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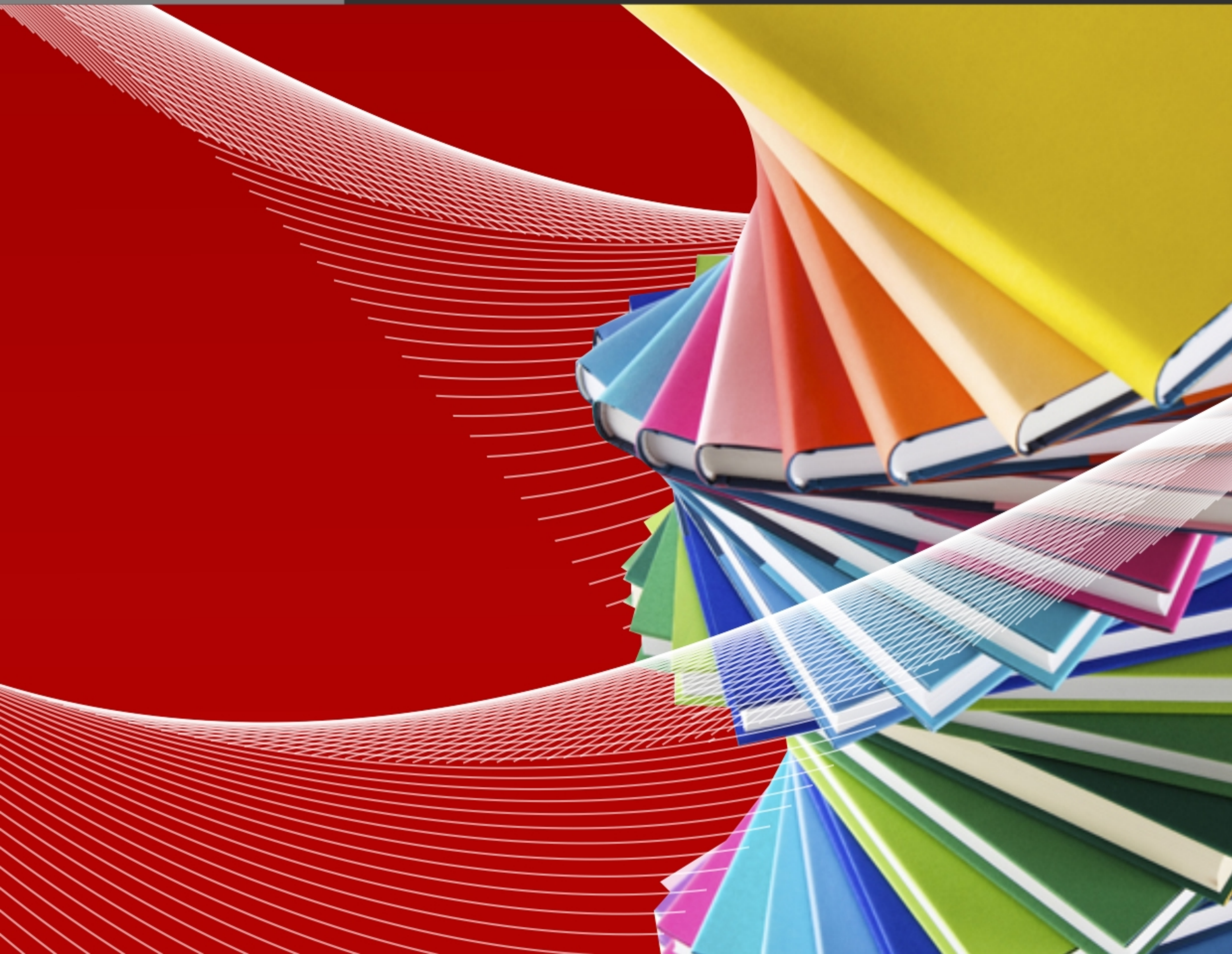

# DESIGN OF A FIRE SAFETY SYSTEM FOR ATRIA UNDER TROPICAL STORM ATTACK

by

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B.Sc. in Electromechanical Engineering

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**Faculty of Science and Technology**
**University of Macau**

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Final Year Project Report submitted in partial fulfillment of the requirements for the degree of

BSc. in Electromechanical Engineering

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Abstract

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Project Supervisor
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BSc. in Electromechanical Engineering

Atria provide spacious indoor environment for various purposes, such as shopping malls and casinos. The current prescriptive-based fire safety laws cannot provide useful guideline in designing a fire safety system in those buildings. More attentions have been attracted to the utilization of performance-based analysis for fire simulation. Some research studies have verified the design using software package of computational fluid dynamics. As a city located at the coast in the eastern Asia, Macau endures several tough typhoon attacks each year. In this proposal, it is assumed that a fire takes place in an atrium when there is a tropical storm. Chaotic winds blow into an atrium, making the smoke movement unpredictable. First, a performance-based design is to be performed to study this harsh situation. Then, a fire safety system is to be designed to handle the smoke movement

TABLE OF CONTENTS

LIST OF FIGURES

*Number* *Page*

# LIST OF TABLES

*Number* *Page*

# LIST OF ABBREVIATIONS

**CFD.** Computational fluid dynamics

**DNS**. Direct numerical simulation

**FDS.** Fire dynamics simulator

**LES**. Large-Eddy Simulation

**NFPA**. National fire protection association

**PDE**. Partial differential equation

**RANS.** Reynolds averaged numerical simulation

**SMV.** Smokeview

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# CHAPTER 1 INTRODUCTION

## 1.1 Atria in Macau:

In recently years, with the development of Macau is rapidly increased, lots of casinos, hotels, shopping malls were currently built in Macau, and most of them consist of atrium, which is a large space usually located beyond the entrance as a lobby and enclosed by large glass window. This design feature is very popular in modern building because it brings luminance and spaciousness into the space.

MGM Grand Macau is one of the world class five star luxury casinos and hotel resorts in Macau; It was built in December, 2007 and cost 1.25 billion US dollars, the total area of MGM Grand hotel is 22,000 $m^2$ and with 154 m height of thirty five storeys. The hotel has a signature lobby, Grande Praça where is a large volume space atria decorated with glass ceiling with a total area of 1088 $m^2$ and 25 m tall.[3] Therefore, the fire safety system for atria is needed and become popular in the research field of fire engineering. However, the fire safety for such large space has been questioned since a serious fire accident in 1980 [16]. Thus many researches were carried for fire safety system of atria but the design of the fire safety system for atrium is still a challenge.

## 1.2 Fire system in atrium

The most challenging in designing the fire safety system of atrium is how to clear out the smoke generated from the fire. Atria provide a barrier free space to the smoke; so that it can spread around the whole build in a very short time. Smoke is considered as the most dangerous factor in a fire accident because it brings lots of harmful effects to us in indoor fire. The toxic chemical in smoke such as carbon monoxide can cause suffocation. Also, if the fire safety system is poor, smoke layer will rapidly subside to the ground and highly decrease the visibility of the escape route. This can create a very messy result in a fire scene; more people may get injury because of this harsh situation. Even worse is high temperature smoke may have potential to cause flashover and backdraft. Therefore, a reliable fire safety system that can manage the smoke is extremely important for occupant.

Many researches reveal that [1,4], when fire appears in atrium, the smoke layer will firstly form at the top of the atrium, and then gradually subside to the ground. The common strategy to deal with this, is installing exhaust fan on the ceiling. However, this method is inefficient when strong air flow appears. This study will prove this in the later part of this study.

## 1.3 Wind effect in atrium

As Macau is located near costal region, which indicated it often suffer from tropical storm attack especially during summer time. Large glass windows mounting on atria may break by the strong wind.

In 24, July, 2012, a typhoon 'Vicente' with a number 9 signal, maximum velocity of 120 km/h attacked to Macau. During the strong typhoon hit Macau, thirty accidents were reported that windows were broken by the strong wind in three high-rise buildings. This example showed there is potential concern that building with window glass can be broken during typhoon.

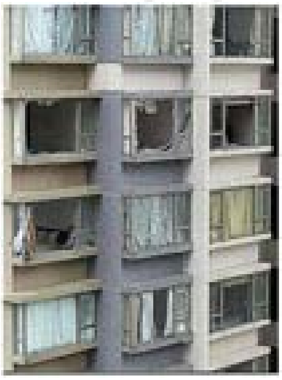


Figure 1. 1 Broken glass window during typhoon 'Vicente'
(source: http://www.chengpou.com.mo/news/2012/7/25/27380.html)

If window is broken during an atria fire, a strong wind from tropical storm will blow into the atria, which will highly affect the smoke pattern. The plume is not able to reach the ceiling to form smoke layer; instead, the smoke will be carried by the strong wind flow and spread around the space. The spread rate of the smoke is much higher when compare with “no wind effect” scenario. Therefore, the original fire safety system for atrium may not applicable for this kind of situation. The goal of this research is to study the turbulent wind effect on atrium fire and attempt to design a fire safety system to handle this messy situation.

## 1.4 Prescriptive based and performance based design for fire safety

Currently, fire safety system can be divided into two categories, prescriptive based design and performance based design.

Prescriptive based design code are codes written by fire department and is based on the history of fire accident. It set up a rigid restriction to the design in order to reach fire safety; modification will be made when there are big fire losses. Nevertheless, the code is complex and unclear. Also, it is quite subjective to the building design or building material. As a result, the code is inappropriate for innovation building design, especially for large space and high rise building. [8]

On the other hand, performance based design code will offer guidelines to establish fire safety goals, which provide more flexibility to engineers to utilize and develop their fire safety design to achieve the goals. After the design process, simulation will be done to verify the feasibility of the design. With the help of fire simulation, engineers are able to minimize the cost of the development of the fire safety system design. [8]

In view of the above, performance based design code do have more advantages than prescriptive design based code when designing fire safety system for atria. Therefore, this research study will be based on the performance based design code.

## 1.5 Objective

- To examine the effect of air movement caused by tropical storm to smoke distribution in an atrium using computational fluid dynamics package FDS.
- To design fire safety system to handle smoke generated during a fire in an atrium, and to prove the effectiveness of the design using FDS.

# CHAPTER 2. LITERATURE REVIEW

This chapter will first introduce the history of atrium fires and a national fire protection association in United Stated, then the literature and methodologies that related to the design procedure will be discussed. Such as studies on fires, wind speed, that helps to define the design criteria of the model. Also, previous work done by other scholars address the smoke management method and smoke plumes will be discussed in this chapter.

## 2.1. History of Atrium fires

Atrium fires happened in the past few decades, some of them were very serious, lots of human lives and properties were lost. One of the most serious examples is the fire catastrophe in MGM Grand Hotel in Las Vegas on 21$^{st}$ November, 1980, which was the second large fire loss hotel fire in US. This fire accident caused 85 people deaths and more than six hundred required hospital treatment. [16] Investigator reported that the fire started by an electrical fault in the small pantry of the restaurant, as the fire spread out to the casino, it spread and strengthens in a very rapid way. It is because the casino provides a large area for fire to growth, and lots of furniture act as fuel for the fire. Lot of smoke were generated and spread upwards through stair, thus it led many people died at smoke inhalation at the upper floors. This fire disaster alerted people on fire safety system in large area space building and later, NFPA create 92B regulations to provide guidance in smoke control management systems in Malls, Atria and Large space.[2]

## 2.2. National fire protection association

NFPA, National fire protection association was formed in 1896 in United States, and it has been published more than hundreds codes and standards for buildings design in United State. Also, their codes and standards are being used as references of fire in many countries as it is a reliable and worth trusty international fire protection association in the world. Macau is also using NFPA as a standard for fire safety system of buildings.



## 2.3. Procedure of designing fire safety system

### 2.3.1. Establish of the fire safety goal

NFPA92B is a performance based design guideline for smoke management systems in Malls, Atria, and large spaces for engineers when they design fire safety system for large spaces. It provides algebraic equations to calculate individual factors that collectively can be used to establish the design requirements of a smoke management system. [2] After calculating the design requirement, engineers are able to develop their own safety system's model based on the result of the calculation.

In this study, all the design parameter, such as mass flow rate and average temperature of plume, maximum volumetric flow rate for a single exhaust inlet, minimum separation between exhaust inlets, will be calculated based on NFPA 92B.

### 2.3.2. Study the fire scene

To design an efficient fire safety system, engineers have to understand the fire scene they are dealing with. Usually, the flow of fluid (air inside the fire scene) is described by the laws of conservation of mass, momentum and energy, which is a set of partial differential equations (PDE). It is very tedious for engineers to solve the PDEs; therefore, computational fluid dynamics, also abbreviated as CFD, was introduced in early 20 century, which is a technique that enable computer numerically solve those PDEs and simulate the fluid flow.[14]

The fundamental problems that CFD deal with are the system of Navier-Stoke equations, which relate the pressure, the temperature, the velocity and the density of the moving fluid. The complexity of these equations is extremely high. Especially for turbulent flow, eddies with different length scales are formed, which level up the complexity of the calculation and it can be impossible to compute. The strategy to handle such complex cases is to create a model that can approximate the unresolved phenomena. There are three models that are extensively used, Direct Numerical Simulation (DNS), Large Eddy Simulation (LES) and Reynolds Averaged Navier-Stoke (RANS). [14]

- For DNS, the motions of all scales of eddies are resolved, every detail information of the flow can be obtained through this approach; however, the computational requirement of this approach is very high. The industrial applications of DNS on the study of turbulence flow are limited, since the computational resource required will be far beyond the capability of computer that currently available.
- For RANS, is a classical approach of turbulence modeling. The approximation made in this model is to average the turbulence equations by time. In contrast to DNS, it greatly reduces the computational cost and is widely used in industrial application. The restriction of this method is, RANS only gives a time-average value to the flow velocity and could not track its time dependent variations.
- In between DNS and RNS, LES provides a intermediate approach. As, DNS, it will directly solve the motion of eddies, but with a filtering equation to remove small scales eddies. The effect of those small eddies will be approximated by a sub-grid model. It can reduce the computational cost and provides a reasonable solution.

The comparison of these three methodologies is shown in the following table. Fig. shows the difference in performance for these three approaches.

| | Accuracy on velocity field | Computational cost |
|---|---|---|
| **DNS** | High | High |
| **LES** | Medium | Medium |
| **RANS** | Only provide mean value | Low |

Table 2. 1 Features of different CFD model

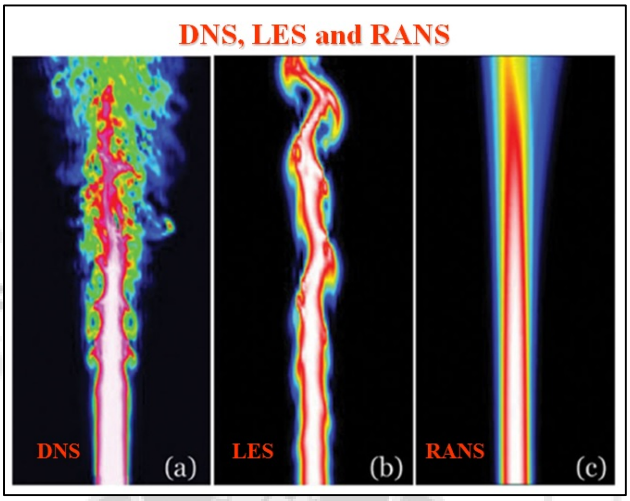



Figure 2. 1 Comparison of DNS, LES and RANS

Source:http://www.uttei.enea.it/combustione-sostenibile/img-combustione-sostenibile/DNSLESRANS.jpg/image_view_fullscreen

### 2.3.3. Validate the design

After studying the fire scene, engineers are able to design their system to handle the situation. As previous phase, computer simulations are used to validate the feasibility of the design. Currently, there are many software available for such purpose, like FLUENT, COMSOL, FDS.

The software used in this project is FDS; further description of this software will be given in later chapter.

## 2.4.Characteristics of fire

Characteristics of fire have to be determined in modeling a real fire source, which include size and shape of the fire, the power, the growth rate, and also the chemical process of combustion. This section will review the literatures that are used to define the properties of the fire.

### 2.4.1. Fire growth behavior

In reality, the development of fire can be divided into four stages, incipient, growth fully developed and decay. The process can be described by the Q-t diagram of the fire, as Fig 2.2 shown. [12]

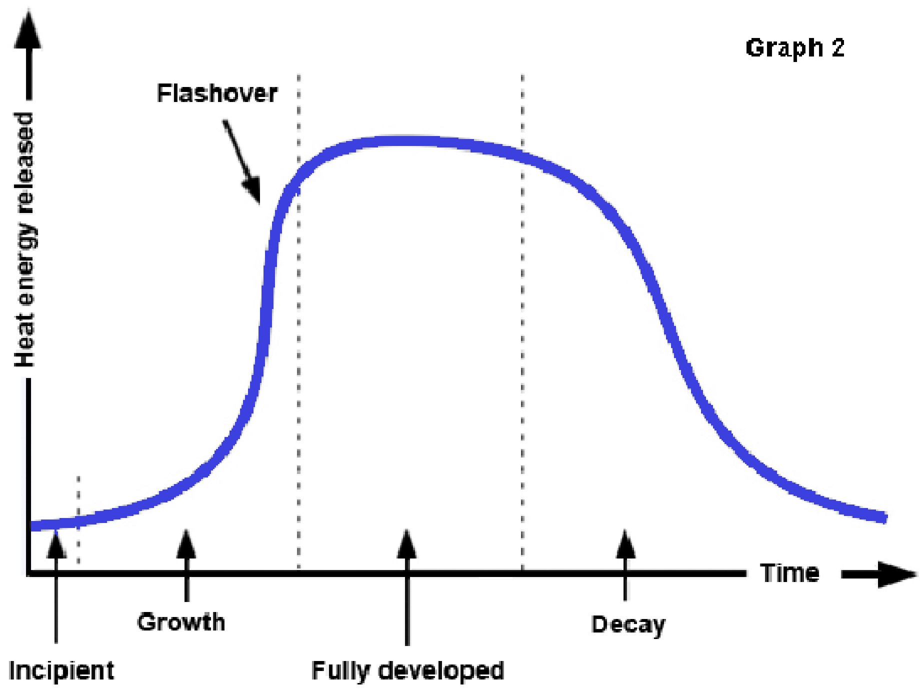



Figure 2. 2 Fire growth process

Source: http://www.tathrafirebrigade.org.au/images/fire_growth_2.png

With the existence of fuel, heat, oxygen, fire is ignited and goes into the incipient stage. At this stage, the heat generated by the fire is still low. Also, the amount of smoke is limited; therefore, defined smoke layer may not be form in the ceiling

If the building provides enough oxygen and additional fuel, the fire is able to growth and then comes into the growth stage. This stage is important, since the heat release rate of the fire may has a huge increment. Smoke become visible and a well-defined smoke layer may appear in the top of the building. If there is no wall or block, the smoke then can spread around the building without restriction.

The temperature in the building rises as the fire grows, when the temperature reaches 500˚C to 600˚C, the surface involvement of all combustible material within the building will under a rapid state transition, this is flashover. It produce a suddenly rise in temperature and amount of smoke. This transition stage occurs in very short time, and then the fire grows to fully-developed stage.

When the fire grows to fully-developed stage, the heat energy reaches to maximum. The temperature inside the building can reaches 700˚C to 1200˚C. Smoke color changes to dark gray, even black. If the ventilation system is poor, the smoke layer may drops to the floor and endangers humans' lives.

When the fuels inside the building have been consumed or the oxygen is not enough, the fire may eventually come into decay stage. The heat release rate may gradually decrease but the temperature may still increase for a short time.

Therefore, the growth behavior of fire should be taken into consideration of modeling a real fire. Following Peng, Fu and Chen's [17] research, their studies is to examine the effect of different air supply system on smoke evacuation system of Large sized indoor Stadium by using CFD based numerical simulation software. In their studies, they mentioned there are two kinds of fire in fire scene modeling steady and unsteady fire. The steady fire is ideal but the real fire should be unsteady and assumed as t squared fire. The speed of the fire growth is controlled by a parameter, called fire growth coefficient.

| Growth rate | Fire growth coefficient ($kW/s^2$) |
|---|---|
| Slow | 0.002931 |
| Medium | 0.01127 |
| Fast | 0.04689 |
| Ultra-fast | 0.1878 |

Table 2. 2 growth coefficient for difference speed fire growth

In this study, fire is chosen to be fast growth and further description will be explained in the later chapter.

### 2.4.2. Chemical process of combustion

Fire is visible form of a combustion process. When oxygen in air counters with fuel and heat, a chemical reaction may occur and produce carbon dioxide, water and heat, this reaction known as combustion.

$$C_xH_y + nO_2 = CO_2 + H_2O + Heat$$

To start combustion, the heat must be high enough to reach the ignition temperature of the fuel. As long as there are sufficient oxygen and fuel, then the heat generated by the reaction will sustain the reaction. The rate of the combustion depends on the amount of oxygen in the surrounding; a very fast combustion is called burning and results in a visible flame.

Fuel plays an important role in the process of combustion. The properties of fuel may influence the conditions of the combustion process. Fuels can be in different phase, solids, liquids or gases. In general, they consist of two chemical elements, hydrogen and carbon. They can be expressed in empirical formula $C_xH_y$. Different fuels may have different properties. The following table 2.3 shows some properties of common fuels.

| Fuel | High heating value (kJ/kg) | Autoignition Temperature (°C) |
|---|---|---|
| Gasoline/E10 | 289227 | 257.2 |
| Low Sulfur Diesel | 322141 | 315.5 |
| Liquefied Natural Gas (LNG) | 55189 | 540 |
| Propane (LPG) | 212652 | 454~510 |
| Methanol | 151661 | 480.5 |

Table 2. 3 properties of common used fuel

Information source: http://www.afdc.energy.gov/fuels/fuel_properties.php

Oxygen is the other important factor of combustion. Depends on the amount of oxygen, combustion can be divided into two types, one is complete and the other is incomplete combustion. The products in complete combustion are only water and carbon dioxide, the condition for complete combustion to occur is enough oxygen for the reactant to react. While in incomplete combustion, the condition for it to occur is insufficient oxygen for the reactant to react. The products in incomplete combustion are some toxic substance such as carbon monoxide and other carbon particles can form, along with water and carbon dioxide. Smoke often can be observed in the incomplete combustion.

## 2.5. Wind speed

### 2.5.1. Wind effect on atria fire

Meroney [5] discuss how external wind distort thermal and smoke columns rising above a fire in the atria. He used a finite-volume CFD program to perform fire simulations of atria. He studied a 3D atrium building model with dimension of $20\text{m} \times 20\text{m} \times 20\text{m}$. Four $1\text{m} \times 3\text{m}$ door openings are placed at the center of four sides of the atria and four exhaust openings are located at the four corners of the ceiling [5]. For schematic diagram, please refer to fig. 2.3. The fire was assumed to be a steady fire with a power 2.5 MW and located in a 2 $m^2$ region at the center of the atria. Uniform wind flow of 0 m/s and 2 m/s was set to flow in one of the door openings.

His research reveals that the external wind flow can cause the plumes to impact against the wall, and alter the filling of smoke. [5]

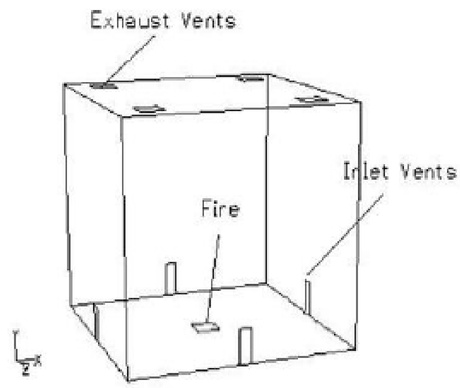



Figure 2. 3 3D atrium model from Meroney's research

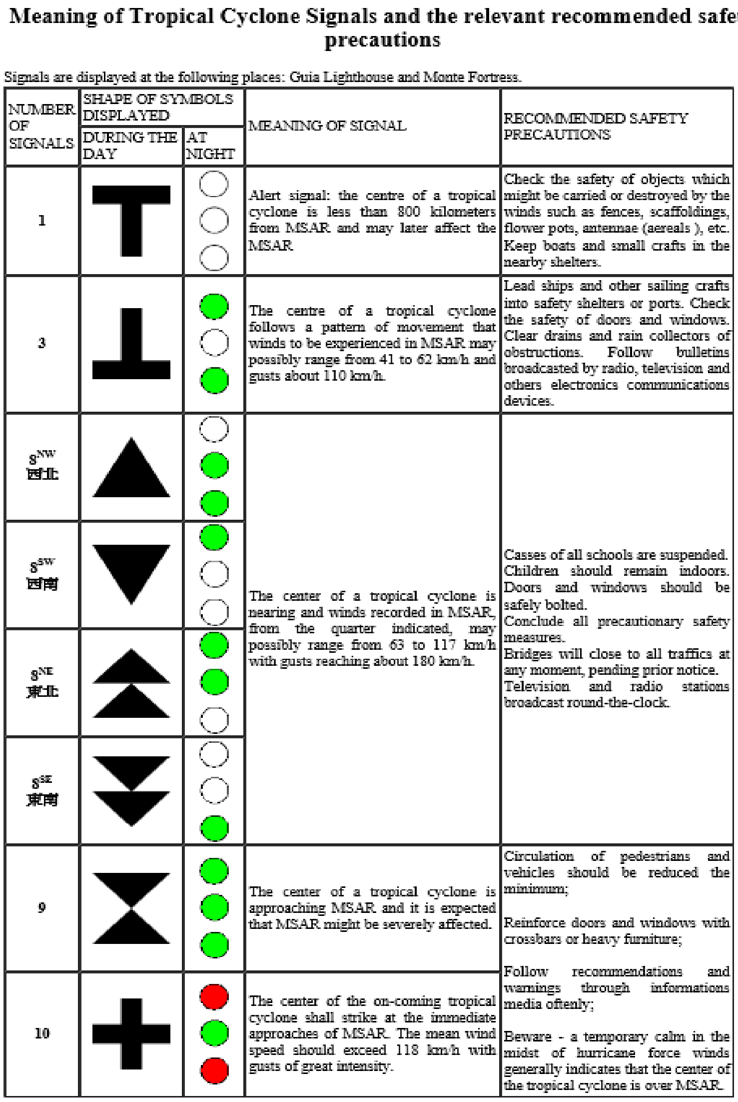
The models in this report are based on his work. The simulations were performed by FLUENT 6.1 in Meroney's research, while FDS5.5.3 is used in this study to perform simulation. Therefore, verification has been done to prove the feasibility of the model in this report; the verification result will be discussed in the later chapter.

### 2.5.2. Wind speed in tropical storm

Tropical storm, also called typhoon, is a weather phenomenon, which is a low pressure system surrounded by high speed rotating storm. It always comes with strong winds and heavy rain, which brings serious damage to public.

In Macao, tropical storms are classified into different levels based on their strength. The meteorological department of Macao (SMG) set up tropical storm signals for citizen. Fig. explains the meanings of the signals and the recommended safety precaution

In this project, signal No.3 was assumed to be hoisted. Wind with speed 41 to 62 km/h and gusts about 110 km/h will blow into the atria and distort the smoke.



**Meaning of Tropical Cyclone Signals and the relevant recommended safety precautions**

Signals are displayed at the following places: Guia Lighthouse and Monte Fortress.

| NUMBER OF SIGNALS | SHAPE OF SYMBOLS DISPLAYED: DURING THE DAY | SHAPE OF SYMBOLS DISPLAYED: AT NIGHT | MEANING OF SIGNAL | RECOMMENDED SAFETY PRECAUTIONS |
|---|---|---|---|---|
| 1 | | | Alert signal: the centre of a tropical cyclone is less than 800 kilometers from MSAR and may later affect the MSAR | Check the safety of objects which might be carried or destroyed by the winds such as fences, scaffoldings, flower pots, antennae (aereals ), etc. Keep boats and small crafts in the nearby shelters. |
| 3 | | | The centre of a tropical cyclone follows a pattern of movement that winds to be experienced in MSAR may possibly range from 41 to 62 km/h and gusts about 110 km/h. | Lead ships and other sailing crafts into safety shelters or ports. Check the safety of doors and windows. Clear drains and rain collectors of obstructions. Follow bulletins broadcasted by radio, television and others electronics communications devices. |
| 8^NW 西北 | | | The center of a tropical cyclone is nearing and winds recorded in MSAR, from the quarter indicated, may possibly range from 63 to 117 km/h with gusts reaching about 180 km/h. | Casses of all schools are suspended. Children should remain indoors. Doors and windows should be safely bolted. Conclude all precautionary safety measures. Bridges will close to all traffics at any moment, pending prior notice. Television and radio stations broadcast round-the-clock. |
| 8^SW 西南 | | | | |
| 8^NE 東北 | | | | |
| 8^SE 東南 | | | | |
| 9 | | | The center of a tropical cyclone is approaching MSAR and it is expected that MSAR might be severely affected. | Circulation of pedestrians and vehicles should be reduced the minimum; Reinforce doors and windows with crossbars or heavy furniture; Follow recommendations and warnings through informations media oftenly; |
| 10 | | | The center of the on-coming tropical cyclone shall strike at the immediate approaches of MSAR. The mean wind speed should exceed 118 km/h with gusts of great intensity. | Beware - a temporary calm in the midst of hurricane force winds generally indicates that the center of the tropical cyclone is over MSAR. |

Figure 2. 4 Meaning of tropical cyclone signals and the relevant recommended safety precautions.

