PREDICTION OF TEMPERATURE DISTRIBUTION DURING FLASHOVER CAUSED BY BACKDRAFT FIRE

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SUPERVISOR'S DECLARATION

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for award of the degree of Bachelor of Occupational Safety and Health.

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STUDENT'S DECLARATION

I hereby declare that the work in this thesis is my own except for quotations and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

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Dedicated to my beloved family, supervisor, and friends.

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ABSTRACT

The effect of ventilation on fire development is one of the most important phenomena to understand modern compartment fire behavior, causing fire behavior shifted from traditional fire behavior to modern fire behavior. Ventilation controls the growth of the fire process and this creates problem in describing fire activities in some ways posing potential hazards to firefighters during fire ground. Backdraft is one of the most deadly fire phenomena in a ventilation limiting building. Backdraft develops from an oxygen starved fire and yet, continue to produce a fuel-rich environment in the compartment. If an opening is made and fresh air is allow to enter the compartment, high temperature hot gases remained in the compartment will rapidly burn once in contact with the incoming fresh air, resulting a fireball associated with a blast wave. Identifying factors that contribute to this extreme fire phenomenon is important. In this paper, a meta analysis of results from related multiple studies to understand and to analyze the meaning of the results obtained of a collection of studies The effect of varying the ventilation by means of changing different geometries of the openings, the location of ignition source, and the mass fraction of unburned gas are discussed. . The results acquired from the meta analysis have shown that the smaller the change of the geometry of the opening, the further the location of ignition source from the opening of the compartment and when the mass fraction of unburned fuel remained in the compartment exceeds a certain critical value, the easier for the backdraft to occur. In addition, the analysis also show that the key parameter determining the backdraft occurrence is the mass fraction of unburned fuel, followed by the ventilation condition.

ABSTRAK

Kesan pengudaraan kepada perkembangan pembakaran adalah salah satu fenomena yang penting untuk memahami tingkah laku bangunan api moden yang menyebabkan tingkah laku api beralih daripada tradisional kepada moden. Pengudaraan mengawal pertumbuhan proses api dan ini menimbulkan masalah dalam menerangkan aktiviti api yang berpotensi untuk membahayakan anggota bomba semasa aktiviti pemadaman api. Backdraft adalah salah satu daripada api yang paling maut untuk bangunan yang mengalami kekurangan oksigen. Backdraft berkembang daripada api yang mengalami kebuluran oksigen dan, terus menghasilkan persekitaran yang kaya dengan bahan api di dalam ruang bangunan. Jika pembukaan dibuat dan oksigen memasuki ruang bangunan, gas yang bersuhu tinggi di dalam ruang tersebut akan membakar dengan pantas selepas berhubungan dengan udara yang mengalir masuk, daripada inilah terhasilnya bola api diikuti oleh letupan. Adalah penting untuk mengenal pasti faktor-faktor yang menyumbang kepada fenomena ini. Dalam penyelidikan ini, satu meta-analisis dijalankan terhadap keputusan dari pelbagai kajian yang berkaitan untuk memahami dan menganalisis makna sebalik keputusan yang didapati daripada koleksi kajian daripada aspek-aspek berikut: perubahan dalam pengudaraan dengan menukarkan geometri bukaan, lokasi sumber pencucuhan, dan pecahan jisim gas yang tinggal sebagai produk pembakaran telah dibincangkan. Keputusan yang diperoleh daripada meta-analisis telah menunjukkan bahawa perubahan geometri yang lebih kecil, lokasi sumber pencucuhan yang jauh daripada bukaan dan pecahan jisim bahan api yang tinggai sebagai produk pembakaran melebihi nilai kritikal tertentu, lebih mudah untuk Backdraft berlaku. Di samping itu, analisis juga menunjukkan bahawa parameter utama yang menentukan Backdraft adalah pecahan jisim bahan api yang tinggal sebagai produk pembakaran, dan ini iikuti oleh keadaan pengudaraan dalam ruang bangunan tersebut.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

