# AN ADVANCED STUDY ON AUTOMATIC WATER-BASED SUPPRESSION SYSTEMS IN SEVERAL BUILDING APPLICATIONS

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# An Advanced Study on Automatic Water-based Suppression Systems in Several Building Applications

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# CERTIFICATE OF ORIGINALITY

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# ABSTRACT

Automatic water-based fire suppression systems, such as sprinkler systems and water mist fire suppression systems are required for special building applications, such as those in new airport and railway projects as a defence in fire safety. Several aspects associated with the system are explored in this thesis.

‘Fast response type’ sprinklers are required in several building applications, where prescriptive requirements on passive fire protection cannot be met. Apart from these settings, thermal sensitivity of sprinklers is not normally specified by the local fire authority. In some cases, even concealed type sprinklers had been used when ‘fast response type’ sprinklers were required. In this thesis, architectural characteristics of the public transport systems in Hong Kong, such as airport and railway stations, will be described. The fire hazards, including life risks and economical loss associated with these occupancies will also be presented, followed by a literature review on local and international code on associated fire protection measures. Research works were focused on:

- Fire risks associated with public transport systems, including airports and railway stations;

- Key aspects of requirements on thermal sensitivity of sprinklers;
- Experimental studies on thermal sensitivity of various kinds of sprinklers;
- Performance evaluation of heat collector plate on thermal sensitivity of sprinklers;

Experiments was conducted with a wind tunnel to study thermal sensitivity of various kinds of sprinklers, including normal response, fast response and concealed type sprinklers. Besides, the effect of heat collector plates on thermal response of sprinkler heads at large halls will be discussed.

In addition, appropriate fire protection systems were proposed for public transport systems. Suppression of sprinkler systems in connection to enhancing fire safety in public transport systems were investigated too. Active water mist fire suppression systems on liquid fire were also investigated. Numerical simulations on different scenarios using Computational Fluid Dynamics Fire Dynamics Simulator (FDS) version 6.7.4 were conducted. Cloud computing had been hired from a commercial service provider for faster simulation. Mitigating measures on these automatic water suppression systems to the associated fire risks will be suggested.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| ASET | available safe egress time |
| BD | Buildings Department |
| BSI | British Standards Institution |
| FDS | Fire Dynamics Simulator |
| FSD | Fire Services Department |
| FSI | fire service installations |
| HAD | Home Affairs Department |
| ISD | Information Services Department |
| km | kilometre |
| kW | kilowatt |
| m | metre |
| MHCLG | Ministry of Housing, Communities and Local Government |
| MTR | Mass Transit Railway |
| NFPA | National Fire Protection Association |
| RSET | required safe egress time |
| SCDF | Singapore Civil Defence Force |

| | |
|---|---|
| XRL | Guangzhou - Shenzhen - Hong Kong Express Rail Link |

## NOMENCLATURE

| | |
|---|---|
| A | area of vent opening, $m^2$ |
| $D_H$ | hydraulic diameter of opening, m |
| P | perimeter of vent opening, m |
| RTI | nominal response time index, $(m \cdot s)^{1/2}$ |
| $t_a$ | actuation time of the heat sensing element, s |
| $\Delta T_A$ | temperature rating of heat sensing element above the initial temperature, K |
| $\Delta T_g$ | temperature above the initial temperature, K |
| $v_g$ | air velocity in the hot wind tunnel, $ms^{-1}$ |
| $\tau$ | nominal time constant |

# CHAPTER 1: INTRODUCTION

## 1.1 Background of the Study

Hong Kong has a land area of just above 1100 km$^2$, with only less than 25% of this area having been developed (Legislative Council Commission, 2018). Evidenced by the presence of about 65.15 million visitors each year (Tourism Commission, 2020), Hong Kong is a proven popular tourist destination. Furthermore, the city is a very important regional transport hub in Asia. Its airport, the Hong Kong International Airport in Chek Lap Kok, is the busiest airport in the world by cargo traffic (Airports Council International, 2019). The airport also provides extensive intermodal passenger connection to the Pearl River Delta region, by means of ferries and coaches.

For the residents, the city is packed with a population of about 7.48 million (Census and Statistics Department, 2021), with most of them living in high-rise buildings. As such, there is an immense need for commute. Being the most popular choice for commuting, the railway system, namely the Mass Transit Railway, is highly efficient and is designed to carry large number of passengers. The railway forms the backbone of the transportation system in Hong Kong and carries 3.39 million passengers each day, accounting about 38% of public transport passenger travel (Transport Department, 2020).

These facilities are essential to the economy of Hong Kong. As such, a high degree of fire safety is expected for the purpose of life and property safety. In Hong Kong, requirements on active fire protection measures in buildings are under the jurisdiction of the Fire Services Department (FSD). In this regard, sprinkler systems are normally required for non-residential buildings with floor area exceeding 230 $m^2$ (FSD, 2012). Thermal sensitivity of sprinklers is only specified for some types of occupancies, such as basements.

On the other hand, passive fire protection measures in Hong Kong are under the purview of the Buildings Department (BD). BD recognises sprinklers as a reliable active fire protection measure. As such, the department adopts different standards on means of escape and fire resisting construction for buildings with and without sprinkler protection (BD, 2011).

Emergency vehicular access are required for buildings in Hong Kong. However, provision of such to some buildings in impractical due to topographical constraints. In this case, sprinkler systems with specific requirements on thermal sensitivity are prescribed as enhancement in fire safety provisions.

## 1.2 Objectives of the Study

The objectives of this study are as follows:

(a) to identify fire risks associated with airports and railway stations;

(b) to review the key aspects of requirements on thermal sensitivity of sprinklers;

(c) to observe and analyse results of experimental studies on thermal sensitivity of various kinds of sprinklers;

(d) to evaluate the performance of heat collector plate on thermal sensitivity of sprinklers;

(e) to analyse the effectiveness of sprinkler systems in enhancing fire safety in transportation buildings; and

(f) to propose measures to mitigate fire risks and hazards in buildings with special applications, in particular airports and railway stations.

## 1.3 Methodology

Research methods adopted in this study are:

(a) literature review on fire safety requirements in airports and railway stations;

(b) experimental studies on thermal sensitivity of various kinds of sprinklers using a wind tunnel;

(c) analysis on the effect on thermal sensitivity of heat collector plate and different forms of sprinklers;

(d) numerical simulations on extinguishing capabilities of sprinklers using a computational fluid dynamics software, namely Fire Dynamics Simulator (FDS) version 6.7.4, on different scenarios; and

(e) numerical simulations on the effect on thermal sensitivity by heat collector plate with FDS version 6.7.4.

## 1.4 Overview of Thesis

This thesis is organized as follows into 10 chapters:

(a) Chapter 1 provides a brief overview of the thesis and introduces the research background, objectives and methodology, as well as the organisation of this thesis;

(b) Chapter 2 describes architectural characteristics of the airport and railway stations in Hong Kong;

(c) Chapter 3 presents the fire hazards, including life risks and economical loss, associated with the airport and railway stations in Hong Kong.

(d) Chapter 4 presents findings of the literature review on local and international code requirements on both active and passive fire protection measures;

(e) Chapter 5 presents the results of numerical simulations on extinguishing capabilities of sprinklers using FDS version 6.7.4 on different scenarios;

(f) Chapter 6 presents the results of experimental study using a wind tunnel on thermal sensitivity of various kinds of sprinklers;

(g) Chapter 7 discusses the effect of heat collector plates on thermal response of sprinkler heads at large halls;

(h) Chapter 8 presents the results of numerical simulations with FDS version 6.7.4 on the effect on thermal sensitivity by heat collector plate;

(i) Chapter 9 suggests measures that could mitigate fire risks in relation to fire risks associated with special building applications, particularly airports and railway stations; and

(j) Chapter 10, being the final chapter, is a conclusion for this research. The summary of this study is presented, followed by a discussion of the key contributions and implications. At last, limitations on the research and recommendations for further research are highlighted.

A schematic diagram is at Figure 1.1 to illustrate the flow of this thesis.

# CHAPTER 2: ARCHITECTURAL CHARACTERISTICS OF THE AIRPORT AND RAILWAY STATIONS IN HONG KONG

## 2.1 Architectural Features of the Airport

The Hong Kong International Airport in Chek Lap Kok was commissioned in 1998. It serves as a gateway to Hong Kong from over 200 destinations worldwide. It has two runways in 2021, and is capable of handling 68 flights per hour at peak hours. In 2019, it handled over 419000 flights with 71.5 million passengers and had an air cargo throughput of 4.8 million tonnes (Airport Authority Hong Kong, 2021). Apart from serving residents and visitors to Hong Kong, the airport is also a multi-modal transportation hub which is connected to 110 cities and towns in the Chinese mainland by bus, as well as 9 nearby ports by ferry.

The smooth operation of the airport is vital to the success of the economy of Hong Kong. Apart from travellers who contributed significantly to Hong Kong's economy, tonnes of food are imported by air to Hong Kong daily to feed the local residents. On the other hand, Hong Kong is a major regional air cargo hub. Hong Kong is a regional hub of a leading international courier and express mail service.

To ensure round-the-clock operation of the airport, as well as for the safety of passengers and cargo, fire safety is of paramount importance to prevent fire or to at least minimise its impact.

Passenger service is provided in four terminals, namely Terminal 1, Terminal 2, North Satellite Concourse and Midfield Concourse totalling a floor area of approximately 730000 $m^2$. Amongst these terminals, Terminal 1 is the biggest one which is an 8-level building covering a total floor plan area of about 515000 $m^2$ ('Terminal 1, HKIA', 2011).

Terminal 1 is a gigantic building with a length of 1200 m with 47 jet bridges. It is also equipped with arrival and departure areas, retail and catering areas, rest lounges as well as other supporting facilities. The objective of the building design is to maintain ease of access by passengers throughout the terminal, as well as to maintain visibility for easier navigation inside it. As such, large halls with very high headroom and enormous fire compartment size exist in the arrivals and departures areas. In many areas, these halls have a headroom of over 10 m. Due to it large span, it is not practical to partition the building into numerous compartments.

Terminal 2, North Satellite Concourse and Midfield Concourse are relatively smaller buildings. Yet, the design with tall headroom is also employed in these buildings. Terminal 2 houses checking-in and processing facilities for passengers, without any departure gates. The North Satellite Concourse is a 2-level building which houses 10 jet bridges. It is linked to Terminal 1 with a footbridge. The Midfield Concourse is a 2-level building which houses 20 jet bridges. Passengers travelling at the Midfield Concourse must take the automated people mover system which is an underground driverless electric train system linking Terminal 1.

Apart from the passenger facilities, there are also 7 air cargo facilities at the airport. The land area occupied by these air cargo facilities ranges from 1.4 to 17 hectares (Hong Kong International Airport, n.d.).

An expansion project is undergoing at the airport to develop a three-runway system. The construction of the three-runway system commenced in August 2016. The project consists of a third runway and the third runway passenger building; expansion of the existing Terminal 2; as well as other airport support infrastructure (Legislative Council Secretariat, 2021). The third runway has been put in use in 2022, while the whole three-runway system will be fully completed in 2024.

## 2.2 Architectural Features of Railway Stations

Railways are an essential mode of transportation for commuters in Hong Kong and is heavily patronised. Every day, 3.39 million passengers depend on the railway for commute (Transport Department, 2020). The railway, namely Mass Transit Railway (MTR), is ever-expanding. Currently, it is a network consisting of 11 heavy rail lines with 96 stations (Transport Department, 2021) coping with local transportation needs on Hong Kong Island, Kowloon Peninsula, the New Territories, as well as Lantau Island.

The purpose of the MTR is to transport large numbers of passengers simultaneously. For instance, 9-car trains, each with a capacity for 2845 people, run every 2.7 minutes during peak hours on the mainly above-ground East Rail Line (MTR Corporation, 2022). Another example is the mainly underground Tsuen Wan Line, on which 8-car trains designed for 2500 passengers run at 2-minute intervals in the rush hour.

In calculating the maximum carrying capacity of train compartments, the railway operator currently adopts a density of 4 persons standing per $m^2$. According to the MTR Corporation (2016), the loading of trains on the busiest lines ranged from 80% to 104% during rush hours. To accommodate such long trains and large number of passengers, railway stations are very large, and the design of these stations vary. Passengers must pass through turnstiles at the station concourse before going up or down to platforms in most stations.

Railway stations in Hong Kong are either elevated, at-grade or underground. In fully developed areas of the city, it was infeasible to build railway without going underground. As such, 44 out of 96 stations are located under road level. Seven of these subterranean stations are even located inside caverns (Wallace and Ng, 2016). Depending on the topography of the surrounding environment and orientation of the rails, underground stations lie at different depths below road surface. HKU Station, being the deepest station in the city, lies 70 m below road level (Sung, 2014).

High headroom is uncommon in these railway stations. Shops are present in most of them. All underground stations are fully enclosed. For some at-grade and elevated stations, platforms are open to the side. Yet, platforms of some elevated stations are fully enclosed by platform screen doors.

Apart from meeting domestic transportation needs, the MTR Corporation also operates two kinds of cross-boundary train services. The intercity through-train runs from Hong

Kong to cities in Guangdong Province, as well as Shanghai and Beijing. In Hong Kong, these trains share tracks of the current East Rail Line, formerly Kowloon Canton Railway (British Section) dating back to 1910.

Since 2018, the MTR Corporation has also been operating the Hong Kong Section of the Guangzhou - Shenzhen - Hong Kong Express Rail Link (XRL) (Legislative Council Secretariat, 2018). The Hong Kong Section of the XRL is a dedicated rail corridor of 26 km in length running from West Kowloon to Shenzhen, where it is linked to the Mainland Section of the XRL. The tracks are entirely underground. Trains run on the Hong Kong Section of the XRL to connect 44 destinations in the Chinese Mainland. On average, about 51000 passengers travel on the Hong Kong Section of the XRL.

The only station of the Hong Kong Section of the XRL, namely Hong Kong West Kowloon Station, is a huge railway station covering floor area of about 430000 m$^2$ (Transport and Housing Bureau, 2018). The ground level of this station is a public transport interchange. On the first basement level, there are restaurants and the ticketing concourse. The arrival concourse and departure concourse occupy the second and third basement levels respectively. On the fourth basement level, there are train platforms of various lengths. A design combining high headroom, atria and large compartment size was adopted for the ease of navigation inside the station, as well as for the comfort of travellers.

Regarding future railway projects, the MTR Corporation is also planning for some other new lines in the New Territories and Lantau Island (Transport Department, 2021).

# CHAPTER 3: FIRE HAZARDS OF AIRPORT AND RAILWAY STATIONS

## 3.1 Fire Hazards of the Airport

Airports are designed to accommodate large numbers of passengers simultaneously. However, airport fires are not uncommon. When they happen, even small fires would cause serious disruption to service as many processes are inter-related therein.

In 2018, a small fire in Auckland Airport (Auckland Airport, 2018) occurred inside a ventilation duct at the arrivals baggage collection area. Although the fire was quickly extinguished by the sprinkler system, the terminal had to be evacuated for over 3 hours. Even after the emergency crews declared it was safe to re-enter the terminal, it took airport workers over 3 more hours to clear the backlog of flights and baggage (Moger, 2018).

In 2015, there was a major fire at the retail areas of Terminal 3 of the Fiumicino Airport in Rome. The airport was closed when the fire broke out after midnight. It was believed that the fire originated from an electrical cabinet which was under maintenance. The airport was down for 12 hours which caused delays and diversions to thousands of passengers (Pullella, 2015).

In 1996, a tragic fire happened at Düsseldorf Airport, Germany (Comeau, 1996?), claiming 17 lives and injuring another 62 people. The fire was reported to be caused by welding works in the retail area, in which no suppression system was in place. In the fire, seven victims were killed in elevators; while another eight people perished in VIP lounges. Two other victims were killed at unknown locations. In the post-fire investigation, it was determined that emergency voice announcements were transmitted by the public address system, which could be turned off in the VIP lounges. On the other hand, some people evacuated by elevators which opened directly into the fire area and were caught by flames and smoke.

