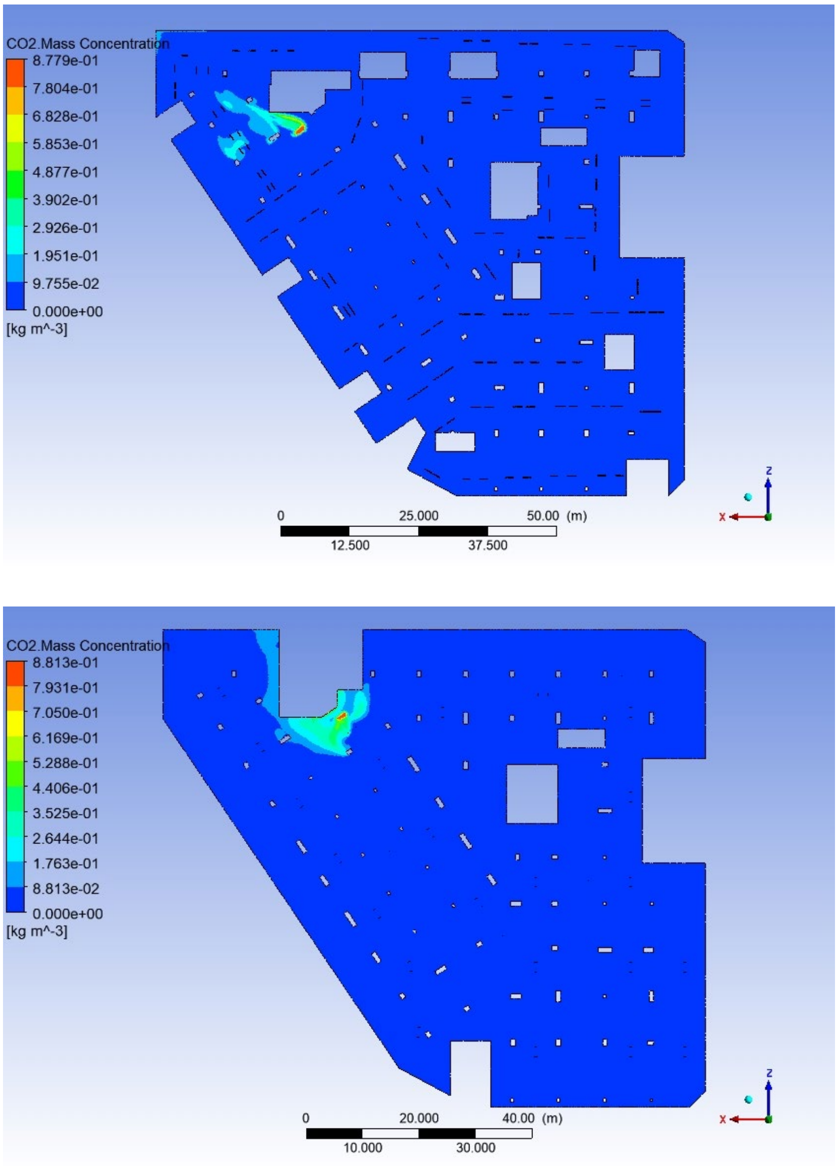


Figure 4.10: CO_2 concentration (local range) at y = 1.7 m of ducted ventilation system (top) and jet fans system (bottom)

Table 4.5: Maximum CO_2 concentration at y = 1.7 m

Model	Maximum CO_2 concentration
Ducted ventilation system	0.8779 kg/m^3
Jet fans system	0.8813 kg/m^3

Based on the contour diagrams in Figure 4.10, the area near the car fire was found to have a higher concentration of CO_2 in both the ducted ventilation system and the jet fans system. The maximum concentration of CO_2 found on the plane y = 1.7 m was 0.8779 kg/m^3 and 0.8813 kg/m^3 in the ducted system and jet fans system respectively. The contour diagrams in Figure 4.10 could not provide a good illustration of the overall CO_2 concentration in other regions outside the car fire because of the wide colour mapping range.

Therefore, the mapping range of the contour diagrams in Figure 4.11 was narrowed down to a smaller range with an upper limit of the CO_2 concentration level fixed at 0.018 kg/m^3 (equivalent to 10000 ppm) which was recommended by the HSE (Health and Safety Executive, 2020) in the United Kingdom for short-term exposure. Maintaining the CO_2 concentration level below the recommended value is a necessary approach for car park ventilation during a fire. Although, the poisoning effect of CO_2 is very rare and less significant than CO, however, being subjected to a high concentration of CO_2 can cause asphyxiation as it will displace the oxygen level in the breathing air since it has a greater molecular mass than oxygen. The range of the colour mapping for the contour diagrams in Figure 4.11 was clipped between 0 to 0.018 kg/m^3. Thus, the area with CO_2 concentration greater than the upper limit will be shown as transparent region and deemed as dangerous for quicker and easier identification.