Source from: (http://www.smg.gov.mo/smg/severeWeather/c_typhoon_def.htm)

Chaotic system, this term is used to describe some things that behave between regularly and randomly. A very good example of chaotic system is nature system. There are some characteristics of chaos, which include, extremely sensitivity to the initial condition; nonlinearity and deterministic. Due to these characteristics, people are only able to predict the system for a very short period of time.

Weather also is considered as a chaotic system and meteorologists has been interested in prediction of weather. Edward Lorenz, who was an american mathematician and meteorologists. He had studied the behavior of weather for many years; he created a mathematical model to predict the weather. His model was composed of 3 simple differential equations (later was named “Lorenz Equations”). At the end, he accidentally discovered his model was extremely sensitive to the initial condition, and was difficult to predict. He summarized this behavior and termed it “chaos”. He concluded that weather is also a chaos, it is hard to predict since the present conditions of atmosphere can’t be completely accurately measured. Every small error can lead to huge failing in the prediction. [11]

In this project, the wind speed was also considered as chaos and the Lorenz equation would be used in modeling the wind.

## 2.6. Fire plumes

Smoke plume is formed when a fire occurred, and as the plume rises to space, surrounding air will be pulled into the plume, which can lead the mass flow rate of plume increase and decrease its temperature.[10] As the plume reaches the ceiling, it diffuse to the whole ceiling and becomes a smoke layer. Smoke will be exhausted from that layer by the atrium smoke control system. If the system is well designed, the smoke layer should be maintained in a constant height and left a safe environment for occupants to evacuate. To design smoke control system, one should know how much smoke that are flowing into the smoke layer. There are different types of smoke plumes and each of them have various mass rate of smoke production which can be calculated on the NFPA 92B. The most commonly used fire plumes in smoke control design are axisymmetric and balcony spill plume.

Klote [1] discussed for a design analysis, it is needed to include the fires location whether it is located in the center of the atrium or communicating spaces. If the fire source is located at the center of ground floor of atria, axisymmetric plume will be formed. The feature of this kind of plume is, it flows upward perpendicularly to the floor and should not flow against the walls, as shown in Figure 2.4 a

Communicating space is an opening space to atrium so that smoke can freely travel from one space to other. [1] If fire starts at here, the smoke generated from it can form a balcony spill plume, which flows under the balcony then flows upward after it reaches the edge of balcony, as shown in Figure 2.4 b

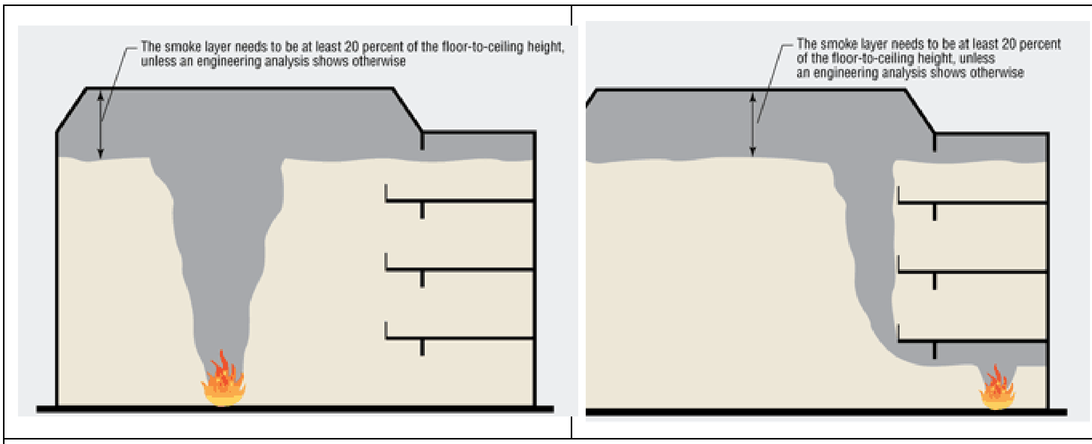



Figure 2. 5 a Illustration of axisymmetric plume (left hand side)

b Illustration of balcony spill plume (right hand side)

Source: http://hpac.com/fastrack/State-of-the-Art-Atrium-Smoke-Control

Also, he didn't suggest the use of sprinklers for high ceiling building because of the temperature drops of the fire plume. As mentioned in the beginning of this paragraph, the temperature of the plume decrease as the plume rises. When the plume reaches the ceiling, its temperature may drop so much that it could not activate sprinklers. It will result in a delay on the sprinkler system. [1]

## 2.7. Smoke control method in Atria

There are three typical method of smoke control method for atria; they are natural smoke filling, mechanic exhaust and natural venting. [1] Mechanical exhaust is mainly used for smoke control in this report.

Smoke filling

Smoke filling can be useful to very large volume spaces only where the time for smoke filling is sufficient enough for occupants to evacuate. This method is effective as it provide enough evacuation time for people to exit the fire scene while the smoke is still filling to the top of the atria spaces.[4,7].

Natural Venting

Its principle is using the buoyancy of hot smoke as driving force to force the smoke out to the open vents on the roof of the atria. This method has been discussed by Doheim,[9] that natural venting in atria can be greatly influenced by the shape of atria (with same height), that is different shape of atrium can have different smoke filling time. In their case, they analyze three shapes, the rectangular, square and triangle. The efficiency of this method can also be affected by other design factor for example the height, size and opening of atrium.

Mechanical exhaust

This method is most widely used in smoke control design; exhaust fan is usually installed at the roof of atria so that smoke can be removed from the upper part of an atrium.[4,7] However, when installing the ceiling exhaust fan the maximum mass flow rate of it should be considered carefully in order to avoid plugholing effect occur. [1,2]

# CHAPTER 3. : MODEL TECHNIQUE AND IMPLEMENTATION

## 3.1. Theory

### 3.1.1. Unsteady fire growth power

In fire scene model, fire can be categorized into two types, steady and unsteady fire. Steady fire is used for idealized model, but in real fire scene, fire should be unsteady and the growth power can be described as the following equation.[17]

$$Q = \alpha t^2 \tag{3. 1}$$

Where

$\alpha$ : Fire growth coefficient, $kW/s^2$

$t$ : Burning time, s

In this report, fire growth was assumed to be fast and the coefficient was 0.04689, and power of fire was 2.5MW. The growth process was illustrated in the Fig 3.1.

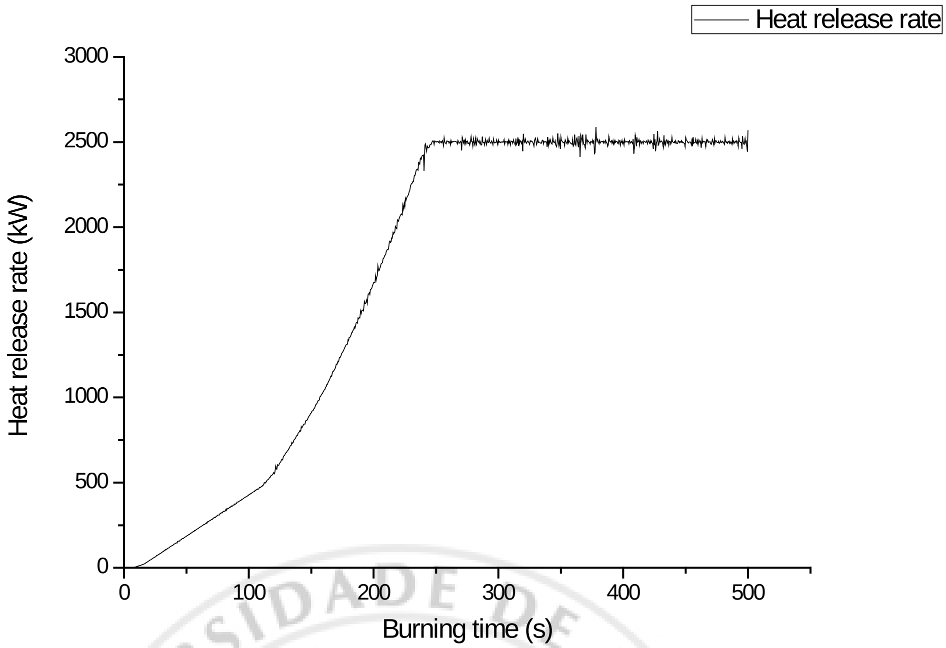



Figure 3. 1 Heat release rate verse burning time

### 3.1.2. Lorenz equations

During tropical storm, the wind speed should be unsteady and fluctuate in a particular range. As mentioned in pervious chapter, the fluctuation of wind speed would be modeled by Lorenz equations.[11]

The Lorenz equations describe as follow,

$$\frac{dx}{dt} = \sigma(y - x) \tag{3. 2}$$

$$\frac{dy}{dt} = x(\rho - z) - y \tag{3. 3}$$

$$\frac{dz}{dt} = xy - \beta z \tag{3. 4}$$

Where $x, y, z$ functions of time are, $\sigma, \rho, \beta$ are system parameters.

### 3.1.3. Estimated smoke exhaust rate

Based on the principle of the conservation of mass, the required smoke exhaust rate for holding the smoke layer in a particular position can be determined by estimating the rate of smoke that flow into the smoke layer.[2]

$$\dot{m}_{ex} = \dot{m}_p \tag{3. 3}$$

NFPA92B provides equations that can predict the smoke production rate for a given heat release rate *Q*. [2]

According to NFPA92B [2], the convective heat release rate is described as follow,

$$\mathrm{Q_c} = 0.7Q \tag{3. 5}$$

The rate of upward mass flow rate of axisymmetric fire plume is,

$$\dot{m}_p = 0.071{Q_c}^{1/3}Z^{5/3} + 0.0018\mathrm{Q}_c \ \ (Z > Z_1) \tag{3. 6}$$

Where,

$\dot{m}_p$： Upward mass flow rate of plume, kg/s

Qc： Convective heat release rate, kW

Q： Heat release rate, kW

Z： Distance between the ground to the smoke layer, m

$Z_1$： Mean flame height, m （$Z_1 = 0.166{Q_c}^{2/5}$）

The average temperature of the plume can be determined using the flowing equation,

$$T_p = T_o + \frac{Q_c}{\dot{m}_p C_p} \tag{3. 7}$$

Where,

$T_p$ : Plume temperature, K

$T_o$ : Ambient temperature, K

$C_P$ : Specific heat of smoke, kJ/kg°C

The volumetric flow rate of the smoke flow into the smoke layer,

$$\dot{V}_i = \frac{\dot{m}_p}{\rho_s} \tag{3. 8}$$

Where,

$\dot{V}_i$ : Volumetric flow rate of smoke flow in to smoke layer, $m^3/s$

$\rho_s$ : Density of the smoke, $kg/m^3$

The density of smoke can be determined by ideal gas law,

$$\rho_s = \frac{\rho_o T_o}{T_p} \tag{3. 9}$$

Where,

$\rho_o$ : Density of the outdoor air, $kg/m^3$

Therefore, the volumetric flow rate can be expressed as follow,

$$\dot{V}_e = \dot{V}_i = \frac{\dot{m}_p}{\rho_o T_o} T_p \tag{3. 10}$$

Based on this value, the exhaust rate of the system can be estimated.

3.1.4. Avoid plugholing effect

The plugholing effect should be avoided when designing the exhaust rate of the fan. Plugholing effect, is a phenomenon that occur when the exhaust rate are too high, which will pull the clear air through the smoke layer into the smoke exhaust. To avoid plugholing, NFPA 92B provide some guideline to follow. [1,2]

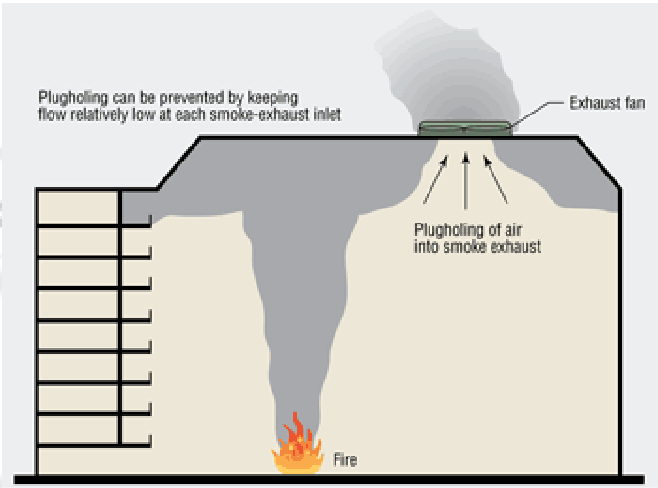



Figure 3. 2 Illustration of Plugholing effect

Source from research of Klote [1]

In order to prevent plugholing, the maximum volumetric flow rate for a single exhaust inlet can be determined by this equation.[2]

$$V_{max} = 0.537\beta d^{5/2}\left(\frac{T_s - T_o}{T_o}\right)^{1/2} \quad (3.\,11)$$

Where,

$V_{max}$ : The maximum volumetric flow rate for single exhaust, $m^3/s$

β : Exhaust location factor, dimensionless

(According to NFPA92B, value of 2 shall be used in common cases.)

d： Depth of smoke layer under the bottom of the exhaust inlet, m

3.1.4 The minimum distance between exhaust inlets

The distance between every exhaust inlets can be determined by,

$$S_{min} = 0.023\beta {V_e}^{1/2} \tag{3. 12}$$

Where,

$S_{min}$： The minimum distance between every exhaust inlets, m

$V_e$： Exhaust rate for one exhaust inlet, $m^3/s$

## 3.2. Modeling technique

This section will give an overview on the software that used in fire modeling in this project and provide some information on the feature of this software.

### 3.2.1. Introduction of FDS

Fire Dynamics Simulator (FDS), is a widely used computational fluid dynamics (CFD) model for fluid flow driven by fire. It will divide the space into numerous small control volumes, so called grids, and solving the Navier-Stoke equations for each grid to calculate the heat and smoke transport from fire. With a large number of useful build in functions in FDS, it can simulate fire in different scenarios, of course atrium fire are included. [6]

In the simulation process, the role of FDS is to solve the equations and describe the growth of fire. It reads input parameter from a text file, calculate the solution of the equations and output the data in specific files.[6]

Smokeview, which is a companion program packaged with FDS. It reads the output files of FDS. Visualize the data and produce 3D animation and image for people to use.[6]

### 3.2.2. Governing equations

The conservation equations solved by FDS are described as follow:[13]

Conservation of mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \boldsymbol{u} = \dot{m}_b''' \tag{3.13}$$

Conservation of momentum:

$$\frac{\partial}{\partial t}(\rho \boldsymbol{u}) + \nabla \cdot \rho \boldsymbol{u}\boldsymbol{u} + \nabla p = \rho \boldsymbol{g} + \boldsymbol{f_b} + \nabla \cdot \tau_{ij} \tag{3.14}$$

Conservation of energy:

$$\frac{\partial}{\partial t}(\rho h) + \nabla \cdot \rho h \boldsymbol{u} = \frac{Dp}{Dt} + \dot{q}''' - \dot{q}_b''' - \nabla \cdot \dot{\boldsymbol{q}}'' + \varepsilon \tag{3.15}$$

Idea gas law:

$$p = \frac{\rho RT}{\bar{W}} \tag{3. 16}$$

Following is a brief description of the terms. $\vec{u} = (u, v, w)$, is velocity vector, where *u*, *v* and *w* are velocity for *x*, *y* and *z* direction respectively. T is temperature, p is pressure, ρ is density, h is sensible enthalpy, which is a function of temperature.

$$h = \int_{T_0}^{T} C_p(T')dT' \tag{3. 17}$$

In the equation of conservation of momentum, $\vec{u}\vec{u}$ is an alternative form of $\boldsymbol{u}^T$ multiply by $\boldsymbol{u}$, $\nabla$ is gradient vector, $\nabla = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right)$, $\boldsymbol{f_b}$ is external force and $\tau_{ij}$ is stress tensor which defined as follow,[13]

$$\tau_{ij} = \mu\left(2S_{ij} - \frac{2}{3}\delta_{ij}\nabla \cdot \vec{u}\right) \; ; \quad \delta_{ij} = \begin{cases} 1 & i = j \\ 0 & i \neq j \end{cases} \; ; \tag{3. 18}$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \; i, j = 1,2,3$$

Where $S_{ij}$ is strain tensor, μ is dynamic viscosity of the fluid.

In the equation of conservation of energy, the term $\dot{q}'''$ is the heat released by the chemical reaction, $\dot{q_b}'''$ is the energy that transferred to evaporate and $\dot{\boldsymbol{q}}''$ represents the conductive and radiative heat fluxes. ε is dissipation rate and can be described as,

$$\varepsilon \equiv \tau_{ij} \cdot \nabla \cdot \vec{u} \tag{3. 19}$$

$$= \mu\left[2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + 2\left(\frac{\partial w}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial x} + \frac{\partial u}{\partial y}\right)^2 + \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 - \frac{2}{3}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial y}\right)^2\right]$$

### 3.2.3. Large Eddy Simulation (LES)

In FDS, Large Eddy Simulation (LES) is the default operation method for simulating turbulent flow. Which is a popular technique for numerically solve the Navior-Stroke equation of fluid flow with high Reynolds number. The feature of LES is that only large eddies will be explicitly solved in calculation while small eddies will be filtered and inexplicitly resolved in sub-grid scale model. The advantage of this approach is, it does not require a very fine grid compare to Direct Numerical Simulation (DNS); as a result, it can reduce the simulating time and requirement on computer source. [14]

### 3.2.4. Multiple Meshes method

The calculation performed by FDS must be within the domain which is constructed by one or more than one rectilinear volumes, namely, meshes. Each mesh is divided into many small grids; the resolution of each mesh depends on the number of the grids. Finer grid size will gives higher resolution but it will also increase the simulation time; therefore, it is inefficient if the whole domain is constructed with fine grids.

FDS allows one to divide the computational domain into meshes with different grid size, termed multiple meshes. With this, the grid size can be finer for those regions which are important. While for those regions which are not so important, the grids can be coarser. This method can let the computer focuses on a specific region and shorten the simulation time. [6]

## 3.3. Model implementation

### 3.3.1. Set up of the fire source

The fire source was set to a 2m × 1m region located at the center of the atrium, with a heat release rate 2.5 MW. The atrium considered as a commercial space, which may include many wooden furniture, lighting; fire power will be rapidly gained. Therefore, the fire growth coefficient for fast growth will be chosen. According to equation 3.1, with power 2.5MW and $\alpha$ is 0.04689, the growth time can be estimated as 230.09 second by using equation (3.1)

### 3.3.2. Building geometry

In the verification phase of this study, the atrium model was set to have a same dimension with Meroney's model, which has the following features[5]:

- 20m × 20m × 20m cubic atrium

- Four 3m × 1m door openings in the center of all four building sides (Case 1&2)
- One 3m × 1m door opening in the center of the wall (Case 3 to 15)
- Four holes (2m × 2m) on the ceiling for natural ventilation
- The thickness of the wall are 1m
- The front wall was set to be transparent for observation

Case1 to case5, these five cases will be made in the verification phase firstly. The aim is to verify the model's reliability also examine the effect of unsteady/steady fire.

In the design phase, the atrium modified to a three story atrium with floor height ranges from 3.5m to 4m, since in real case, large atrium more likely to be multi story. Fig3.3 gives an illustration for this.

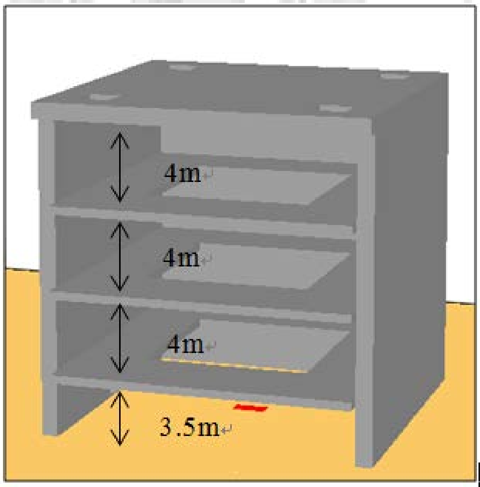



Figure 3. 3 Atrium floor setting

Some modifications that are made in the atrium are the following:

- Different location of opening is made for the purpose of window/glass broke
- Unsteady fire (T- squared ) is originated at the center of the atrium

- Unsteady wind velocity

### 3.3.3. Mesh arrangement

The domain of the model was set to a 60m × 60m × 40m retangular space. Multiple mesh method was used in order to reduce the simulation time. The computainal domain was divided into 5 meshes. The figure below shows the the arrangement of the meshes. The conditions of outdoor envirnment were calculated in mesh 1, 2, 4, 5, which were composed of crose grain with dimension 1m × 1m × 1m. On the other hand, the environment near the atrium, which was the fire scene, was calculated in mesh 3 with finer grid size, 0.25 m × 0.25 m × 0.25m.

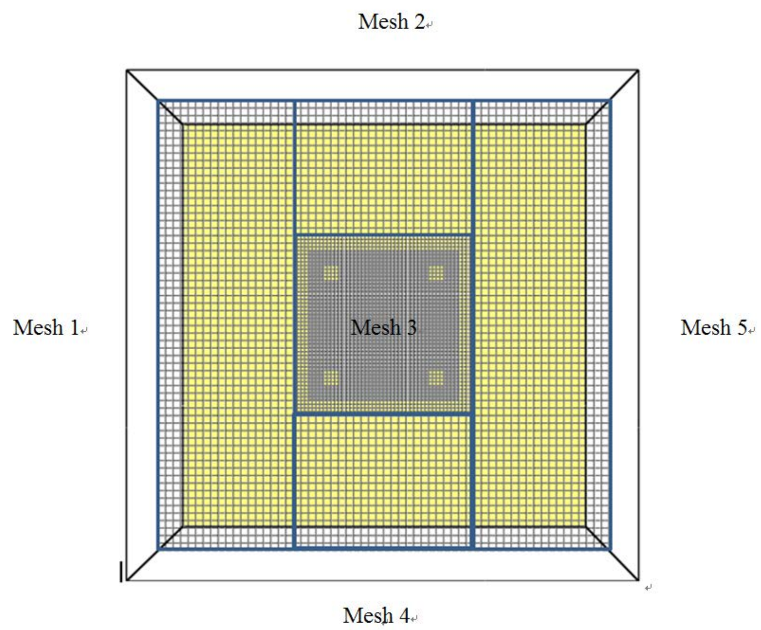



Figure 3. 4 Meshes arrangement

### 3.3.4. Modeling of wind speed

Matlab was used to numerically solve the Lorenz equations. With the initial value $(x, y, z) = (0.2, 0.2, 0.2)$, the equation then can be solved. The solution of z was chosen to be based model of the wind speed, since all the values of z were positive and the following figure gives an illustration for the solution.

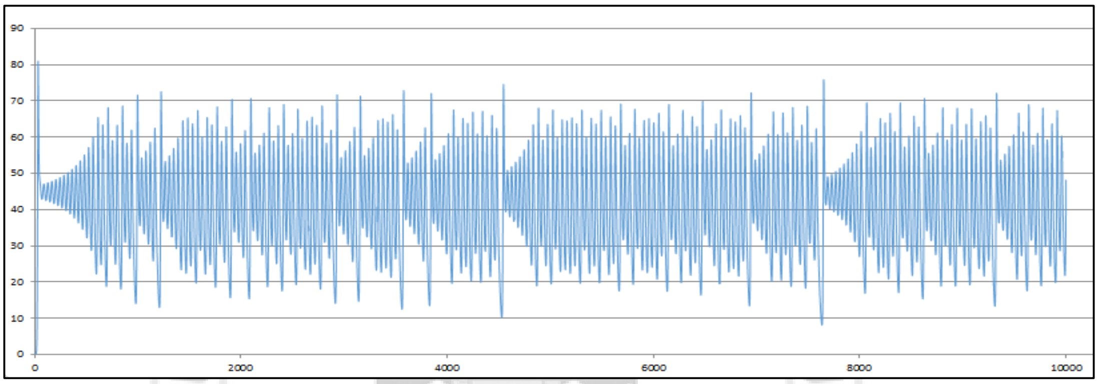



Figure 3. 5 Numerical solution of time series z

Then a portion of function z was selected to do further modification. The signal from the time series z then normalized to a range from 0 to 1. Then multiply the signal by 30.55 m/s which is the maximum wind speed in signal no.3. The figure below is the wind velocity after medication.

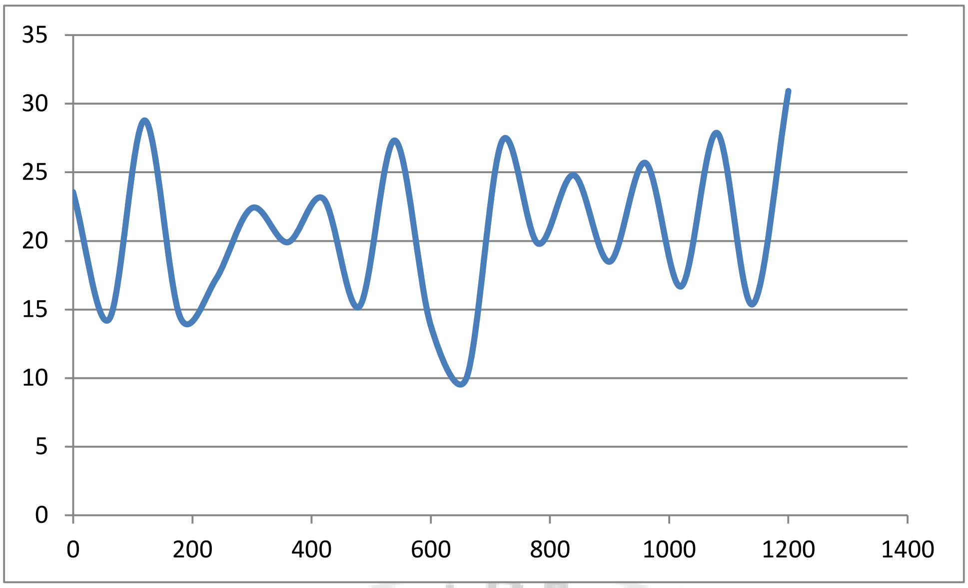



Figure 3. 6 Wind velocity model

Equations (3.6) to (3.10) were applied in calculation on the smoke exhaust rate:

$Q_c = 0.7\,Q = 0.7 * 2500kW = 1750kW$, The outdoor temperature was 19.8°C

Z = 16.5 + 2 = 18.5 m, 2m above the highest standing floor,

With the given parameter, the mass flow rate of the smoke can be calculated $m_{pl} = 113.87 kg/s$

- Volume flow rate of the plume,

$$V = \frac{m_{pl}}{\rho_0 T_0}\left[T_0 + \frac{Q_c}{m_{pl} C_p}\right]$$

Therefore, V=101.13 ($m^3$/s)

| Case NO. | Time (s) | Wind speed (m/s) | Situation |
|---|---|---|---|
| 1 | 500 | 0 | 4 openings at 4 sides of atrium |
| 2 | 500 | 2 | 4 openings at 4 sides of atrium |
| 3 | 500 | 0 | 1 opening on the left side wall, GF |

| | | | |
|---|---|---|---|
| 4 | 500 | 0.5 | 1 opening on the left side wall, GF |
| 5 | 500 | 2 | 1 opening on the left side wall, GF |
| 6 | 500 | Signal No.3 | 1 opening on the left side wall, GF |
| 7 | 500 | Signal No.3 | 1 opening on the left side wall, GF |
| 8 | 500 | Signal No.3 | 1 opening on the left side wall, GF |
| 9 | 500 | Signal No.3 | 1 opening on the left side wall, GF |
| 10 | 500 | Signal No.3 | 1 opening on the left side wall, GF |
| 11 | 500 | Signal No.3 | 1 opening on the left side wall, GF |
| 12 | 500 | Signal No.3 | 1 opening on the left side wall, GF |
| 13 | 500 | Signal No.3 | 1 opening on the left side wall, GF |
| 14 | 500 | Signal No.3 | 1 opening on the left side wall, GF |
| 15 | 500 | Signal No.3 | 1 opening on the left side wall, 1F |
| 16 | 500 | Signal No.3 | 1 opening on the left side wall, 2F |

Table 3. 1 Case preview I

| Case NO. | Dimension of the domain | Dimension of the atrium | Number of grids in mesh 3 |
|---|---|---|---|
| 1 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |
| 2 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |
| 3 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |
| 4 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |
| 5 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |
| 6 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |
| 7 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |
| 8 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |
| 9 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |
| 10 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |
| 11 | 60m × 60m × 40m | 20m × 20m × 20m | 112,112,80 |
| 12 | 60m × 60m × 40m | 20m × 20m × 20m | 112,112,80 |
| 13 | 60m × 60m × 40m | 20m × 20m × 20m | 112,112,80 |
| 14 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |
| 15 | 60m × 60m × 40m | 20m × 20m × 20m | 56,56,40 |

Table 3. 2 Case preview II

| Case | Smoke exhaust system |
|---|---|
| 1 | Natural ventilation |
| 2 | Natural ventilation |
| 3 | Natural ventilation |
| 4 | Natural ventilation |
| 5 | Natural ventilation |
| 6 | Natural ventilation |
| 7 | Roof exhaust fan 100$m^3/s$ with 4m height smoke reservoir |
| 8 | 25$m^3/s$ ceiling exhaust fan $\times 4$ |
| 9 | 25$m^3/s$ ceiling exhaust fan $\times 4$, 20$m^3/s$ exhaust duct $\times 8$ |
| 10 | 20$m^3/s$ ceiling exhaust fan $\times 4$, 7.5$m^3/s$ exhaust duct $\times 8$ |
| 11 | 20$m^3/s$ ceiling exhaust fan $\times 4$, 7.5$m^3/s$ exhaust duct $\times 8$ |
| 12 | 8.75$m^3/s$ ceiling exhaust fan $\times 4$, 9.375$m^3/s$ exhaust duct $\times 8$ |
| 13 | 18.75$m^3/s$ ceiling exhaust fan $\times 4$, 4.375$m^3/s$ exhaust duct $\times 8$ |
| 14 | 20$m^3/s$ ceiling exhaust fan $\times 4$, 7.5$m^3/s$ exhaust duct $\times 8$ |
| 15 | 20$m^3/s$ ceiling exhaust fan $\times 4$, 7.5$m^3/s$ exhaust duct $\times 8$ |

Table 3. 3 Case preview III

# CHAPTER 4. RESULT AND DISCUSSION

## 4.1. Verification phase

### 4.1.1. Case1

The model of case1 was shown in figure4.1; all the boundaries of the domain were set to be open boundary except the ground. the atrium was located at the center of the domain, with four 1m×3m opening on the wall and four 2m×2m vent holes on the roof. A 5 MW steady fire source located over a 2m$^2$ region (denoted with red color in Fig 4.1) For case1, the simulation time was set to 500s.