%	Percentage

LISTS OF ABBREVIATIONS

CO	Carbon Monoxide
COHb	Carboxyhaemoglobin
HCN	Hydrogen Cyanide
HRR	Heat Release Rate
IFSTA	International Fire Service Training Association
ISO	International Organization for Standardization
LPG	Liquefied Petroleum Gas
M CH4	Total fuel mass flows into the compartment
M total	Total gas mass in the compartment
NFPA	National Fire Protection Association
LEL/LFL	Lower Explosive Limit or Flammable Limit
UEL/UFL	Upper Explosive Limit or Upper Flammable Limit
UL	Underwriters Laboratory
Yf	Mass fraction of unburned fuel
Y CO2	Mass fraction of carbon dioxide
Y CO	Mass fraction of carbon monoxide

CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION

This chapter dealt with the general idea of this study in conjunction with the problem statements, objectives, significance of study, scope of study and the limitation of study.

1.2 BACKGROUND OF STUDY

The behavior of compartment fire today has changed steadily over the past several decades from a traditional fire behavior to a modern fire behavior, and they hold significant challenges for firefighters safety. As a consequence of the changes to the modern fire environment, which can speed up the stages of fire development and creating a high probability for the occurrence of ventilation-limited fire, causing conventional firefighting methods are not effective enough to protect the firefighters. These changes of fire environment include larger homes, different home geometries, increased synthetic fuel loads, and changing of construction materials. Several experiments were conducted to compare the effects of fuel loads changing in residential houses and the results revealed that flashover times of less than five minutes was needed when they used to be on the order of 30 minutes (Kerber, 2012). Owing to these changes, fire behavior should be understood thoroughly as to improve our situational awareness, especially for firefighters to make a correct decision on the fire ground.

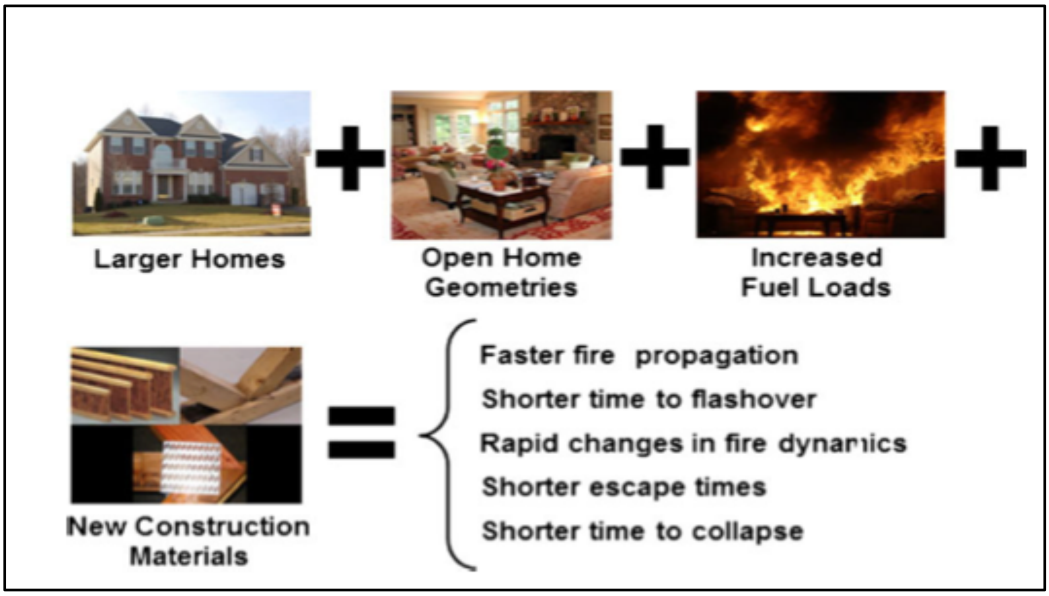


Figure 1.1: Modern Fire Formula

Source: Analysis of Changing Residential Fire Dynamics and Its Implications on Firefighter Operational Timeframes. [Image]. (2012).

While seeming to be so fundamental, basic fire behavior is the starting point for understanding the modern fire development. The definition for and the differences between flashover and backdraft are important in development of fire control operations. A backdraft is defined as a smoke explosion that can occur when additional air is introduced into an oxygen-exhausted fire environment and heated gases enter their flammable range, igniting with explosive force. In contrary, flashover is known as the sudden involvement of a compartment caused by thermal radiation feedback (Flatley, 2005).