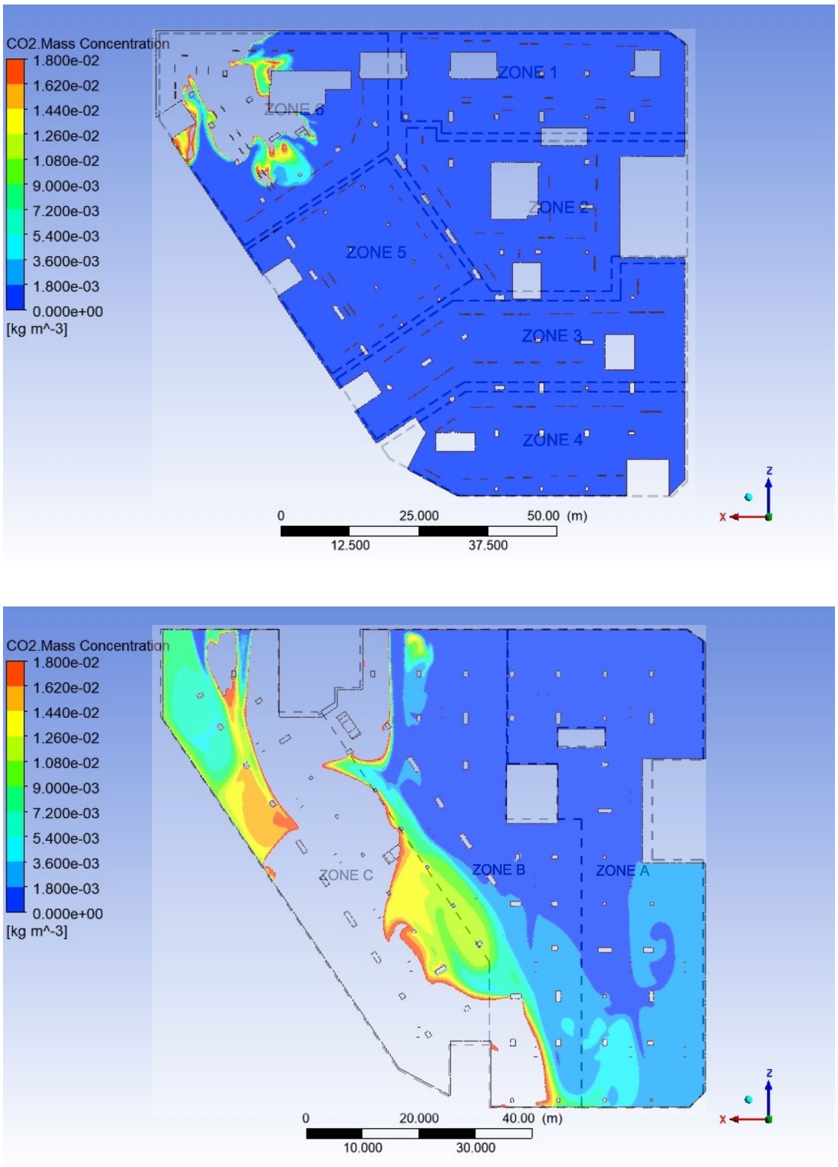


Figure 4.11: CO_2 concentration at y = 1.7 m of ducted ventilation system (top) and jet fans system (bottom)

As can be observed from the contour diagrams in Figure 4.11 (top), the ducted ventilation system was found to have a smaller area of transparent mapping than that of the jet fans system, this also means that it has a smaller dangerous area with a high concentration of CO_2 greater than safety limit of 0.018 kg/m^3. In the ducted ventilation model, the highly concentrated CO_2 accumulated in the top left corner of the car park in zone 6 which consists of 23 points of exhaust grilles that were responsible to remove the combustion products from the car park. Due to the proximity of those exhaust grilles in zone 6 to the location of car fire, the CO_2 that originated from the car fire was removed through the nearby exhaust grilles and did not have enough time to spread to a wider area outside the affected zone. As a result, most of the areas located outside the car fire were found to have a significantly low concentration of CO_2 as indicated by the blue colour mapping. In overall, the ducted ventilation system was found to have a better containment of CO_2 than the jet fans system during a fire.

On the other hand, in the jet fans system, the CO_2 dispersed to a much wider area throughout the affected smoke control zones (zone B & C) with the CO_2 concentration exceeding the safe exposure limit of 0.018 kg/m^3. Zone C, in particular, contained the highest concentration level of CO_2 with most of the areas mapped as transparent. Whereas, in zone B, fewer transparent areas were observed with only a small fraction of transparent mapping located near the car fire location and the exhaust grilles in zone B.

Similar to the explanation discussed in Chapter 4.3, the main reason that led to such a wide spread of combustion products throughout the car park was because of the ventilation characteristic of the jet fans system which involves mixing of combustion products and air in an open manner without the use of ductwork. The working principle of the jet fans ventilation system is to push and direct the combustion products from the initial fire location towards the exhaust grilles with the help of the momentum generated by the thrust of jet fans. As a result, the combustion products will diffuse into the surrounding air along the ventilation path from the fresh air supply grilles to the exhaust grilles to create a mechanical cross ventilation.

In this project, the fire was simulated at a location furthest away from exhaust grilles in order to simulate the worst-case scenario. Therefore, a greater mixing effect was observed along the ventilation paths in zone B and C which contained a high concentration of CO_2.

Although, in overall, the CO_2 containment in the jet fans system was not as good as the ducted ventilation model, the CO_2 still managed to be contained within the affected zones (zone B and C) without spreading to the adjacent zone A. Therefore, the jet fans system can be claimed to have satisfied the design criteria of car park jet-fans system as per required by the local authorities (British Standard Institution, 2006; Singapore Civil Defence Force, 2008).