In Hong Kong, fires near the airport terminal are also not uncommon. Fortunately, they were tackled quickly without causing any fatality. In 2016, some fabric surrounding a VIP lounge under renovation inside the restricted area of the Midfield Concourse caught fire. The fire spread to the entire lounge before it was extinguished by the sprinkler system (Leung, 2016).

Five other fires involving batteries or electronic products were also reported at passenger and cargo terminals, as well as the aprons (Chan, 2021; Guan, 2016; Lee, 2019; Oriental Daily 2016 and 2017). Three vehicle fires near the terminals and aprons were also noted from the media (Apple Daily 2019; Liu, 2017; Mok, 2017). A list of fires at the Hong Kong International Airport reported in the media is listed in Table 3.1.

The objectives of fire safety at the airport (Chow and Ng, 2003) are to ensure life safety of staff, occupants and firefighters. Furthermore, the airport is such a sophisticated building with expensive equipment and aircrafts which cost billions of dollars. To prevent them from being damaged in fire is the next main objective. As illustrated in Chapter 2 of this thesis, it is of paramount importance for the Hong Kong International Airport to operate without disruption. Thus, minimising disturbance to normal operation is another objective of fire safety. Also, the products of combustion would lead to environmental concerns, especially with the large of amounts of plastics inside the airport. Therefore, fires should be tackled as safely and speedily as possible should they happen in the airport. Nevertheless, the airport is not just an ordinary building. Its special features create challenging fire hazards.

The initial design of the city's airport was 35 million passengers annually (Chow, 1997). Over the years, it has grown to its peak at 71.5 million in 2019 (Airport Authority Hong Kong, 2021). A field study (Chow and Ng, 2010) revealed that there was only a floor area of 2.1 $m^2$ for each person in a retail area of the airport, while the prescriptive code suggested an occupant density of 3 $m^2$.

Staff and passengers are not evenly distributed inside the airport terminal (Ng, 2003). The aim of the airport is to allow passengers to embark and disembark aircrafts. As such, there is much space utilised as circulation areas. Most of the passengers can be found at the arrivals hall, departures hall, security and immigration control, as well as retail areas.

With a large number of occupants inside a single building, evacuation from an airport terminal is a complex process, especially due to security concerns. Airports are divided into non-restricted areas and restricted areas, also known as landside and airside. Generally speaking, people are free to enter the landside without hinderance. In order to proceed to the airside, all passengers and staff must undergo security procedures even at domestic airports nowadays. At international airports, the situation is even more complicated because passengers must undergo customs, immigration and quarantine controls.

Occupants of landside and airside are usually separated. There will be security concerns if landside and airside passengers mix. As such, the choice of means of escape and assembly points are limited in the design of airports and it is not always possible to use the shortest route for egress (Bateman and Majumdar, 2020).

In other buildings, occupants are usually advised to leave behind their belongings during evacuation. However, passengers in airports may be required to carry their luggage during evacuation as unattended items are regarded as security risks. Even if they are not so required, many passengers would like to keep their luggage during evacuation as valuables are likely to be packed in their luggage (Bateman and Majumdar, 2020). As there is an upward trend in the size of luggage (Chow, 2015), this would defeat the design of the means of escape.

The fire load density in some areas of the airport, especially the retail area, can be particularly high (Chow, 2015). However, Hong Kong's airport is not fully covered by suppression system due to its architectural design with high headroom and atria. As a result, fire suppression highly depends on the intervention of airport staff or firefighters. Although the airport operates round-the-clock, time slots of passenger flights are not evenly distributed during the day. At times, there are vacant aircraft parking stands and boarding gates, especially after midnight. Therefore, there would be unoccupied locations at which airport staff takes considerable time to arrive due to the enormous size of the terminal building.

Worse still, the delay in fire suppression may result in spread of fire before the arrival of firefighters. Due to the large size of the airport terminals, firefighters may need to traverse long distances from the fireman’s lift to the fire location, as well as to effect search and rescue inside the terminals. This creates additional risks and difficulties in firefighting (Chow, 2015).

In Terminal 1 of the local airport, departures hall and arrivals hall are not fully covered by automatic suppression systems. Retail areas of higher fire load density are compartmented into relatively smaller cabins which are equipped with sprinklers and smoke extraction system (Chow, 1997). The cabins are covered by ceilings, but open sides are found at their perimeters. The assumption of the cabins concept is that the fire would be suppressed by sprinklers and combustion products would be removed by smoke extraction systems. However, this design highly depends on the effectiveness of the sprinkler system and smoke extraction system (Ng and Chow, 2005). Fire safety would be jeopardized in case these systems are defective or shut down for maintenance or repair.

### 3.2 Fire Hazards of Railway Stations

The railway forms the backbone of Hong Kong’s transport system and is heavily patronised by local citizens. Trains run between 96 stations where large numbers of passengers are served every day. Coupled with the importance in the economies, railways worldwide have always been a favourite target for attacks (Luxton & Marinov, 2020). As a result, there are currently debates on whether arson fires should be taken into account fire safety strategies of railways (Cheng, Chow & Chow, 2021). Furthermore, due to the complex geometry, there are high fire hazards in railway stations.

Since the turn of the century, there have been three significant railway arson fires causing massive casualties. In 2013, an arsonist set fire on a passenger train on the Daegu subway (Hong, 2004). The train stopped at the next station. Soon after this, another train arrived at the opposite platform. The fire quickly spread to fully engulf the two trains. The deadly incident killed 192 persons; while another 192 were injured.

In 2004, an arsonist set fire inside a Hong Kong MTR train travelling in an undersea tunnel with newspaper, turpentine and gas canisters (Chow, 2004a) during the peak hours in the morning. Due to the limited combustible materials fixed inside the train compartment, the fire was localised. Passengers were quickly evacuated when the train reached the next station. In the fire, 14 passengers were injured.

There was another arson on the Hong Kong MTR in 2017 (Blundy, 2017). Another arsonist set fire with accelerants on a train travelling in the same undersea tunnel as the 2004 fire, but in the opposite tube. As it was the peak hours in the evening, the train was fully packed with passengers. Three passengers, including the arsonist, were critically injured. Another 16 passengers sustained other degrees of injuries. The arsonist died in hospital months after the fire.

There have also been notable train fires in Japan in the past 10 years. In 2015, a man committed suicide by self-immolation inside a high-speed ‘bullet train’ travelling from Osaka and Tokyo. It was reported that the man poured flammable liquid on himself and ignited it with a cigarette lighter at the front of the train. Besides the suicidal man, a woman also died in the fire and another 26 people were injured (Soble, 2015). In October 2021, a man stabbed passengers in a train in Tokyo, and set fire to the train. The train continued through and made an emergency stop at a train station where passengers fled. In the incident, 17 people were injured (Brown, 2021). In November 2021, another man set fire in a ‘bullet’ train in Kyushu by lighting liquid poured on the floor. The fire was put on quickly and no one was injured (Parry, 2021).

Apart from arsons, fires caused by electric products are also on the rise. The battery of an electric scooter caught fire around midnight at the lost and found of a train station in London. A week later, the battery of another electric scooter exploded on a train carrying passengers also in London (Davis, 2021). After this series of incidents, Transport for London carried out a review and found that defective lithium batteries could cause electric scooters to catch fire. Therefore, it banned all electric scooters from its entire network (O’Reilly, 2021).

In recent years, the railway has become more crowded. During interruption of train service, the number of passengers inside stations surges even more (Ku, Chow & Yue, 2019). Even in stations with only one level of platforms, the travel distance for passengers is long due to the geometry of stations. This also means that firefighters must make a long walk with heavy firefighting equipment in case of fire at locations far away from the station entrance, for instance, at the end of the platforms.

Amongst the 96 railway stations in the city, 44 of them are located underground. Due to the lack of vents on the sides, smoking filling process is faster in basement fires than in fires occurring above ground. On the other hand, firefighters must traverse against smoke and heat once they enter the basement. On contrast, firefighters do not usually encounter heat and smoke in other buildings until they get close to the fire. It is noteworthy that one of these underground stations which serves as the interchange of four railway lines has four levels of platforms upon the recent completion of a new line which crosses the harbour. This would definitely add challenge to fire safety.

Yet, underground railway stations are not ordinary basements. Firstly, there is minimal compartmentation inside railway stations to facilitate rapid passenger movement. Secondly, there is hardly any protected routes for the egress of occupants to leave the station, nor for the access of firefighters towards the fire. Therefore, the required safe egress time (RSET) for staff and passengers to reach a place of safety is increased (Chow, Qu & Pang, 2011). Likewise, there is reduced available safe egress time (ASET)

(Chow & Qu, 2014). It was demonstrated in a simulation that full evacuation from a typical MTR station would take considerable time (Qu & Chow, 2013). The situation would definitely be aggravated by bulky luggage carried by travellers.

The evacuation in above ground railway stations can also be challenging. Chow and Ku (2014) conducted a simulation study on train fire at the platform of a naturally ventilated, at-grade station. In that study, it was revealed that the RSET is greater than the ASET. In other words, there may be inadequate time for safe egress. In addition, although heat and smoke can naturally dissipate on the sides of the station, the temperature near the ceiling may reach as high as 600 ºC.

Chest-height automatic platform gates are installed at most above-ground platforms on the MTR to prevent people or objects falling from the platform onto the tracks. On underground platforms, full-height platform screen doors used for added benefits of energy efficiency of air conditioning and reduction of dust and dirt from tunnels. In Hong Kong, these platform gates and screen doors are wider than train doors. However, Qu and Chow (2012) pointed out that there have been incidents where trains could not align correctly with platform gates and screen doors. If trains cannot align correctly, or if the platform gates and screen doors malfunction and could not open, evacuation would be seriously delayed.

Apart from stations serving local commuters, there is also a dedicated station, namely Hong Kong West Kowloon Station, for the XRL. Trains of both long and short haul operate from this station. This station is connected to two other railway stations by pedestrian subways. Since the opening of the XRL Hong Kong Section, it is observed that there are more passengers use local commuter trains to reach the XRL station. These passengers travel with them more bulky luggage and it would impede evacuation in case of fire.

Although fire hazards associated with railway stations are high, the MTR Corporation has conducted reviews after the arsons in 2004 (Environment, Transport and Works Bureau, 2004) and 2017 (MTR Corporation, 2017). It was concluded that the staff handled the incidents smoothly and the emergency procedures were adequate and appropriate. There were also external comments confirming that there were sufficient procedures in place to safeguard passenger safety (Chow, 2004b).

# CHAPTER 4: CODE REVIEW

Requirements on fire protection systems vary amongst different jurisdictions. Even in located in the same continent, there is big difference in requirements from the Hong Kong, Taiwan and Singapore authorities. The requirements in these Asian locations are also compared with those in England and the United States in this chapter.

## 4.1 Regulatory Regime of Active Fire Protection Systems in Hong Kong

In Hong Kong, the Buildings Department (BD) is the lead government department responsible for building safety. Amongst other aspects like planning, design and construction, fire safety is a prime concern. While passive fire protection systems are mainly under the jurisdiction of the BD, the Fire Services Department (FSD) takes part in the building approval process by regulating the provision, design and installation of active fire protection systems, locally known as fire service installations (FSI). This is achieved by a two-step process during the design stage and the occupation stage of the building.

As stipulated by the Buildings Ordinance (1964a), a certificate issued by FSD is a prerequisite for building plans approval by BD. Plans are examined by FSD and certified as incorporating the minimum FSI necessary having regard to the intended purpose of the building. To serve this purpose, a code of practice has been published by FSD (2012) as the prescriptive requirements.

The Buildings Ordinance (1964b) also states that another certificate from FSD is required to signify that FSI shown on approved building plans have been provided in an efficient working order. Only with this certificate from FSD, BD would issue an occupation permit before the new building can be used.

Once the building is occupied, FSI owners have the responsibility to keep FSI in efficient working order, as well as to arrange a registered contractor to inspect the FSI at least every 12 months according to the Fire Service (Installations and Equipment) Regulations (1972), which is administered by FSD.

Although passive and action fire protection systems are administered by different departments, these requirements are inter-related. For instance, the discharge value of staircases in sprinkler-protected buildings are higher than those in buildings not protected by sprinklers. On the other hand, BD may require enhancing active fire protection systems in order to compensate deficiencies of passive protection. For example, sprinklers are required in a unit with open kitchen, or a building without emergency vehicular access. Further details will be given in the next section.

## 4.2 Fire Services Installations Requirements in Hong Kong

In Hong Kong, FSI requirements are mainly dependent on the type of occupancy. Any building with the topmost floor situating less than and more than 30 m from the street level are defined as low-rise and high-rise building. Once defined as a high-rise building of a particular occupancy, they are not further categorised into ranges of height, so that the requirements on FSI would be the same for buildings with a large range of height.

The airport, just like residential buildings or hotels, is regulated by the Buildings Ordinance (1964a). As such, the code of practice issued by FSD (2012) is applicable. The code of practice stipulates prescriptive requirements on the type and extent of FSI required for various types of occupancies. However, it is stipulated in the code of practice that FSI requirements on the airport is subject to individual consideration by FSD, taking into account of its size and complexity.

Railway projects are exempted from the Buildings Ordinance so that the code of practice (FSD, 2012) is inapplicable. Nevertheless, FSD (2016) issued guidelines on the provision of FSI in railway infrastructures. The guidelines are prescriptive in nature and recommend FSI for various railway premises. Neither the code of practice nor the guidelines have retrospective effect on existing buildings. A summary of FSI requirements on the mentioned occupancies in Hong Kong are given at Table 4.1. Sprinklers are generally required new railway stations in Hong Kong.

There are several applications where sprinklers of specific thermal sensitivity are prescribed by FSD or BD. Firstly, sprinklers provided to compensate deficiencies in emergency vehicular access are required to be of 'fast response type', which is equivalent to quick response sprinklers in the British Standards (British Standards Institution (BSI), 2020). Secondly, shops and concession areas in railway stations also require 'fast response type' sprinklers. Thirdly, basements with total floor areas exceeding 230 $m^2$ shall be covered by 'fast response type' sprinklers. Furthermore, for buildings with mixed residential and other uses, there would be staircases communicating between these portions. 'Fast response type' sprinklers are required for some floors of these staircases, even in the residential portion.

## 4.3 Requirements on Fire Safety Equipment in Taiwan

In Taiwan, the requirements on provision of fire safety equipment depend on both the occupancy and the height where the premises are situated.

The provision of fire safety systems in airports is governed by the National Fire Agency (2018). In railway premises, this is regulated by the Ministry of Transportation and Communication (2008 & 2012). A summary of requirements on fire safety systems in various occupancies are at Table 4.2.

Sprinklers are generally required in Taiwanese airports and railway stations (except trainway and platform areas). With reference to thermal sensitivity, both 'standard' and 'fast response' sprinklers can be used, but the requirement on spacing is different.

## 4.4 Requirements on Fire Protection Systems in Singapore

Fire precautions for buildings in Singapore are regulated by the Singapore Civil Defence Force (SCDF, 2017 & 2018). Requirements on fire protection systems in Singaporean buildings depend largely on the occupancy. Sprinklers are generally required in the airport, but are generally exempted for railway stations. Table 4.3 shows the requirements on fire protection systems in buildings of various occupancy.

‘Fast response’ sprinklers are required to protect building atria with heights from 9 m to 18 m (SCDF, 2019). In other applications, thermal sensitivity of sprinklers is not specified in the standard (SPRING Singapore, 2004).

### 4.5 Requirements on Fire Protection Systems in England

In England, statutory guidance on how building regulations can be met in respect of fire safety are set out in ‘approved documents’, published by the Ministry of Housing, Communities and Local Government (MHCLG) (2020a, 2020b). A summary of requirements on fire safety systems is at Table 4.4. For airports and railway stations, sprinklers are required where the building height exceeds 30 m (MHCLG, 2020b).

With respect to thermal sensitivity, only quick response sprinklers are allowed in inhabited areas in residential buildings (BSI, 2014). In all other occupancies, quick response sprinklers shall be used unless in rooms of 500 $m^2$ or bigger in area, or at areas of 5 m or above in height (BSI, 2020).

### 4.6 Requirements on Fire Protection Systems in the United States

In the United States, requirements on fire protection systems are governed by individual states, while standards and codes published by the National Fire Protection Association (NFPA) are often adopted or referred to.