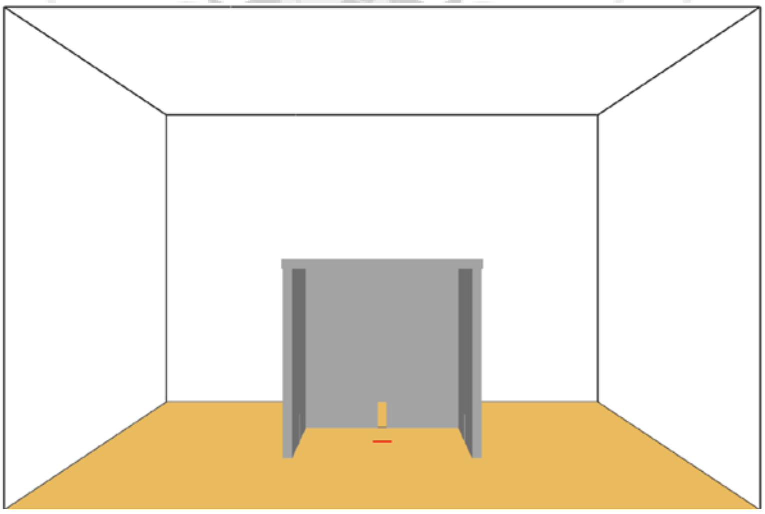


Figure 4. 1 Setting of case1

As shown in Figure 4.2(a), when the velocity is 0m/s, the direction of the plume does not change and it rises straight to the ceiling. This matches to the figure 4.3(a). When time =200s, figure 4.2(c) and figure 4.3(c) both of them show the deflection of the plume, and both of the smoke layer reaches the opening heights.

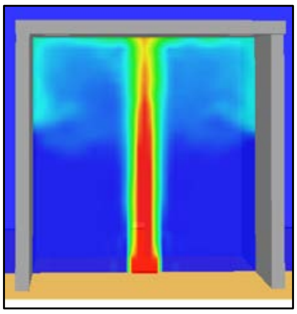
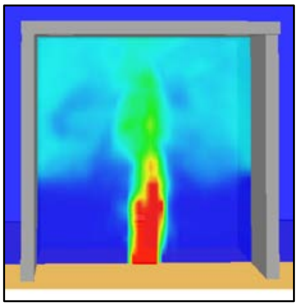
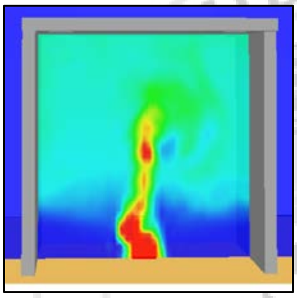
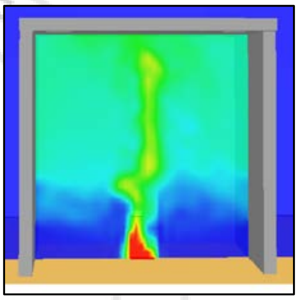
| | |
|---|---|
|  |  |
| (a) T=50s | (b) T=100s |
|  |  |
| (c) T=200s | (d) T=330 |

Figure 4. 2Temperature distribution at the middle of the atrium. 4 openings, zero wind velocity. (a) 50s, (b) 100s, (c) 200s, (d) 330s

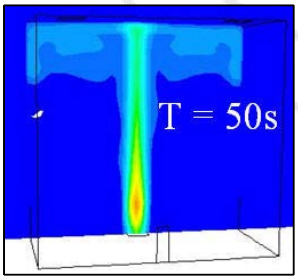
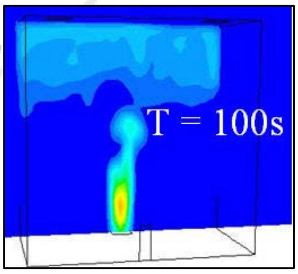
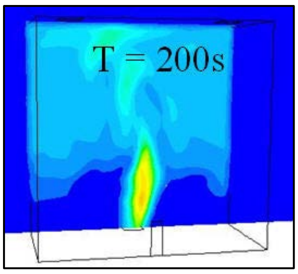
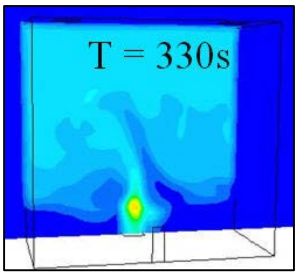
| | |
|---|---|
|  |  |
| (a) | (b) |
|  |  |
| (c) | (d) |

Figure 4. 3Result from Meroney's research. Temperature distribution at the middle of the atrium 4 openings, zero wind velocity. (a) 50s, (b) 100s, (c) 200s, (d) 330s

### 4.1.2. Case2

With the same setting as Case1, but wind velocity of 2m/s were applied into the atrium. The wind-blown from the boundary is shown in blue color.

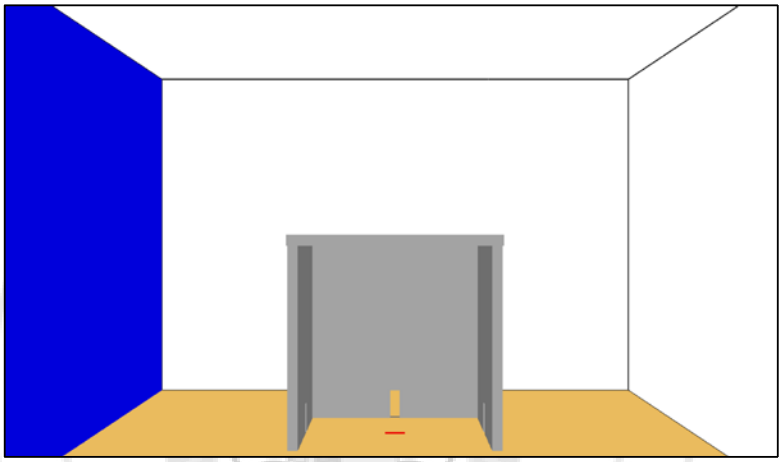
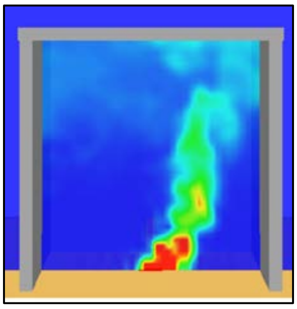
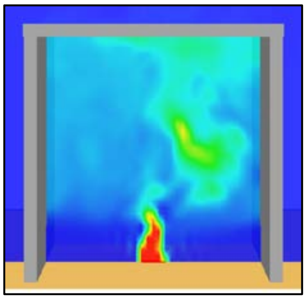


Figure 4. 4 Setting of case2

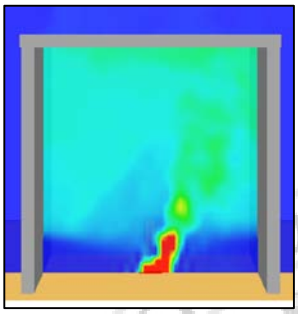
Figure 4.5(a) shows when the wind velocity of 2m/s, the plume is bent and the smoke layer is not uniformly distribute over the ceiling. Same scenario happens in figure 4.6(a). Similarly, when time=200s, both of the smoke layer reach to the opening height.



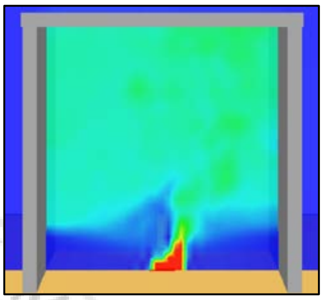
(a) 50s



(b) 100s

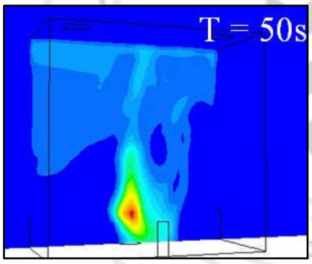


(c) 200s

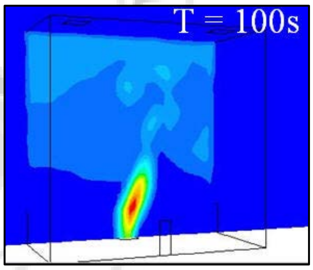


(d) 340s

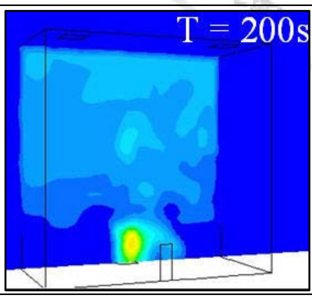
Figure 4. 5 Temperature distribution at the middle of the atrium. 4 openings, 2m/s wind velocity. (a) 50s, (b) 100s, (c) 200s, (d) 340s



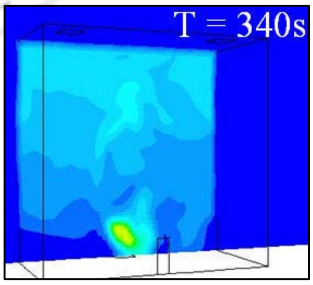

(a) 50s




(b) 100s




(c) 200s




(d) 340s

Figure 4.6 Result from Meroney's research. Temperature distribution at the middle of the atrium 4 openings, 2m/s wind velocity. (a) 50s, (b) 100s, (c) 200s, (d) 340s

#### 4.1.3. Case3 & 4

For case 3 and case 4, only one upwind door was opened for analysis the wind effect on the smoke plume. Zero wind velocity was applied in case 3 and 0.5m/s wind velocity was applied in case 4.

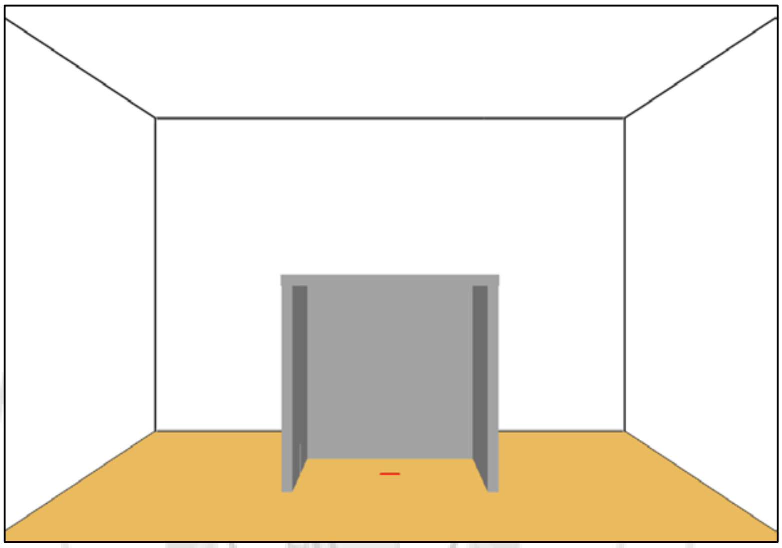


Figure 4. 7 Setting of Case3

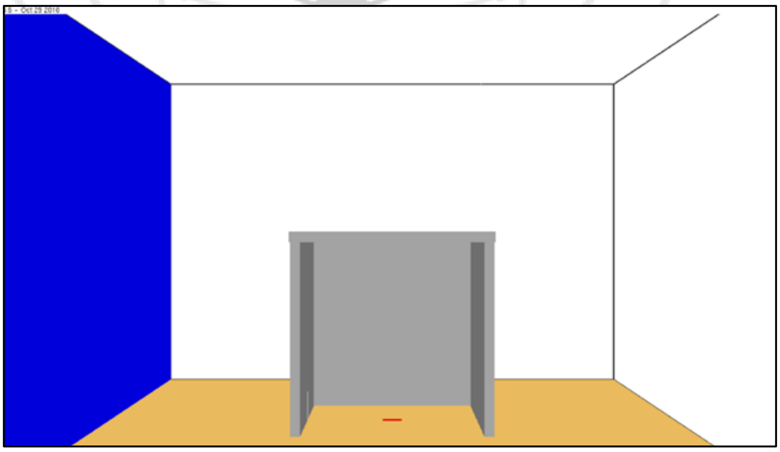


Figure 4. 8 Setting of Case4

In case 3, when wind velocity is 0m/s, similar pattern of the deflection of smoke plume in figure 4.8 (c) at time=150s when compare to the figure 4.9. Case 4 also show the similar behavior of the smoke plume with wind velocity of 0.5m/s at time=150s when compare to figure 4.10. Both of the smoke plumes in case 3 and case 4 bent toward to the wall of atrium. This is also the same pattern happens in Meroney's result.

However, in case 3 and case 4, the time required to get the similar pattern is about150s, while in Meroney' case, the time is 30s. The account for the time difference may be due to the flows is for two dimensional in figure 4.9 and figure 4.10, according to Meroney, the effective buoyancy fluxes and time scales is totally different in two and three dimensional [5].

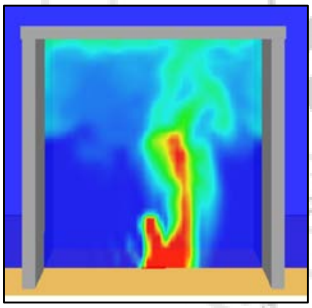
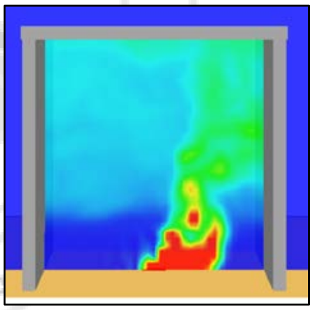
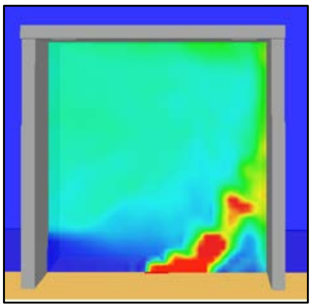
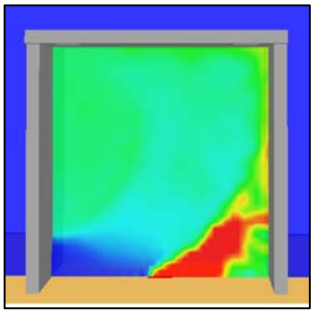
| | |
|---|---|
|  |  |
| (a) 50s | (b) 100s |
|  |  |
| (c) 150s | (d) 200s |

Figure 4. 9 Temperature distribution at the middle of the atrium. One left door openings, zero wind velocity. (a) 50s, (b) 100s, (c)150s, (d) 200s

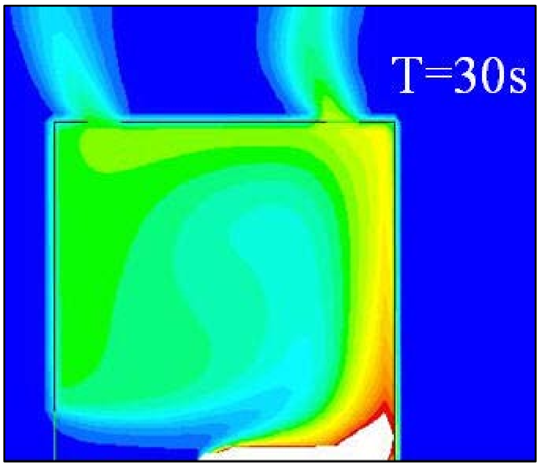



Figure 4. 10 Result from Meroney's research. Temperature distribution at the middle of 2D atrium only left openings, zero wind velocity. 30s

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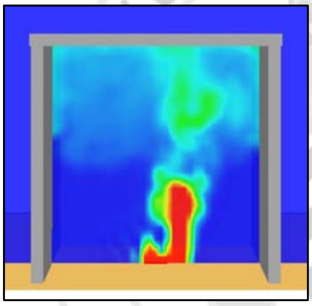
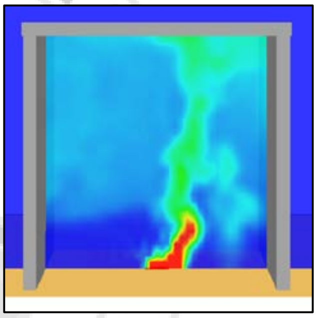
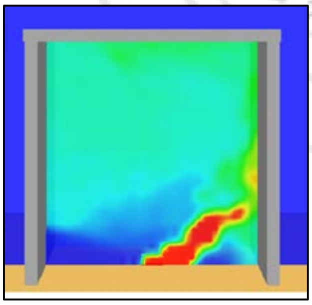
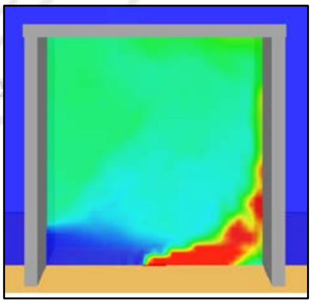
|  |  |
| (a) 50s | (b) 100s |
|  |  |
| (c) 150s | (d) 200s |

Figure 4. 11 Temperature distribution at the middle of the atrium. One left door openings, 0.5m/s wind velocity. (a) 50s, (b) 100s, (c)150s, (d) 200s

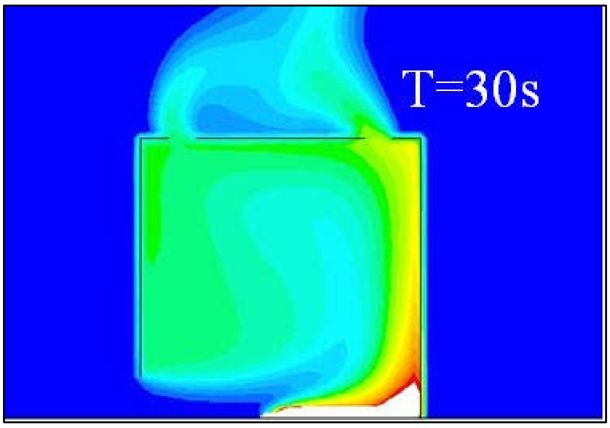



Figure 4. 12 Result from Meroney's research. Temperature distribution at the middle of 2D atrium only left openings, zero wind velocity

## 4.2. Design phase

### 4.2.1. Case5

For case 5, with zero wind velocity, four doors open and the same heat release rate 2.5MW but the fire was set to unsteady fire which is different with Meroney's research. This should show the difference between unsteady and steady fire.

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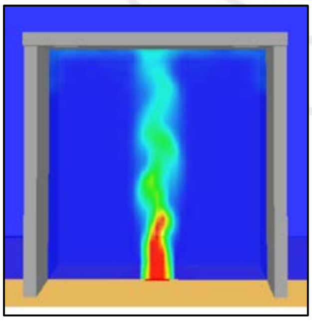
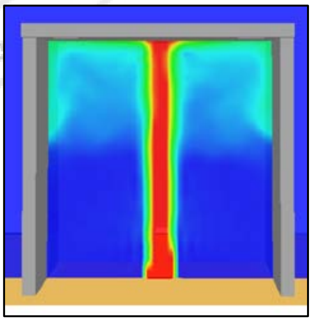
|  |  |
| (a) 50s | (b) 100s |

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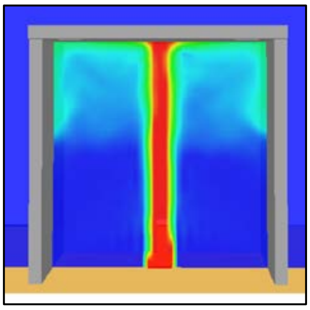
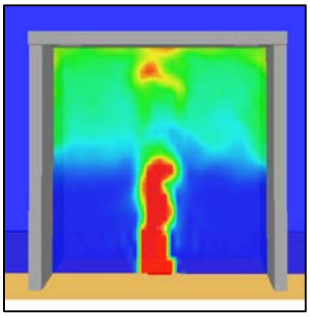
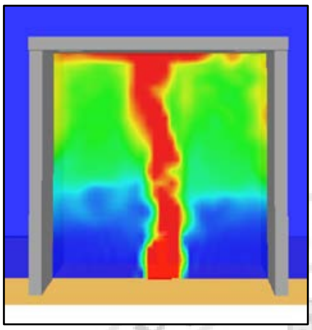
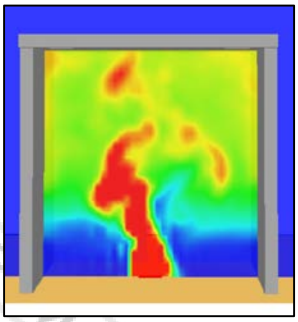
|  |  |
| (c) 150s | (d) 200s |
|  |  |
| (e) 250s | (f) 300s |

Figure 4. 13 Temperature distribution at the middle of the atrium.4 openings, zero wind velocity with 2.5 MW unsteady fire (a) 50s, (b) 100s, (c) 150s, (d) 200s, (e) 250s, (f) 300s

By comparing the case 1 and case 5, the unsteady fire shows obvious change in the fire plume. As shown from figure 4.14 at time=50s, the smoke plume does not rise to the ceiling and no smoke layer form on the ceiling whereas in case 1, figure 4.2a at time=50s smoke layer has already formed in the ceiling. Also, the temperature of plume increases significantly when time=300s and the temperature of the smoke layer increases when compare to case 1. This shows the difference of fire plume between unsteady fire and steady fire.

After the verification phase, the next purpose of this study is to study the smoke movement under tropical storm attack, and then design a fire safety for that situation.

For the design phase, all of the cases will apply a signal no.3 typhoon to the atrium by passing through the left door opening and unsteady fire will use

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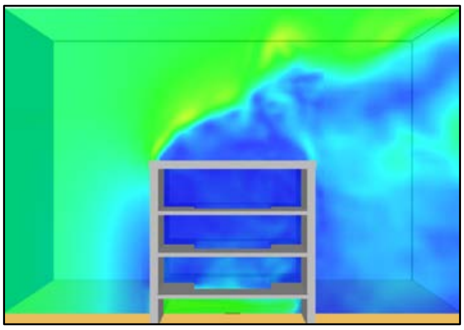
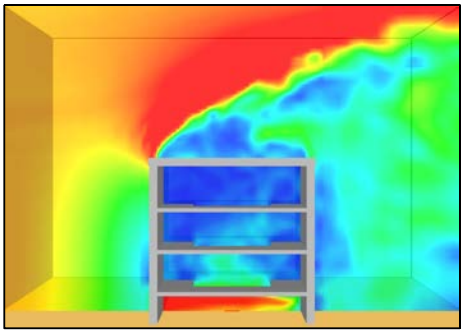
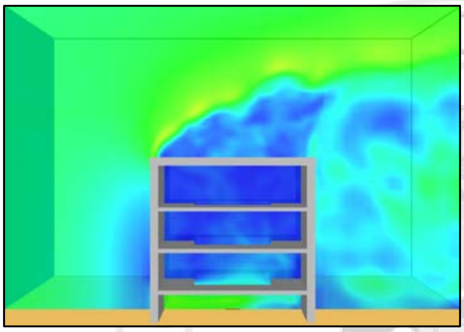
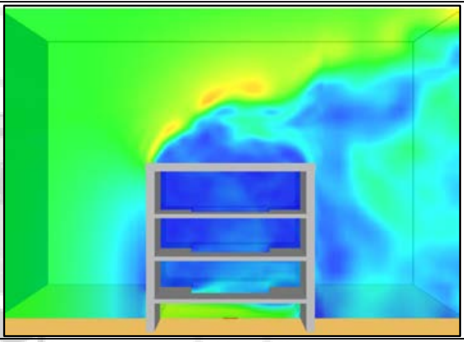
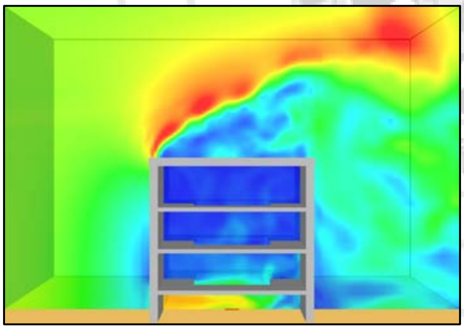
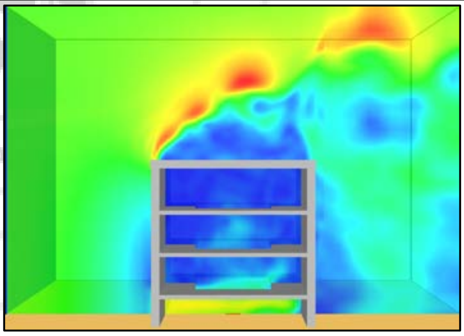
|  |  |
| (a) 60s | (b) 120s |
|  |  |
| (c) 180s | (d) 240s |
|  |  |
| (e) 300s | (f) 360s |

Figure 4. 14 Variation of the wind speed in FDS in different time period. (a)60s, (b)120s, (c)180, (d)240s, (e)300s, (f)360s

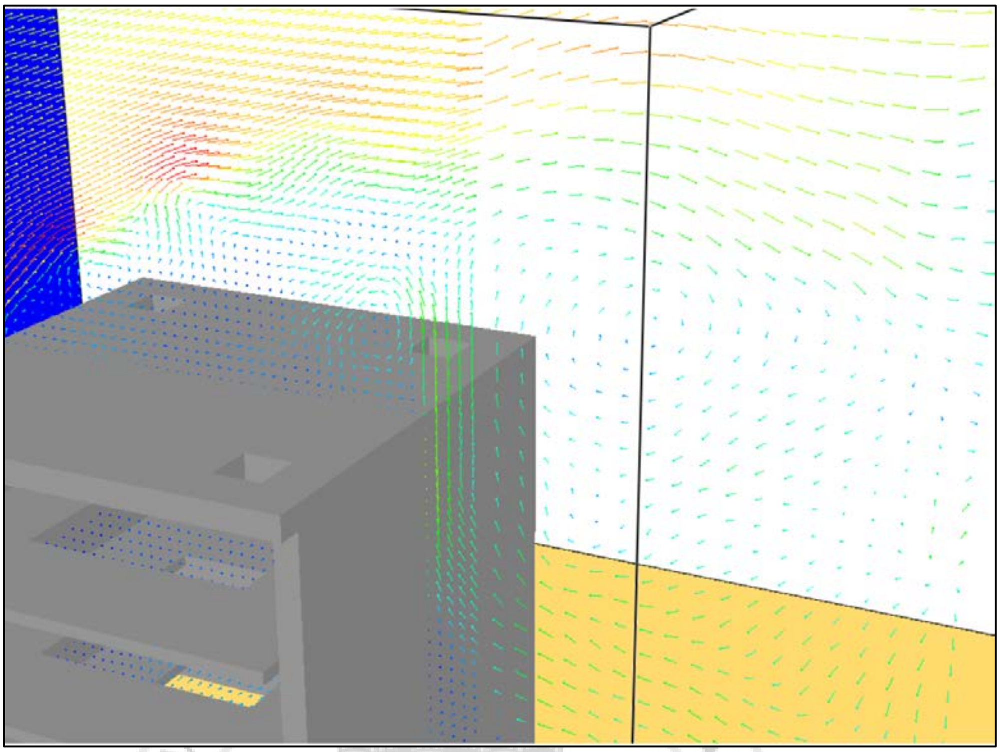


Figure 4. 15 Vortex flow at thr right side of the atrium

As shown in figure 4.14, the colored slice represents the wind velocity field slice. The color change in figure 4.14a to f indicates the wind velocity varies with time. The wind velocity ranges from 11m/s to maximum 30m/s since the gusts is also taken in to consideration. Some vortex swirls form at the right side of building due to the strong turbulent wind flow in figure 4.15

#### 4.2.2. Case6

For case 6, with signal no.3 typhoon wind velocity, one door opening and four vent holes on the roof of atrium. Smoke exhaust method- natural ventilation, was applied to observe the smoke movement under typhoon. Figure 4.14 shows the setting of the atrium and three-story floors was added in the atrium.