4.5 Airflow velocity

The contour diagrams as shown in Figure 4.12 illustrate the airflow velocity across the virtual horizontal plane at y = 1.7 m. The range of the colour mapping in the contour diagrams was set as local range with the maximum velocity set as the upper limit and the minimum velocity set as the lower limit.

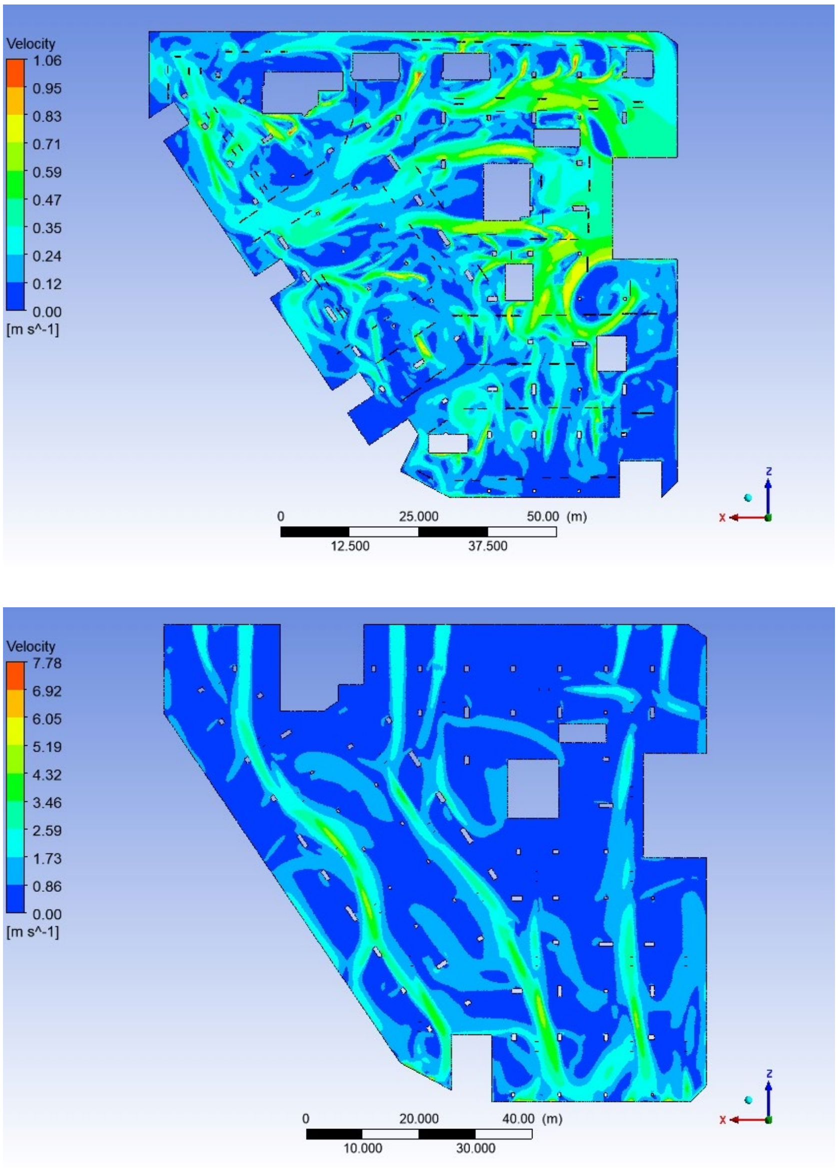


Figure 4.12: Airflow velocity (local range) at y = 1.7 m of ducted ventilation system (top) and jet fans system (bottom)

Table 4.6: Maximum velocity at $y = 1.7$ m

Model	Maximum velocity
Ducted ventilation system	1.06 m/s
Jet fans system	7.78 m/s

Based on the contour diagrams in Figure 4.12, the maximum airflow velocity in the ducted ventilation system and jet fans system was 1.06 m/s and 7.78 m/s respectively. The jet fans system was found to have a much greater airflow velocity than that of the ducted ventilation system, mainly because of the thrust of jet fans that induced a high velocity jet while pushing the combustion products towards the exhaust grilles. Due to the difference in the range of colour mapping as shown, the contour diagrams in Figure 4.12 were unable to provide a good illustration for the comparison of airflow velocity between the two ventilation systems.

Therefore, the range of the colour mapping in the contour diagrams as shown in Figure 4.13 was standardized at the same range between 0.20 m/s to 5 m/s. The lower limit of velocity was set at 0.20 m/s in accordance with the minimum required velocity to prevent smoke stagnation in the car park as per mentioned in (Singapore Civil Defence Force, 2008; British Standards Institution, 2013). Whereas the upper limit was set at 5 m/s which was regarded as the maximum allowable airflow velocity for a safe evacuation process during an emergency. Any area with an airflow velocity lower than 0.20 m/s or greater than 5 m/s will be plotted as transparent for easier and quicker identification of areas with stagnation flow or areas with excessively high air flow velocity.