How does a backdraft differ from a flashover? The main difference between backdraft and flashover is that backdraft is an explosive and an "air-driven" event while flashover is not and it is a "heat-driven" event. The shock waves during a backdraft will break the confining structure and part of the structure may collapse. Sudden increased in ventilation triggers a backdraft to occur when an opening is made. Meanwhile, flashover is a rapid-fire development but it stops short of an explosion's speed of chemical reaction. The radiated-heat back into a burning compartment will raise the gases and the content in the compartment to the auto-ignition temperature, triggering a flashover. Notable changes occur when the fire transits from fuel controlled to ventilation controlled, and these changes have a great impact of firefighters tactics based on the stage of fire development. The temperature curve for flashover, which has only one temperature peak, on the other hand, temperature in backdraft may have more than one peak value (Zhang et. al., 2014).

Backdraft and flashover need to be understood, as several factors are to increase their likelihood of occurrence. Both extreme fire behaviors are equally dynamic and deadly. Recognizing the signs and being able to develop tactical strategies will give a chance for survival.

1.3 PROBLEM STATEMENT

In the field of fire safety, lack of available and organized scientific information and lack of sustained research in fire contributed to the lack of awareness and knowledge regarding fire behavior and its causation factors among both firefighters and civilians. The problem in describing fire activities in some ways presents potential hazards to firefighters, specifically, during fire ground. This failure of recognizing fire activities has lead to the high percentage of firefighters injuries and fatalities, mostly resulting from extreme fire behavior (flashover and backdraft), in which the conventional methods are not effective enough to suppress the fire and protect the firefighters from performing their tasks. However, predictability of extreme fire behavior is difficult because the occurrence of such fires is dependent, to some extent, on their environment.

Lack of predictability, high spread rates, high fire intensities and area-wide spot ignitions of extreme fire behavior reduce fire suppression effectiveness and threaten firefighters safety. Flashover and backdraft are known to be the leading cause that contributes to the injuries or fatal of firefighters (Table 1.1). The tragic loss of firefighters and civilians is due to the lacking of understanding of fire behavior in the compartment fires resulting from the dynamic changes in fire environment. NFPA reported that from 2010 to 2012, United State fire departments recorded an average of 31.2% of firefighters injuries was due to the fire development.

Table 1.1: General Factors Contributing to Fire-Related Firefighters Injuries (2010-2012)

General Factor Contributing to Injury	Percent
Fire development	31.2
Slippery or uneven surfaces	23.5
Other factor	20.2
Collapse or falling object	15.4
Holes	3.9
Vehicle or apparatus issue	3.1
Lost, caught, trapped or confined	2.3
Civil unrest/Hostile acts	0.4
Total	100.0

Source: NFIRS 5.0.
Notes: Includes only injuries where a factor contributing to injury was specified. The factor contributing to injury was specified in 48 percent of reported injuries.

Source: Related Firefighter Injuries Reported to the National Fire Incident Reporting System (2010-2012). (2014). Retrieved from https://www.usfa.fema.gov/downloads/pdf/statistics/v15i6.pdf

By conducting this study, we aim at analyzing how the changes in rate of ventilation will contribute to the occurrence of backdraft and how the changes in ventilation will affect the temperature distribution during flashover caused by backdraft. It is hope that the finding of this research will be given attention and will be helpful for further improvement on the tactical strategies of fire grounding for firefighters due to the limited research regarding extreme fire behavior in our nation.

1.4 RESEARCH QUESTIONS

The following research questions are formulated:

I. What are the critical conditions in the compartment for flashover caused by backdraft to occur?
II. How the rate of ventilation affects the fire behavior?
III. What is the key parameter in determining backdraft occurrence?

1.5 RESEARCH OBJECTIVES

The principle goals of this research are:

I. To characterize the condition in the compartment for flashover caused by backdraft to occur.
II. To assess the effect of rate of ventilation on fire behavior by varying the opening geometries.
III. To identify the key parameter in determining the backdraft occurrence.