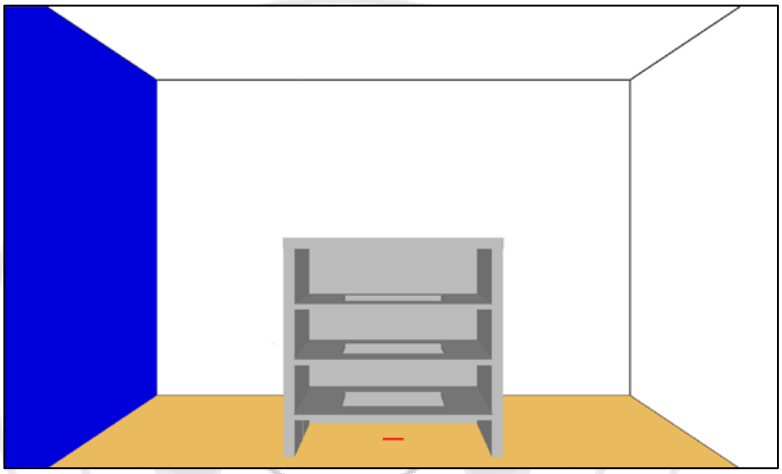
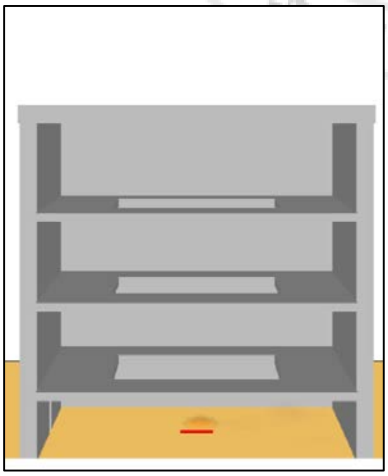
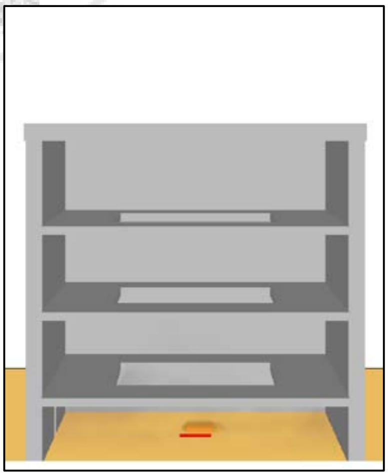


Figure 4. 16 setting of case6

|  |  |
| --- | --- |
| (a) 50s | (b) 100s |

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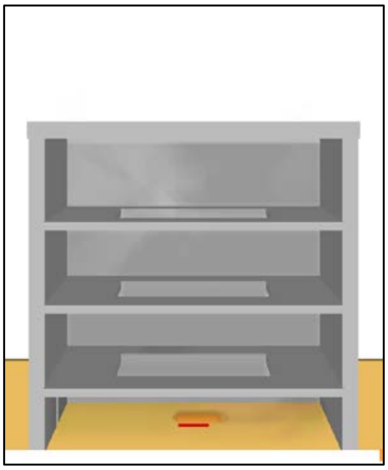
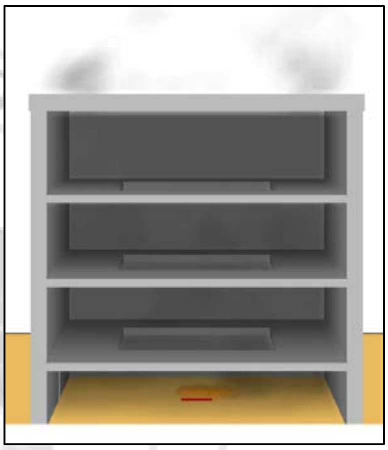
|  |  |
| (c) 150s | (d) 200s |
|  |  |
| (e) 250s | (f) 300s |

Figure 4. 17 Smoke filling pattern for atrium fire in Case6. (a)50s (b)100s, (c)150s, (d) 200s, (e)250s, (f) 300s

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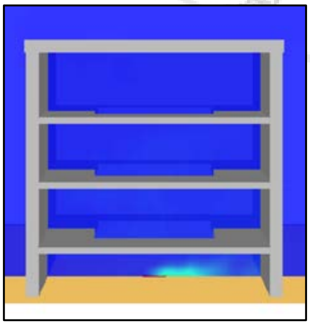
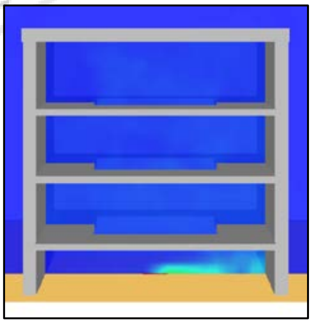
|  |  |
| (a) 50s | (b) 100s |

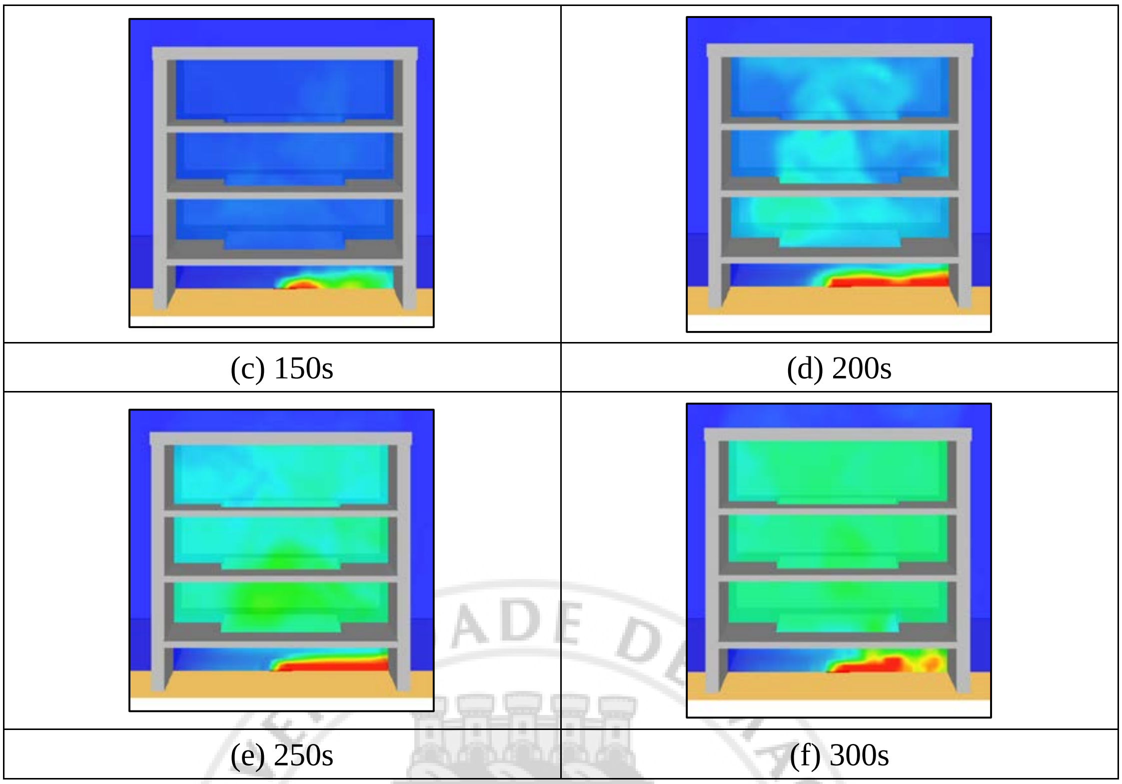



Figure 4. 18 Temperature distribution for atrium fire in Case6. (a)50s, (b)100s, (c)150s, (d) 200s, (e)250s, (f) 300s

As shown in figure 4.1 b, the smoke layer no longer forms on the top of ceiling, instead the smoke layer forms at the ground. As time goes to 150s, smoke spreads over the atrium in a short period of time. At time=300s, the visibility of building becomes poor as the smoke completely fills all over the atrium.

While in figure 4.1, the plume bends towards the right side of the wall of building by the effect of strong wind, the smoke concentrate at the center of the atrium and move spirally to the space.

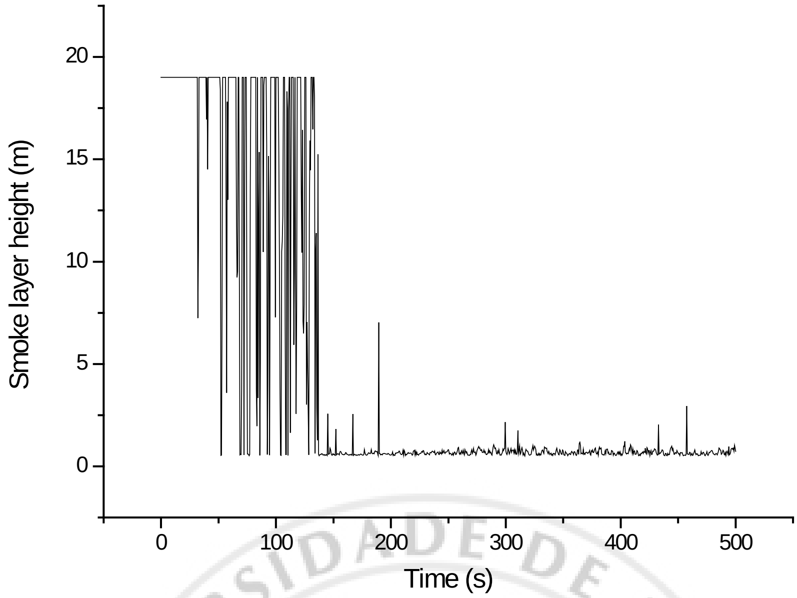



Figure 4. 19 Smoke layer height of case6 (center of the atrium)

The smoke layer is extremely unstable between time=50s to 140s from figure 4.1 , This is due to the fact that the strong wind effect that cause the smoke move disorderly and the smoke layer is around 0m after time=200s. This means the smoke have lowered to the ground.

### 4.2.3. Case7

For case 7, a smoke reservoir 10m x 10m, an exhaust fan with volumetric flow rate $100m^3/s$, was added to the atrium for smoke exhaustion, the setting of case 7 was showed in figure4.1. Mechanical fan exhaustion was a popular smoke control method in fire safety system of atrium so it was made for comparison of natural ventilation in case 6. This method was used to demonstrate which method is better for the smoke control in such messy situation.

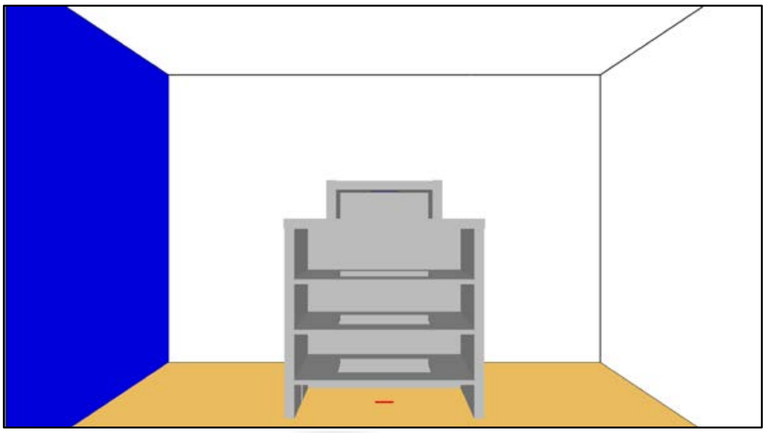
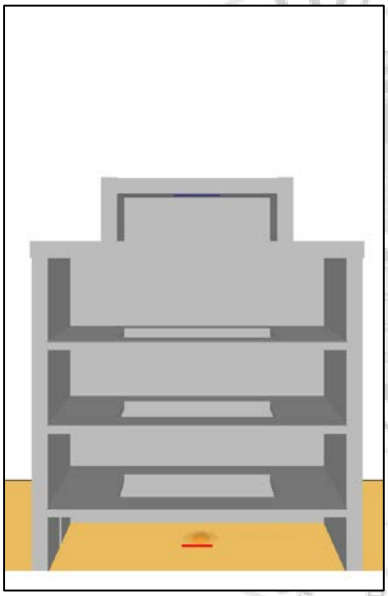
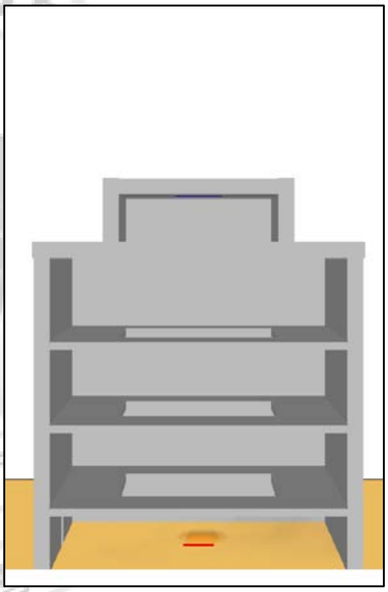


Figure 4. 20 Setting of case7

|  |  |
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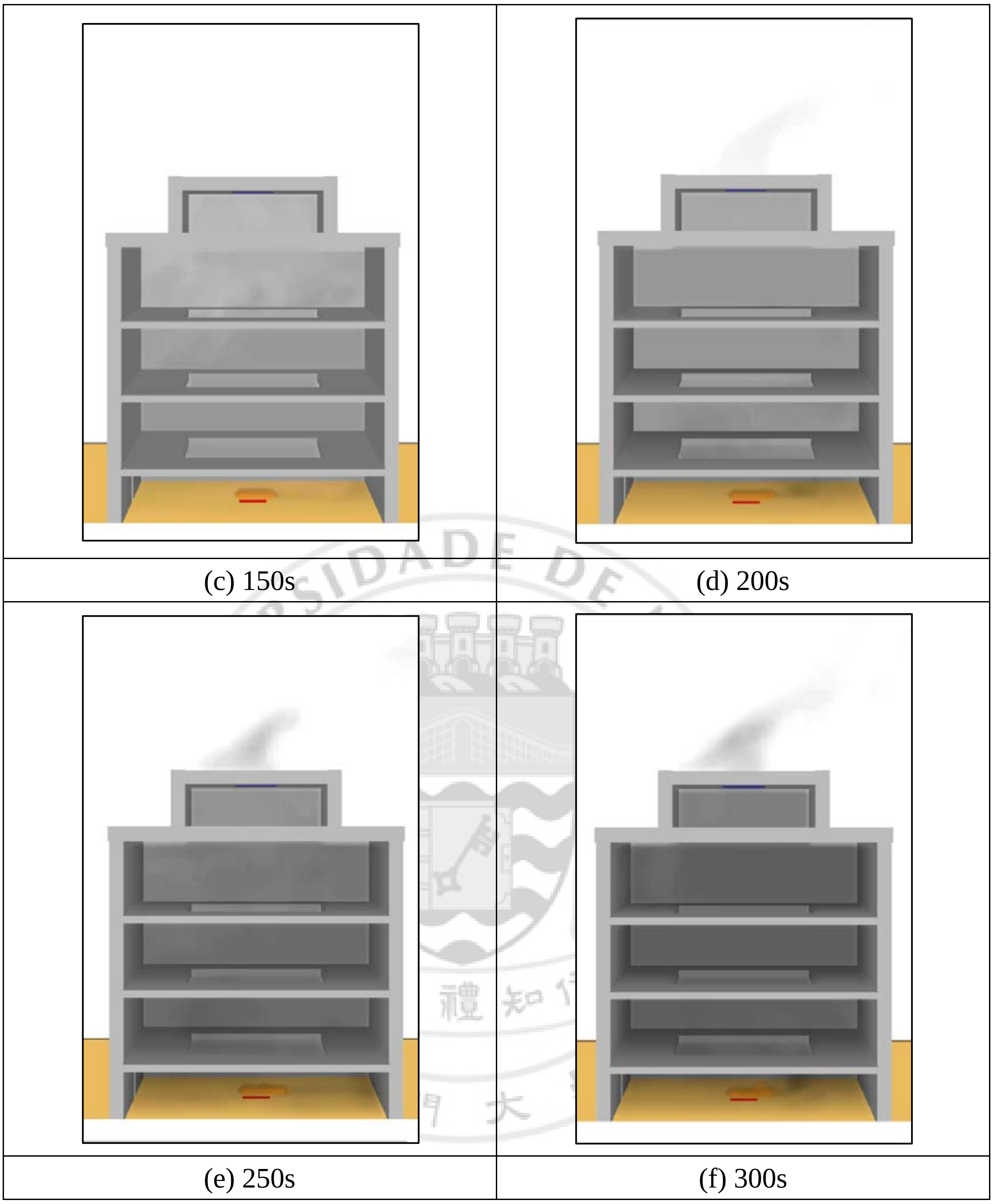
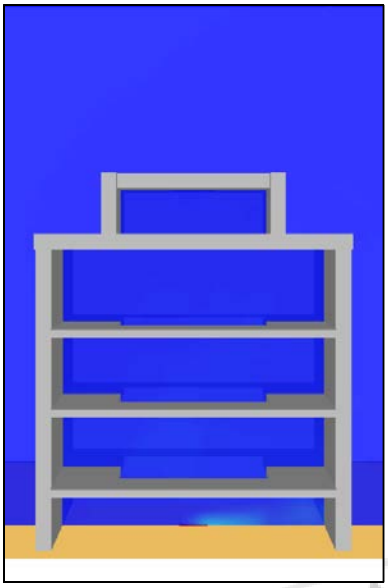
| (a) 50s | (b) 100s |



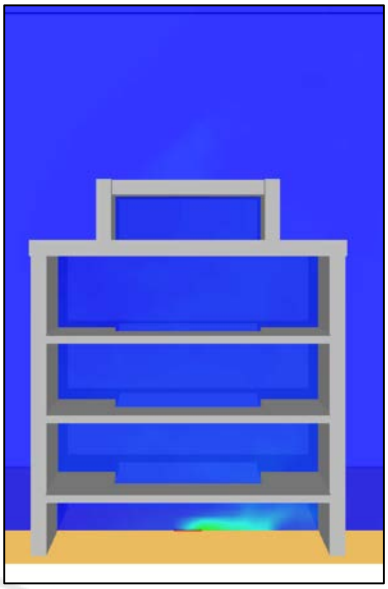
(c) 150s (d) 200s

(e) 250s (f) 300s

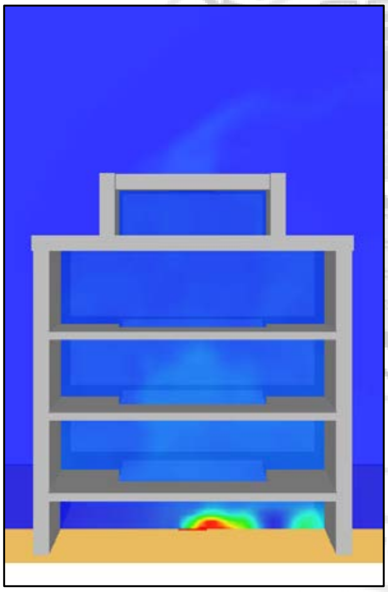
Figure 4. 21 Smoke filling pattern for atrium fire in Case7. (a)50s (b)100s, (c)150s, (d) 200s, (e)250s, (f) 300s



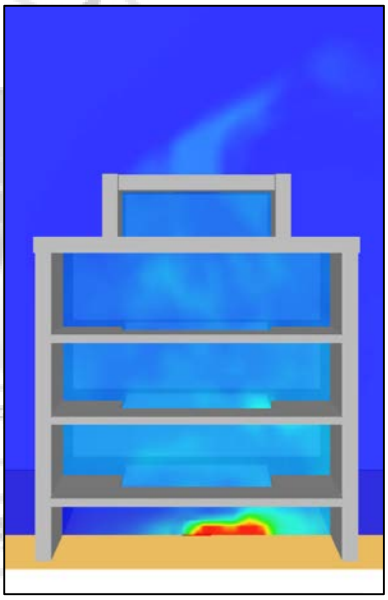
(a) 50s



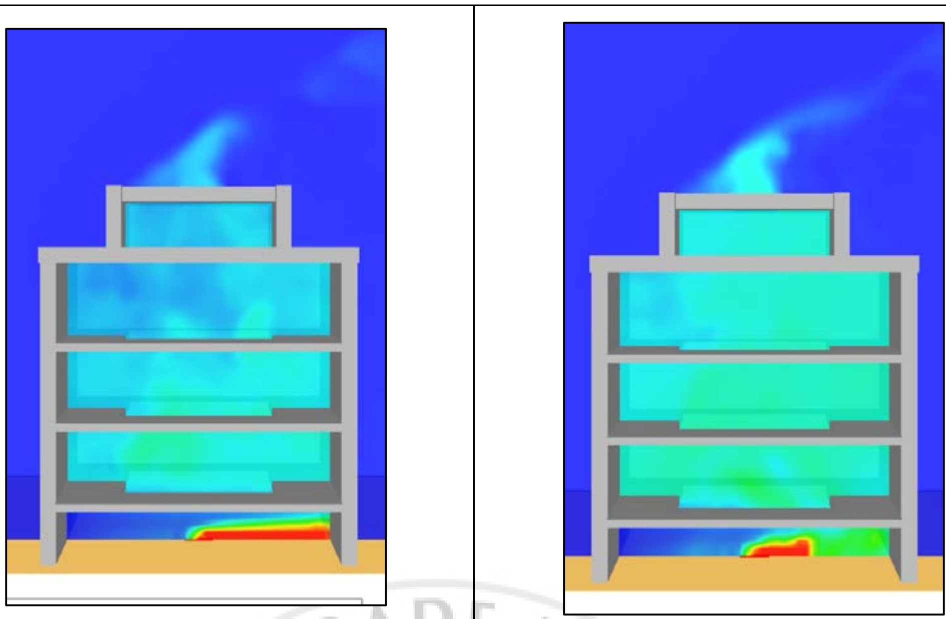
(b) 100s



(c) 150s



(d) 200s



(e) 250s | (f) 300s

Figure 4. 22 Temperatures distribution for atrium fire in Case7. (a)50s, (b)100s, (c)150s, (d) 200s, (e)250s, (f) 300s

As shown in figure 4.22 the smoke movement is similar to the case 6, which shows the smoke forms at the ground level at first 100s. The smoke completely fills the space at time=200s.

While in figure 4.22b, t=150s, it reveals smoke is exhausted upward by the exhaust fan which means smoke does not diffuse as much as to the space of building. The plume bends towards to the wall when time=250s which differ to case 6. The temperature at the first and upper floor is lower than that of temperature of case 6. This indicates that the smoke tends to move upward which is better than the natural ventilation in case 6.

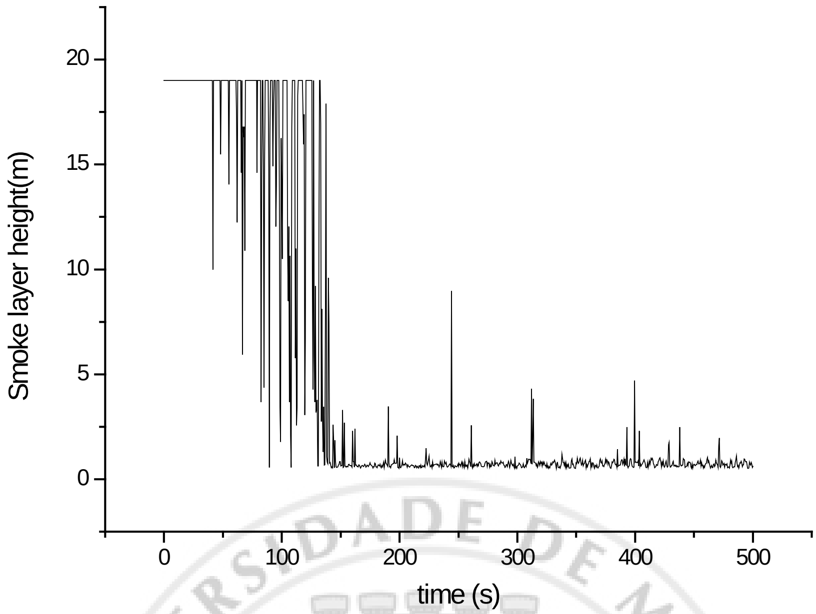



Figure 4. 23 Smoke layer height of case7 (center of the atrium)

The smoke layer height is unstable between time=90s and 130s, when compare to smoke layer height of case 6,

#### 4.2.4. Case8

For case 8, fire curtain was added and dropped down to 2m (around 1/3 of floor height) the edge of each floor of atrium with same setting with case 7, see figure 4.23. The purpose of addition of fire curtain was provided a relatively smoke free space by avoiding smoke goes into the communicating space.

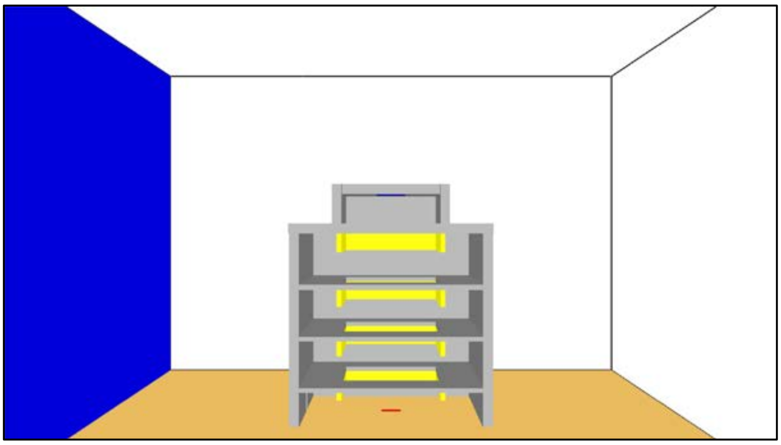
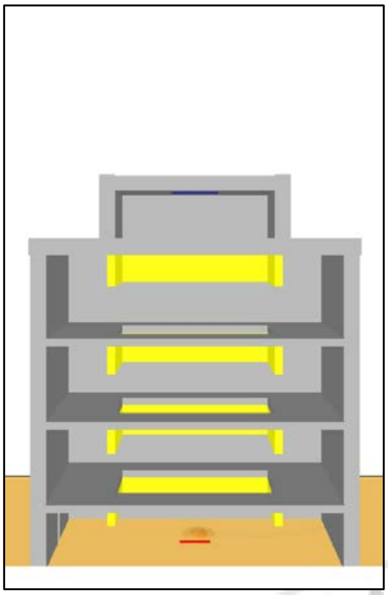
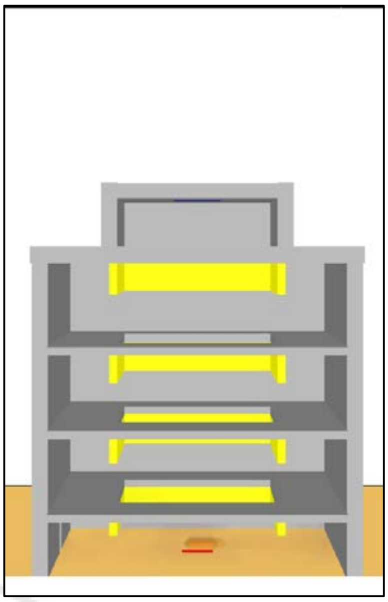


Figure 4. 24 Setting of case8

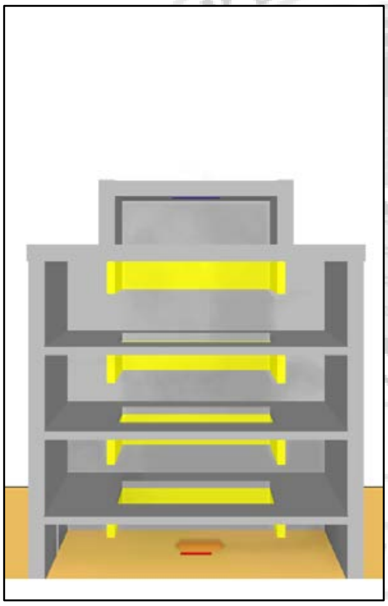
By comparing the figure 4.21c and figure 4.24c at time=150s, the later one clearly shows the effect of fire curtain which provide smoke free space behind fire curtain at the second and third floor. However, when time=200s, the smoke fills into all of the communicating space, this is similar to case 6. While figure 4.25 e,f, they show the smoke is mainly accumulated at center of atrium instead of accumulate in communicating area. This indicates an important effect of fire curtain in atrium fires and therefore, fire curtain is added to the later remaining work.