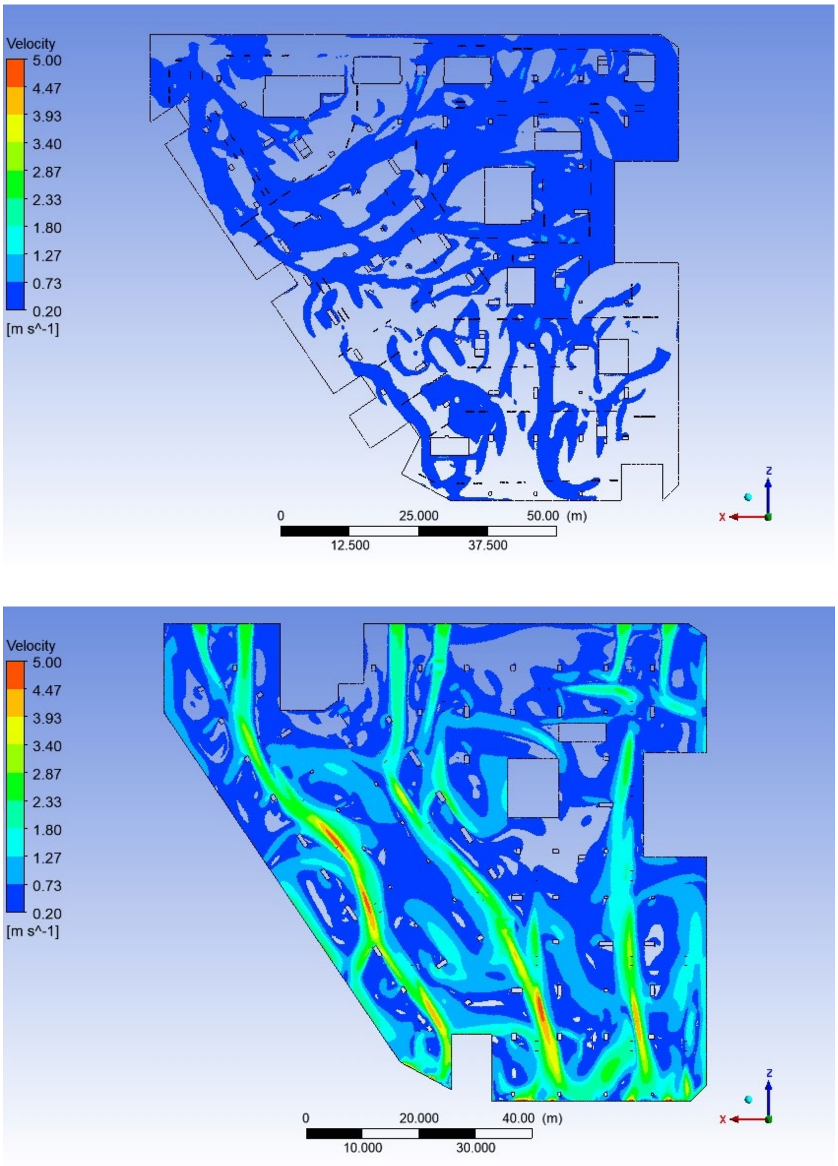
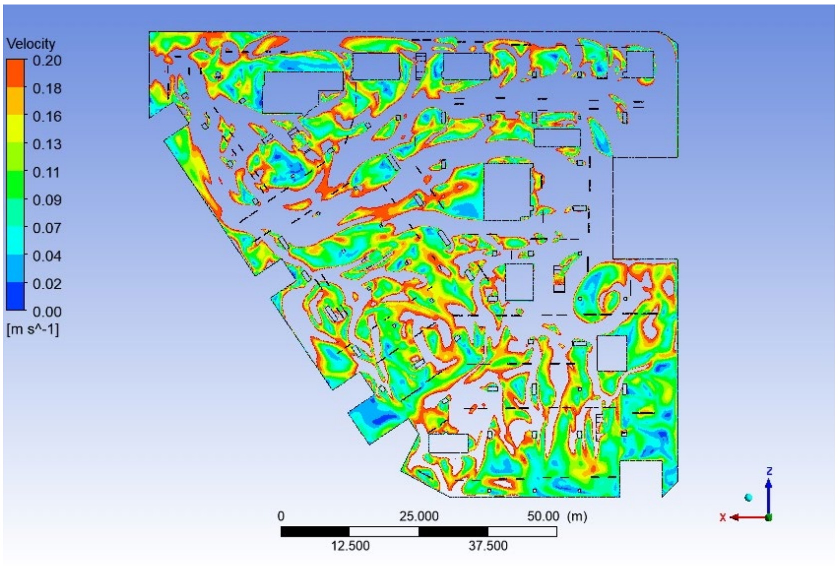


Figure 4.13: Airflow velocity at y = 1.7 m of ducted ventilation system (top) and jet fans system (bottom)

The contour diagrams as shown in Figure 4.13 illustrate the stagnation areas which have an airflow velocity smaller than 0.2 m/s. The upper limit of the colour mapping range was set at 0.2 m/s which is the minimum required airflow velocity to prevent stagnation. The colour mapping range was clipped between 0 m/s to 0.2 m/s, thus, areas with colour mapping will represent areas with stagnation airflow.