These requirements depend on both occupancy and building height. Sprinklers are generally required for airports (NFPA, 2016) and railway stations (NFPA, 2020). Regarding thermal sensitivity, sprinklers installed within dwelling units of residential buildings, guest rooms of hotels, as well as peaked roofs and ceilings of all buildings shall be of the ‘quick-response’ type (NFPA, 2019).

### 4.7 Discussion

Requirements on fire protection systems differ amongst jurisdictions. This is due to the difference in perceived level of danger of the same occupancy in the five sampled regions, namely Hong Kong, Taiwan, Singapore, England and the United States. For instance, sprinklers are required for railway stations in all but one jurisdiction, namely Singapore.

Regarding thermal sensitivity, quick-response sprinklers are specified in Hong Kong basements, shops inside the railway system, as well as buildings not provided with emergency vehicular access. Quick-response sprinklers are required for atrium of Singaporean buildings, as well as American attics, hotel guest rooms and apartment units. In England, quick-response sprinklers are generally prescribed for life-protection applications. These areas are considered to be more vulnerable in case of fire.

In the coming chapters, the significance of thermal sensitivity of sprinklers will be discussed.

# CHAPTER 5: NUMERICAL SIMULATIONS ON SUPPRESSION CAPABILITY OF SPRINKLERS

## 5.1 Introduction

Sprinklers are generally known to be effective in suppressing fires. In Hong Kong, sprinklers are generally required in premises that are not intended to be used for dwelling. These premises include hotels, offices, shopping arcades, factories and so on (FSD, 2012). There are some old buildings and premises where sprinklers were not required during the time of construction. Even for these, the Fire Safety (Commercial Premises) Ordinance (1997), the Fire Safety (Buildings) Ordinance (2007) and the Fire Safety (Industrial Buildings) Ordinance (2020) require sprinklers to be retrofitted if the floor area reaches a certain extent.

As for the case of the airport, the Fire Services Department does not explicitly require sprinklers. There are no sprinklers in the majority of arrivals and departures hall in Terminal 1 of the airport. The fire engineering strategy is to limit the amount of combustibles and let the vast volume of the arrivals and departures hall as a giant smoke reservoir. The combustibles are arranged in small groups known as ‘islands’. A distance is maintained between these islands so that the fire size is assumed to be small whenever there is a fire. For areas where there is higher fire load, for example, shops and restaurants, these areas are semi-enclosed and fitted with sprinklers.

For railways, sprinklers were not required in the past. Sprinklers are absent from the majority of those areas built before the 1990s. These include the East Rail Line, the Kwun Tong Line, the Tsuen Wan Line and the Island Line. In the past, there were minimal commercial activities in the stations of these lines. Most of the station areas were used for the circulation of passengers, and there used to be minimal combustibles. More shops and services were added to these stations at a later stage. Sprinklers are installed only at these shops during such conversion, but not to the entire station.

Despite the airport and the railway stations are heavily patronised, the above-mentioned legislation requiring retrofitting of sprinklers are not yet applied to these locations. However, there have been fires at the airport and railway stations in the past in both Hong Kong and overseas. Given the recent upward trend of arsons, the once reliable assumption of a single, small origin of fire should be reviewed. In fact, the characteristics of the airport and railway stations as transportation hubs with a lot of people make them more prone to arsons or other sorts of attacks than other type of premises.

Hong Kong Fire Services Department adopts 1135 $MJ/m^2$ as the threshold of fire load density. If the design fire load is above that value, additional fire service installations would be required (FSD, 2012).

Woo et al. (2017) conducted full-scale burning tests of common furniture and household materials at a fire chamber with a floor area of 3.5 m by 3.5 m and a height of 2.4 m to demonstrate the effectiveness of sprinklers in fire suppression. The fire load of combustibles in the burning test follows the threshold of 1135 $MJ/m^2$. As such, the total fire load was about 14 GJ. They consisted of a bed, a sofa, a wooden television stand, 4 wooden cabinets and 16 boxes of paper.

The full-scale burning test of Woo et al. were conducted twice to contrast the extent of fire with and without sprinkler protection. In the test without sprinklers, the temperature within the fire chamber quickly rose to 600 °C. In contrast, the temperature in the fire chamber never reached above 200 °C with the protection of just one sprinkler. These tests demonstrated that sprinklers are very effective in suppressing fires.

Woo (2020) also conducted full-scale burning tests in the same fire chamber using wood cribs. Again, the fire load density of 1135 MJ/m$^2$ was adopted in the tests. Samples of the wood sticks constructing the wood cribs were sent for analysis of calorific values before the burning tests. 25 cribs were used to make up the fire load. Each crib consisted of 16 layers each of 6 wood sticks. Each wood stick is 0.6 m in length. In contrast to the success in suppressing fires of household items, sprinkler was not very effective in suppressing the wood crib fires. Temperature in the fire chamber increased despite the activation of the sprinkler.

Real burning tests involve vast amount of resources, especially the cost of purchasing combustibles being tested. The objective of using numerical simulations to repeat the full-scale burning tests by Woo et al. (2017) and Woo (2020) is to verify the effectiveness of sprinklers in suppressing fires.

Despite the majority of buildings used for transportation is made up of large compartments, small compartments such as storerooms and airport lounges can also be found in these buildings. Furniture was used to make up a fire load density of 1135 MJ/m$^2$, which is the maximum limit where FSD regards as occupancies with low fire load. The combination of articles varies from different premises. As such, a representative scenario in terms of wood equivalent is also studied. The objective is to examine the capability of sprinklers in suppressing fire at the incipient stage at these areas. As such, temperature is used as the measurement parameter of this study.

## 5.2 Simulation Setup

Fire Dynamics Simulator (FDS) is a large-eddy simulation based software which solves combustion equations on a rectilinear grid over time (McGrattan et al., 2020). Version 6.7.4 of the software was used in the study. FDS assumes that solid surfaces consist of multiple layers, while each layer is made up of multiple material components that undergo multiple thermal degradation reactions. In the simulation, the thermal radiation from the surrounding gases is assumed to be absorbed within an infinitely thin layer at the boundary of the solid.

Upon the actuation of sprinklers, the mass and energy exchange between the water droplets and the surrounding gases and solids surfaces is calculated droplet by droplet. When the water droplet hits a horizontal surface, the water cools the surface whether it is burning or not. In the FDS model, the cooling of unburned surfaces and the reduction of pyrolysis are calculated locally in the cell whether the water droplets come to contact with the solid surface. After calculating the temperature of the water droplet, the vaporised liquid is added to the mesh cell, and that the gas temperature of the mesh cell is slightly reduced based on the energy lost to the water droplet.

Cloud computing had been hired from a commercial service provider for faster simulation.

### 5.2.1 Simulation of burning furniture and boxes of paper

The fire chamber of 3.5 m in length, 3.5 m in width and 2.4 m in height was created in the model. An opening of 1.5 m in width and 2 m in height simulating the door was also used for ventilation. The computational domain is extended beyond the opening by 1 m.

As suggested by He et. al. (2008), the computational domain is recommended to be extended by half of the hydraulic diameter of the opening in order to maintain the validity and to increase the accuracy of simulation results:

$$D_H = 4A/P \qquad (6.1)$$

where

$D_H$ is the dydraulic diameter of opening, m

A is the area of vent opening, $m^2$

P is the perimeter of vent opening, m

To compare the effectiveness of sprinklers, a sprinkler was placed at the middle of the fire chamber at 0.2 m below the ceiling in one of the simulations. Thermocouples were placed at strategic locations to monitor the change of temperature during the tests.

The frame of the bed, the television stand and the 4 cabinets were assumed to be made entirely of wood. For the bed and the sofa, the upholstery was assumed to be made of foam and the frame was assumed to be wooden. There are also boxes of paper in the model. A hot surface of 0.6 m by 0.6 m with a heat release rate per unit area of 14.8 $kW/m^2$ is placed under the sofa. As such, the heat release rate of the ignition is 5.3 kW.

The size of each cell in the simulation is 0.05 m by 0.05 m by 0.05 m. As such, there were about 414500 cells in each simulation. A grid sensitivity analysis using a cell size of 0.025 m by 0.025 m by 0.025 m was also conducted. There was no significant difference in the results obtained. The setup of the simulation is shown in Figure 5.1. The result of the grid sensitivity study is shown in Figure 5.2.

### 5.2.2 Simulation of burning wood cribs

The same fire chamber used in the furniture and paper scenario was used in the simulations on burning wood cribs. The same cell size of 0.05 m by 0.05 m by 0.05 m was used. A grid sensitivity analysis using a cell size of 0.025 m by 0.025 m by 0.025 m was again conducted.

Each of the 25 wood cribs has a length of 0.6 m, a width of 0.6 m and height of 0.64 m. There were 16 layers of wood sticks. Each layer consists of 6 wood sticks. As such, there are altogether 2400 wood sticks in the simulation. The setup is shown in Figure 5.3. The result of the grid sensitivity study is shown in Figure 5.4

## 5.3 Simulation Results

### 5.3.1 Results of the furniture and paper burning simulations

Having considered the similarity of the average body build of people in Hong Kong and Singapore, a thermocouple near the opening of the fire chamber at a level of 1.8 m from floor level was chosen for comparison of the comparison of the tenability conditions (SCDF, 2015). This location simulated the exit of the room involved in fire. As shown in Figure 5.5, the temperature remained stable during the first 140 seconds of the simulation. This is due to the low heat release rate of the heat source and it took considerable time to pyrolyze the combustibles before starting a self-sustained combustion. The temperature then increased rapidly above 200 $^{o}$C without sprinkler protection. In contrast, in the scenario which is protected by a sprinkler, the temperature dropped rapidly to around 100 $^{o}$C. It is also shown in Figure 5.6 that the heat release rate is much reduced with the protection of sprinklers.

### 5.3.2 Results of the wood cribs burning simulations

A thermocouple near the opening of the fire chamber at a level of 1.8 m from floor level was chosen for comparison of the comparison of the tenability conditions. This location simulated the exit of the room involved in fire. As shown in Figure 5.7, the temperature increased rapidly about 200 °C without sprinkler protection. In contrast, in the scenario which is protected by a sprinkler, the temperature dropped rapidly to around 100 °C upon its actuation.

## 5.4 Discussion

Two scenarios were used to demonstrate that sprinklers can quickly cool a fire compartment. In the first scenario simulating the burning of common household furniture and paper, the temperature was dropped significantly after the actuation of the sprinkler. The cooling was achieved swiftly and effectively lowered the temperature. The result echoed the findings by Woo et al. (2017). Sprinklers would create a longer available safe egress time for occupants.

The simulations on wood cribs did not agree with the findings by Woo (2020). The temperature in Woo's study kept increasing regardless of whether there is sprinkler. As the fire source is under the wood cribs, Woo suggested that the increasing temperature in the fire chamber may be due to water being unable to penetrate deep down the wooden cribs. Nevertheless, the fire damage was obviously more severe without sprinkler protection. In the current simulation, the temperature dropped instantly from about 175 °C to about 100 °C after the actuation of sprinkler.

The simulations in this study demonstrated that sprinklers are very effective in reducing the temperature of the fire compartment. Although areas in the airport and railway stations that are not protected by sprinklers are assumed to contain only limited combustibles, it would require a lot of management measures to enforce this requirement. Furthermore, there are times when goods are being transported to the shops or left on a temporary basis for whatever reason. Areas in the airport and railways stations without sprinkler protection are often very large fire compartments with a lot of passengers. If bulks of goods catch fire at those locations, the potential damage would be very serious. Furthermore, there has been an upward trend in arsons. If arsonists bring their own fuel into these crowded locations, the assumption on low fire load density could not be relied upon. As such, it is recommended that the fire safety strategy of these places be reviewed when renovations are being undertaken, so as to safeguard the passengers and the smooth operation of these important transportation infrastructures. With the vast floor area, it may be technically feasible to house the components if sprinkler systems are retrofitted. Further simulations on tall hall fires are recommended to further explore the effectiveness of sprinklers under this application.

# CHAPTER 6: EXPERIMENTAL STUDY ON THERMAL SENSITIVITY OF SPRINKLERS USING A WIND TUNNEL

## 6.1 Introduction

In typical fire scenarios, heat release rate increases over time. In incipient stage of fires, sprinklers can effectively control the heat release rate. Consequently, the peak heat release rate, maximum heat flux and maximum temperature would be reduced. These are significant factors to increase the available safe egress time for occupants inside a building. Architectural features and fire hazards of selected occupancies have been discussed in previous chapters.

If properly installed, sprinkler systems can suppress or even extinguish fires quickly by spraying water. Fire suppression is achieved by several steps. Most notably, when water droplets are vaporised, heat is extracted from the gaseous combustion products. Furthermore, oxygen around the fire could be displaced when water droplets expand and vaporise. Its ability in suppressing fire is also enabled by spraying water to absorb thermal radiation thus reducing heat feedback from the fire plume. Surfaces of combustibles are also cooled by water droplets, thus preventing ignition (Marshall and

Di Marzo, 2004).

Sprinklers are normally operated by heat by means of heat sensing elements, which is made of fusible link or frangible glass bulb. For heat sensing elements in the form of frangible glass bulbs, they are filled with an expandable liquid. When the fire develops, the room temperature increases. The liquid expands and builds up the pressure inside the glass bulb. Eventually, the glass is shattered, the valve cap is released, and the water is discharged.

In contrast, fusible links of the other type of heat sensing elements consist of piece of metal which are held together by solder. At the specific temperature, the solder melts so that the bonding of the metal piece is lost. Thus, the valve cap is released, and water is discharged.

Sprinklers are very effective in fire suppression. If sprinklers are operated in the incipient stage of fire, they will effectively limit fire growth or even extinguish the fire. It is of paramount importance to life and property safety. Therefore, it is in great interest to get sprinklers into operation as soon as possible, in other words, to shorten the response time.

There are two major factors contributing to the response time of sprinklers. Firstly, it is the temperature at which the heat sensing element of the sprinkler will be activated, known as the temperature rating. The temperature rating of a sprinkler is determined by immersing it in a liquid bath to check the maximum temperature at which the heat sensing element can withstand. The lower the temperature rating, the less time it would take the heat sensing element to reach the operating temperature. However, if the temperature rating is too close to the ambient temperature, the fluctuation in ambient temperature could cause accidental actuation. This will result in unnecessary water damage. Therefore, it is suggested that the temperature rating of sprinklers should be at least 25 $^{o}$C above the ambient temperature (BSI, 2020).

Another factor, thermal sensitivity measures how quick the heat sensing element of sprinklers reacts to heat. This parameter can be measured by the plunge test (Heskestad and Smith, 1980). In a plunge test, the sprinkler is immersed in a uniform flow of hot gas with constant velocity and temperature. The time taken to activate the sprinkler is then used to calculate the response time index of the sprinkler.

In the past decade, more and more building designers preferred concealed sprinklers over conventional sprinklers for aesthetic reasons (Tsang, 2004). Although these concealed sprinklers may be more pleasing in the physical appearance, the issue of thermal sensitivity could not be overlooked.

In a fire, hot gases in the fire plume rise above the fuel that is burning and finally impinge the ceiling. Upon reaching the ceiling, the hot gases are deflected and move horizontally under the ceiling. This relatively fast-moving air flow near the ceiling is the know the ceiling jet (Fong and Fong, 2003).

Heat sensing elements of conventional sprinklers are exposed. If correctly installed near the ceiling, the heat sensing element is immersed directly in the ceiling jet. As such, the actuation of sprinklers is prompt.

On the other hand, activation of concealed sprinklers requires two actions. The heat sensing element of concealed sprinklers is hidden inside the casing. The casing is in turn hidden inside the false ceiling. There is a cover plate at the bottom of a concealed sprinkler. The cover plate is flushed against the false ceiling and linked to the casing by solder. In case of fire, the hot air near the false ceiling melts the solder linking the casing and the cover plate. When the solder melts, the cover plate is detached form the casing. It is only at this juncture that the defector, but not the heat sensing element, may be lowered below the ceiling. The heat sensing element is not exposed in the ceiling jet. Therefore, it was hypothesized that it would take a much longer time to activate concealed sprinklers.