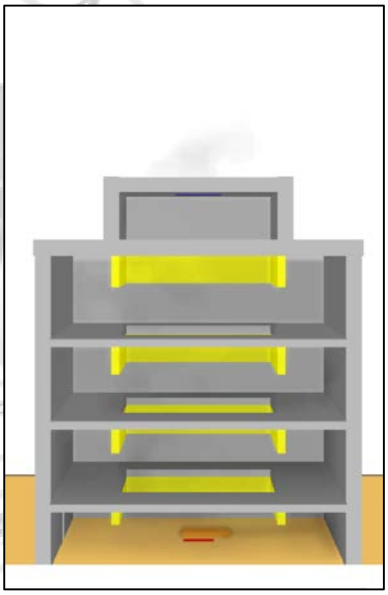
(a) 50s



(b) 100s



(c) 150s



(d) 200s

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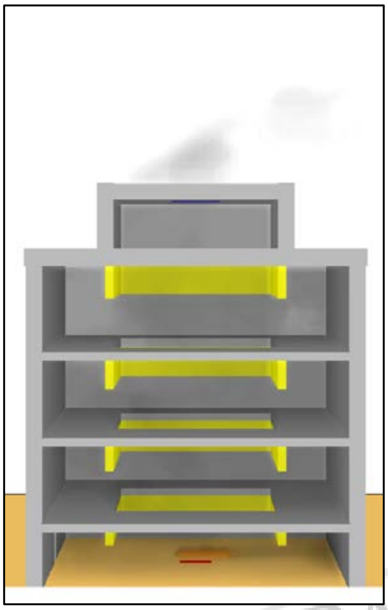
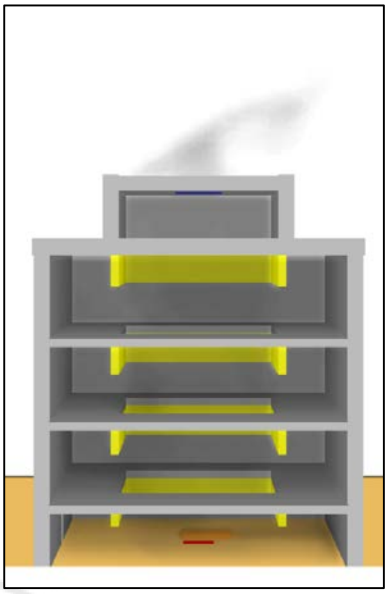
|  |  |
| (e) 250s | (f) 300s |

Figure 4. 25 Smoke filling pattern for atrium fire in Case8. (a)50s (b)100s, (c)150s, (d) 200s, (e)250s, (f) 300s

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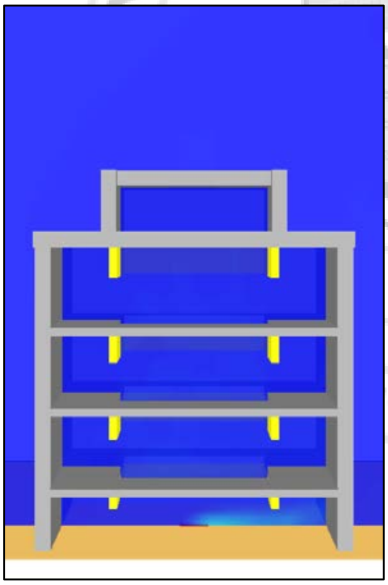
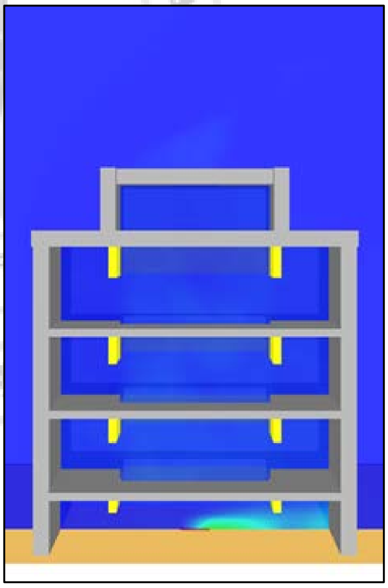
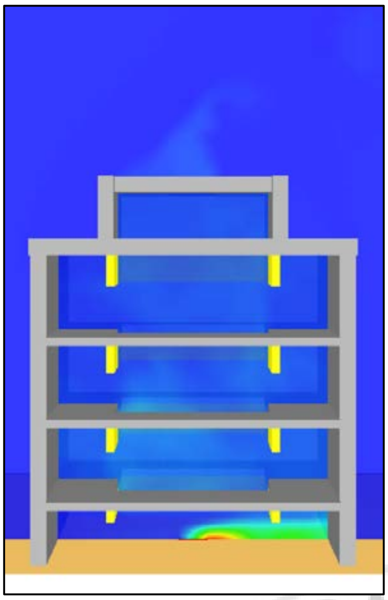
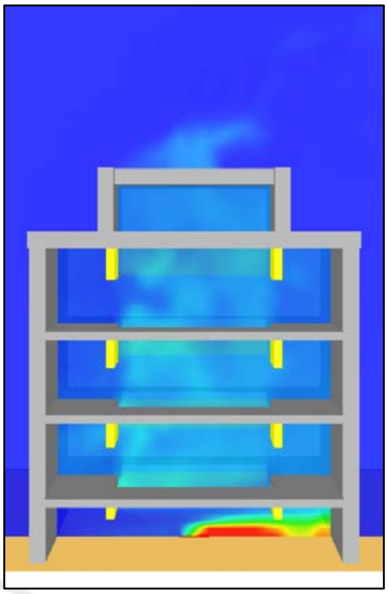
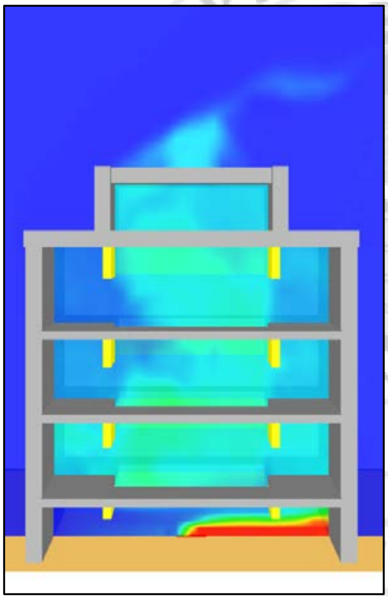
|---|---|
|  |  |
| (a) 50s | (b) 100s |



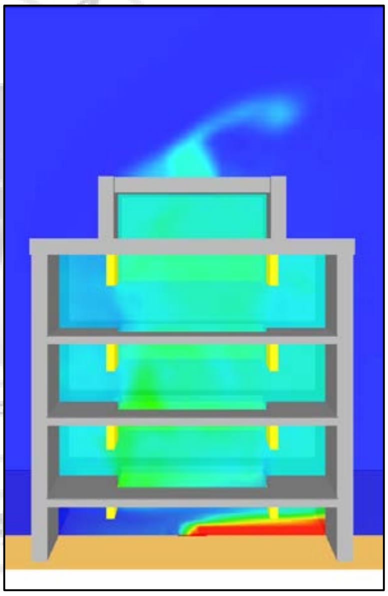
(c) 150s



(d) 200s



(e) 250s



(f) 300s

Figure 4. 26 Temperature distribution for atrium fire in Case6. (a)50s, (b)100s, (c)150s, (d) 200s, (e)250s, (f) 300s

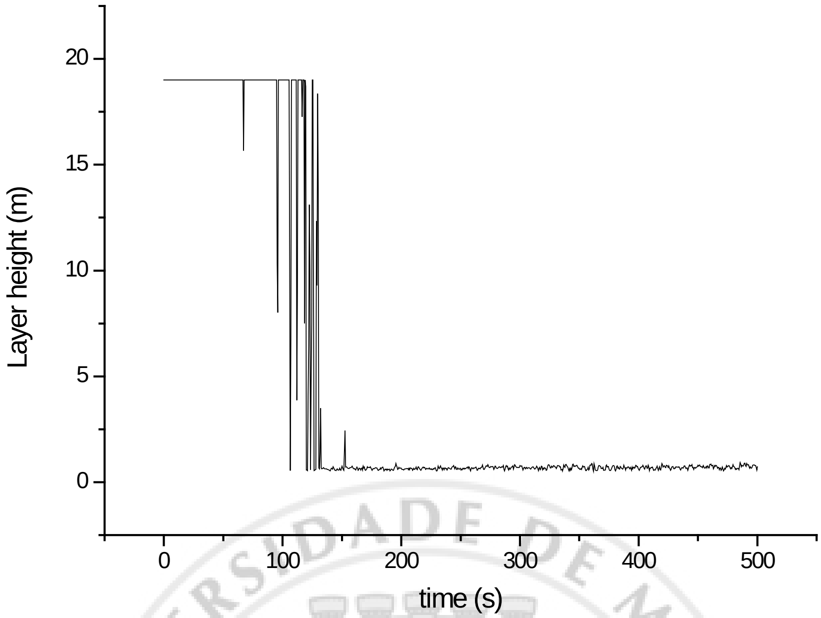



Figure 4. 27 Smoke layer height of case8 (center of the atrium)

Compare to case6 and case7, the smoke layer height was relatively stable, at the time t=130, the smoke layer hit the ground and fill the whole space.

### 4.2.5. Case9

For case 9, four ceiling fans with area of 2m x2m, total volumetric flow rate of $100m^3/s$ was installed to atrium for smoke exhaustion. According to Chun[15], the efficiency of using four ceiling fans is better than using one exhaust fan with same amount of volumetric flow rate.

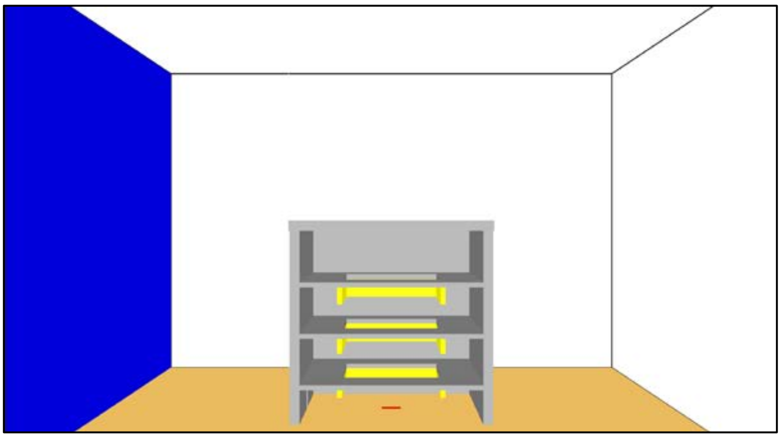
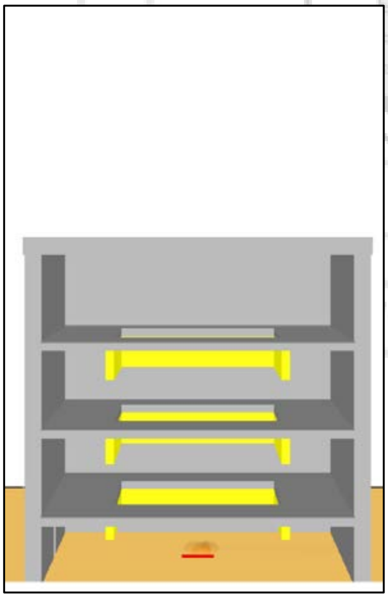
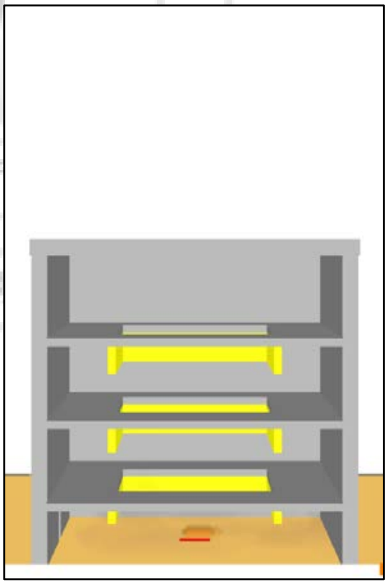
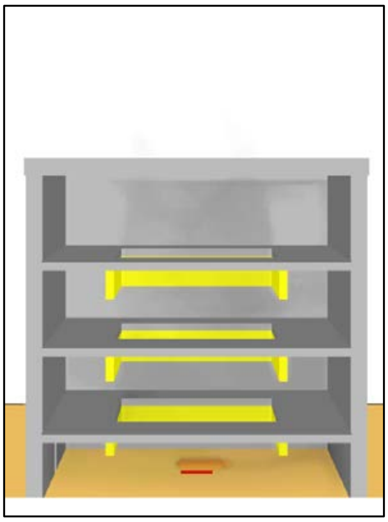


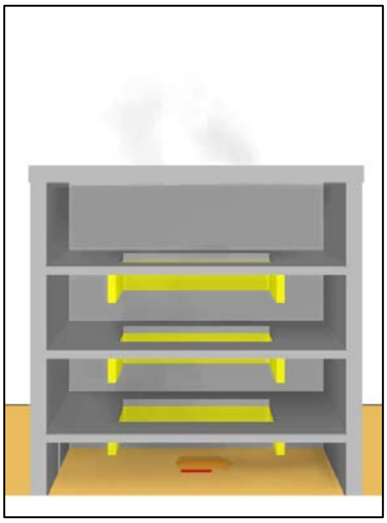
Figure 4. 28 Setting of case9

As shown in figures 4.29, the smoke distribution is similar to the smoke distribution in case8. However, an important discovering is found in figure 4.30g, the temperature of air movement is better than that in case 8, at time=300s. This reveals that the four ceiling vents is indeed better than one exhaust fan in case 8.

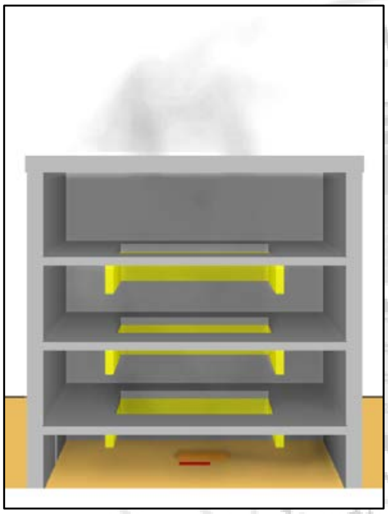
|  |  |
|---|---|
| (a) 50s | (b) 100s |



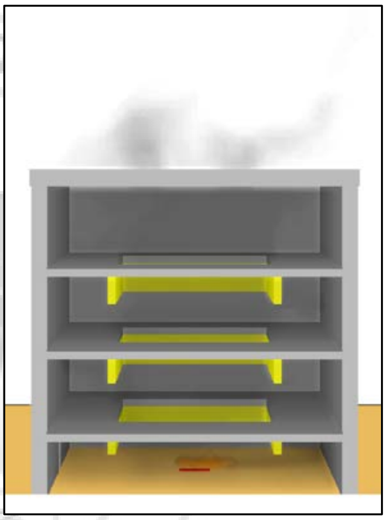
(c) 150s



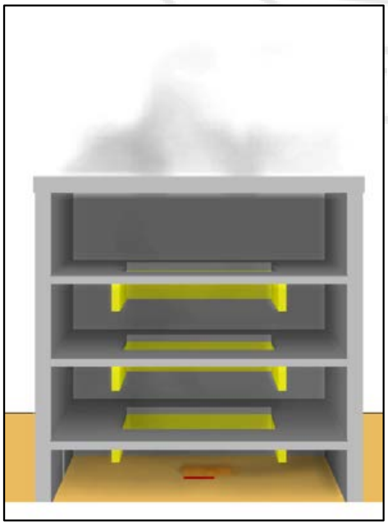
(d) 200s



(e) 250s

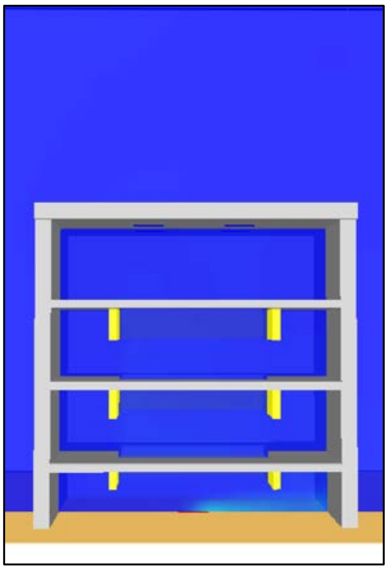


(f) 300s

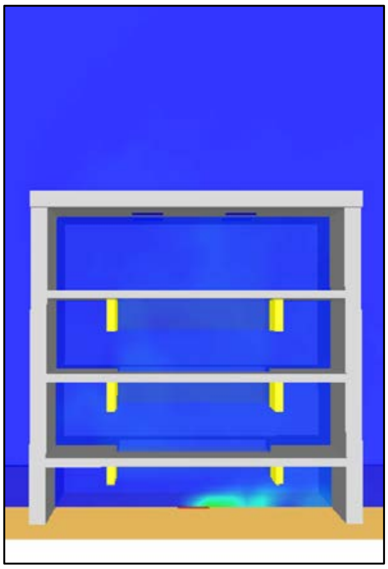


(g) 350s

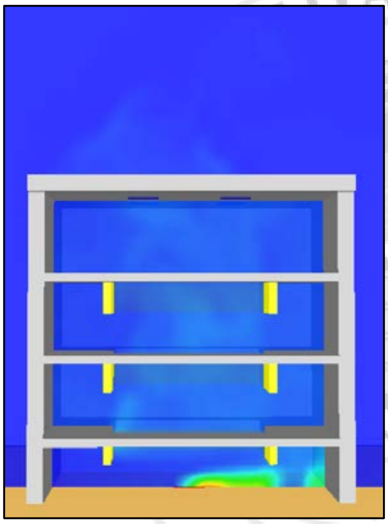
Figure 4. 29 Smoke filling pattern for atrium fire in Case9. (a)50s (b)100s, (c)150s, (d) 200s, (e)250s, (f) 300s, (g) 350s



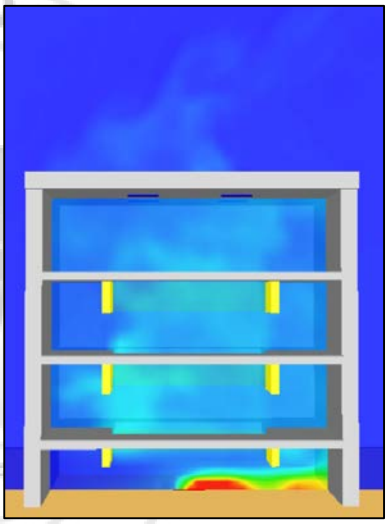
(a) 50s



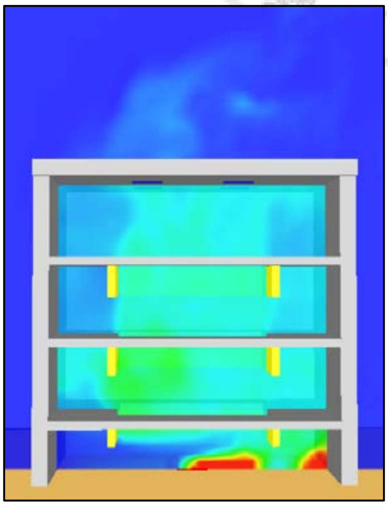
(b) 100s



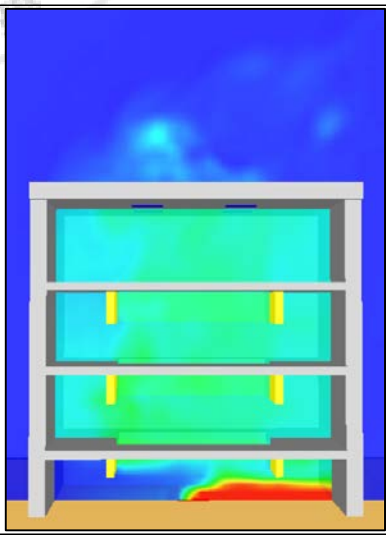
(c) 150s



(d) 200s



(e) 250s



(f) 300s

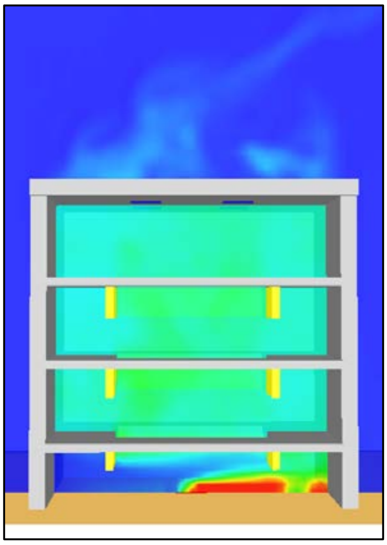
| | |
|---|---|
|  | |
| (g) 350s | |

Figure 4. 30 Temperatures distribution for atrium fire in Case9. (a)50s, (b)100s, (c)150s, (d) 200s, (e)250s, (f) 300s, (g)350s

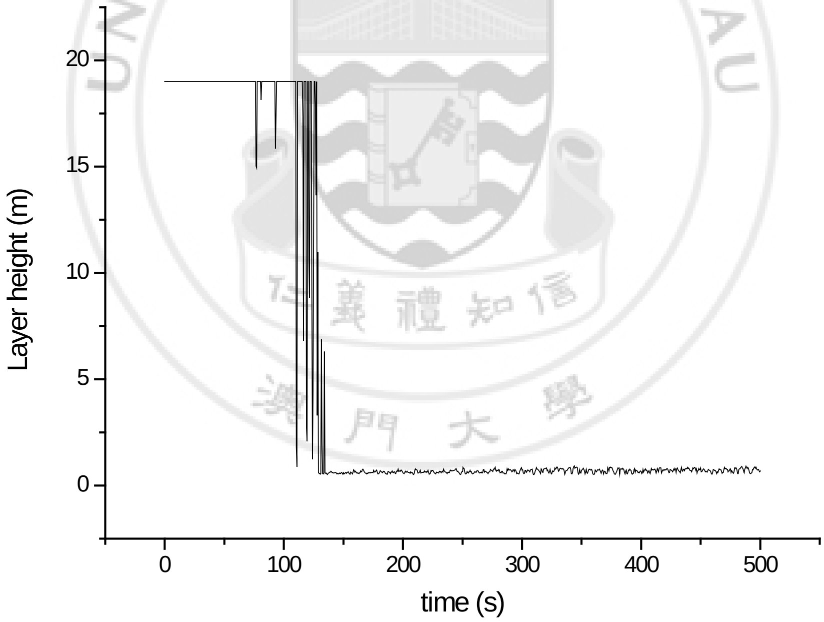



Figure 4. 31 Smoke layer height of case9 (center of the atrium)

### 4.2.6. Case10

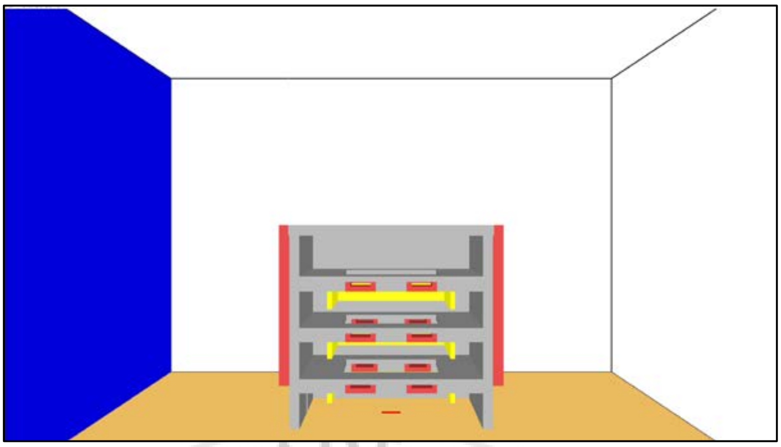


Figure 4. 32 Setting of case10

In case10, exhaust ducts were installed at the bottom of every floor. There were eight ducts in each floor. Each duct had a $1m^2$ inlet area and they were connected to exterior ducts which equipped with exhaust fan. The fan was set to have $20m^3/s$ exhaust rate and totally 160 $m^3/s$ exhaust rate was added to the system. The positions of the duct system are shown in figure 4.32. Also the fire curtain position was offset 1m from the edge of the floor. The intension is to block and store smoke under the floor, and then let the exhaust fan suck in the smoke. Figure 4.33 may give a clear explanation on this.