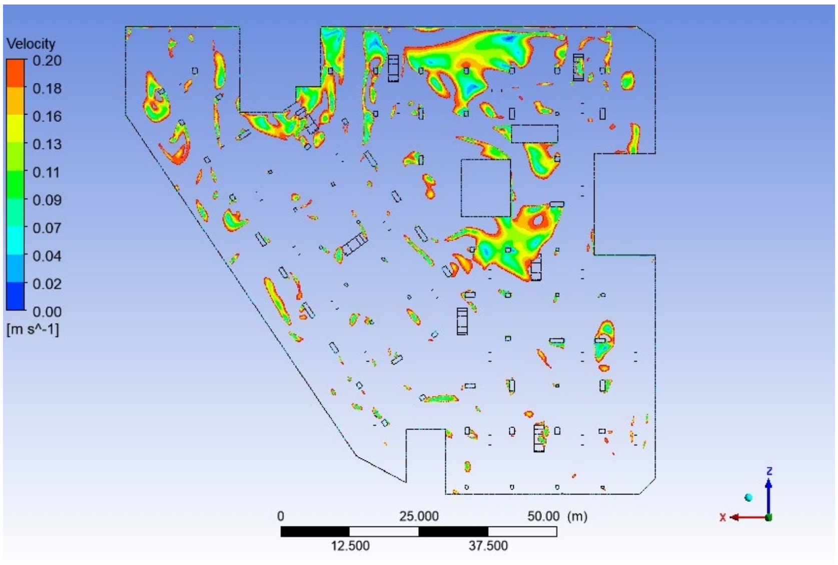


Figure 4.14:. Stagnation area in ducted ventilation system (top) and jet fans system (bottom)

Based on Figure 4.13 (top), majority of the contour diagram in the ducted ventilation system consisted of mainly blue and light blue colour mapping which referred to a relatively low airflow velocity of around 0.20 m/s to 0.73 m/s. Besides, a significantly large area of transparent plotting was observed in the ducted ventilation system. In this case, the transparent mapping referred to areas with air velocities lower than 0.20 m/s which have a higher chance of stagnation airflow and will affect the overall ventilation rate in the car park. In Figure 4.13 (bottom), a significantly smaller area of transparent plotting was observed in the jet fans system as compared to the ducted ventilation system. In other words, the jet fans system created a higher overall airflow velocity throughout the car park space than that of the ducted ventilation system. This also meant that the jet fans system has a lower possibility of having stagnation airflow. As can be seen from Figure 4.14, the total area of stagnation airflow (as plotted in colour) found in the jet fans system was much smaller than that of the ducted ventilation system. The reason that led to such phenomenon was mainly because of the high thrust created by the jet fans that induced a high velocity jet throughout the car park space which then resulted in the mixing of air and combustion product that was pushed towards the exhaust grilles at the opposite ends of the fresh air grilles at a relatively high velocity.

In addition, the velocity contour of the jet fans system in Figure 4.13 (bottom) shows a high-velocity air flow movement (as plotted in green to red colour mapping) along the ventilation flow path that extended from the fresh air grilles located along positive z-axis towards to the exhaust air grilles located along the negative z-axis. The high airflow velocity (as plotted in red colour mapping) was mostly found in the downstream direction (outlets) of the jet fans. The high airflow velocity was caused by the momentum thrust generated by the jet fans that compressed and pushed the surrounding air forwards and ultimately towards the designated exhaust grilles. As can be seen from the contour diagram of the jet fans system in Figure 4.13 (bottom), the overall airflow velocity fell within the range of 0.2 m/s to 5 m/s which fulfilled both the minimum velocity requirement of 0.2 m/s to avoid stagnation flow and the maximum allowable velocity of 5 m/s that will impede the evacuation process. In overall, in terms of airflow velocity and stagnation air flow, the jet fans system exhibits a better performance than the ducted ventilation system for car park ventilation during a fire.

4.6 Smoke flow pattern

The diagrams shown in Figure 4.15 illustrate the smoke flow pattern throughout the car park space that originated from the initial car fire location when being subjected to the influence of different ventilation systems. The smoke flow pattern was plotted using the streamline feature available in ANSYS CFX-Post.