Some manufacturers market their concealed sprinklers as having quick response. This may be misleading because only their heat sensing element is tested to have a quick response, but not the whole sprinkler assembly. Modelling on the plunge test, the concealed and conventional sprinklers are suddenly immersed in the uniform gas flow of constant temperature and air velocity. Due to its construction, the heat sensing element is recessed in the ceiling and cannot be immersed in such a gas flow. The main purpose of the experiments carried out under this chapter is to contrast the actuation time of concealed sprinklers from conventional sprinklers.

## 6.2 Experimental Setup

A hot wind tunnel, named as BSE hot wind tunnel, was used to investigate the thermal sensitivity of 6 models of sprinklers using plunge test. The BSE hot wind tunnel is 0.7 m in width and 3 m in length. Air speed inside the hot wind tunnel is controlled by adjusting the frequency of a fan. On the other hand, the temperature inside the hot wind tunnel is regulated by a heater. The heater is controlled by a feedback mechanism and is turned on whenever the temperature inside the hot wind tunnel is lower than the predetermined value.

The fan blows air at the inlet of the hot wind tunnel. Then, it passes through the heater so that the air reaches the desired temperature. The heated air then passed through a contraction for reduction of turbulence. Further downstream, it is the working section where sprinklers are suddenly immersed into the air stream to conduct the plunge test. The working section is accessed through an entrance on the ceiling of the hot wind tunnel. There is a hinge cover at the entrance of the working section where a sprinkler can be mounted for the plunge test. A lid is provided to close the entrance of the working section when tests are not being carried out. A glass viewing window is provided at the other end of the hot wind tunnel so that the activation of sprinklers can be observed. The schematic layout of the hot wind tunnel is shown in Figure 6.1.

The hot wind tunnel was calibrated before the plunge tests were carried out. Before determining the measurement point for temperature and wind speed, the location of heat sensing element has been taken into consideration.

Due to variation in construction, the position of heat sensing element is different for various kinds of sprinklers. For pendent sprinklers and upright sprinklers selected for this study, the centres of heat sensing elements are located 57 mm below the ceiling therefore temperature and wind speed readings were taken at that level. For concealed sprinklers, the heat sensing element is concealed inside the ceiling. In other words, the heat sensing element is outside the wind tunnel during the plunge tests. Therefore, measurements had to be taken as close to the ceiling as possible. Eventually, readings at a level of 10 mm below the ceiling of the hot wind tunnel were used during the calibration for tests involving concealed sprinklers.

The temperature was measured by a thermometer inserted into the working section through a hole in its lid. The wind speed was also determined by inserting an anemometer. Seven sets of testing parameters comprising different temperatures and air speeds were employed in the plunge tests. Before actually carrying out the plunge tests, trial run of 900 seconds was conducted for each set of pre-determined temperature and wind speed. Constant wind speed and temperature could be maintained throughout the trial run.

Sprinklers were conditioned to the same temperature before the plunge tests by placing them in the room containing the hot air tunnel overnight. The ambient temperature of the laboratory was maintained at 22 °C throughout the period of this experiment. All plunge tests were recorded by video. The actuating time of cover plate, or heat sensing element, or both, were noted. All models were tested with 5 repetitions, except only 2 repetitions if the heat sensing element could not operate.

Although the plunge test is not normally used to test concealed sprinklers (Heskestad and Smith, 1980), it is of research value to compare the actuation time of them with that of conventional sprinklers. Therefore, the following formula was used to calculate the nominal time constant, regardless of the type of sprinkler:

$$\tau = -\frac{t_a}{\ln(1 - \frac{\Delta T_A}{\Delta T_g})} \qquad (6.1)$$

where

$\tau$ is the nominal time constant

$t_a$ is the actuation time of the heat sensing element, s

$\Delta T_A$ is the temperature rating of heat sensing element above the initial temperature, K

$\Delta T_g$ is gas temperature above the initial temperature, K

Then, the following formula was used to calculate the nominal response time index of the sprinkler heads:

$$\mathrm{RTI} = \tau\sqrt{\nu_g} \qquad (6.2)$$

where

RTI is the nominal response time index, $(\mathrm{m{\cdot}s})^{1/2}$

$\tau$ is the nominal time constant

$v_g$ is the air velocity in the hot wind tunnel, $\mathrm{ms}^{-1}$

## 6.3 Experimental Results

The following types of sprinklers were tested –

(i) Concealed sprinklers with glass bulb heat sensing element as shown in Figure 6.2 (model 'CB1'; 68 °C rating);

(ii) Concealed sprinklers with quick response glass bulb heat sensing element as shown in Figure 6.3 (model 'CB2'; 68 °C rating);

(iii) Concealed sprinklers with fusible link heat sensing element as shown in Figure 6.4 (model 'CF1'; 68 °C rating);

(iv) Pendant sprinklers with glass bulb heat sensing element as shown in Figure 6.5 (model ‘PB1’; 74 °C rating);

(v) Pendant sprinklers of quick response with glass bulb heat sensing element as shown in Figure 6.6 (model ‘PQ1’; 68 °C rating); and

(vi) Upright sprinklers with glass bulb heat sensing element as shown in Figure 6.7 (model ‘UB1’; 68 °C rating).

For cases where the heat sensing element of the sprinkler could be actuated, 5 repetitions were carried out. However, for concealed sprinklers, only detachment of cover plate could be observed in scenarios involving concealed sprinklers with a lower air speed of 1.75 $ms^{-1}$. Only 2 repetitions were conducted for these scenarios.

The range of actuation time is very large. For instance, under a wind speed of 2.5 $ms^{-1}$ and a temperature of 130 °C, model PBQ would take only 9.2 s to operate, while it took 190.4 s and 396.4 s to actuate model CB1 and CF1 respectively.

Amongst the 5 repetitions in each scenario, the results on actuation time for a given set of test parameters are consistent for pendant and upright sprinklers. However, there is larger variation in the actuating time of concealed sprinklers. It is also observed that the actuating time for pendant and upright sprinklers are very similar.

For those scenarios involving concealed sprinklers where only the cover plate is detached but the heat sensing element remains intact, the temperature near the heat sensing element was measured to be 37.1 °C to 53.0 °C.

Experimental results are summarised in Table 6.1

## 6.4 Discussion

From the experimental results, it is observed that sprinklers with quick response have the shortest actuation time. It is very impressive that model PBQ operated in less than 30 s in all scenarios. In a scenario with wind speed of 2.5 $ms^{-1}$ and temperature of 130 °C, model PBQ operated in just 9.2 s. The ability for quick response sprinklers to actuate quickly is of great significance in limiting the size of fire during the incipient stage. In contrast, conventional pendant and upright sprinklers would operate in the range of 27.4 to 28.6 s. Worst still, concealed sprinklers operated in the range of 164.8 s to 396.4 s.

Despite the fact that sprinklers are a very reliable automatic suppression system, they would be the most effective if they could actuate quickly during the incipient stage of fire. With the high fire load density at all types of occupancies in Hong Kong, the intensity of fire grows very rapidly. The much longer time needed by concealed sprinklers to actuate may affect the available safe egress time for occupants. Furthermore, if the fire had spread beyond the assumed maximum area of operation of the sprinkler system, there may be insufficient capacity in tanks, pumps and other components.

In Hong Kong, the Fire Services Department does not require any specific thermal sensitivity for sprinkler systems, except under some special application, for example, basements. However, in some countries, for example, the United Kingdom, quick response sprinklers must be used if the sprinkler system is intended for life safety.

The price of sprinklers makes up only a small portion of the cost of constructing a building. It is recommended that only quick response sprinklers be used in new developments in Hong Kong. If there is absolute need for using concealed sprinklers for aesthetic reasons, it is suggested that they be used only at locations where the fire risk is low and that occupants are ready to tackle the fire by hose reel or fire extinguishers during the incipient stage, or to evacuate, for instance, offices.

# CHAPTER 7: EXPERIMENTAL STUDY ON EFFECT ON THERMAL SENSITIVITY OF SPRINKLERS BY HEAT COLLECTION PLATE

## 7.1 Introduction

Tall halls are a common feature in public transport facilities, including airports and railway stations. As discussed earlier, the reason for tall halls is to make navigation inside the facilities easier for passengers.

Sprinklers are supposed to be immersed inside hot smoke layers and be heated up to the activation temperature. If sprinklers are located high up the ceiling, it may take a very long time to accumulate heat for the sprinklers to reach the temperature rating of the sprinklers. Therefore, sprinklers are sometimes installed at an extended distance from the ceiling.

On the other hand, it would also take an extended period for the smoke layer to descend to lower levels under the ceiling in tall halls to give a smoke reservoir to immerse the sprinkler heads. As such, heat collection plates are fitted above sprinklers in some tall halls in the Asia-Oceania region, for example in high-speed railway stations in Taiwan.

Heat collection plates are said to be able to collect heat and accelerate sprinkler activation. However, very few literatures cover their effectiveness.

In Hong Kong, Taiwan, Korea and Japan, heat collection plates are fitted above sprinklers in tall halls with perforated ceilings. In Taiwan, it is a code requirement for a heat collection plate if the sprinkler is more than 0.3 m below the ceiling (National Fire Agency, 2018). An European standard also stipulates that water shield shall be provided to sprinklers installed at a lower level, if they may be wetted by those at a higher level (British Standards Institution, 2020).

However, the views are divided amongst different jurisdictions. In North America, the National Fire Protection Association (2019) does not recommend the use of heat collection plates. It was suggested that objects above a sprinkler may cause delayed activation in case the fire in not directly below it.

Burning tests were conducted to test the effectiveness of heat collection plates.

### 7.2 Experiment Setup

An 800 mL propanol fire in a fire chamber with a height of 3.4 m was used to in this study. The sprinklers were fixed 1.8 m above the floor level and 1.6 m below the ceiling. Four sets of experiments were carried out –

(i) Without heat collection plate;

(ii) Heat collection plate type A of 90 mm diameter (Figure 7.1);

(iii) Heat collection plate type B of 110 mm diameter (Figure 7.2);

(iv) Heat collection plate type C of 165 mm diameter (Figure 7.3).

The fire was placed directly under the sprinklers. The experimental setup is shown in Figure 7.4. The tests were named E1 to E12. The sprinkler actuation time was recorded in each of the experiments.

### 7.3 Experiment Results

Activation time of sprinkler heads with heat collection plate type A is 3% to 25% shorter than bare sprinkler heads. Heat collection plate type B, which is larger in size than type

A even has a much shorter activation time, at 44% to 59% shorter than bare sprinkler heads. Heat collection plate type C, being the largest in size amongst the three, has the shortest activation time, ranging from 51% to 61% shorter than bare sprinkler head. The activation time of sprinklers in the tests are shown in Table 7.1.

## 7.4 Discussion

It is shown from this study heat collection plates collect convective heat to accelerate the actuation of heat sensing elements of sprinklers. In this study, the larger the heat collection plate, the more heat it could collect and thus the faster the sprinkler is actuated. For type C heat collection plate which has the largest diameter of the three types being tested, the actuation time of sprinkler was even halves from that of bare sprinklers not fitted with any heat collection plate in this given fire scenario.

However, there are two limitations in this study. Firstly, due to the size constraint of the fire chamber, both the sprinklers and the pool fires had to be located at the centre of the fire chamber. This is to avoid placing either the sprinklers or the pool fires at the edge of the fire chamber, consequently creating air movement significantly different from that in real fires in big halls. As such, it limited the scope of the study only to fires directly under the sprinklers.

Secondly, the tests were conducted in enclosed fire chambers which are the opposite of open, tall halls. The ventilation is very much different between an enclosed fire chambers and a tall hall. Smoke filling is an enclosed fire chamber would be very fast as compared to that in a tall hall. In a tall hall, the heat is easily dissipated away from the fire.

Therefore, although many resources would be required to produce such a thick smoke layer to immerse sprinklers which are suspended at an extended distance from the ceiling, it is still suggested to conduct full-scale burning tests to study the effectiveness of heat collection plates when resources permit.

# CHAPTER 8: NUMERICAL SIMULATIONS ON EFFECTIVENESS OF HEAT COLLECTION PLATES

## 8.1 Introduction

The background information of heat collection plates has been presented in the previous chapter. As the current resources prohibit full-scale burning tests to examine the effectiveness of heat collection plates, numerical simulations have been employed.

## 8.2 Simulation Setup

Like Chapter 5, Fire Dynamics Simulator (FDS) (McGrattan et al., 2020) version 6.7.4 was used in the study. Cloud computing had also been hired from a commercial service provider for faster simulation. Four sprinklers with spacing complying the requirements from the standard adopted in Hong Kong (British Standards Institute, 2020) were placed in the model.

A simulation grid of 5.2 m in length, 6.2 m in width and 9.4 m in height was created in the model. To simulate a very large hall, all four sides of the simulation grid were open for maximum ventilation. The setup of the simulation is shown in Figure 8.1.

A simulated fire of 2 MW magnitude were placed at different locations in the model, namely L1 to L4. The relative locations are illustrated by Figures 8.2 to 8.5. The sprinkler with heat collection plate of 0.16 m by 0.16 m was suspended at 0.1 m, 0.5 m and 0.9 m below the ceiling. The simulations were then repeated with the heat collection plates removed. The simulation would end if any of the sprinklers actuated.

The size of each cell in the simulation is 0.2 m by 0.2 m by 0.2 m. As such, there were about 38000 cells in each simulation. A grid sensitivity analysis using a cell size of 0.1 m by 0.1 m by 0.1 m was also conducted. There was no significant difference in the results obtained. The results of the grid sensitivity analysis are shown in Figure 8.6.

## 8.3 Simulation Results

When the sprinkler was 0.1 m below the ceiling, the sprinkler was actuated by the fire at all four locations. When the sprinkler was 0.5 m or 0.9 m below the ceiling, the sprinkler could only be actuated by a fire at location L1, which is directly below the sprinkler. In those scenarios where the sprinkler could be actuated, the actuation time with and without heat collection plate is similar. In other words, heat collection plates did not accelerate the actuation of sprinklers. As the sprinkler actuation time is similar, the heat release rates in the simulations are similar with and without heat collection plate. Figure 8.7 depicts the comparison on heat release rate for fire location ‘L1’ with sprinklers installed 0.1 m below the ceiling.

Results of the simulations are listed in Table 8.1.

### 8.4 Discussion

Sprinklers did not actuate in some of the fire scenarios. In these simulations, the grid was open to all sides so that heat and smoke could be easily dissipated. Therefore, a thick smoke layer could not be formed. As such, sprinklers only actuated when they are placed near the ceiling or directly over the fire.

Heat collection plates did not accelerate sprinkler actuation in these simulations. The simulated heat collection plates were assumed to be flat piece of metal. Therefore, they could not converge the heat collected to the heat sensing element. Similar to the situation of ceiling jet, the heat collection plate may divert the heat to any direction. This may explain the reason why they could not deflect the heat to the heat sensing element. However, even the heat collection plates were curved inwards, it would still need the correct radius to best converge the heat collected to the heat sensing element.

Furthermore, heat collection plates would work best near the centre of the fire plume to capture the most heat. Depending on the size of the heat collection plate, it may only capture a portion of the convection heat from the fire. Since a reasonable size must be maintained for heat collection plates, the amount of heat that can be collected is highly dependent on the location of the fire.

As opposed to the findings in the previous chapter, heat collection plates did not accelerate actuation of sprinklers in these given fire scenarios. Further study by way of full-scale burning tests is recommended to study its effect, especially in tall halls where sprinkler actuations is prone to long delays.

# CHAPTER 9: MEASURES TO MITIGATE FIRE HAZARDS

## 9.1 Introduction

In this study, a number of fire hazards in the airport and railway stations have been identified. Many of them are similar in nature. Both the airport and railway stations are crowded with passengers. Evacuating large numbers of occupants from these huge buildings brings great challenges for the staff and the fire brigade.

Furthermore, a large part of the airport and railway stations are not protected by sprinklers. It is demonstrated in the study that sprinklers can effectively cool the fire compartment and hence lengthen the available safe egress time. The basis of the non-requirement of sprinklers is the assumption on limited amount of combustibles. Yet, it is highly dependent on the housekeeping. Also, large floor areas in the airport and railway stations are leased to vendors. The adherence to the original fire engineering design can only be achieved through monitoring of the management of these transportation facilities.