1.6 RESEARCH HYPOTHESIS

In view of the above research questions, these hypothesis are formulated:

I. The critical conditions determining the occurrence of flashover caused by backdraft is excessive amount of hot fuel remained in the compartment, high temperature to ignite the fuel, low concentration of oxygen and increased ventilation.
II. The fire behavior is dependent on the rate of ventilation.
III. The critical mass fraction of unburned fuel is the key parameter in determining backdraft occurrence.

1.7 SCOPE OF STUDY

This study is a meta analysis of past researches in order to study and to identify the critical condition for the occurrence of backdraft fire. This research will be conducted by studying and analyzing the related past researches, which should meet the primary criteria of including the critical conditions in determining the occurrence of backdraft fire. The researches that have included in this meta analysis are experimental tests. The main source of fuel used in this study is liquid fuel, which produces flammable vapor upon burning.

1.8 SIGNIFICANCE OF STUDY

Apparently, limited research has been done on flashover caused by backdraft, resulting the lack of awareness and knowledge in anticipating and responding to such extreme fire behavior continues to be a hazards that may cause death of people in situ and the collapse of building. The focus of this study is to determine how ventilation affects the behavior of fire and how it contributes to extreme fire behavior. The findings of this study will be beneficial to educate and to shift the paradigm of operational group, specifically, firefighters from traditional methods to a modern one on fire grounding. Lastly, the information collected and analyzed at the end of study can be used for further study of related issues in Malaysia.

1.9 CONCEPTUAL FRAMEWORK

Figure 1.2 illustrates the conceptual framework of this study related to the relationship of rate of ventilation by varying the geometries of the window in influencing on the temperature during flashover.