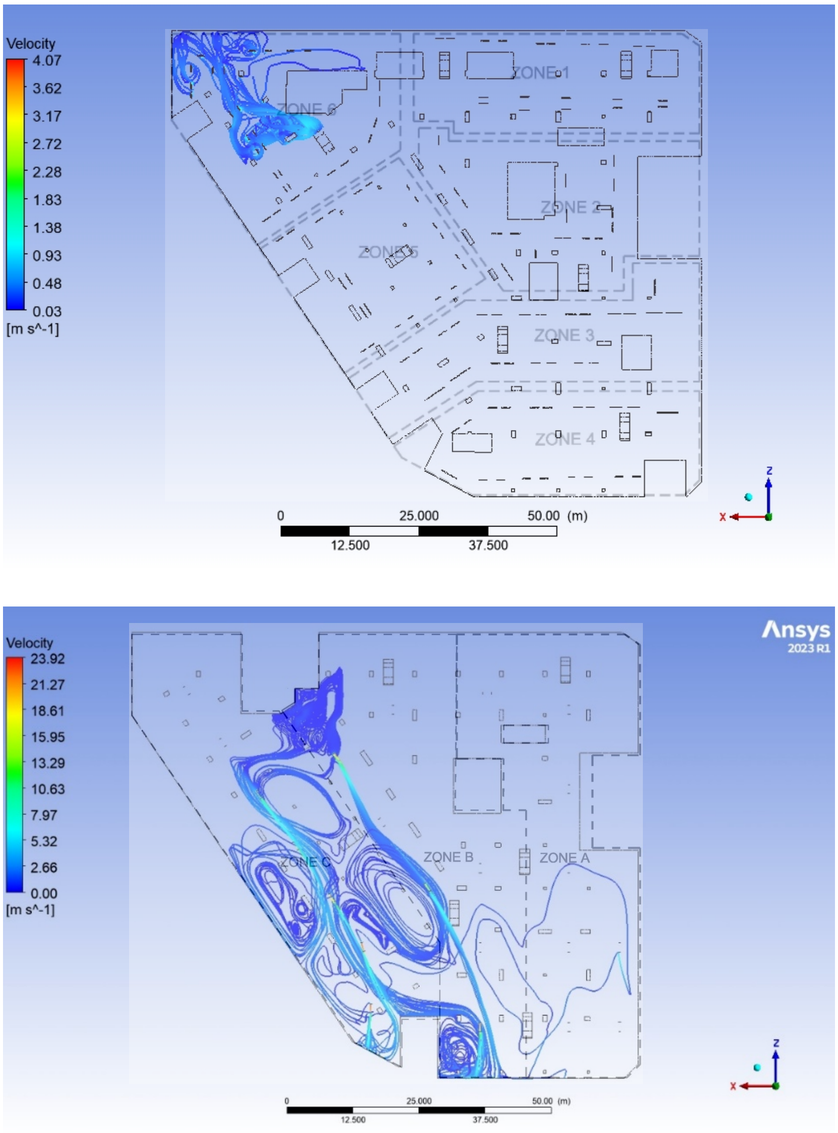


Figure 4.15: Smoke flow pattern in ducted ventilation system (top) and jet fans system (bottom)

Table 4.7: Maximum smoke flow velocity

Model	Maximum smoke velocity
Ducted ventilation system	4.07 m/s
Jet fans system	23.92 m/s

Based on Figure 4.15, the maximum smoke flow velocity in the ducted ventilation system and the jet fans system was 4.07 m/s and 23.92 m/s respectively. The maximum smoke flow velocity in the jet fans system was much higher than that of the ducted ventilation system, mainly because of the high velocity jet generated by the jet fans. As can be seen from the diagram in Figure 4.15 (bottom), the higher smoke flow velocity was observed at the inner bore of the jet fan units.

Based on the smoke flow pattern of the ducted ventilation system as shown in Figure 4.15 (top), the flow of smoke was contained within the affected area at zone 6 because of the smoke extraction system. The smoke extraction system created a region of low air pressure near the exhaust grilles, as a result, the higher-pressure smoke will be pushed towards the exhaust grilles due to pressure differential. Several recirculation flows of smoke were noticed near the walls and exhaust grilles located at the top left corner. These recirculation flows were the main reason that caused the build-up of high-temperature smoke and high concentration of CO and CO_2 in this region as discussed in Chapter 4.2, 4.3 and 4.4. The ducted ventilation system exhibits an excellent containment of smoke within the affected zone by preventing smoke dispersal to the remaining zones.

On the other hand, with reference to the smoke flow pattern of the jet fans system as shown in Figure 4.15 (bottom), the smoke propagated to a wider area along the ventilation path in both zones B and C. The velocity of smoke flow accelerated to a high value (as can be seen from the yellow colour streamlines) when it passed through the inner bore of the jet fans because of the high velocity jet caused by the thrust of the jet fans. Thus, the smoke flow velocity was accelerated at the outlet of the jet fans. Besides, a few recirculation flows of the smoke can also be observed in zone C. The recirculation flow of smoke was mainly caused by momentum loss which reduced the kinetic energy and velocity of the smoke flow. Consequently, the low-velocity smoke flow recirculated back to the inlet of jet fans due to pressure differential. The recirculation flow of smoke could possibly the main reason that causes the build-up of high temperature, high concentration of CO and CO_2 in the jet fans system as explained in Chapter 4.2, 4.3 and 4.4. Besides, a small recirculation flow of smoke was also noticed near the exhaust grilles in zone B. The recirculation formed in this region was mainly caused by the separation of flow occurred at the corner edge of the wall as shown in Figure 4.16 below. Flow separation will cause significant losses in momentum and velocity of the fluid flow which later promote recirculation flow. Recirculation at this region is the main reason that caused the build-up of high-temperature air and high concentration of CO and CO_2 in this region in zone B as discussed in Chapter 4.2, 4.3 and 4.4.