What's more, the fire scenarios change over time. In the past, the airport and railways stations used to be less crowded. The ignition sources have also been changing. With the increased use of electronic products, fires originating from lithium-ion batteries have increased. Furthermore, being eye-catching landmarks with lots of people, transportation facilities worldwide have become targets of arsonists. As such, the assumption on having low fire load may no longer be valid.

For underground railway stations, fully enclosed underground environment poses tough challenges on evacuation and smoke management. The airport operates round the clock, so that works involving dangerous goods have to be carried out in the presence of passengers who are often unfamiliar with its layout.

While it is impossible to eliminate all the fire hazards, it is possible to reduce the risk level by mitigation measures.

## 9.2 The Mitigation Measures

It is not practical to substantially change the layout nor to reduce the number of passengers in these existing transportation facilities. As discussed above, the basis of non-provision of an automatic suppression system may have become invalid nowadays.

It is recommended that the management of transportation facilities to engage a holistic review on the fire safety strategy when major renovation is carried out. The study has demonstrated that sprinklers are very effective in cooling the fire compartment and hence suppressing the fire at the incipient stage. To protect the passengers and to avoid lengthy disruption of service, it would be of great interest for the airport and railway management to retrofit sprinklers. With such a vast amount of land area to accommodate components of the system, such retrofitting should be technically feasible. In fact, sprinklers have been retrofitted even in small old commercial buildings.

It is also demonstrated that quick response sprinklers have a much smaller response time index and hence a shorter actuation time. Therefore, if there are any normal response sprinklers, it is recommended to replace them with quick response sprinklers during maintenance of the system as long as the hydraulic calculations of the system remain valid after such replacement. The public should be advocated that the difference in the cost of quick response and normal response sprinklers is minimal as compared to the project sum of the whole development, but this would provide maximum protection to their passengers and staff. On the other hand, concealed sprinklers require the detachment of the cover plate before the heat sensing element would be exposed. As such, the use of such is not recommended in premises with such high fire risk.

Furthermore, it is noticed that heat collection plates can effectively reduce the sprinkler actuation time within small fire compartments when they are directly above the fire. The use of such may further mitigate the situation in locations with higher fire risk, such as kitchens. However, its application in fire scenarios in which the sprinkler is not directly above the fire needs further study.

Finally, before the upgrading of fire service installations, it is recommended that staff of the airport and railway stations step up monitoring to ensure that the amount of combustibles present in the premises in kept to a minimum. It is recommended that control be stepped up in controlling the fire load permitted, for example, the amount of goods during delivery, storage in shops, and the separation of 'islands' in the airport. Also, there is a worldwide uptrend in arsons and terrorism. As the current fire safety strategy of most buildings is to protect life in case of accidental fires, it is recommended that security be stepped up to deter arsonists. Furthermore, it is suggested that training on fire safety management be provided to staff and tenants of these buildings. Reference could be made to the mandatory security training before obtaining airport restricted area permits.

# CHAPTER 10: CONCLUSIONS AND RECOMMENDATIONS

## 10.1 Conclusions

The requirements on fire protection equipment are different around the globe. In Hong Kong, however, they were not provided in a major part of the airport and railway stations in Hong Kong.

Fire hazards in airports and railway stations have been identified in this study. They are usually crowded and are prone to fire due to accidents or arsons. Coupled with the lack of sprinklers in major parts of them, this can lead to grave fire hazards to passengers and severe consequences in case of fire.

In this study, numerical simulations demonstrated that sprinklers can effectively decrease the temperature in fire compartments and hence maintain tenable conditions of evacuation.

There are two factors determining the actuation time of sprinklers, namely temperature rating and thermal sensitivity. While a lower temperature rating leads to speedier actuation, it must be chosen to be above the ambient temperature to avoid unwanted actuation due to fluctuations in the ambient temperature. Therefore, sprinklers with high thermal sensitivity are preferred for better protection of the occupants.

Thermal sensitivity is measured in terms of response time index. The lower the response time index, the more sensitive the sprinkler is. Experimental study in this study demonstrated that concealed sprinklers have a much longer response time than normal response sprinklers.

Also, normal response sprinklers in turn have a longer response time than quick response sprinklers. This indicates that quick response sprinklers are preferred in areas with high fire risk, such as the airport and railway stations.

The working principle of heat collection plates is that they absorb the heat from hot gas in the air around the sprinkler, then transmit it to its heat sensing element. However, the effectiveness of these heat collection plates is still under debate. While some jurisdictions require its use if sprinklers are a certain distance below the ceiling, some other jurisdictions recommend to not use it.

In the study, experimental results show that heat collection plates are effective in an enclosed fire chamber with a low headroom. On the contrary, no significant difference was noted when heat collection plates are used in simulations involving a grid which has a high headroom and is open on all sides for ventilation.

## 10.2 Recommendations

It is obvious that sprinklers can protect live and property in case of fire. The fire hazards associated with the airport and railway stations are high. In case of fire, the potential consequences would be severe in view of the high occupant load. Furthermore, there may be extensive property damage due to the lack of automatic suppression system. It would lead to prolonged service disruption which would lead to inconvenience to a lot of passengers. Therefore, it is recommended that sprinklers be retrofitted in existing parts of the airport and railway stations which are not protected by such system.

In Hong Kong, thermal sensitivity is not specified for sprinklers in the local fire code, except for basements and some special applications to augment deficiencies in passive fire protection. Nevertheless, quick response sprinklers react much quicker than concealed sprinklers. It is recommended to review the code requirements so that thermal sensitivity of sprinklers may be included for places other than basements. These may include areas of higher risk such as the airport and railway stations, as well as areas of special risk such as hospitals, elderly homes and hotels. There are a lot of occupants at these premises and evacuation therefrom would be difficult.

Regarding heat collection plates, results from this study is divided. In burning tests in enclosed fire chambers, heat collection plates were very effective in reducing actuation time of sprinklers. However, heat collection plates were not of any significance in shortening the sprinkler reaction time in numerical simulations involving tall halls with open sides. Therefore, further study including numerical simulations, as well as full-scale burning tests be conducted to explore the characteristics of them. If proved to be effective, it would significantly shorten sprinkler reaction time in tall halls.