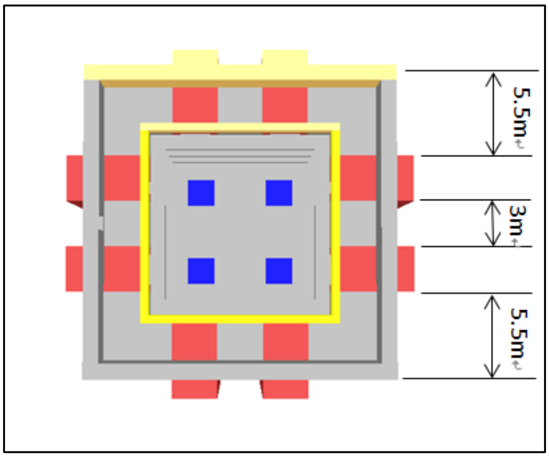



Figure 4. 33 Exhaust duct system position

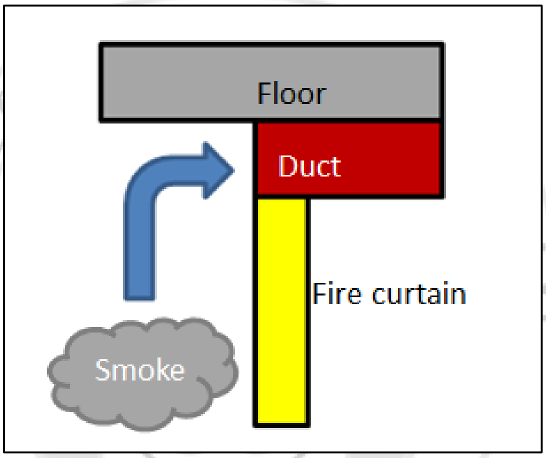
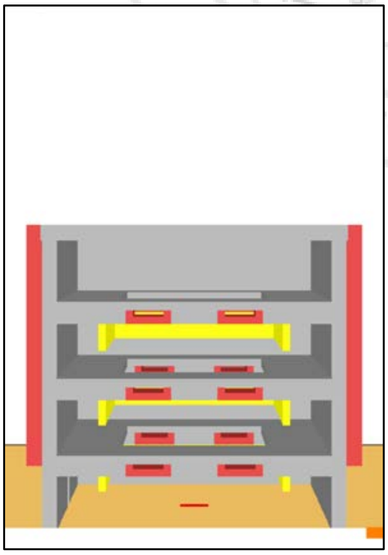
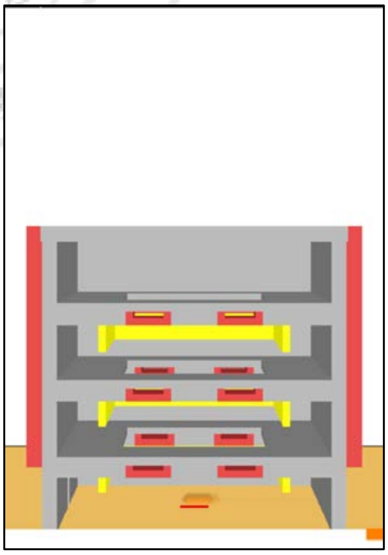



Figure 4. 34 Smoke exhaust design mechanism

| | |
|---|---|
|  |  |
| (a) 50s | (b) 100s |

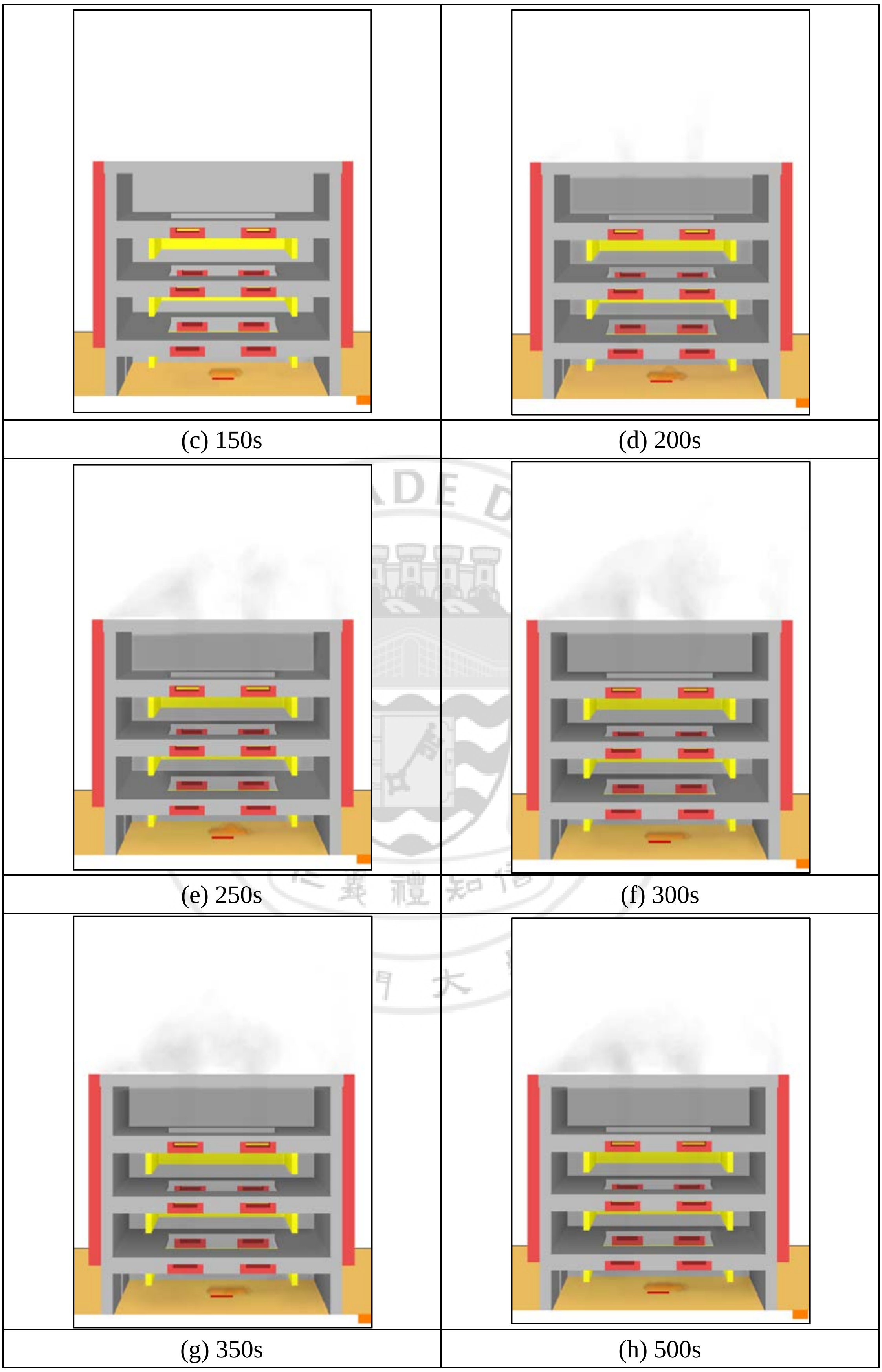
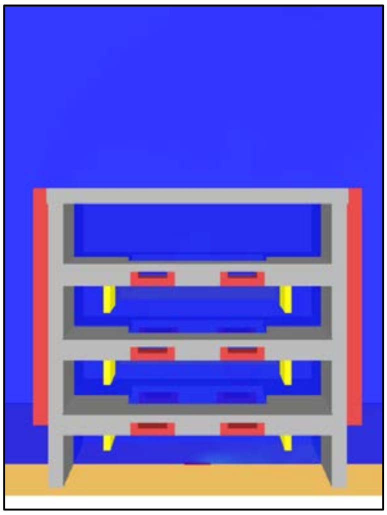
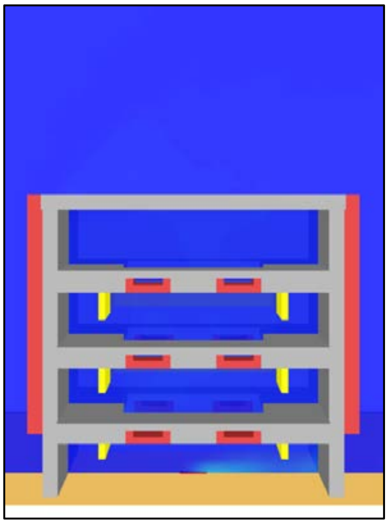


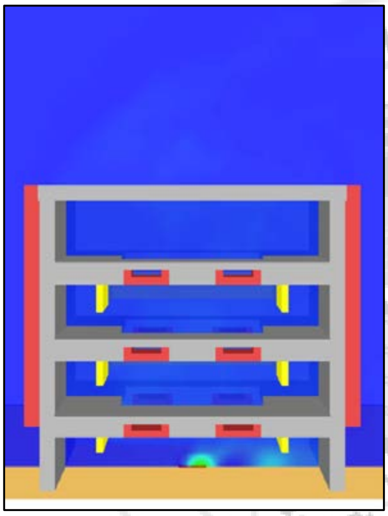

Figure 4. 35 Smoke filling pattern for atrium fire in Case10. (a)50s (b)100s, (c)150s, (d) 200s, (e)250s, (f)300s (g)350s, (h)500s



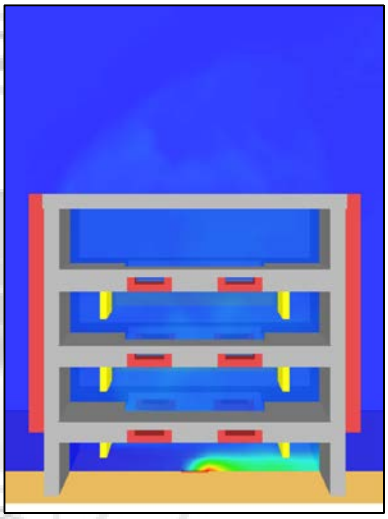
(a) 50s



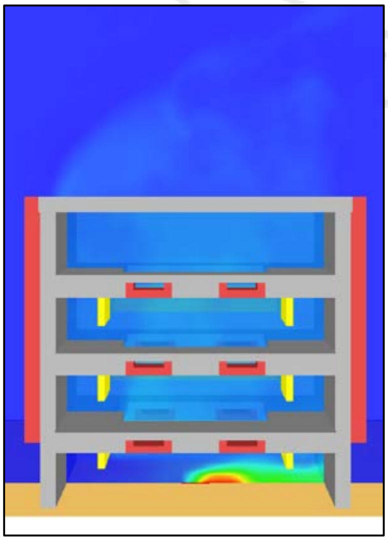
(b) 100s



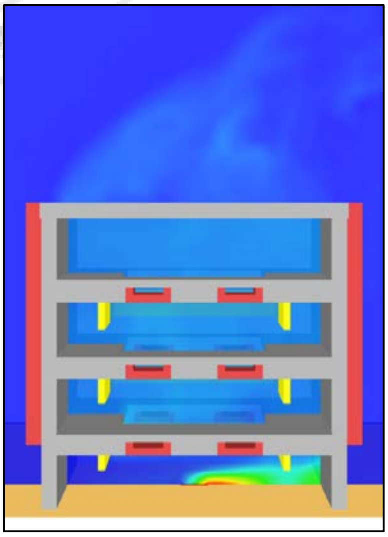
(c) 150s



(d) 200s



(e) 250s



(f) 300s

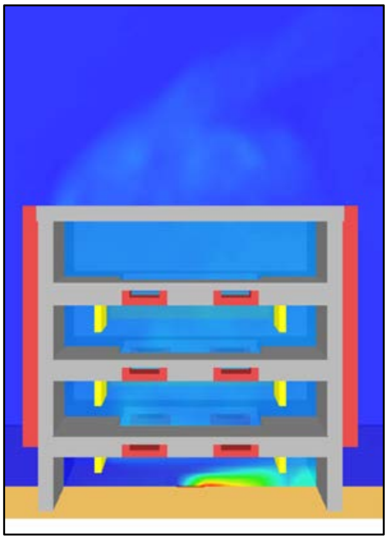
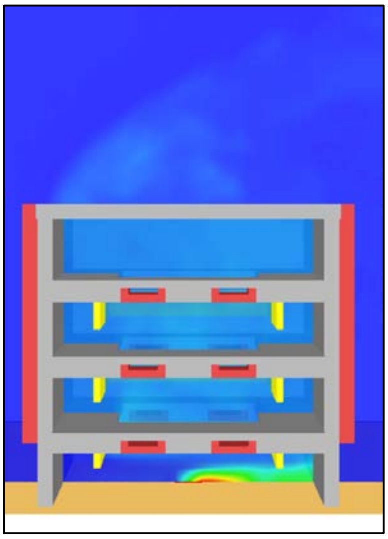
| | |
|---|---|
|  |  |
| (g) 350s | (h) 500s |

Figure 4. 36 Temperature distribution for atrium fire in Case10. (a)50s, (b)100s, (c)150s, (d) 200s, (e)250s, (f)300s, (g)350s, (h)500s

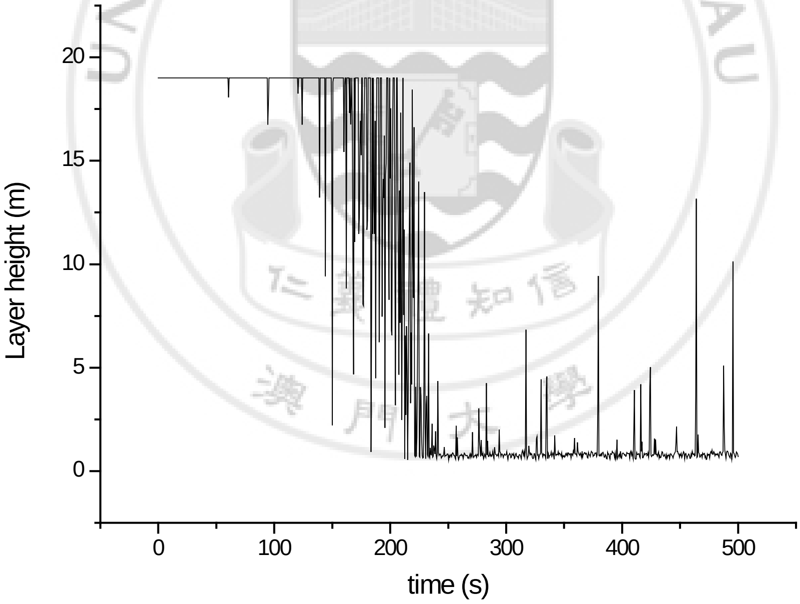



Figure 4. 37 Smoke layer height of case10 (center of the atrium)

From figure 4.35, there was nearly no smoke in the first 150s; however, when it came to 170s, the smoke rose at the groud floor, and spreaded to the whole atria in around 20 second. Compare to pervirous case, the spread rate was relativly fast. While figure

4.36 gives the temperature distrubution of the building, it indicates that the fire plume was highly distorted, also the temperature inside the atrium was quite low when compare to other cases.

Since the reuslt this case was quite different to others, a further investigation was done for this. Both figure 4.35 and 4.36 shows that there might be a very strong wind flow in from the opening; therefore, checking on the velocity field was needed. After checking on the velocity field, a high speed wind flow, nearly 85m/s, was found out at the opening of the atrium, as shown in Figure 4.38. Which was the origin of the rapid smoke spread rate and the low temperature. A conclusion was made that this strong wind was caused by the high exhaust rate. Due to the high exhaust rate, the pressure difference between the indoor and outfoor became lager, the out side air were pushed into the atrium and caused the strong wind flow.

A series of test was done in order to determine the maximum exhaust rate without accelerating the incoming flow. After the test, the result prove that the total exhuast rate for this study should not be larger than $110m^3/s$.

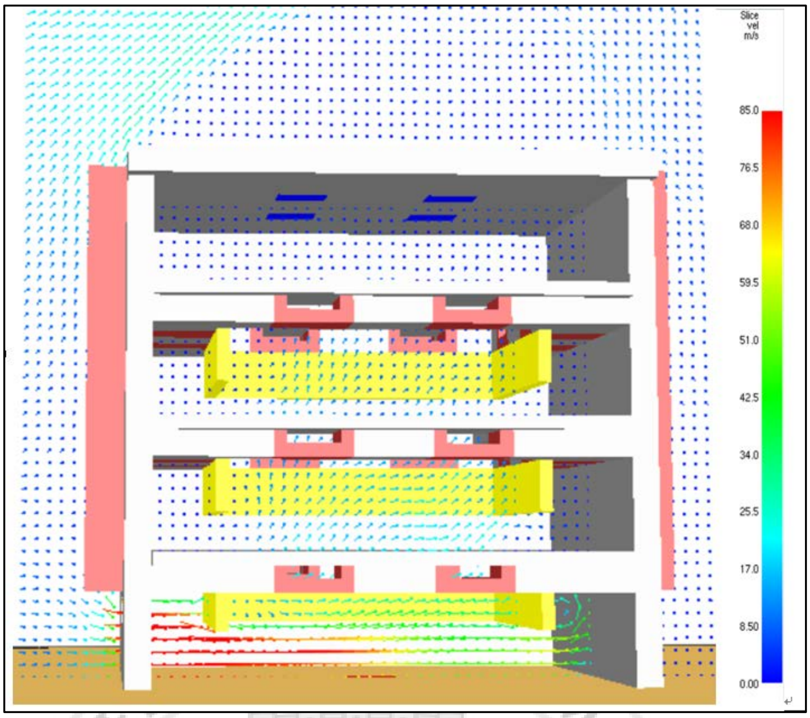


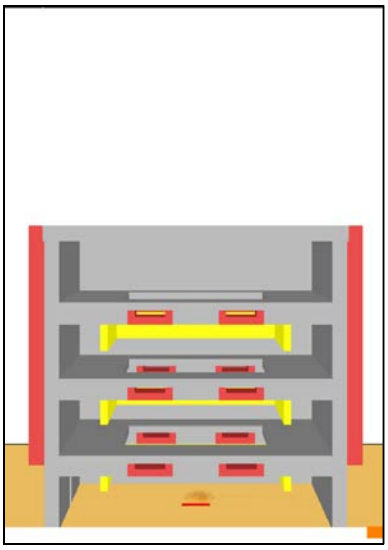

Figure 4. 38 High speed wind flow into the atrium

### 4.2.7. Case11

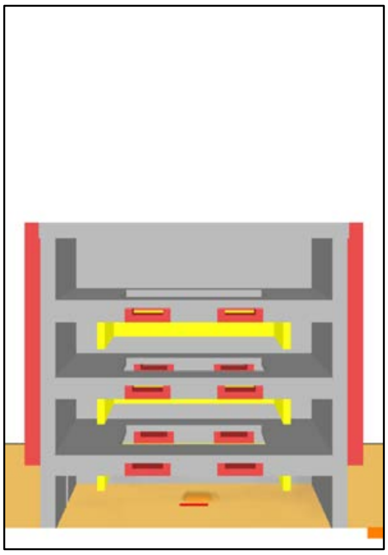
In case 11, the same exhaust system was applied but with reasonable exhaust rate. The arrangement of the exhaust rate is shown below:

| Components | Quantity | Exhaust rate |
|---|---|---|
| 12.5 $m^3/s$ ceiling exhaust | 4 | $12.5 \times 4 = 50m^3/s$ |
| 7.5 $m^3/s$ exhaust fan inside each exterior duct | 8 | $7.5 \times 8 = 60m^3/s$ |
| | | Total: 110$m^3/s$ |

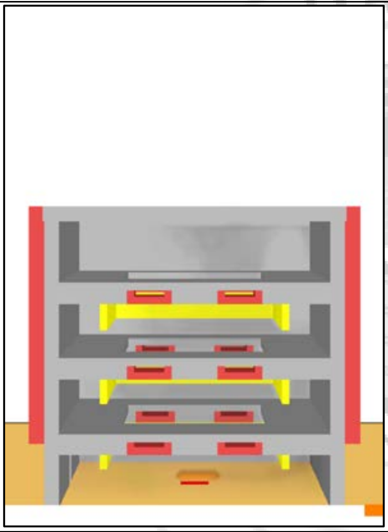
Table 4. 1 Exhaust rate arrangement in case 11



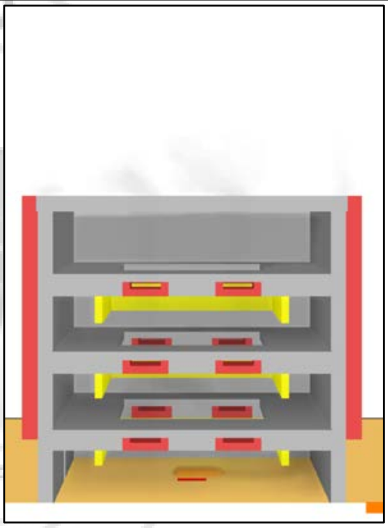
(a) 50s



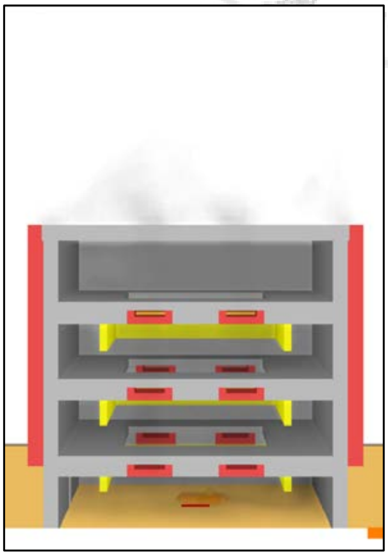
(b) 100s



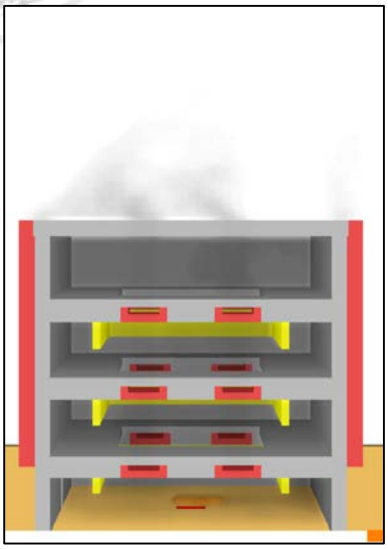
(c) 150s



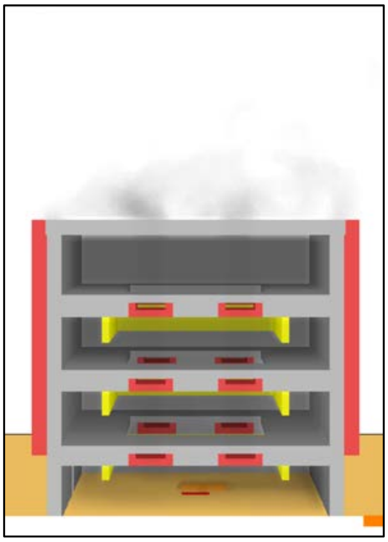
(d) 200s



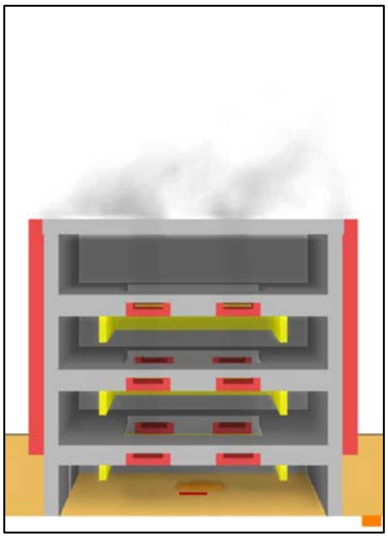
(e) 250s



(f) 300s

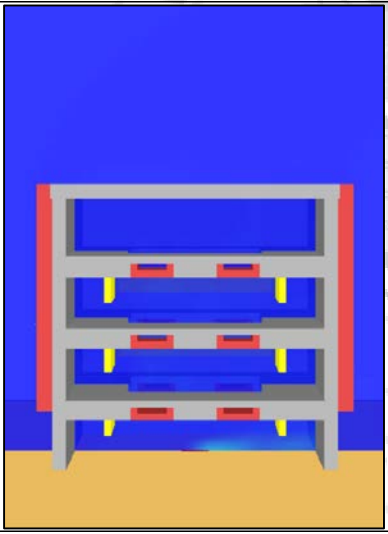


(g) 350s

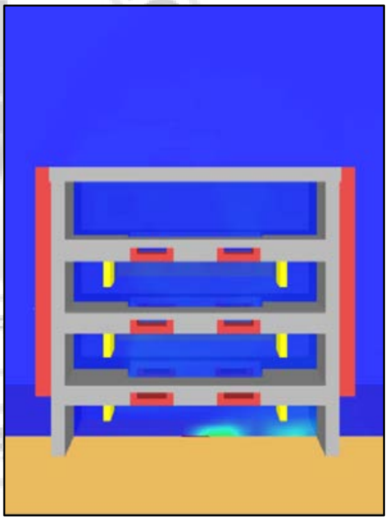


(h) 500s

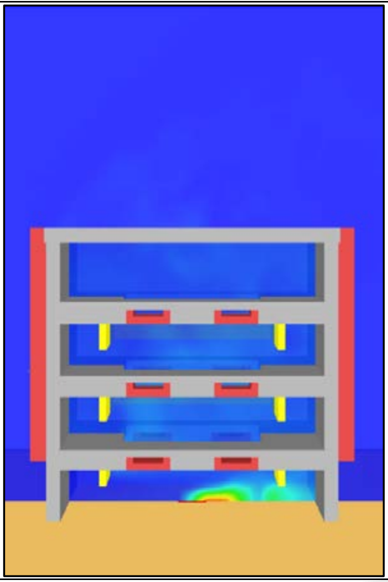
Figure 4. 39 Smoke filling pattern for atrium fire in Case11. (a)50s (b)100s, (c)150s, (d) 200s, (e)250s, (f)300s (g)350s, (h)500s



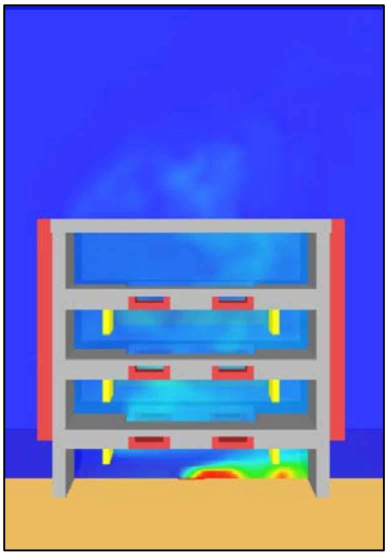
(a) 50s



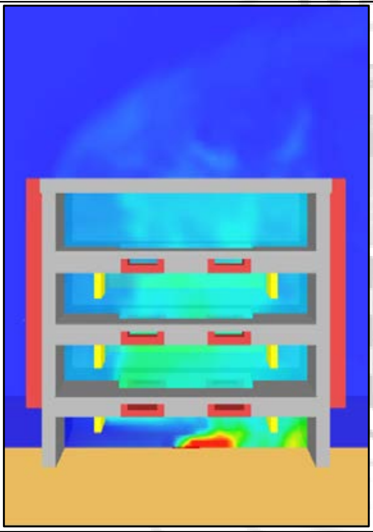
(b) 100s



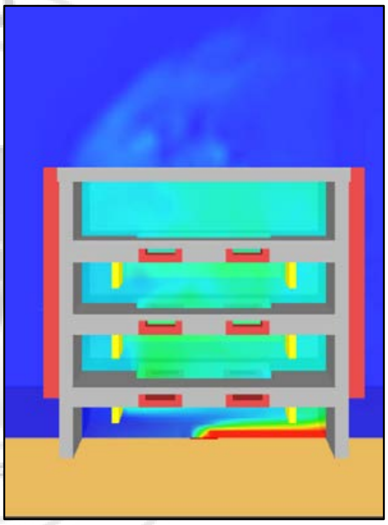
(c) 150s



(d) 200s



(e) 250s



(f) 300s

Figure 4. 40 Temperature distribution for atrium fire in Case11. (a)50s, (b)100s, (c)150s, (d) 200s, (e)250s, (f)300s

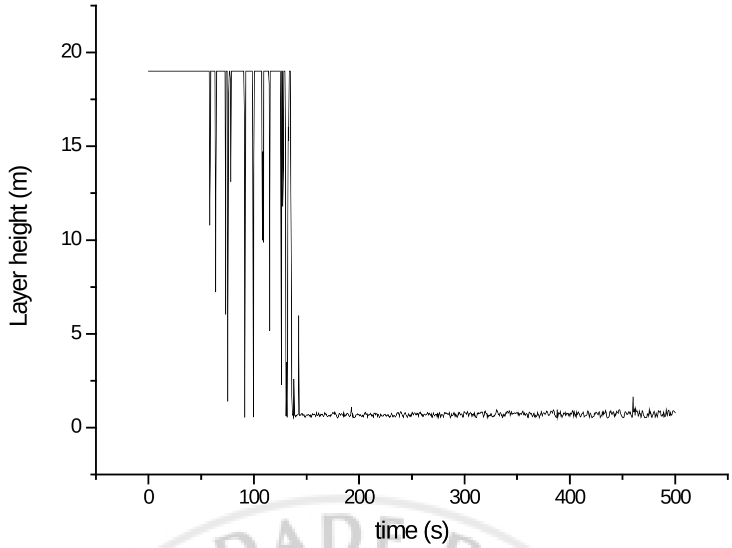



Figure 4. 41 Smoke layer height of case 11

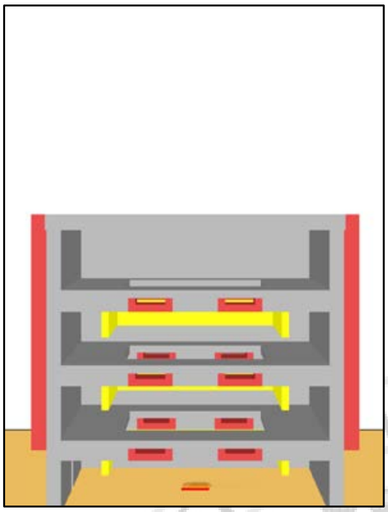
With the rearrangement in the exhaust rate, the accelerated wind flow disappeared. As shown in Figure4.39, the smoke rose guardedly and contact with the ceiling in 150s. Much smoke was exhausted from both ceiling fans and exterior ducts but the smoke still fill up the whole atrium. After 250s, since the fire was fully developed, the smoke became darker.

While Figure 4.40 shows that the temperature in the commutating space was lower than the center of the atrium, and those hot air can store in the top floor.

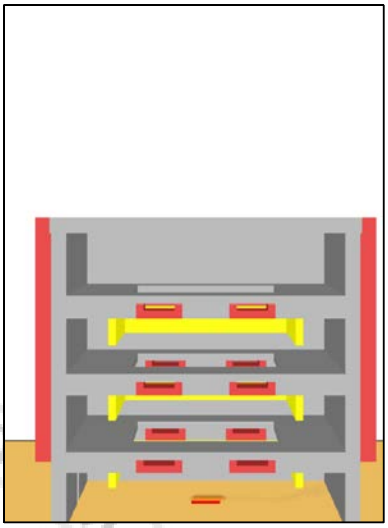
The Figure 4.41 also reveals that the smoke layer took a little much time to reach the ground.

#### 4.2.8. Case12

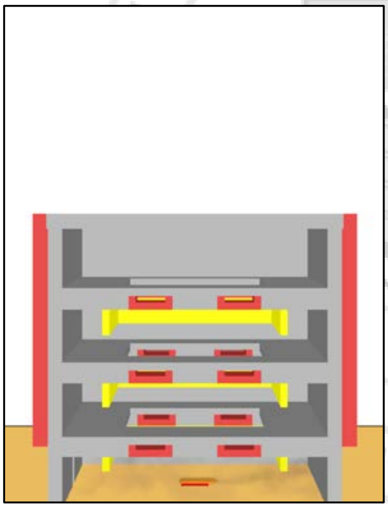
To further examine the design, a more accurate model was needed; therefore, case 12 will repeat what Case 11 done with a smaller grid size. The grids were half sized when compare to case 11, with dimension 25cm×25cm×25cm.