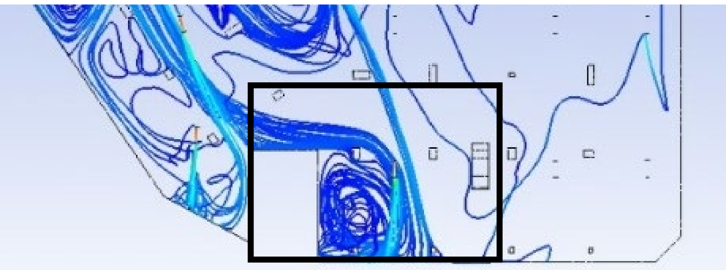


Figure 4.16: Separation of flow at the corner edge of wall

4.7 Summary

In this project, a total of 3 CFD simulations were performed for each ventilation model at different mesh sizing from 400 mm, 200 mm to 100 mm. The deviation in simulation results across three different mesh sizing in both models was well below 5% which fulfilled the general satisfactory criteria for mesh independence analysis. Simulation results of the finest mesh sizing of 100 mm were used for the analysis in this project.

In overall, the ducted ventilation system exhibits a better containment of high-temperature smoke and high concentration of CO and CO_2 within a smaller area than that of the jet fans system. The ventilation approach of the jet fans system which involves a turbulent open mixing of smoke in large zoning areas results in a greater propagation of smoke throughout the ventilation path in the affected zones. Despite of that, the jet fans system managed to contain the high temperature and contagious combustion products within the affected zones in zone B and C. On the other hand, the jet fans system was found to have a significantly lesser stagnation airflow and greater airflow velocity than the ducted ventilation system due to the high-velocity jet generated by the jet fans. Therefore, the jet fans system can be claimed to have a higher ventilation rate than that of the ducted ventilation system. To conclude, both ventilation systems were found capable to contain the smoke within the affected zones which fulfilled the general requirement by the local authority for car park ventilation.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The main objective of this project is to study and analyse the ventilation performance between the ducted ventilation system and impulse jet fans system in an enclosed car park during a fire. The combustion products resulting from the vehicle fire are of extremely high temperature and contain high concentrations of toxic gases such as CO and CO_2 that could pose detrimental hazards to the life safety of evacuees and firefighters. An efficient ventilation system shall be capable to contain the combustion products within the smallest possible area near the car fire and finally extracting them out from the car park to create a safe and tenable environment.

The findings of this project have shown that the ducted ventilation system exhibits a more effective performance in smoke and heat ventilation as well as containment of toxic combustion products within the affected zone of the car fire than that of the impulse jet fans system. However, in terms of airflow velocity, the impulse jet fans system supersedes the ducted ventilation system by having a higher airflow velocity throughout the car park space. As a result, the impulse jet fans system is capable to deliver a higher air change ventilation rate with minimal stagnation airflow throughout the car park space.

Although the overall ventilation performance of the impulse jet fans system is not as effective as the ducted ventilation system, it still managed to satisfy most of the stringent ventilation criteria for car park ventilation system during a fire required by the local authorities. For example, most of the high-temperature and toxic combustion products managed to be safely contained within the affected smoke control zones without significant dispersal to the adjacent zones.

In overall, the main reason that led to the significant difference in ventilation performance between the two ventilation systems was mainly because of the difference in the ventilation approach of the systems. The impulse jet fans system which involves open mixing of smoke in a ductless manner can result in a less effective containment of combustion products.

Aside from the ventilation performance aspect, the jet fans system offers exemplary advantages over the ducted system in terms of space-saving, cost reduction and energy saving. For enclosed car parks with ceiling height and space limitation, the jet fans system could be considered as the ventilation solution as it does not require bulky ductwork that requires high ceiling clearance. The elimination of ductwork will also contribute to significant cost savings for the installation of the ventilation system as well as the construction cost of the basement car park due to the lower excavation required. Besides, the elimination of ductwork with high static losses will result in smaller extraction fan capacity, lower noise level, and significant energy saving.

5.2 Recommendation

In this project, the transient simulation could not be done due to the limitation of computer hardware systems and time constraint reasons which causes several critical parameters involving time-constant to be unidentifiable for a thorough critical evaluation of ventilation performance such as visibility and air change rate. Therefore, an investment could be made on suitable hardware upgrades of computer systems to allow the transient simulation to be performed in future research for a more accurate analysis of ventilation performance with respect to time constant.

In addition, continual design optimisation can be carried out for the impulse jet fans system with the intention to obtain a more effective ventilation performance. Design optimisation of impulse jet fans system will enable designers to accurately determine the appropriate design for an effective ventilation performance. The design optimisation can be done in several ways, such as modifying the ventilation rate, adding of jet fans unit, placing of jet fans unit, changing the thrust value of jet fans, etc. Additional analyses could also be done to study the effects of ventilation rate, number of jet fans, location of jet fans, and thrust of jet fans on the overall ventilation performance.

Besides, a smoke barrier like smoke curtain can be added along the boundary lines of each smoke control zones of the jet fans system to improve the effectiveness of smoke containment within the affected zones.

Lastly, various fire locations can be assigned in the CFD simulation to study the effect of fire location relative to the ventilation performance. For instance, the design fire can be assigned at different locations in different smoke control zone to further validate the ventilation performance of the system as fire can happen anywhere in the car park.