## FIGURES

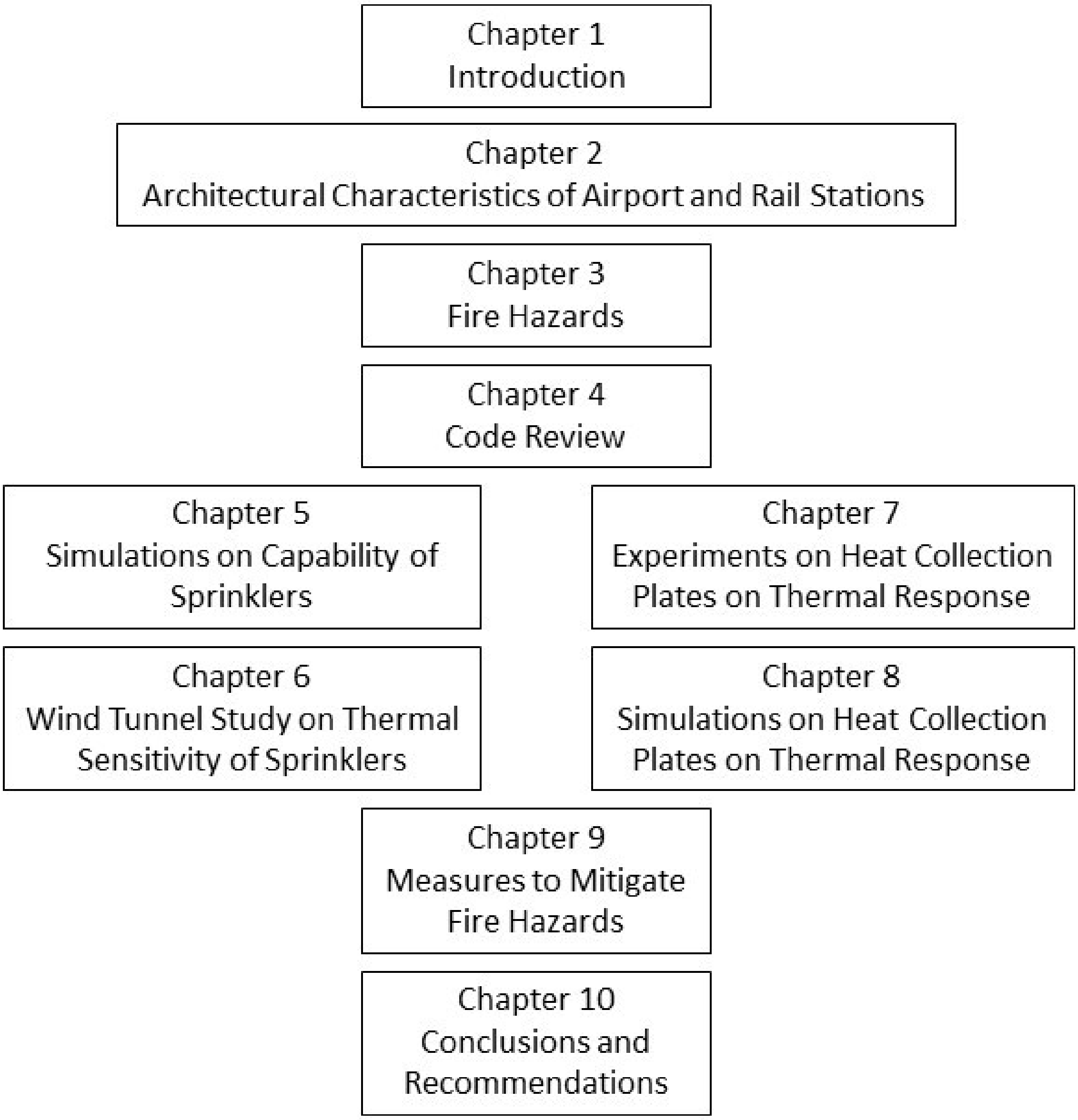


**Figure 1.1: Flow chart of this thesis**

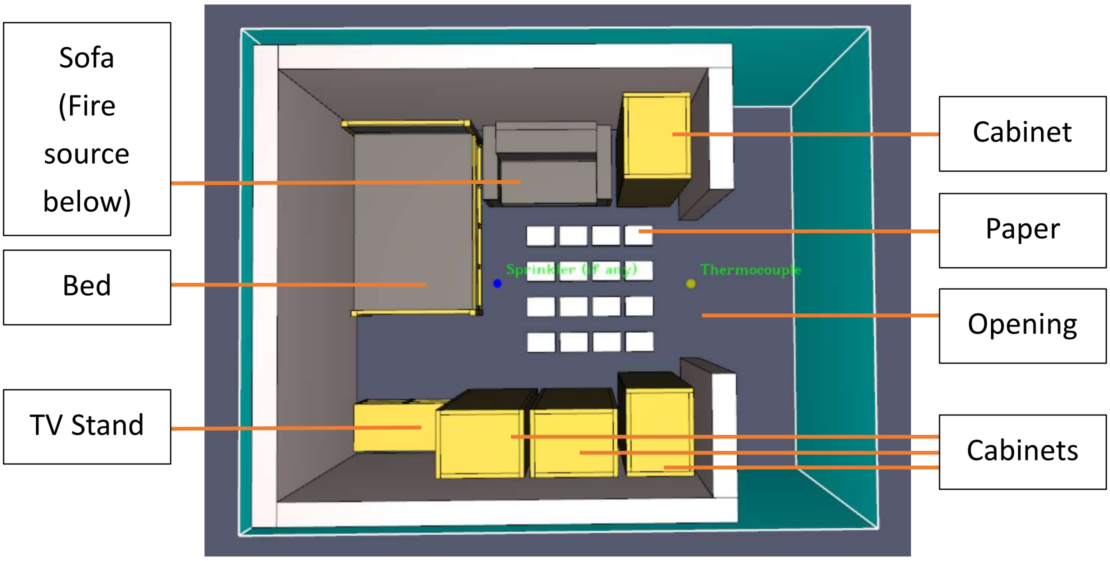


Figure 5.1: Setup of the furniture and paper burning simulation

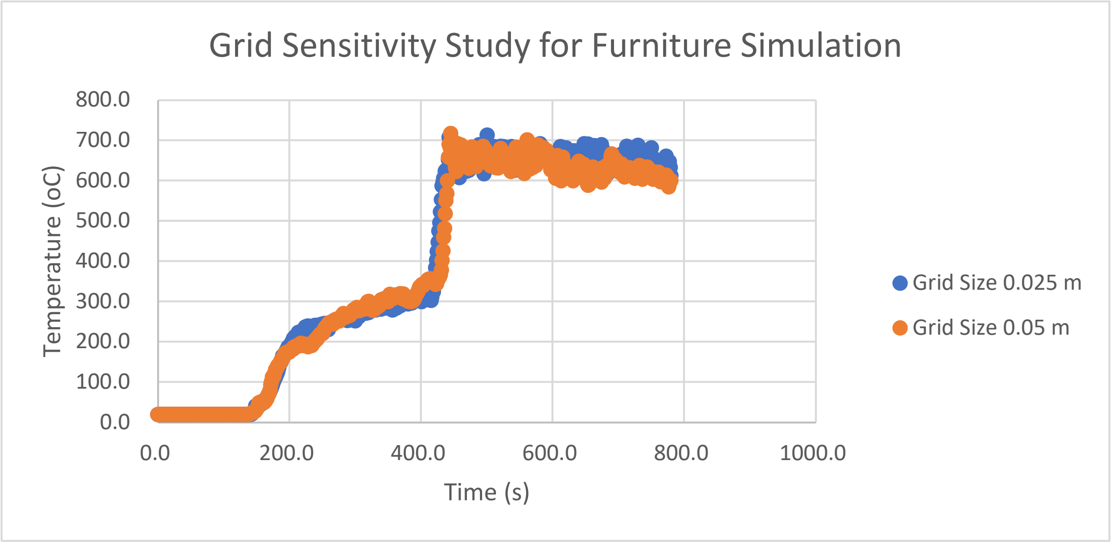


Figure 5.2: Grid sensitivity for furniture simulation

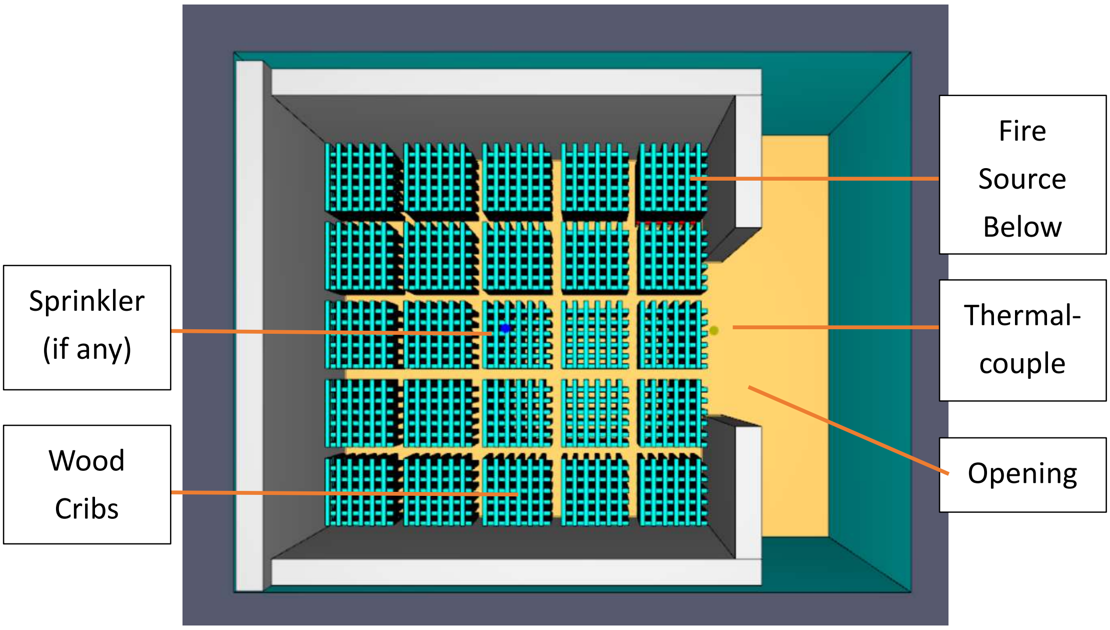


Figure 5.3: Setup of the wood crib simulation

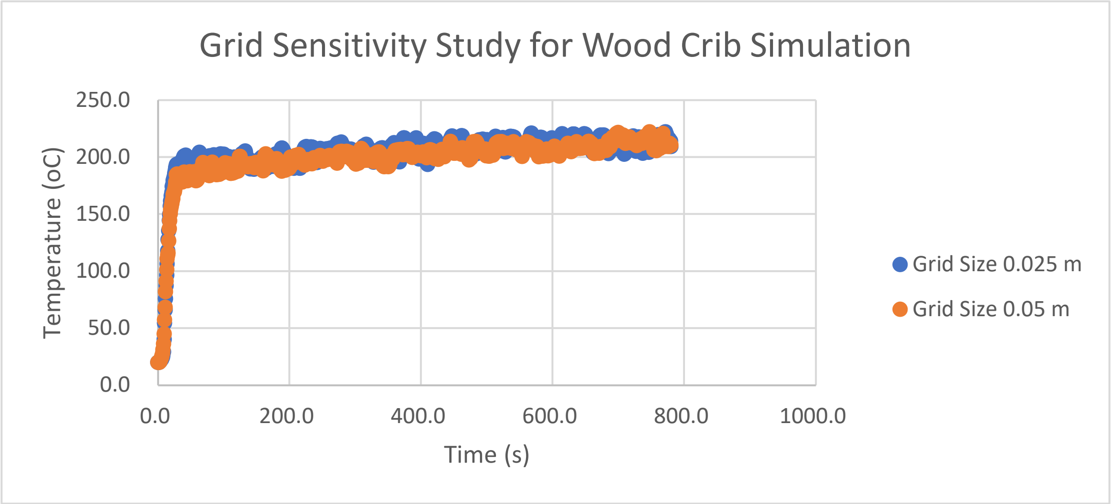


Figure 5.4: Grid sensitivity for wood crib simulation

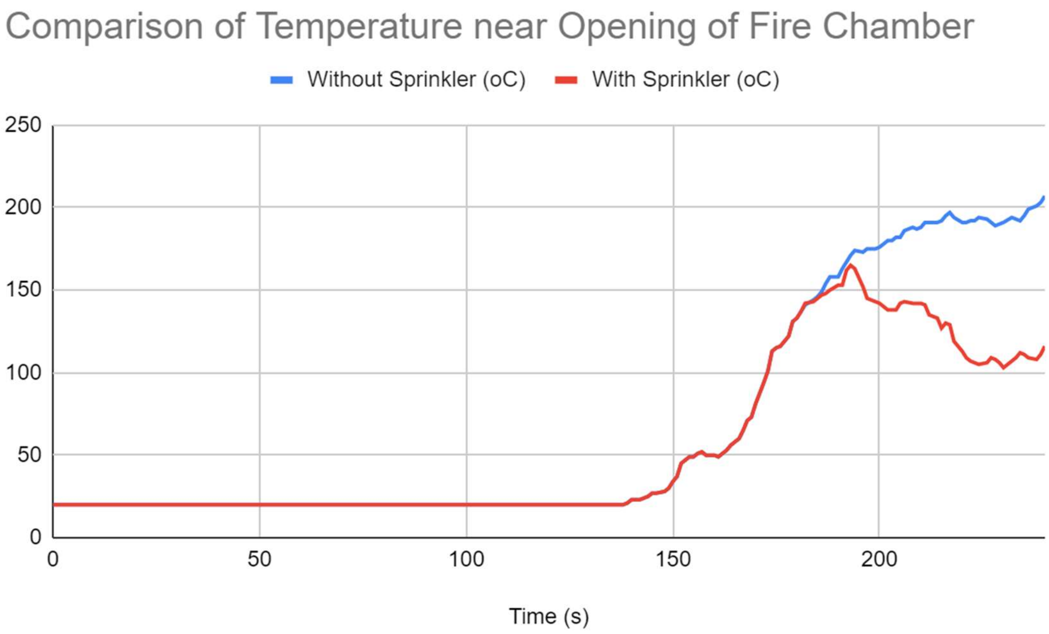


**Figure 5.5: Result of the furniture and paper burning simulation**

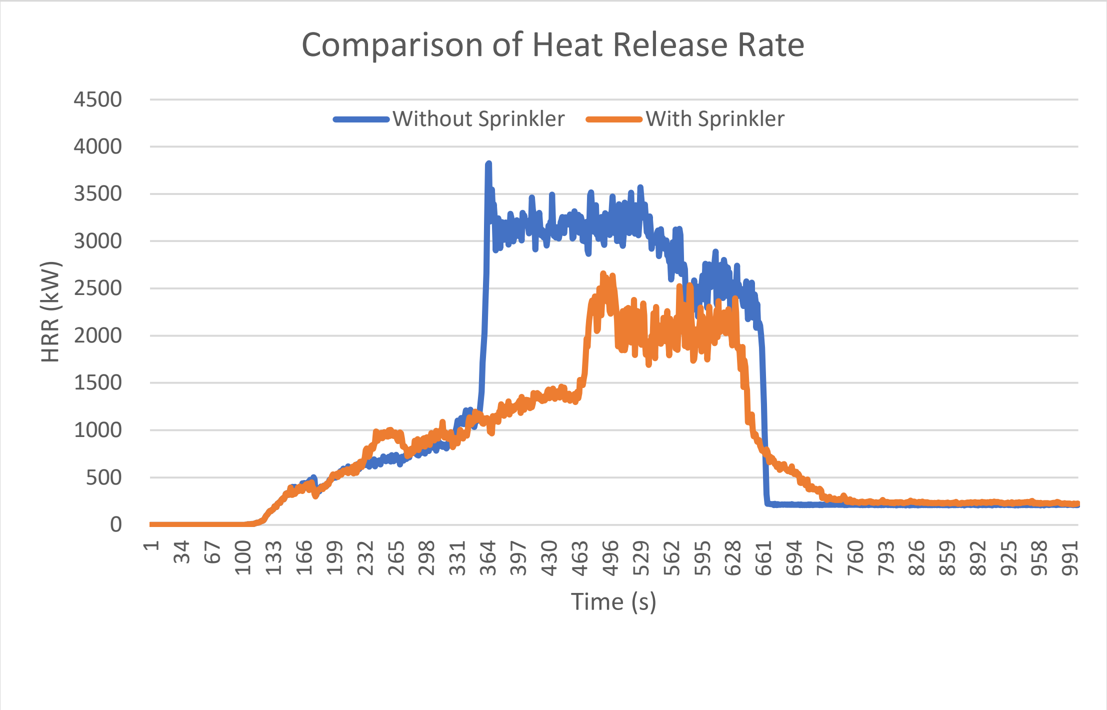


Figure 5.6: Heat release rate during furniture and paper burning simulation

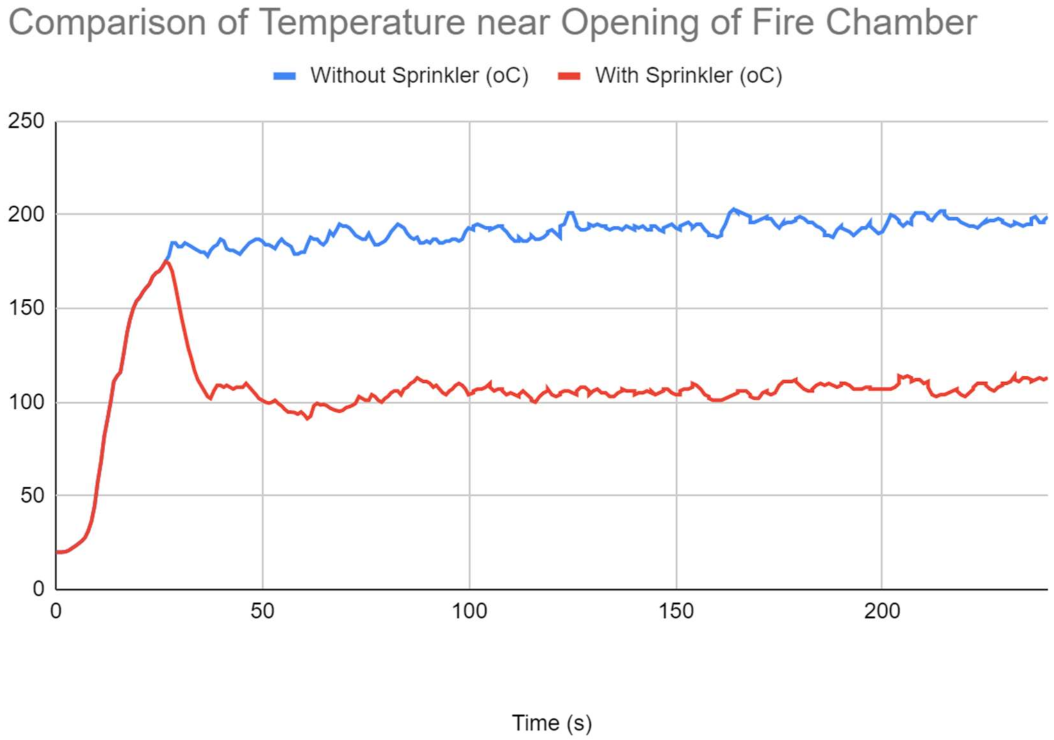


Figure 5.7: Result of the wood crib burning simulation

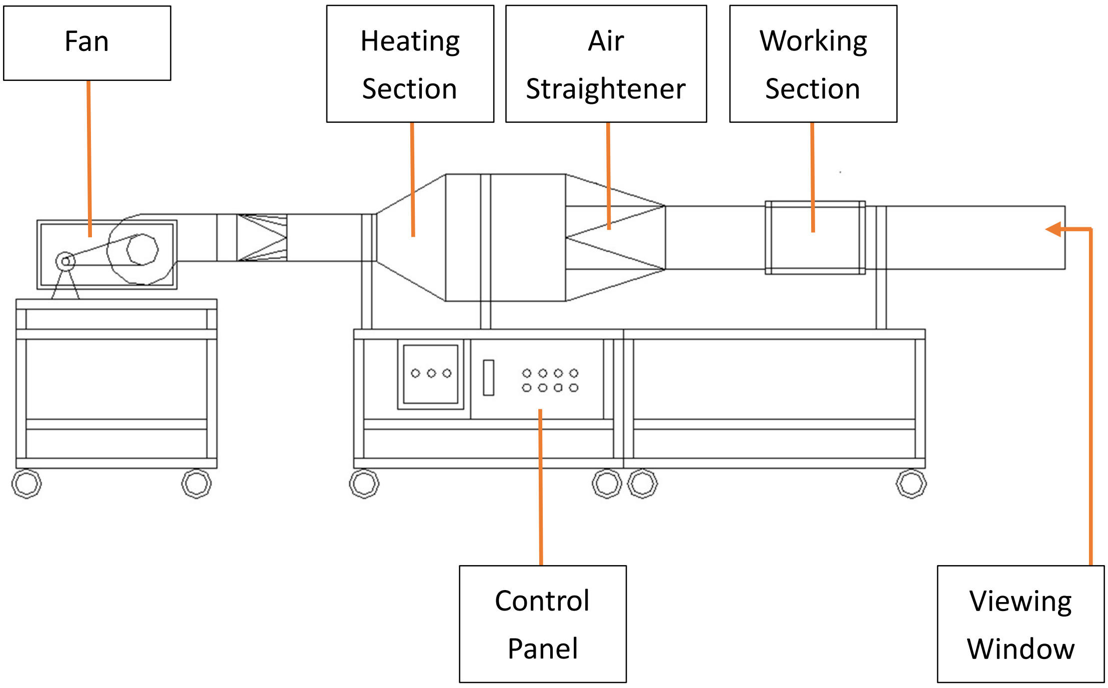


Figure 6.1: Schematic diagram of the hot wind tunnel

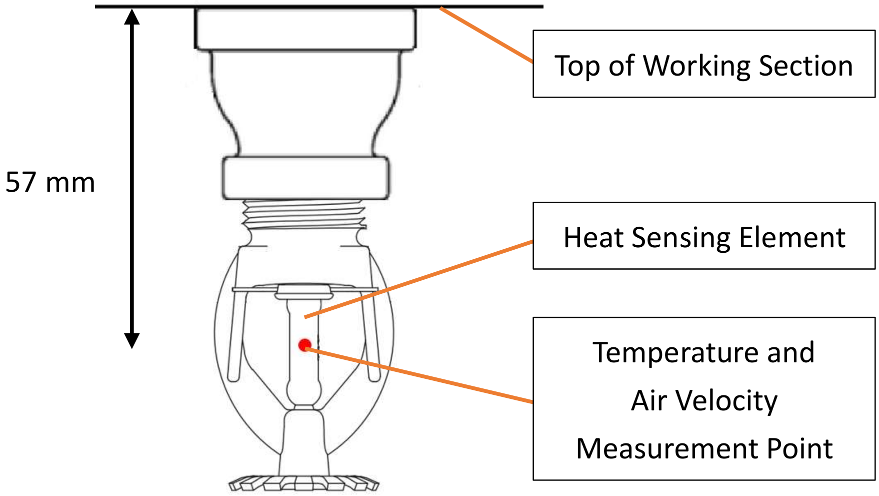


Figure 6.2: Schematic diagram of installation of pendant and upright sprinkler in the hot wind tunnel

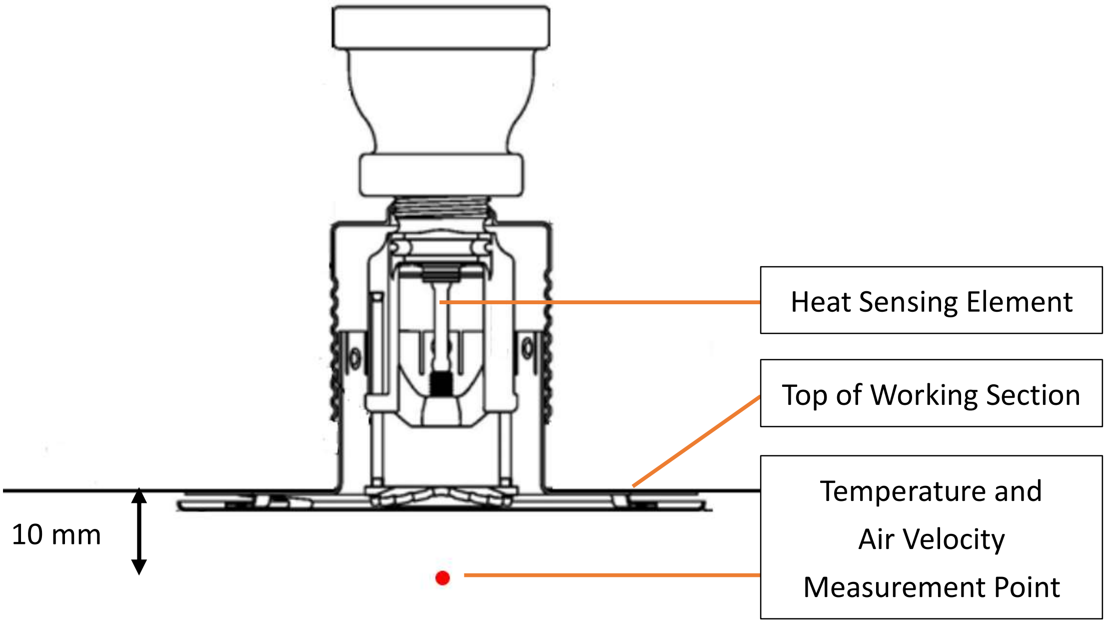


**Figure 6.3: Schematic diagram of installation of concealed sprinkler in the hot wind tunnel**

**Figure 6.4: Sprinkler model ‘CB1’**

Figure 6.5: Sprinkler model ‘CB2’