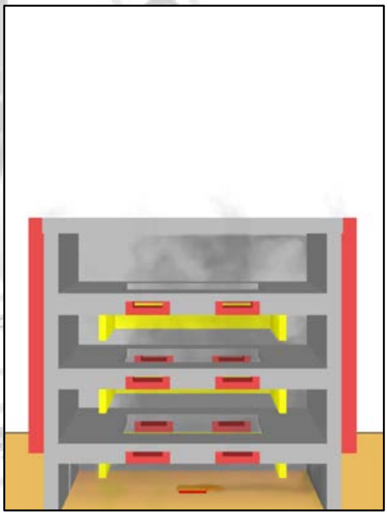
(a) 50s



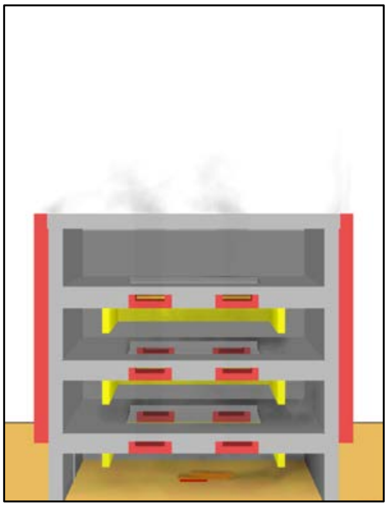
(b) 100s



(c) 150s

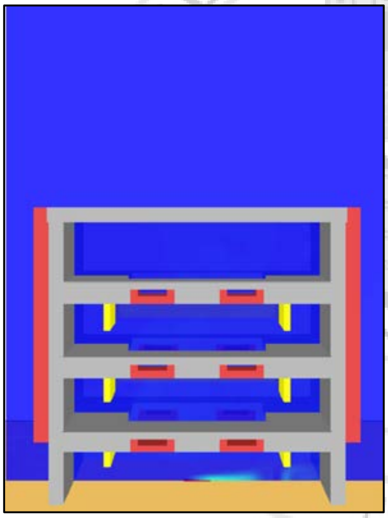


(d) 200s

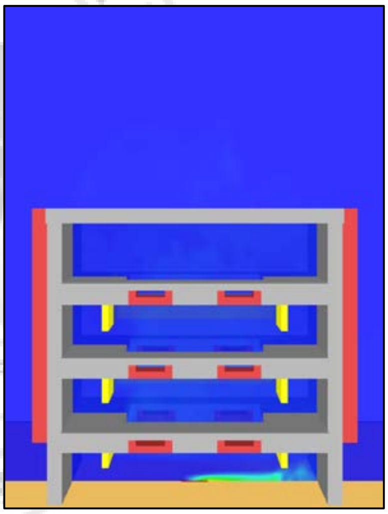


(e) 250s

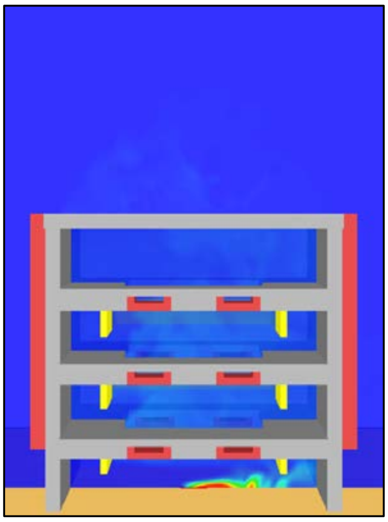
Figure 4. 42 Smoke filling pattern for atrium fire in Case12 (a)50s (b)100s, (c)150s, (d) 200s, (e)250s.

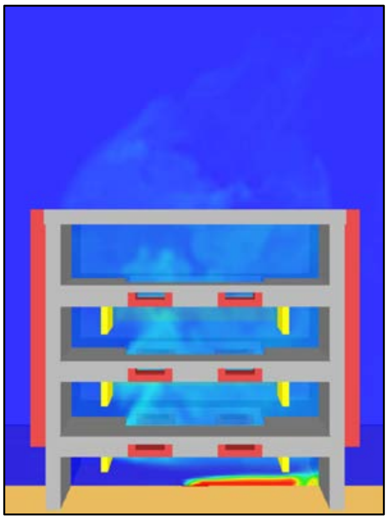


(a) 50s



(b) 100s





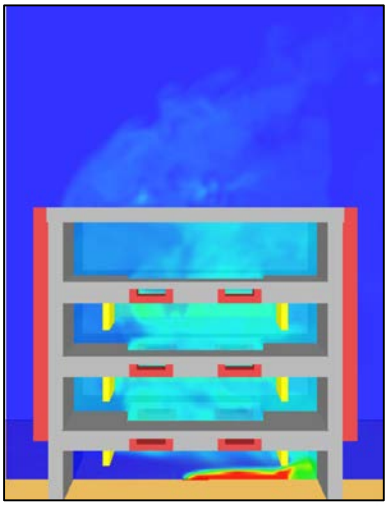
| (c) 150s | (d) 200s |
| --- | --- |
|  | |
| (e) 250s | |

Figure 4. 43 Temperature distribution for atrium fire in Case12. (a)50s, (b)100s, (c)150s, (d) 200s, (e)250s

The result from case12 gives a higher resolution on the result, the vortex inside the atrium were described in more detail. Compare the above figures with the results of case11. There was some small difference in Figure4.42 (d). In case 11, the smoke filled up all the space in 200s, while in this case, the commutating space were still clear. In terms of temperature distribution, they were similar to each other.

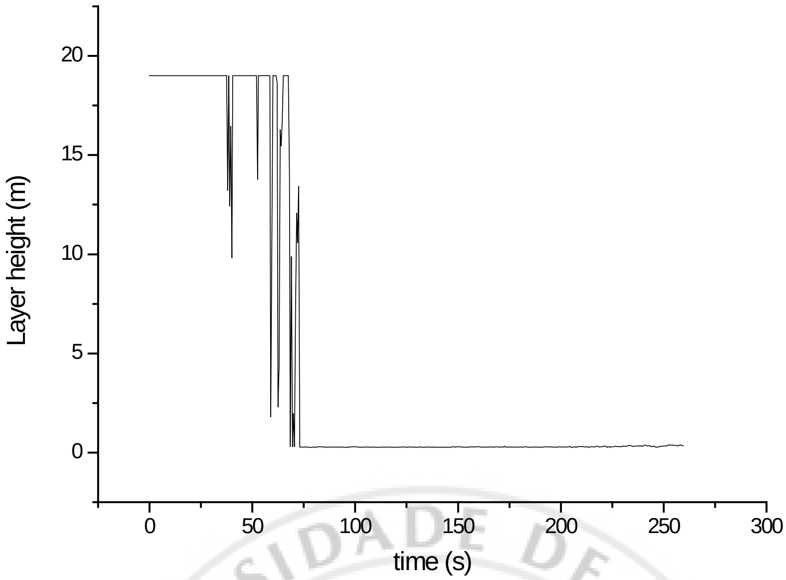



Figure 4. 44 Smoke layer height of case 12

The major difference of case 11 and case 12 was the smoke layer height. In Figure 4.44 the smoke layer height quickly drops to nearly 0 in about 75 second, while in case 11was about 130 second.

However, according to the 3D smoke animation from the smokeview ( Figure 4.42), the smoke layer had not even form when 100 second. This accuracy of the smoke layer height device is questioned.

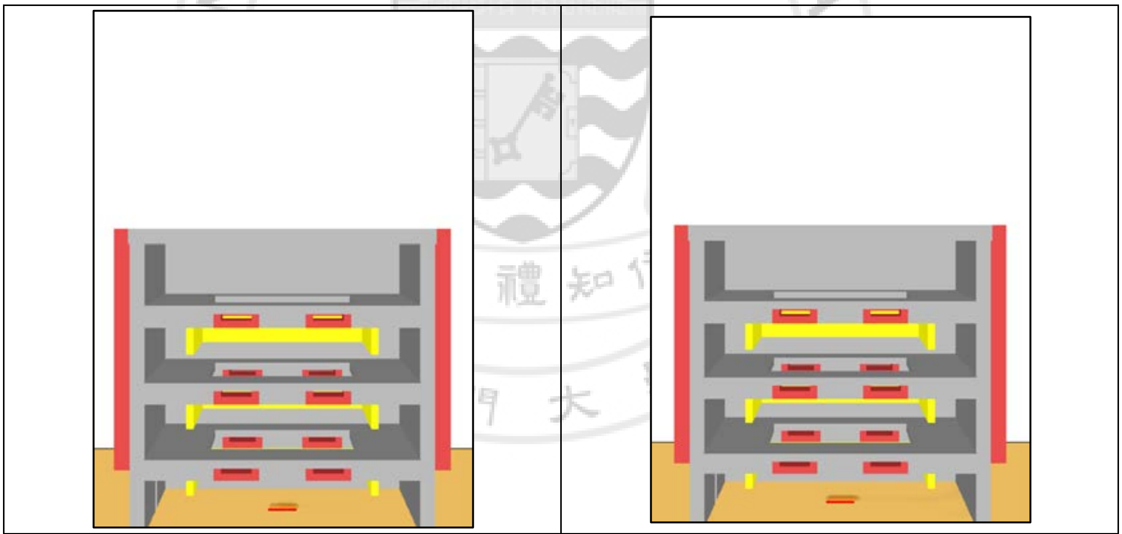
### 4.2.9. Case13

After case 10, the maximum exhaust rate was proven to be 110m$^3$/s. This value would be divided into two portions, one for the ceiling exhaust fans, another one for the exhaust duct. It was worthwhile to examine in what ratio the system may give a best performance. In this case, there was different arrangement on the exhaust rate and the simulation was done in small grid size model. In order to capture detail difference between this case and case 12

The arrangement of the exhaust rate was shown below

| Components | Quantity | Exhaust rate |
|---|---|---|
| 8.75 $m^3/s$ ceiling exhaust | 4 | $8.75 \times 4 = 35m^3/s$ |
| 9.375 $m^3/s$ exhaust fan inside each exterior duct | 8 | $9.375 \times 8 = 75m^3/s$ |
| | | Total: 110$m^3/s$ |

Table 4. 2 Exhaust rate arrangement in case 13



(a) 50s    (b) 100s

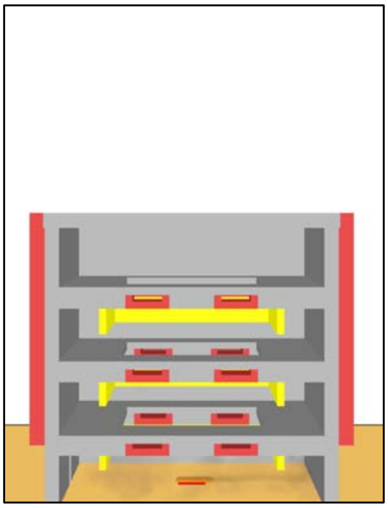
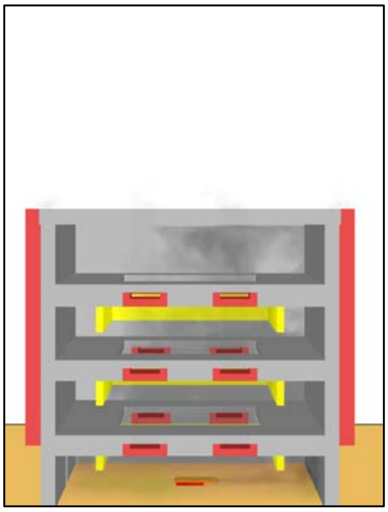
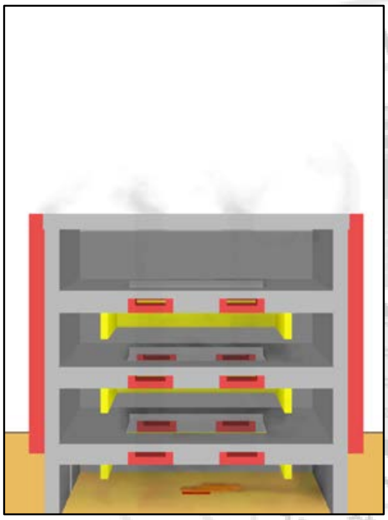
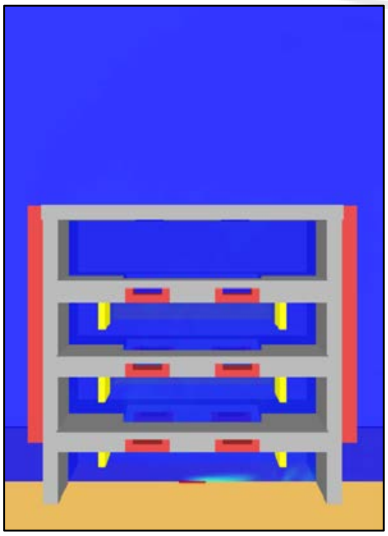
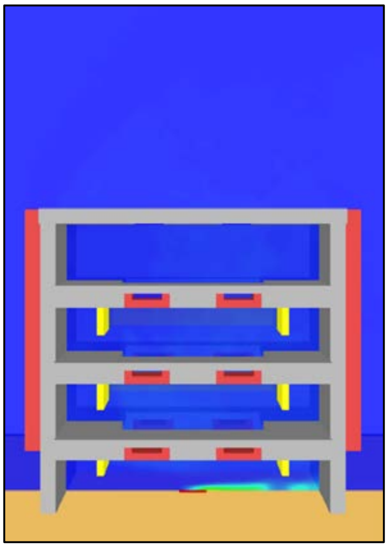
| | |
|---|---|
|  |  |
| (c) 150s | (d) 200s |
|  | |
| (e) 250s | |

Figure 4. 45 Smoke filling pattern for atrium fire in Case13. (a)50s (b)100s, (c)150s, (d) 200s, (e)250s

| | |
|---|---|
|  |  |

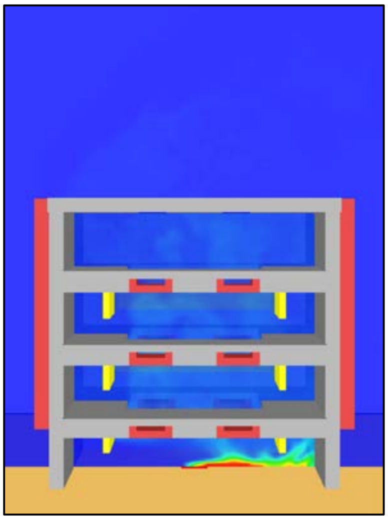
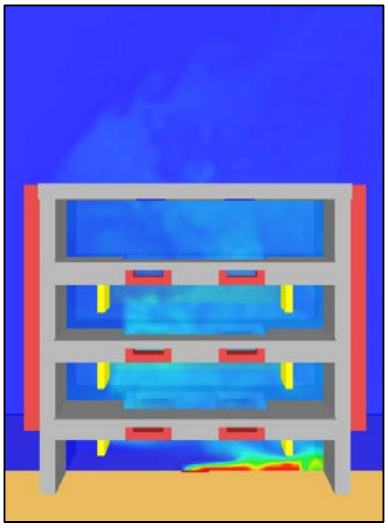
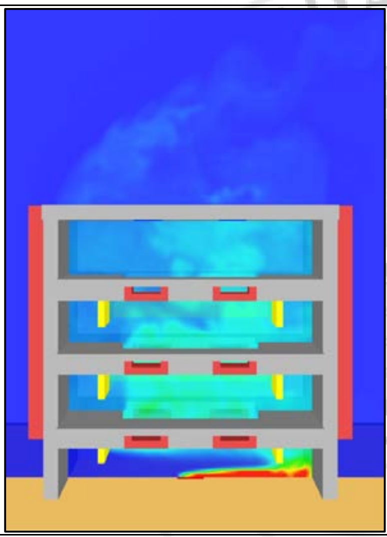
| (a) 50s | (b) 100s |
|---|---|
|  |  |
| (c) 150s | (d) 200s |
|  | |
| (e) 250s | |

Figure 4. 46 Temperature distribution for atrium fire in Case13. (a)50s, (b)100s, (c)150s, (d) 200s, (e)250s

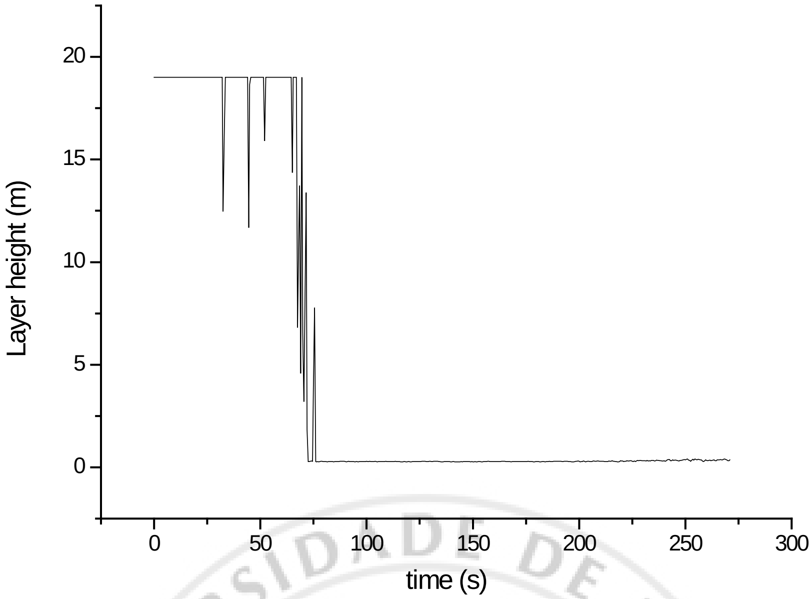



Figure 4. 47 Smoke layer height of case 13

Similar to case 12, the smoke layer height drop to nearly zero at 75 second, this was inconsistent with the 3D smoke animation from smokeview.

### 4.2.10. Case14

In case13, a system with emphasis on the exhaust duct was examined. On the contrast, a system with emphasis on the ceiling exhaust would be studied in this case. The arrangement of the exhaust rate was shown below

| Component | Quantity | Exhaust rate |
|---|---|---|
| 18.75 $m^3/s$ ceiling exhaust | 4 | $18.75 \times 4 = 75m^3/s$ |
| 4.375 $m^3/s$ exhaust fan inside each exterior duct | 8 | $4.375 \times 8 = 35m^3/s$ |
| | | Total: 110$m^3/s$ |

Table 4. 3 Exhaust rate arrangement in case 14

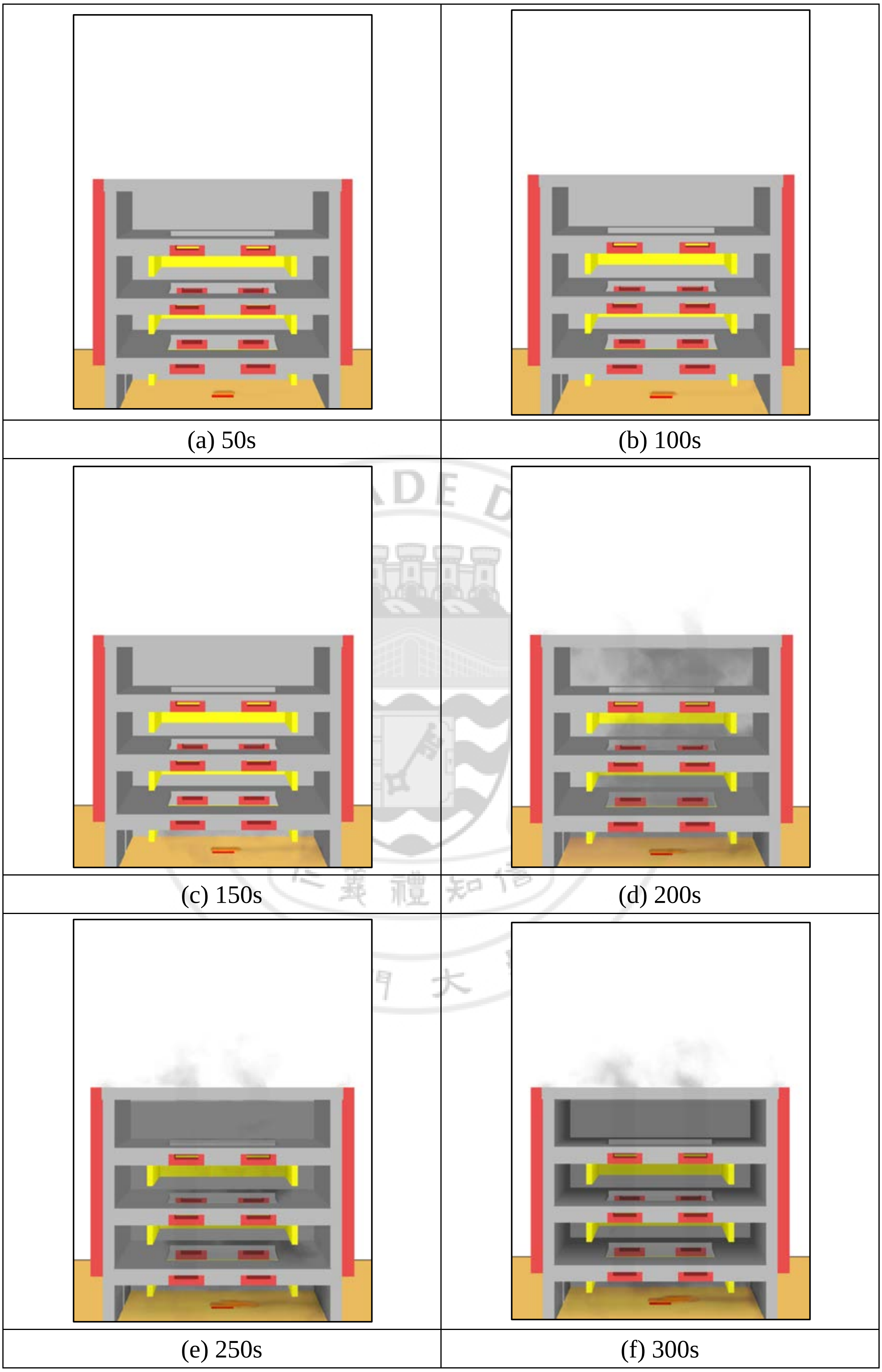
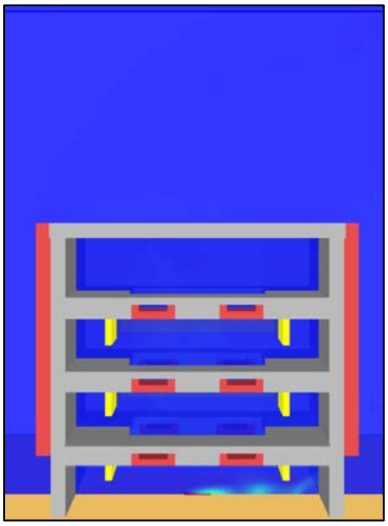
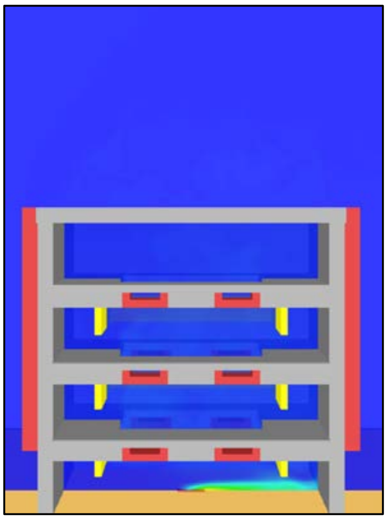


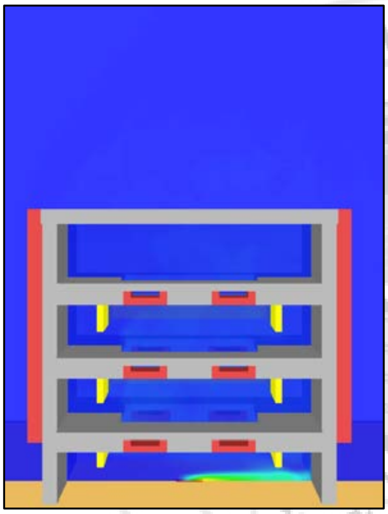

Figure 4. 48 Smoke filling pattern for atrium fire in Case14. (a)50s (b)100s, (c)150s, (d) 200s, (e)250s, (f)300s



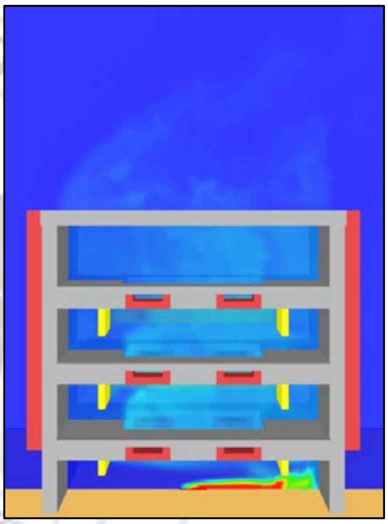
(a) 50s



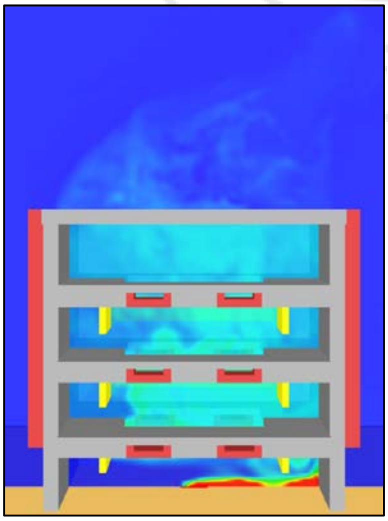
(b) 100s



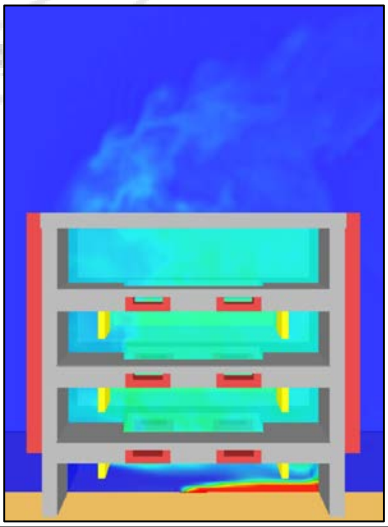
(c) 150s



(d) 200s



(e) 250s



(f) 300s

Figure 4. 49 Temperature distribution for atrium fire in Case14. (a)50s, (b)100s, (c)150s, (d) 200s, (e)250s, (f)300s

Again, there was no significant difference according to the result. In Figure4.48, there seems to be more smoke in 1st and 2nd floor when t=200s. After t=250s the smoke filled the whole building and became darker in t=300s. In terms of temperature distribution, more hot air was store in the top floor at t =250s.

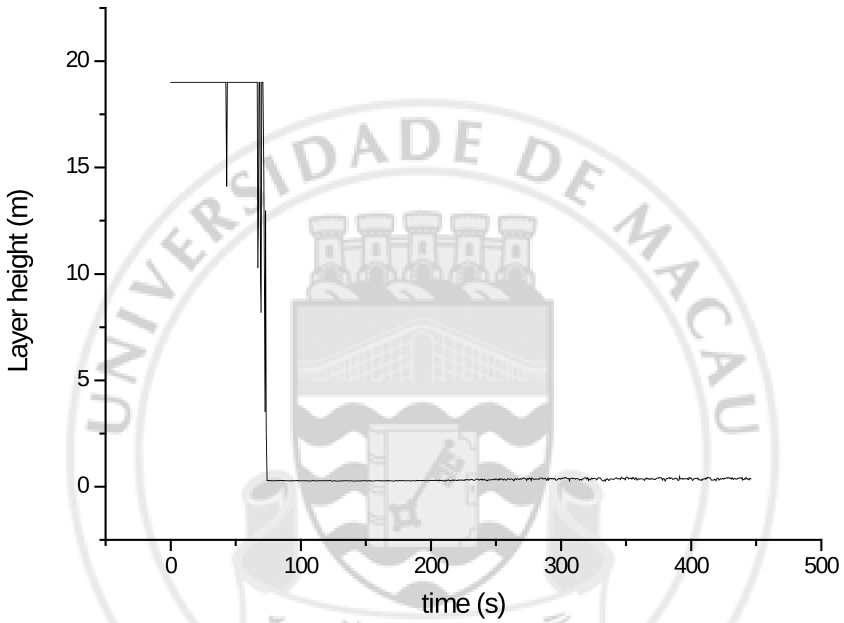



Figure 4. 50 Smoke layer height of case 14

According to the above figure, the smoke layer height drop to nearly zero at about 80 second with no many fluctuations. The result still was inconsistent with the 3D smoke animation from smokeview.