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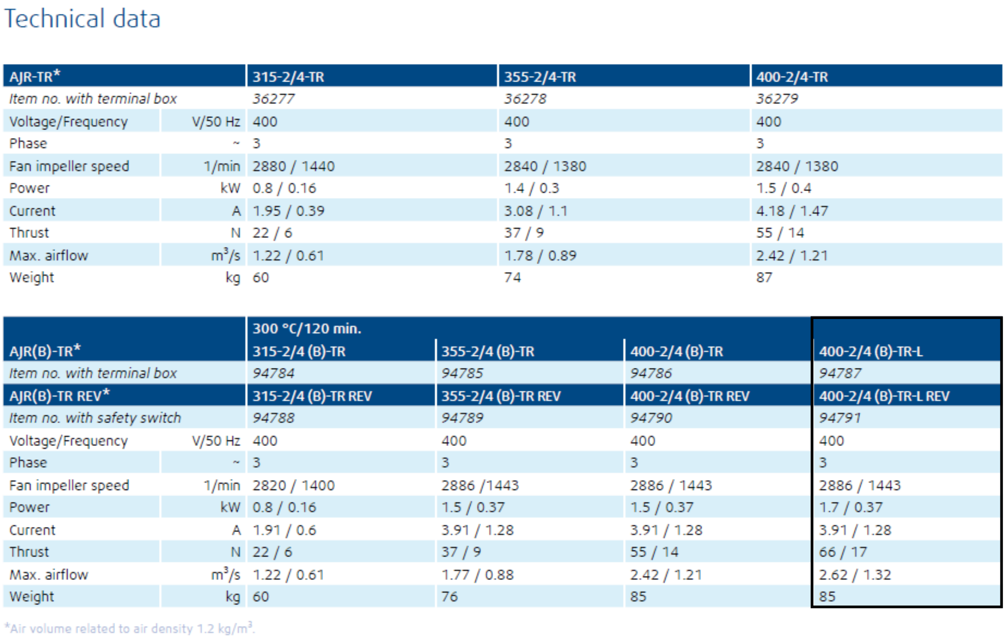
APPENDICES

Appendix A: Specification of jet fans



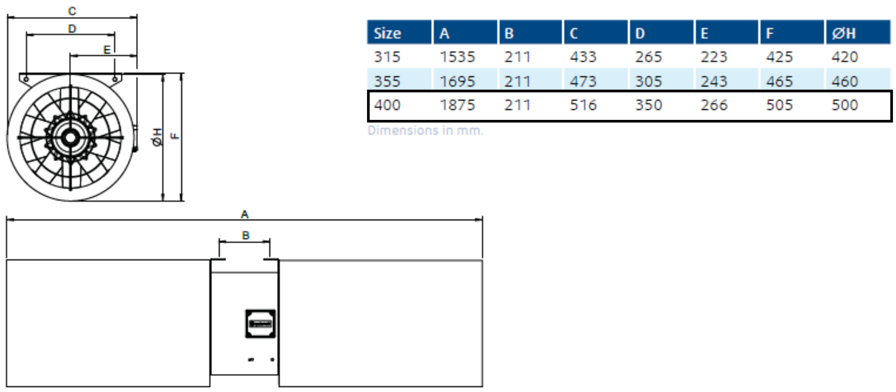
Technical data

AJR-TR*		315-2/4-TR	355-2/4-TR	400-2/4-TR
Item no. with terminal box		*36277*	*36278*	*36279*
Voltage/Frequency	V/50 Hz	400	400	400
Phase	~	3	3	3
Fan impeller speed	1/min	2880 / 1440	2840 / 1380	2840 / 1380
Power	kW	0.8 / 0.16	1.4 / 0.3	1.5 / 0.4
Current	A	1.95 / 0.39	3.08 / 1.1	4.18 / 1.47
Thrust	N	22 / 6	37 / 9	55 / 14
Max. airflow	m^3/s	1.22 / 0.61	1.78 / 0.89	2.42 / 1.21
Weight	kg	60	74	87

		300 °C/120 min.			
AJR(B)-TR*		315-2/4 (B)-TR	355-2/4 (B)-TR	400-2/4 (B)-TR	400-2/4 (B)-TR-L
Item no. with terminal box		*94784*	*94785*	*94786*	*94787*
AJR(B)-TR REV*		315-2/4 (B)-TR REV	355-2/4 (B)-TR REV	400-2/4 (B)-TR REV	400-2/4 (B)-TR-L REV
Item no. with safety switch		*94788*	*94789*	*94790*	*94791*
Voltage/Frequency	V/50 Hz	400	400	400	400
Phase	~	3	3	3	3
Fan impeller speed	1/min	2820 / 1400	2886 /1443	2886 / 1443	2886 / 1443
Power	kW	0.8 / 0.16	1.5 / 0.37	1.5 / 0.37	1.7 / 0.37
Current	A	1.91 / 0.6	3.91 / 1.28	3.91 / 1.28	3.91 / 1.28
Thrust	N	22 / 6	37 / 9	55 / 14	66 / 17
Max. airflow	m^3/s	1.22 / 0.61	1.77 / 0.88	2.42 / 1.21	2.62 / 1.32
Weight	kg	60	76	85	85

*Air volume related to air density 1.2 kg/m^3.

Dimensions



Size	A	B	C	D	E	F	ØH
315	1535	211	433	265	223	425	420
355	1695	211	473	305	243	465	460
400	1875	211	516	350	266	505	500

Dimensions in mm.

Appendix B: As-built drawing of the existing ducted ventilation system at UTAR block KB basement car park