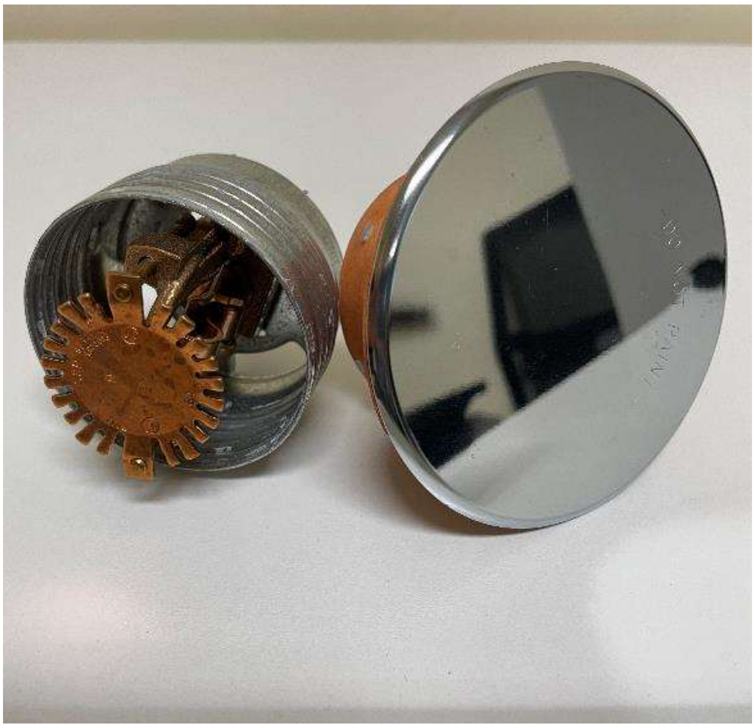


Figure 6.6: Sprinkler model 'CF1'

Figure 6.7: Sprinkler model 'PB1'

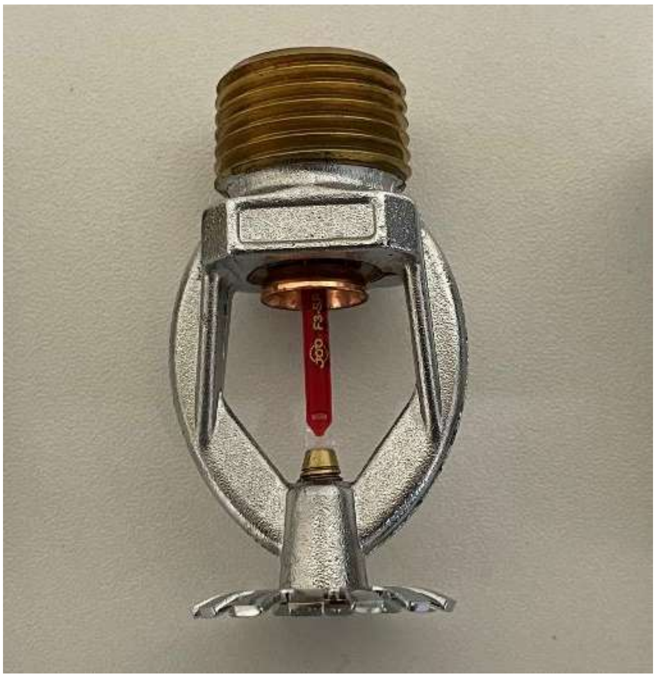


Figure 6.8: Sprinkler model ‘PBQ’

Figure 6.9: Sprinkler model ‘UB1’

Figure 7.1: Heat collection plate type ‘A’

Figure 7.2: Heat collection plate type ‘B’

Figure 7.3: Heat collection plate type ‘C’

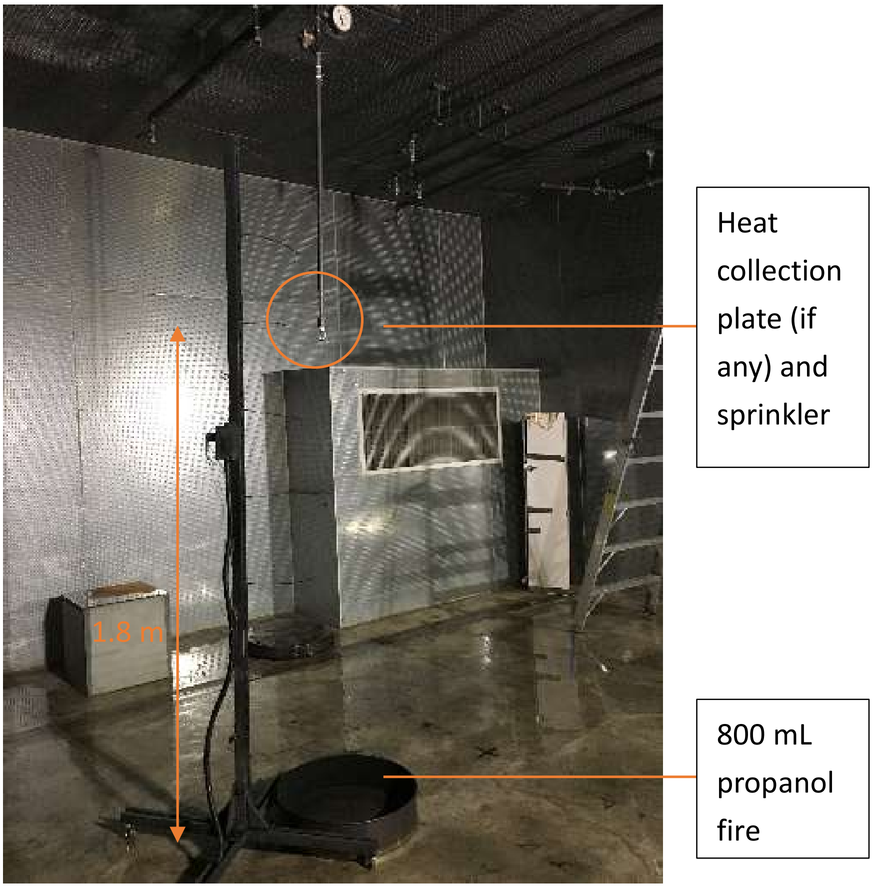


Figure 7.4: Experimental setup for fire test on heat collection plates

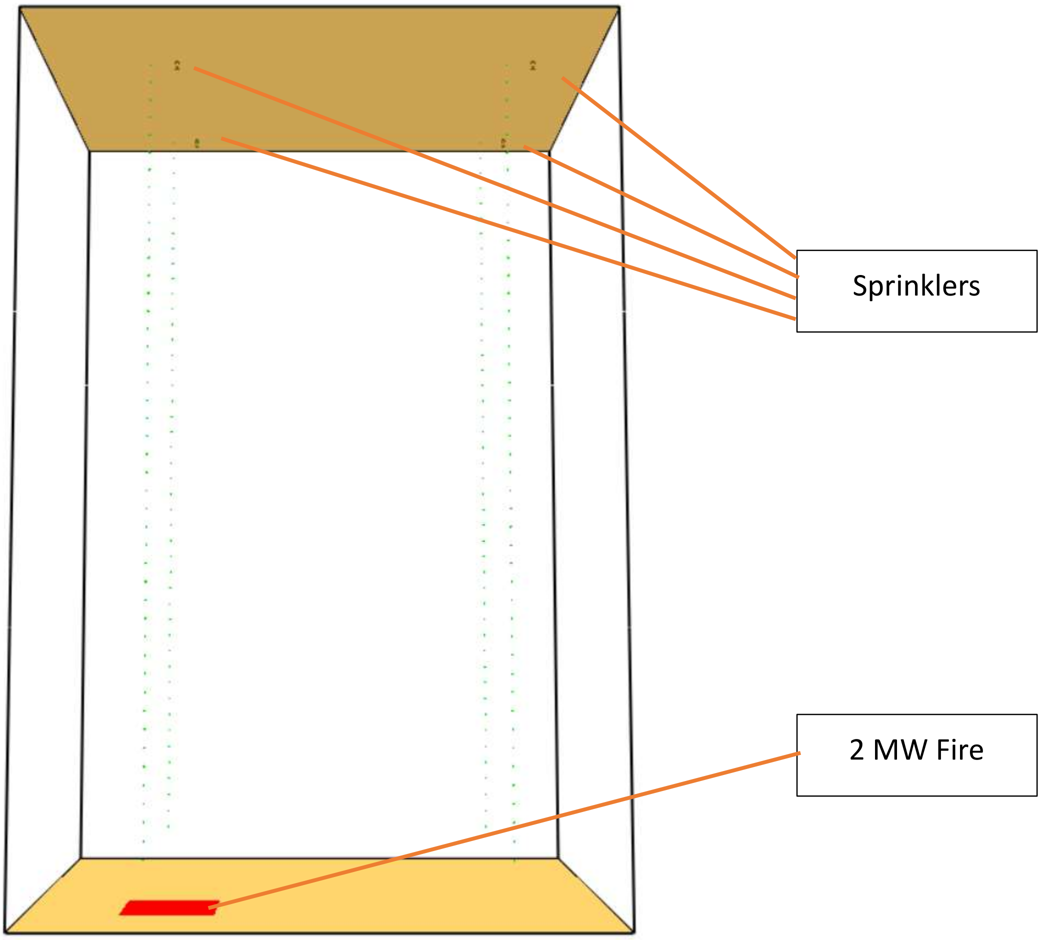
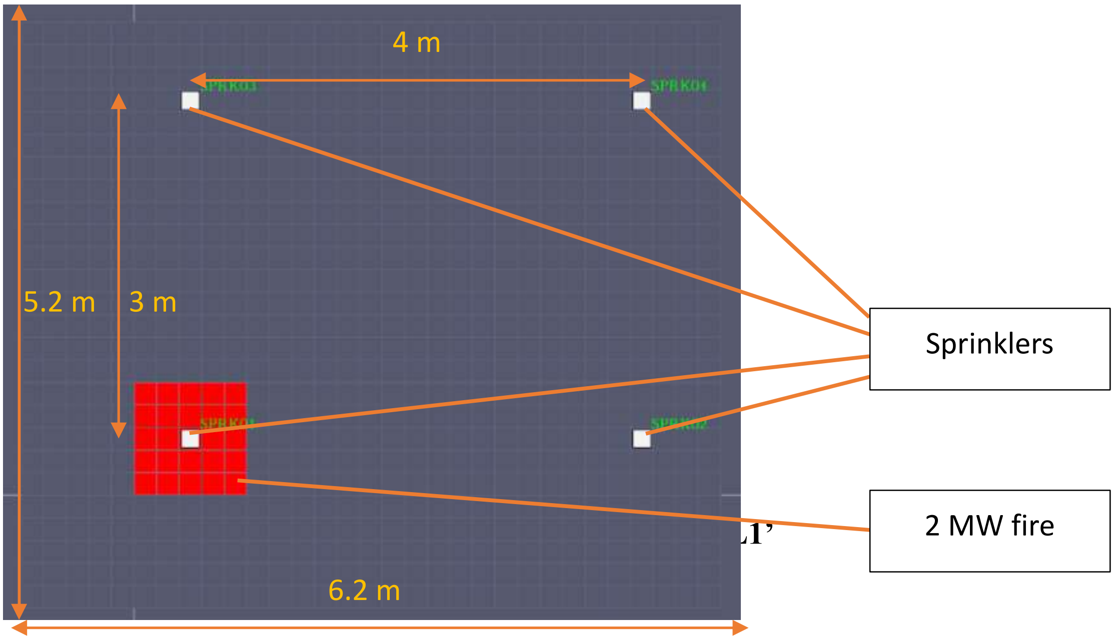


Figure 8.1: Setup of the heat collection plate simulation



L1’

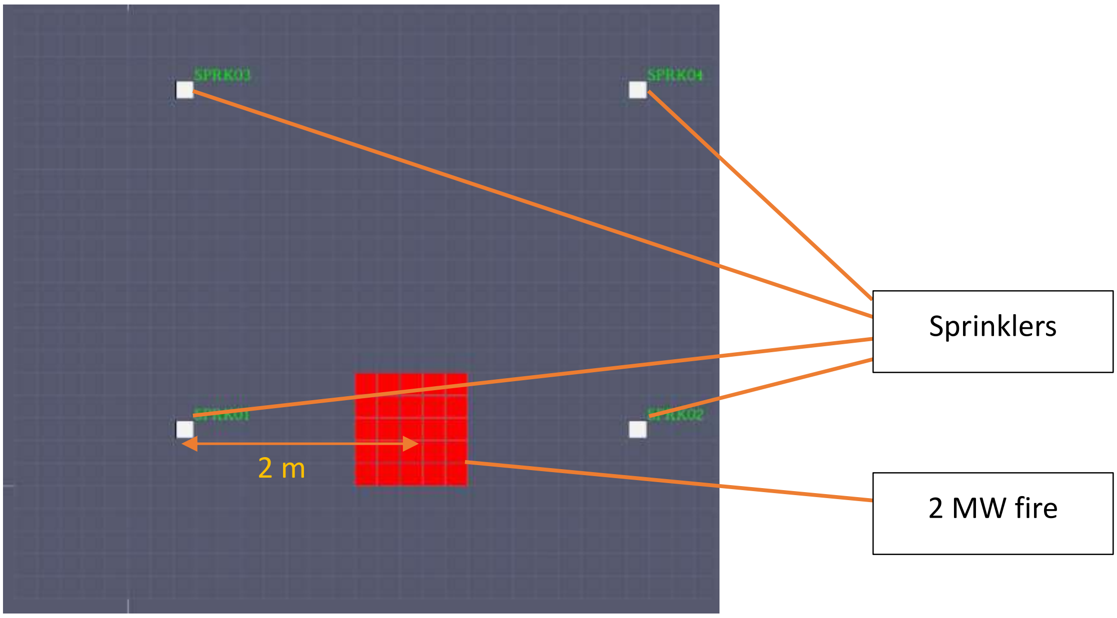


Figure: 8.3: Location of fire ‘L2’

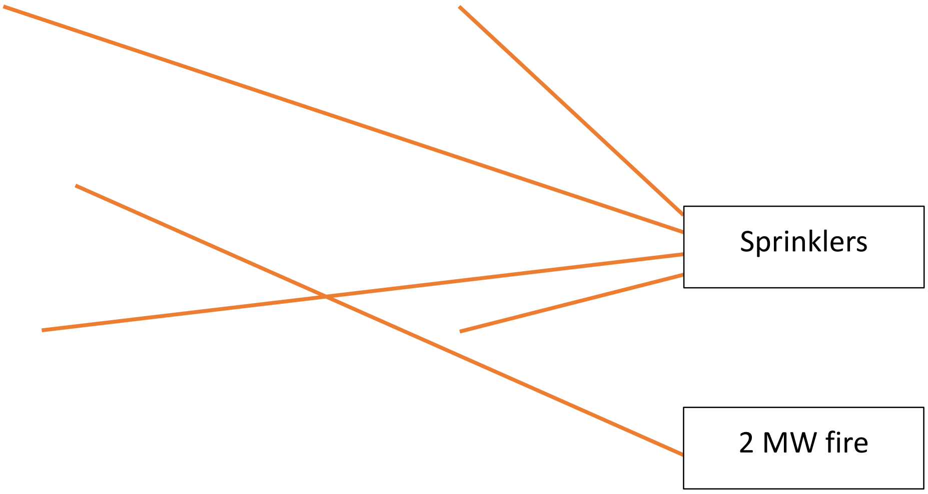


Figure: 8.4: Location of fire ‘L3’