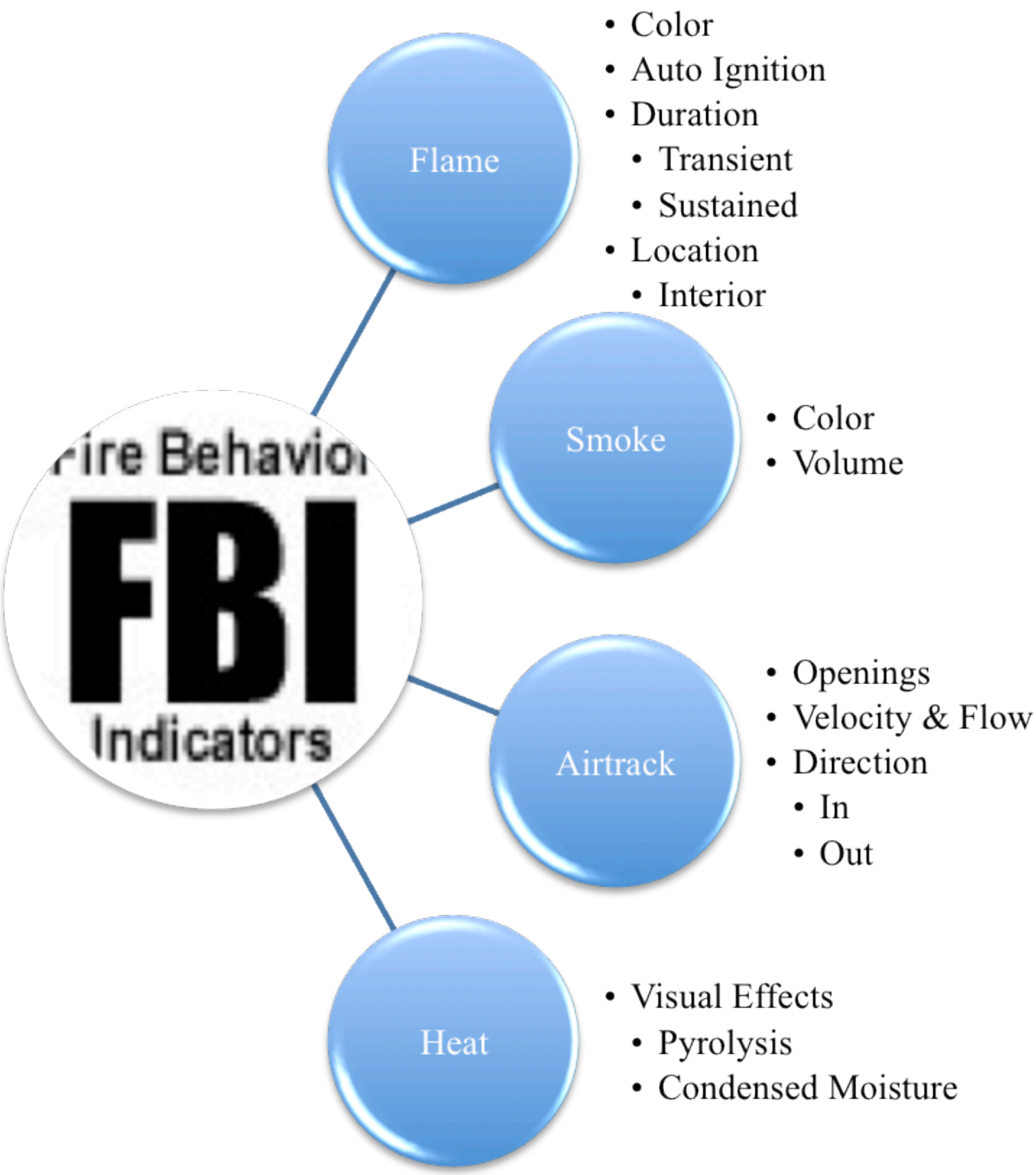


Figure 1.2: Relationship of rate of ventilation by varying the geometries of the window on influencing the temperature distribution during flashover.

1.9.1 Smoke

1.9.1.1 Height of Neutral Plane

The neutral plane is the boundary between the heated smoke and the cooler air (Shan, 2011). As fire develops, neutral plane will lower and the thickness of the smoke gases will increase. A very low neutral plane indicates very rich backdraft conditions and gradually lowering indicates an accumulation of fire gases and lead to flashover.

1.9.1.2 Color & Thickness

Dark smoke often produced under restricted air supply (ventilation-controlled). If the air supply is good, some of the soot is burnt which will result in less smoke and a yellow flame.

1.9.2 Air Track

Air track is the flow of air toward the firebase and the movement of heated combustion products up and out of the compartment.

1.9.2.1 Velocity & Direction

Sudden inward movement of air track leads to a potential backdraft event, when an opening is created, heated gases will flow out of the top of the opening and cooler air will flow in through the bottom of the opening, thus, gravity current is created.

1.9.2.2 Flow – Turbulent

If the air track is fast and turbulent with a low neutral plane, the fire is in the ventilation-controlled phase and there is a potential backdraft event.

1.9.2.3 Pulsation & Whistling Sounds

Pulsing in and out of smoke from small opening indicates variation in pressure from limited ventilation. Whistling sound is a classic indicator of backdraft. Cooling of gases and surfaces is necessary before ventilation is introduced to prevent backdraft from occurring.

1.9.3 Heat

1.9.3.1 Blackening of Windows with no Flame Showing

This indicates rich condition for backdraft to occur.

1.9.3.2 Cracking of Crazing of Glass

Cracking of glass is caused by rapid build-up of heat in the compartment.

1.9.4 Flame

Reddish-orange flames are the indicator for less oxygen and fuel-rich condition in a compartment fire.

Recognizing both types of flashover and understand how the factors contribute to this extreme fire behavior phenomena is important. Some factors are relatively unchanged, for example, building construction, yet, other factors are dynamic, changing as the fire develops, i.e. smoke condition and flames). However, there are some differences among fire behavior indicators for fuel-controlled flashover and ventilation-controlled flashover. Table below shows the indicators of potential flashovers. Many of these indicators are common to both vent-induced flashover and backdraft.

Table 1.2: Indicators for Fuel-controlled and Ventilation-controlled Flashover.