In view of the case13 and case 14, the ratio of the exhaust rate of ceiling fan and exhaust duct did not play an important role in the system.

### 4.2.11. Case15

In this case, the opening was changed to the 1st floor to mimic there was a glass window broken. A 1m × 3m opening located at the center of the 1st floor, wind would flow into the atrium from that hole.

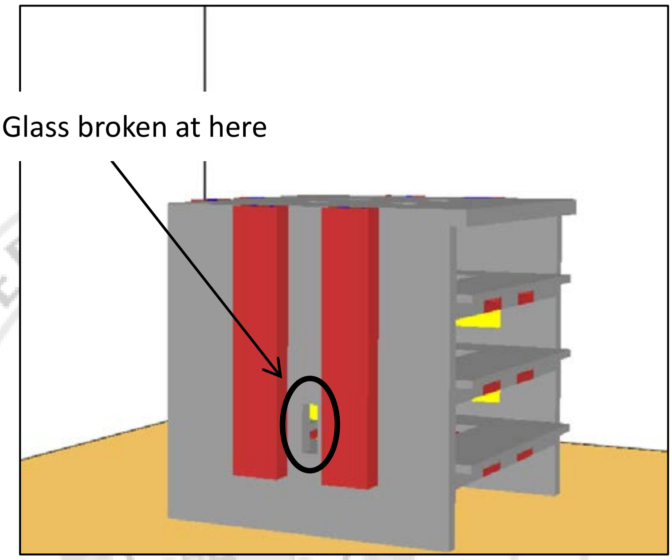
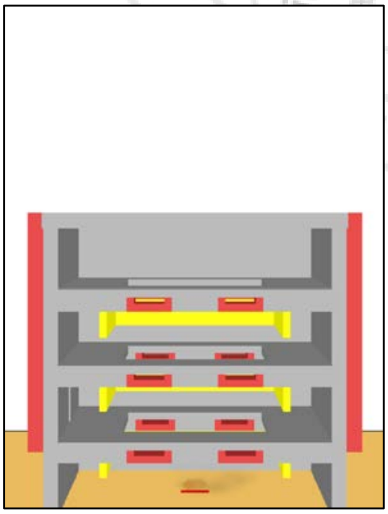
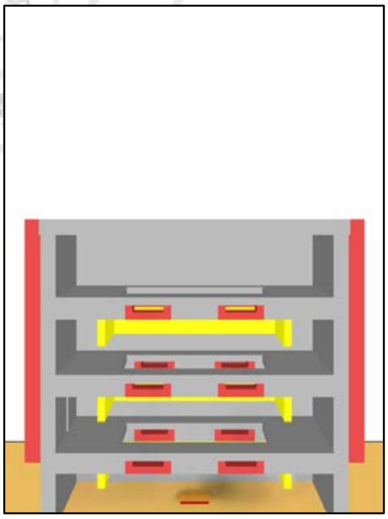
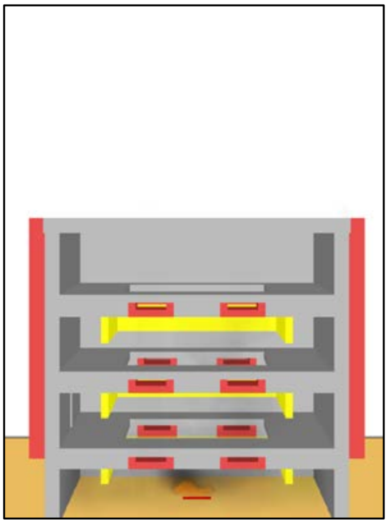
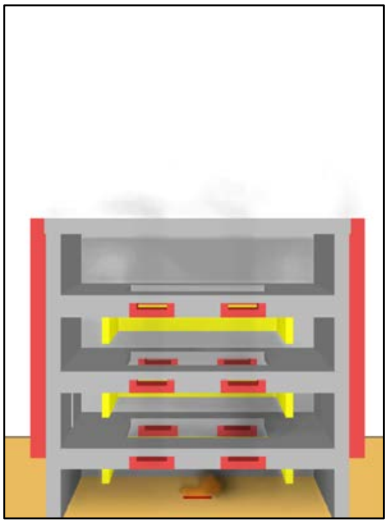



Figure 4. 51 Setting of case15

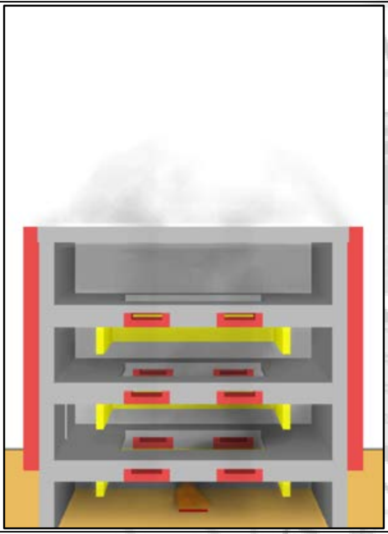
| | |
|---|---|
|  |  |
| (a) 50s | (b) 100s |



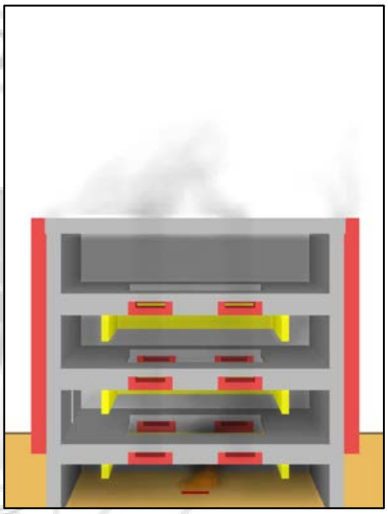
(c) 150s



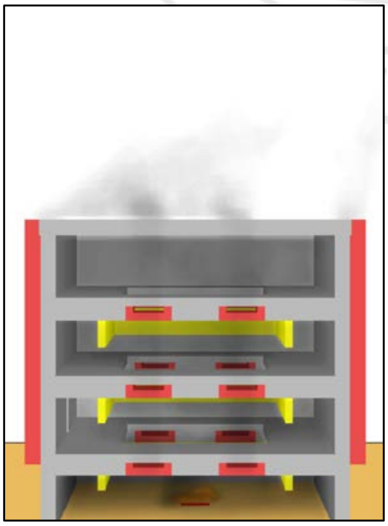
(d) 200s



(e) 250s

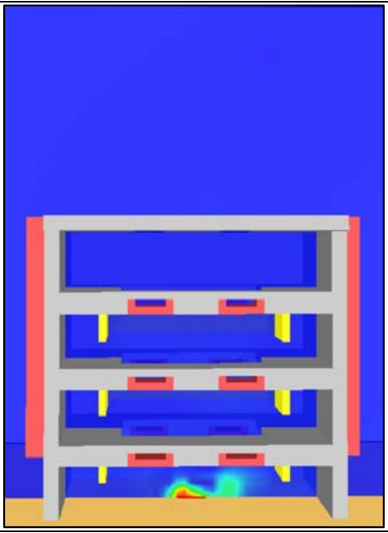


(f) 300s

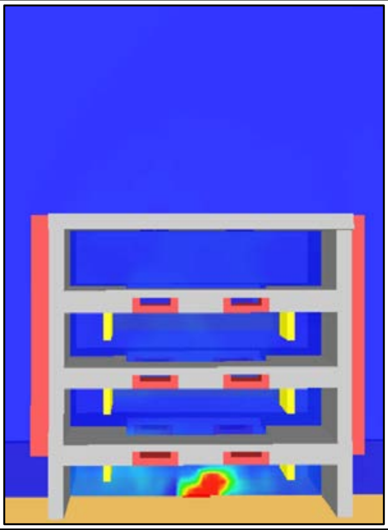


(g) 350s

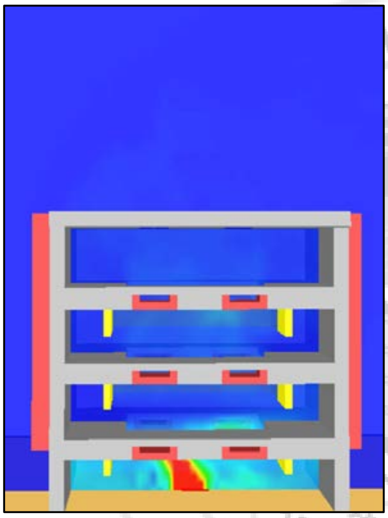
Figure 4. 52 Smoke filling pattern for atrium fire in Case15. (a)50s (b)100s, (c)150s, (d) 200s, (e)250s, (g) 350s



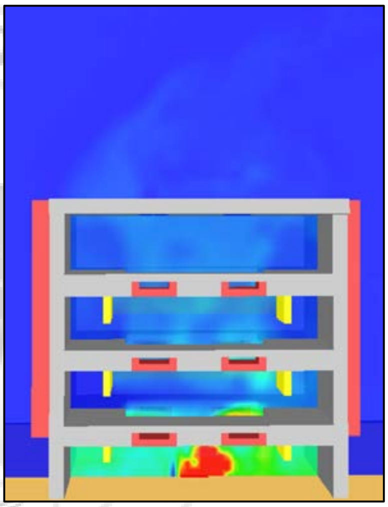
(a) 50s



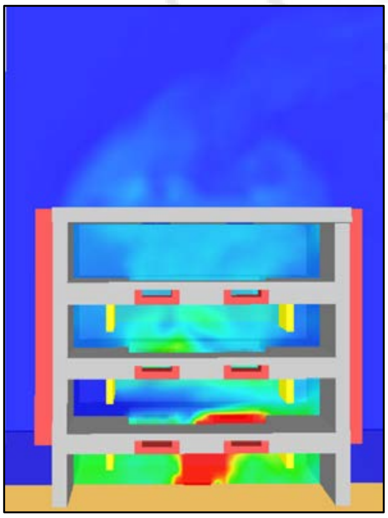
(b) 100s



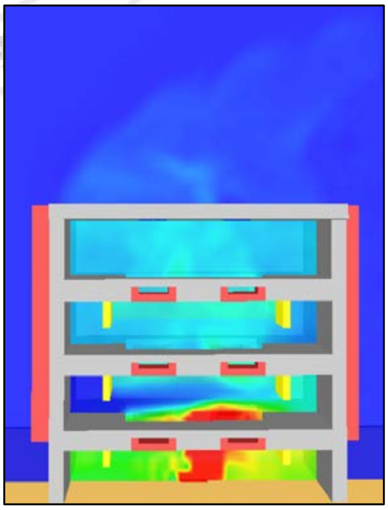
(c) 150s



(d) 200s



(e) 250s



(f) 300s

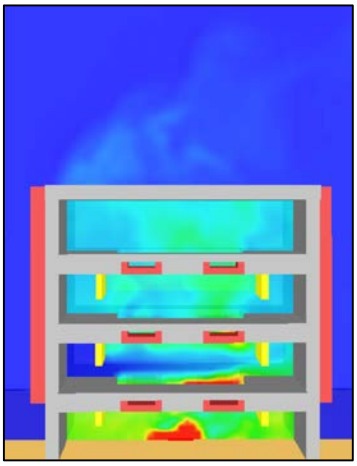
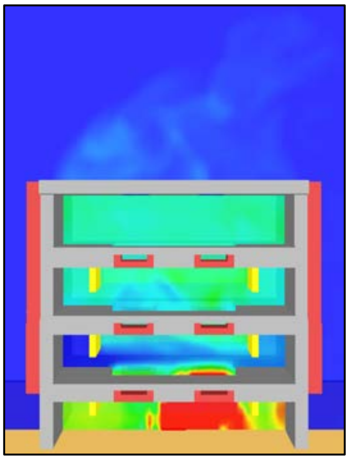
|  |  |
|---|---|
| (g) 350s | (h) 400s |

Figure 4. 53 Temperature distribution for atrium fire in Case15. (a)50s, (b)100s, (c)150s, (d) 200s, (e)250s, (f)300s, (g)350s, (h)400s

Figure 4.52 reveals that the smoke appeared in the early period and the wind flow block the smoke at the 1st floor, the smoke could not flow upward and was trapped in the ground floor. This kind of fire can be very horrible if it happen in real world, since those dark smokes may highly decrease the visibility of the ground floor (the main evacuation route). Besides, the high temperature air store at the ground floor, which may provide more energy for the fire to growth. If the temperature is too high, there is a potential that flashover and backdraft may occur, which will interrupt fire fighter to extinguish the fire.

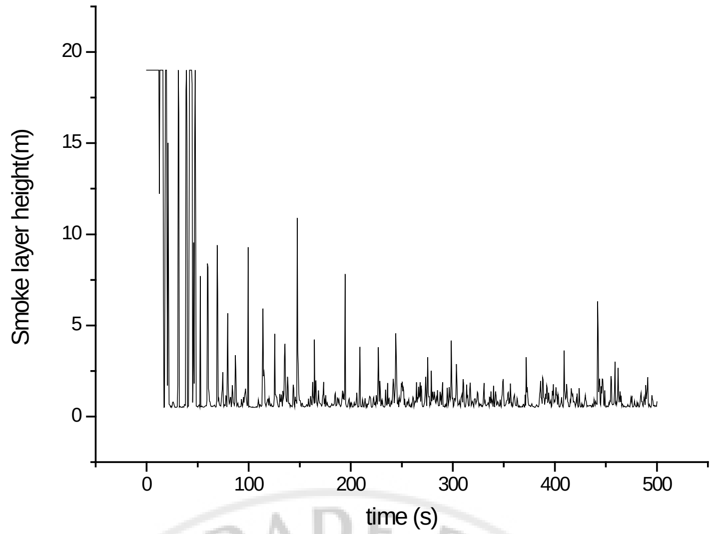



Figure 4. 54 Smoke layer height of case15

### 4.2.12. Case16

Similar to case15, an opening with same dimension was set at the $2^{nd}$ floor. Strong wind blow in into the atrium and distort the smoke filling pattern.

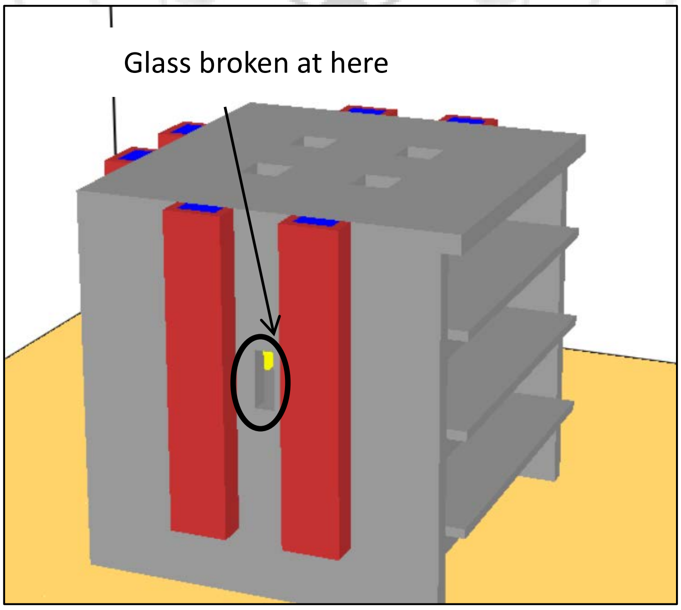
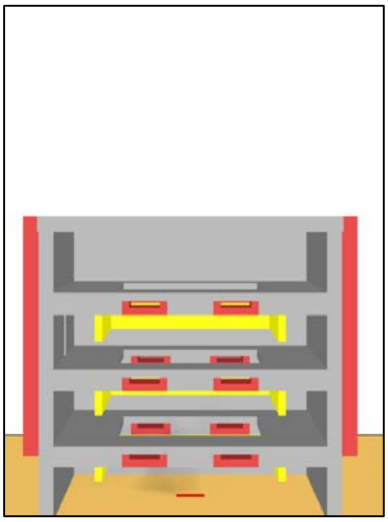
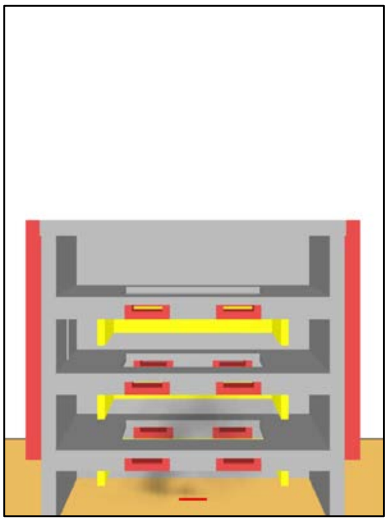


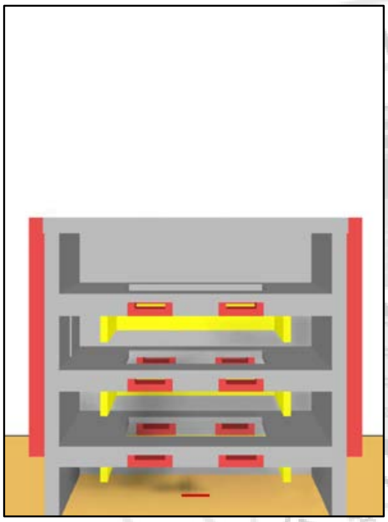

Figure 4. 55 setting of case 16



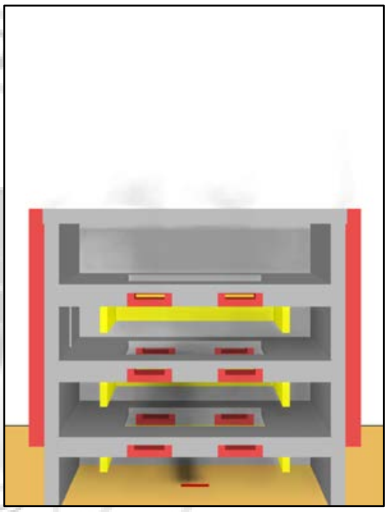
(a) 50s



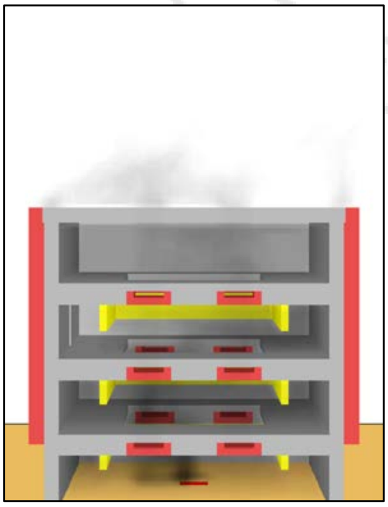
(b) 100s



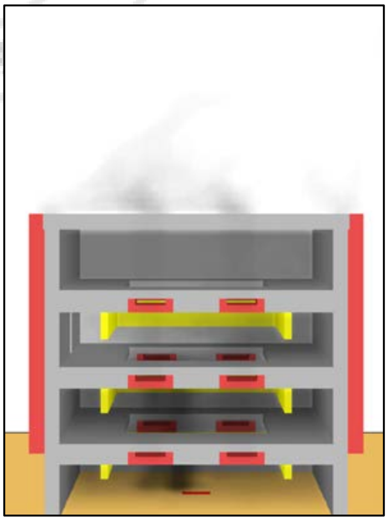
(c) 150s



(d) 200s



(e) 250s



(f) 300s

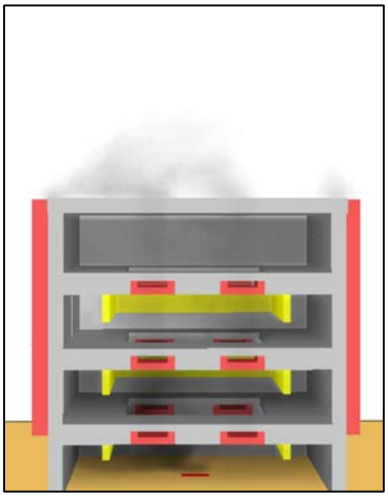
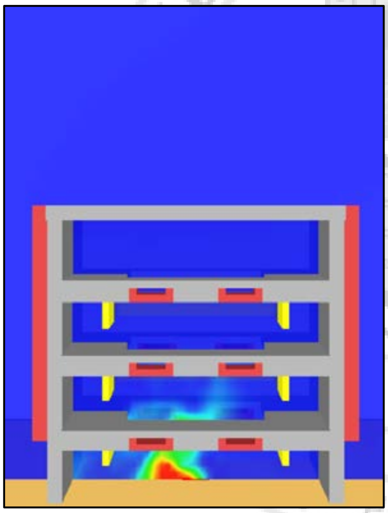
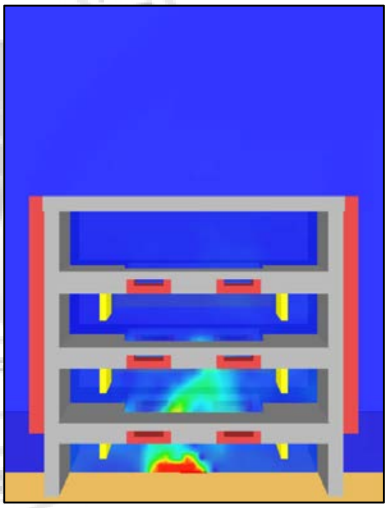
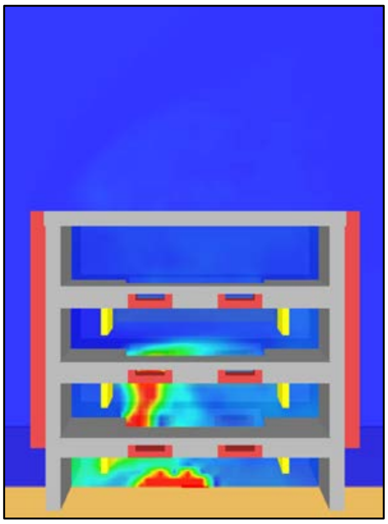
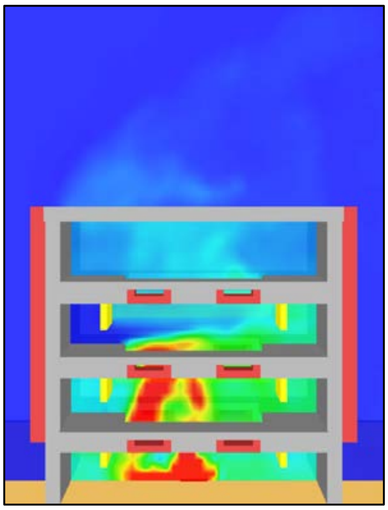
| | |
|---|---|
|  | |
| (g) 350s | |

Figure 4. 56 Smoke filling pattern for atrium fire in Case16. (a)50s (b)100s, (c)150s, (d) 200s, (e)250s, (g) 350s

| | |
|---|---|
|  |  |
| (a) 50s | (b) 100s |
|  |  |

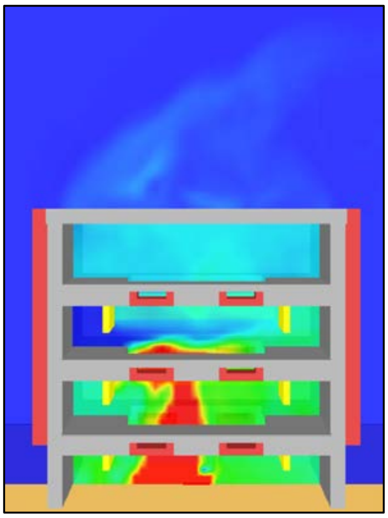
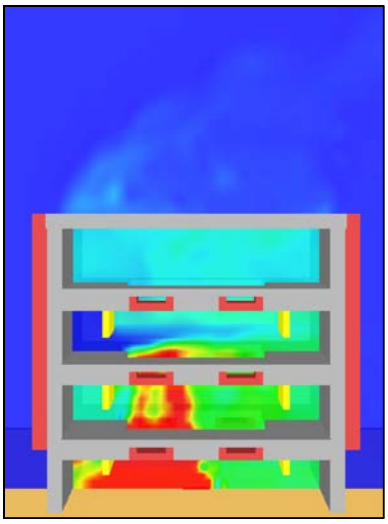
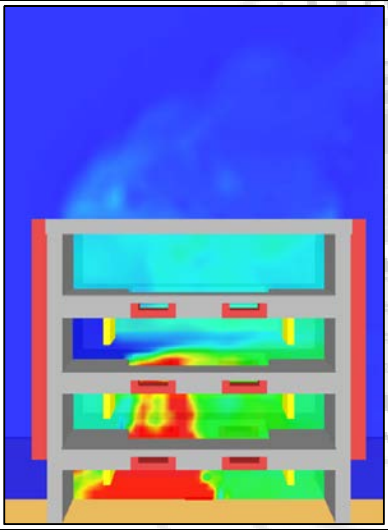
| (c) 150s | (d) 200s |
| --- | --- |
|  |  |
| (e) 250s | (f) 300s |
|  | |
| (g) 350s | |

Figure 4. 57 Temperature distribution for atrium fire in Case16. (a)50s, (b)100s, (c)150s, (d) 200s, (e)250s, (f)300s, (g)350s

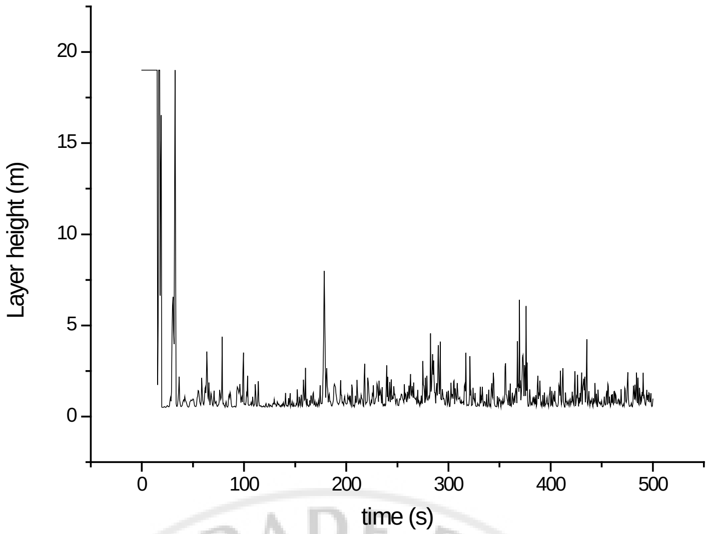



Figure 4. 58 Smoke layer height of case16

In case 16 figures, the air temperature tends to higher at the left side of building while in case 15 figures, the air temperature tends to higher at the middle of the ground floor. This is because the smoke seems trap at the bottom and it cannot rise upward because of the strong wind blow into second floor.

## 4.3. Summary

Some observations can be made from case6 to case 16 in this case study, they are:

- Smoke layer does not able to form at the ceiling due to the signal no.3 wind velocity.
- Smoke layer height can be lowered to zero meter in the first 50s
- Smoke completely fills in the atrium when time=250s

Error analysis and Limitation:

- Much longer simulation time is required when the grid size is halved using FDS.
- Smoke layer height may not be effective in this situation since the smoke has been distorted by the strong wind of signal no.3.
- The size of the grid can affect the accuracy.
- Easy to make mistakes by syntax error so carefulness is required when coding the program especially sometimes too much words in coding.
- Lots of attempting works and unsuccessful cases were done in the designing phases which a lot of time was wasted because time required for simulation. This is the most difficult part in this research.
- Some technical computer problems encountered during running simulation, e.g. insufficient of space of hard disk cause the simulation stop.
- Difficult to exhaust the smoke under signal no.3 even using the calculated

exhausted rate of fans from NFPA.

- Limitations in design phase since FDS has some constraints on geometry.

# CHAPTER 5. CONCLUSION

Lots of researches have conducted on the atrium and large space fires, but not many of them were studied for wind effects, especially for tropical storm in atrium fires.

In this research project, simulations were done to examine the smoke distribution in atrium under tropical storm attack by using FDS. Also similar results were obtained in the verification phase when compare to other studies that using CFD. These can prove the effectiveness of the design using FDS. In designing phase, results showed how the chaotic wind affects the plume and formation of smoke layer, and most important one, smoke distribution in atrium fires. Moreover, a fire safety system of atrium was designed step by step to handle this difficult situation under tropical storm.

The results did not appear as good as expected however some improvement of smoke distribution could be seen after considering many factors such as the different arrangement of exhaust fans installed, the maximum volumetric exhaust rate required in the system, adding the fire curtain and exhausted ducts. These improvements could help to provide a little bit time for occupants to evacuate in the atrium fire.

Recommendation of Future work

- Using a smaller grid size to improve the accuracy of fire models.
- Using other programs such as PYROSIM can be used to aid FDS
- Trying different fire safety design such as sprinklers or smoke detectors
- Trying different wind velocity such as signal no.1 typhoon to analysis the effect of smoke

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# APPENDIX

Work load breakdown