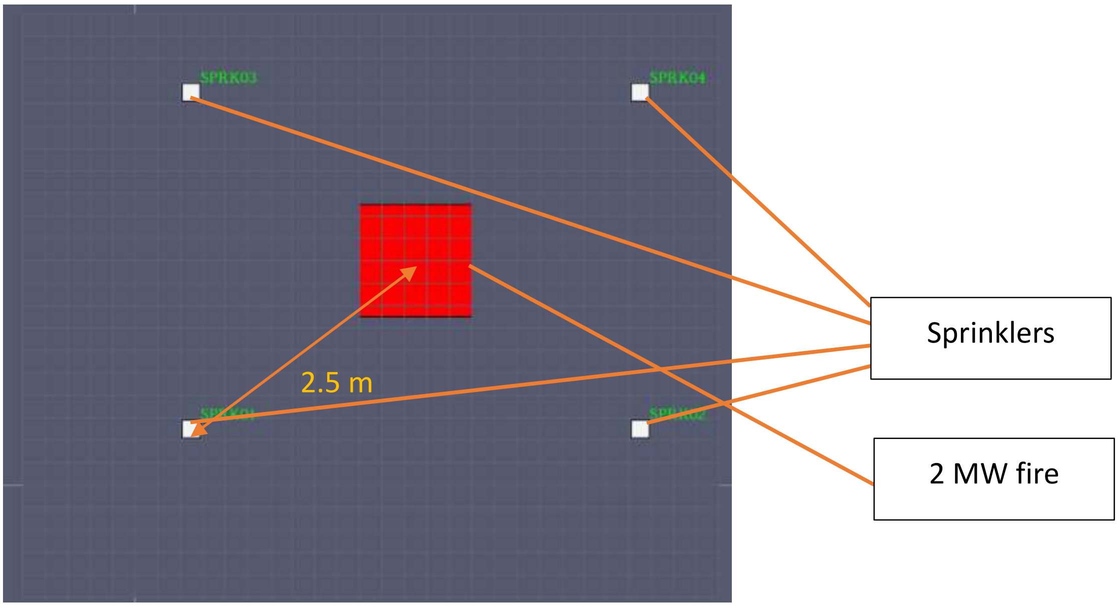


Figure: 8.5: Location of fire ‘L4’

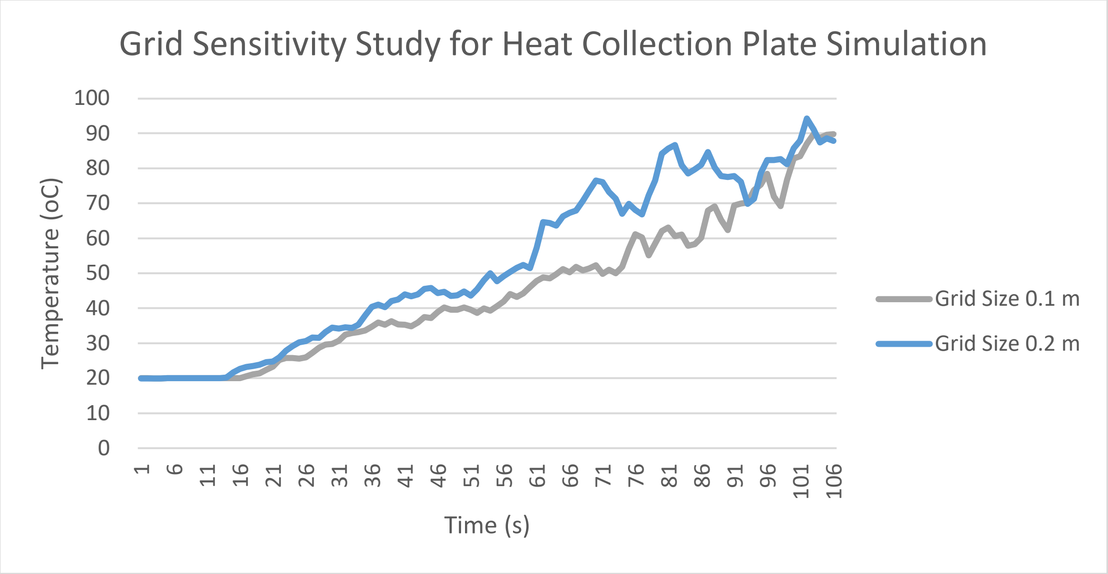


**Figure 8.6: Grid sensitivity for heat collection plate simulation**

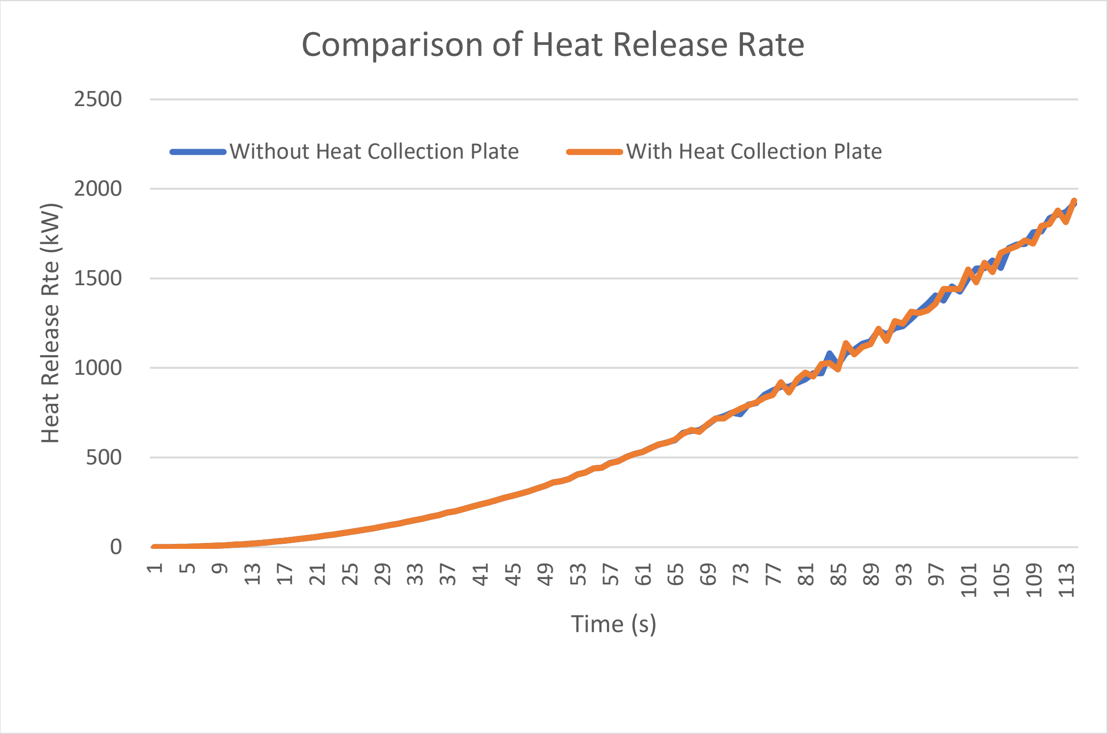


**Figure 8.7: Comparison of heat release rate for heat collection plate simulation**

# TABLES

## Table 3.1 Fires at the Hong Kong International Airport Reported by Media

| Date | Location | Objects Involved |
|---|---|---|
| 3 April 2016 | Air Cargo Terminals Super Terminal 1 | Lithium battery (Oriental Daily, 2016) |
| 16 May 2016 | Terminal 1 | Lithium battery (Guan, 2016) |
| 16 December 2016 | Midfield Concourse | VIP Lounge under renovation (Leung, 2016) |
| 9 October 2017 | Apron | Cargo loading vehicle (Mok, 2017) |
| 4 November 2017 | Air Cargo Terminals Super Terminal 1 | Mobile phones (Oriental Daily, 2017) |
| 29 December 2017 | Terminal 1 | Christmas tree (Liu and Lai, 2017) |
| 8 January 2019 | Apron | Lithium battery (Lee, 2019) |
| 5 June 2019 | Apron | Light goods vehicle (Liu, 2019) |
| 11 September 2019 | Ground Transportation Centre | Bus (Apple Daily, 2019) |
| 11 April 2021 | Apron | Mobile phones (Chan, 2021) |

**Table 4.1 Requirement on Fire Safety Installations in Hong Kong**

| Type of Fire Service Installation | Airport | Railway Stations |
|---|---|---|
| Audio/visual advisory system | As required by the Fire Services Department | Required |
| Emergency generator / emergency power supply | | Required |
| Emergency lighting | | Required |
| Exit sign | | Required |
| Fire alarm system | | Required |
| Fire control centre | | Required |
| Fire detection system | | Required |
| Fire hydrant/hose reel system | | Required |
| Fire Services communication system | | Required |
| Pressurization or natural ventilation of staircase | | Required |
| Smoke extraction system | | Required |
| Sprinkler system | | Required |
| Ventilation/air conditioning control system | | Required |

**Table 4.2 Requirement on Fire Equipment for Buildings in Taiwan**

| Type of Fire Equipment | Airports | Railway Stations |
|---|---|---|
| Fire Extinguishers | Required | Required |
| Indoor fire hydrant |  | Required |
| Sprinkler system | Required | Required |
| Automatic fire alarm | Required | Required |
| Manual alarm | Required | Required |
| Exit signs | Required | Required |
| Emergency lighting | Required | Required |
| Connecting water delivery pipe | Required | Required |
| Smoke exhaust equipment |  | Required |

**Table 4.3 Requirement on Fire Protection Systems for Buildings in Singapore**

| Type of Fire Protection System | Airports | Railway Stations |
|---|---|---|
| Secondary power supply | Required | Required |
| Portable extinguishers | Required | Required |
| Rising main | Required | Required |
| Hose reel | Required | Required |
| Electrical fire alarm | Required | Required |
| Sprinkler system | Required | |
| Pressurisation or natural ventilation of staircase | Required | Required |
| Smoke control system | Depending on compartment size | Required |
| Emergency lighting | Required | Required |
| Exit signs | Required | Required |
| Voice communication system | Required | Required |
| Fire command centre | Required | |

**Table 4.4 Requirement on Fire Protection Systems for Buildings in England**

| Type of Fire Protection System | Airports | Railway Stations |
|---|---|---|
| Fire detection and alarm system | Required | Required |
| Sprinkler system | Required | Required |
| Fire mains | Required | Required |
| Ventilation and air-conditioning control system | Required | Required |
| Escape lighting | Required | Required |
| Exit signs | Required | Required |
| Standby power supply | Required | Required |

**Table 4.5 Requirement on Fire Protection Systems for Buildings in the United States**

| Type of Fire Protection System | Airports | Railway Stations |
|---|---|---|
| Standpipe system | Required | Required |
| Sprinkler system | Required | Required, except open stations |
| Fire extinguishers | Required | Required |
| Detection and alarm system | Required | Required |
| Emergency lighting | Required | Required |
| Exit signs | Required | Required |
| Standby power supply | Required | Required |
| Emergency command centre | | Required |
| Emergency communication system | | Required |

## Table 6.1 Sprinkler Actuation Time and Calculated Nominal Response Time Index in Hot Wind Tunnel Experiment

| Model | Air velocity ($ms^{-1}$) | Air temperature (°C) | Mean cover plate response time (s) | Mean heat sensing element actuation time (s) | Mean RTI $(m \cdot s)^{1/2}$ | Standard deviation of RTI $(m \cdot s)^{1/2}$ |
|---|---|---|---|---|---|---|
| CB1 | 1.75 | 130 | 46.5 | Did not actuate within 900 s | | |
| CB1 | 1.75 | 140 | 40.0 | Did not actuate within 900 s | | |
| CB1 | 2.5 | 130 | 30.2 | 190.4 | 542.43 | 161.01 |
| CB1 | 3 | 90 | 57.8 | 193.6 | 297.15 | 17.76 |
| CB1 | 3 | 100 | 46.4 | 165.2 | 321.15 | 32.09 |
| CB1 | 3 | 110 | 35.4 | 129.8 | 303.95 | 27.32 |
| CB2 | 1.75 | 130 | 33.5 | Did not actuate within 900 s | | |
| CB2 | 1.75 | 140 | 47.5 | Did not actuate within 900 s | | |
| CB2 | 2.5 | 130 | 32.0 | 164.8 | 469.50 | 103.75 |
| CB2 | 3 | 90 | 45.0 | 225.0 | 345.35 | 46.80 |
| CB2 | 3 | 100 | 34.2 | 134.4 | 261.27 | 38.50 |
| CB2 | 3 | 110 | 29.8 | 111.6 | 261.33 | 36.39 |
| CF1 | 1.75 | 130 | 107.0 | Did not actuate within 900 s | | |
| CF1 | 1.75 | 140 | 90.0 | Did not actuate within 900 s | | |
| CF1 | 2.5 | 130 | 109.4 | 396.4 | 954.30 | 239.66 |
| CF1 | 3 | 90 | 211.8 | 590.6 | 706.98 | 155.36 |
| CF1 | 3 | 100 | 131.8 | 363.4 | 572.93 | 99.38 |
| CF1 | 3 | 110 | 103.0 | 313.2 | 606.92 | 141.34 |
| PB1 | 1.75 | 130 | N.A. | 31.6 | 75.32 | 1.17 |
| PB1 | 1.75 | 140 | N.A. | 28.0 | 74.98 | 2.40 |
| PB1 | 2.5 | 130 | N.A. | 27.4 | 78.06 | 3.42 |
| PB1 | 2.5 | 140 | N.A. | 25.0 | 80.01 | 3.51 |
| PB1 | 3 | 90 | N.A. | 55.4 | 85.03 | 2.08 |
| PB1 | 3 | 100 | N.A. | 41.6 | 80.87 | 3.16 |
| PB1 | 3 | 110 | N.A. | 34.0 | 79.62 | 3.92 |

| Model | Air velocity ($ms^{-1}$) | Air temperature (°C) | Mean cover plate response time (s) | Mean heat sensing element actuation time (s) | Mean RTI $(m\cdot s)^{1/2}$ | Standard deviation of RTI $(m\cdot s)^{1/2}$ |
|---|---|---|---|---|---|---|
| PBQ | 1.75 | 130 | N.A. | 11.2 | 26.7 | 3.81 |
| PBQ | 1.75 | 140 | N.A. | 10.2 | 27.31 | 3.94 |
| PBQ | 2.5 | 130 | N.A. | 9.2 | 26.21 | 2.13 |
| PBQ | 2.5 | 140 | N.A. | 9.0 | 28.81 | 0.00 |
| PBQ | 3 | 90 | N.A. | 27.0 | 41.44 | 8.52 |
| PBQ | 3 | 100 | N.A. | 18.0 | 34.99 | 0.00 |
| PBQ | 3 | 110 | N.A. | 12.8 | 29.97 | 1.75 |
| UB1 | 1.75 | 130 | N.A. | 32.2 | 76.75 | 1.78 |
| UB1 | 1.75 | 140 | N.A. | 30.2 | 80.87 | 2.00 |
| UB1 | 2.5 | 130 | N.A. | 28.6 | 81.48 | 3.86 |
| UB1 | 2.5 | 140 | N.A. | 26.2 | 83.85 | 3.14 |
| UB1 | 3 | 90 | N.A. | 55.6 | 85.34 | 3.71 |
| UB1 | 3 | 100 | N.A. | 42.6 | 82.81 | 4.19 |
| UB1 | 3 | 110 | N.A. | 35.6 | 83.36 | 1.87 |

**Table 7.1 Sprinkler Actuation Time in Heat Collection Plate Experiment**

| | Actuation Time (s) | | | |
|---|---|---|---|---|
| Test Number | No HCP | HCP Type A | HCP Type B | HCP Type C |
| E1 | 81 | 69 | 38 | 35 |
| E2 | 77 | 75 | 35 | 33 |
| E3 | 85 | 68 | 43 | 39 |
| E4 | 89 | 73 | 45 | 40 |
| E5 | 92 | 78 | 39 | 40 |
| E6 | 83 | 69 | 34 | 38 |
| E7 | 76 | 72 | 42 | 30 |
| E8 | 90 | 70 | 40 | 42 |
| E9 | 79 | 68 | 44 | 39 |
| E10 | 92 | 69 | 38 | 36 |
| E11 | 84 | 70 | 39 | 38 |
| E12 | 88 | 73 | 36 | 34 |

**Table 8.1 Sprinkler Actuation Time in Heat Collection Plate Simulations**

| | Actuation Time (s) | | | | | |
|---|---|---|---|---|---|---|
| Distance of Sprinkler from Ceiling | 0.1 m | | 0.5 m | | 0.9 m | |
| Location of Fire | With HCP | Without HCP | With HCP | Without HCP | With HCP | Without HCP |
| L1 | 102 | 97 | 98 | 90 | 99 | 95 |
| L2 | 116 | 113 | / | / | / | / |
| L3 | 104 | 109 | / | / | / | / |
| L4 | 122 | 121 | / | / | / | / |

/ denotes sprinkler did not actuate

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