	Fuel-controlled Flashover	**Ventilation-controlled Flashover**
Smoke	Increasing volume, darkening color, and optical density, lowering level of the hot gas layer.	Increasing volume, velocity and turbulence, darkening color and optical density, low and lowering level of fire hot gas layer.
Air Track	Strong bi-directional air track (smoke out at the top and air in at the bottom), any air track that shows air movement increasing the velocity and turbulence.	High velocity and turbulence, pulsing (in & out) air track (which may be a backdraft indicator).
Heat	Observation of pyrolysis, feeling increased temperature.	Darkened windows, hot surfaces (doors & windows), high interior temperature.
Flame	Flame at ceiling level of the compartment.	Ignition of fire gases escaping from the fire compartment, isolated flames in the hot gas layer (strong indicator of vent controlled fire)

When the fire is ventilation controlled, increasing the ventilation to the fire will result in increased heat release rate and may lead to extreme fire behavior such as vent-induced flashover and backdraft. Remember, the main difference between ventilation-induced flashover and backdraft is fuel gas and vapor in the smoke is below its ignition temperature for vent-induced flashover, while, fuel gas and vapor is above its ignition temperature and the rate of combustion is generally much faster leading to a backdraft.

In short, common indicators of the potential backdraft occurrence are as below:

- Confined or excessive heat in enclosed buildings
- Pulsating fire with smoke leaving the building in puffs but being inwardly sucked back into the buildings (appearance that the "building is breathing")
- Little or no visible flame (as backdraft occurs in the stage of decay)
- Black smoke becoming dense gray-yellow
- Pressurized smoke exiting small openings
- Heat-induced cracking of glass of windows
- Whistling sounds around doors and windows

1.10 OPERATIONAL DEFINITION

1.10.1 Air Track

The flow of air toward the firebase and the movement of heated combustion products up and out of the compartment.

1.10.2 Backdraft

Smoke explosion that can occur when additional air is introduced into a smoldering fire and heated gases enter their flammable range and ignite with explosive force, which is known as an "air-driven event" (Flatley, 2005).

1.10.3 Deflagration

All combustion (fires) can be defined as deflagration and the combustion propagates at a velocity less than the speed of sound. However, the ignition of a fuel-oxidizer mixture or suspended cloud of combustible dust in a confined environment cause rapid increase in pressure and lead to catastrophic damage. These extreme phenomena are normally associated with gas explosion, vapor explosion, dust explosion and some reactive chemicals (Explosions, Deflagrations & Detonations, n.d.).

1.10.4 Fire behavior

The manner in which fuel ignites, flame develops and fire spread and exhibits other related phenomena, also known as the rate of speed (feet/hour) and the intensity (how hot the fire burns and how long the flame is) (Fire Behavior Basic, n.d.).

1.10.5 Fire dynamics

Study of how chemistry, fire science, material science, and the mechanical engineering disciplines of fluid mechanics and heat transfer interact to influence fire behavior (The National Institute of Standards and Technology (NIST), 2010).

1.10.6 Fire triangle

The three important elements to sustain a fire, (i) heat or ignition source, (ii) fuel and (iii) oxygen. Lack of any one of these, the fire goes out (or does not start at all).

1.10.7 Flashover

The transition phase in the development of a enclosed fire in which surfaces are exposed to the thermal radiation, from fire gases with temperature of 600° C, reach ignition temperature more or less simultaneously and fire spreads rapidly throughout the space. This is the most dangerous stage of fire development (The National Institute of Standards and Technology (NIST), 2010).

1.10.8 Flash point

The temperature at or above which a given liquid combustible will produce sufficient flammable vapor and mixes with air that can be ignited by the contact of source of heat. The lower the flash point, the greater the fire hazards.

1.10.9 Fuel-controlled fire

A fire in which the heat release rate and the growth rate are controlled by the amount of fuel.

1.10.10 Gravity current

Used to describe the interaction between two different densities of two fluids, which a vertical interface exists between the fluids, and cause the heavier fluids to flow horizontally beneath the lighter fluids. In backdraft, gravity current is often referred as air-track when the smoke is pushing out of an opening or doorway with a clear interface below which clear air is entering the compartment of structure.

1.10.11 Heat flux

The rate of heat energy transferred per surface unit area - kW/m^2.

1.10.12 Heat release rate

The rate at which fire releases energy, also known as power and is measured in units of Watts (W).

1.10.13 Lower Explosive Limit or Flammable Limit (LEL/LFL)

The minimum concentration of fuel vapor in air to support burning, which means combustion will not occur if the concentration of fuel vapor is below this limit. LEL for Gasoline is 1.4%.

1.10.14 Neutral Plane

The boundary between the heated smoke and the cooler air (Shan, 2011).

1.10.15 Pyrolysis

A process in which a material is decomposed or broken down, into simpler molecular compounds by the effects of heat alone: pyrolysis often precedes combustion. (NPFA 921).

1.10.16 Upper flammable limit (UFL) or upper explosive limit (UEL)

The highest concentration of fuel vapor in air that causes fire. Above this limit, fire is vigorous and consumes oxygen at a higher rate causing the oxygen to be insufficient to support combustion. UFL for gasoline is 7.6%.

1.10.17 Ventilation-limited fire

Fire burns in conditions of limited ventilation and flammable gaseous pyrolysis products accumulate.

1.11 SUMMARY

This dissertation comprises five chapters. The first chapter provides a basic introduction to the study and briefly presents the research questions, research objectives, research hypothesis, the scope, the limitation, the significance of this study and the conceptual framework.

Chapter 2 provides a context for the research by examining relevant literature. In Chapter 2, the literature introduces the definition of backdraft and flashover, the differences among these two types of fire behavior and the condition for each fire behavior to occur.

Chapter 3 addresses the research design, research instrument, the experimental procedure and software used in this study.

Chapter 4 focuses on the meta analysis and findings on five experimental studies, which were conducted with the intended outcome of identifying the essential elements of backdraft occurrence.

Chapter 5 concludes the main part of the thesis, and gives recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

The overall goals of this chapter were to study on the past researches related on the definition of backdraft fire and flashover, the phenomenon of backdraft and flashover, comparison of two different types of flashover and comparison of backdraft and flashover, and lastly, the ventilation controlled fire hazards. The bulk of this chapter was to critically determine and analyze how ventilation affect the backdraft occurrence and the temperature distribution during flashover caused by backdraft as to gain more knowledge and understanding on this extreme fire behavior phenomenon.

2.2 BACKDRAFT FIRE

To many, backdraft fire and smoke explosion are often confused, however, there are more or less straightforward differences between these two extremely dangerous fire behavior phenomena. Smoke explosion involves ignition of pre-mixed fuel (smoke) and air that is within its flammable range and does not require mixing with air (increased ventilation). On the contrary, backdraft fire requires a higher concentration of fuel that requires mixing with air (increased ventilation) in order for it to ignite and deflagration to occur. Another significant difference between flashover and backdraft fire is flashover will occur within few minutes of first flame while backdraft fire will occur only in tightly sealed building. In short, backdraft fire is defined as a smoke explosion that can occur when additional air is introduced into a smoldering fire and heated gases enter their flammable range and ignite with explosive force, which is known as an "air-driven event" (Flatley, 2005).

Backdraft is a complex and fascinating phenomenon. Several factors are identified and discussed in order to explain the phenomenon. Karlsson & Quintiere, 2000 defined backdraft as when a sudden opening is introduced into rich-unburned gases produced by an enclosure fire under limited-ventilation, a mixture of combustible gases is created and the presence of any ignition source will ignite the flammable gas mixture, leading to an extreme burning of these gases. High pressure caused by the expansion of the heat created by the combustion presses against the wall of the building and the burning gases tend to escape out through the opening and this causes a fireball outside the enclosure.

Figure 2.1: Backdraft

Source: Explosion at Harrington NJ Commercial Fire. [Online Image]. (2013). Retrieved from http://cfbt-us.com/wordpress/?tag=backdraft

According to Weng & Fan (2003), they claimed that both ordinary and ignitable liquids that become oxygen starved however still continue to produce a fuel-rich environment in a limited-ventilation building give rise to the occurrence of backdraft fire. In the matter of limited ventilation, the fire does not normally flame out but in oppositely becomes ventilation-controlled and the reignite of remaining fuel is very dependent on the geometry of the opening (Wu et al., 2011). Given a situation of fresh air entering into the oxygen-limited space through an opening, etc. door or window, a gravity current is created between the mixing of colder air into the compartment and the hot fuel-rich gases out from the compartment. Localized flammable mixture is formed and in contact with the remaining fuel in the compartment, the fuel-rich gases will ignite decently and leads to the sudden rise of temperature. At this stage, either flash over or deflagration will occur. Deflagration results in a fireball and a blast wave when the flame in the compartment transverses the building and ignites the gases outside the building space. A representation of this process is shown in Figure 2.2. Undoubtedly, occurrence of backdraft fire is the main cause of the death of people and the collapse of building, yet meager experimental research has done on backdraft.

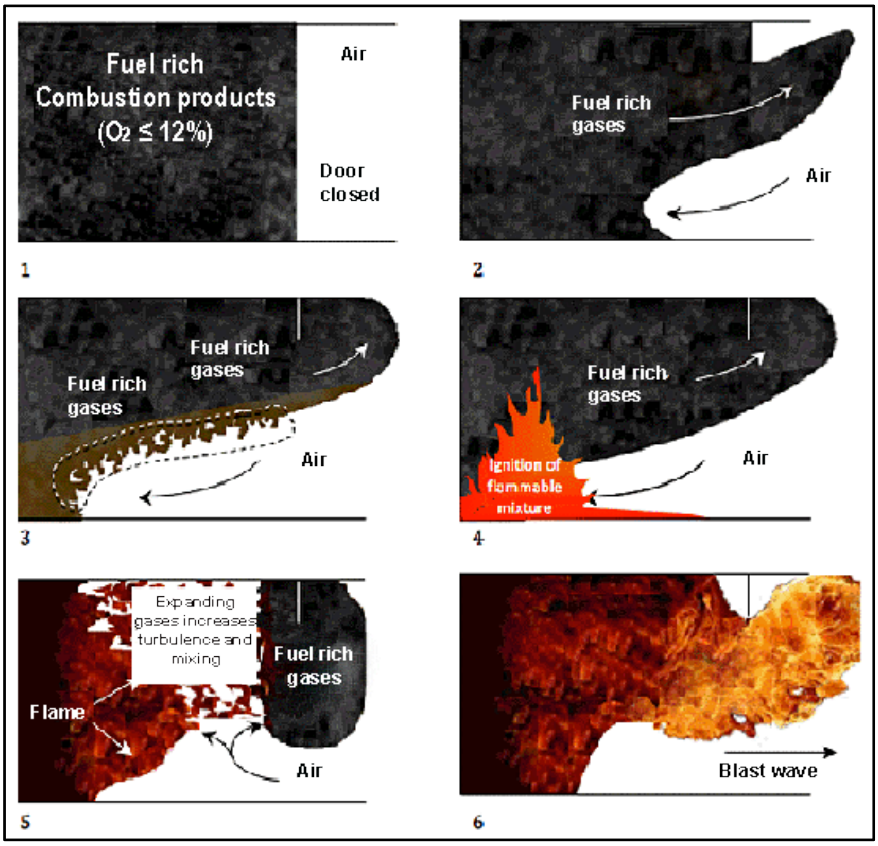


Figure 2.2: The development of a backdraft.

Source: Stages in Fire Behavior III. [Online Image]. (2014). Retrieved from http://www.tathrafirebrigade.org.au/index.php?option=com_content&view=article&id=82&Itemid=173

The purpose of the Fleischmann's preliminary study on the backdraft phenomena (as cited in Grimwood, 2003) was to develop a basic physical understanding of backdraft phenomena. His research was divided into three phases namely, exploratory simulations, gravity current modeling, and quantitative backdraft experiments. Gravity current is used to describe the interaction between two different densities of two fluids. The interaction occurs in such a way that a vertical interface exists between the fluids and cause the heavier fluids to flow horizontally beneath the lighter fluids. In backdraft fire, gravity current is often referred as air-track when the smoke is pushing out of an opening or doorway with a clear interface below which clear air is entering the compartment of structure. As the gravity current of cold fresh air enters the compartment, it will generate turbulence. The turbulence mixes oxygen and the remaining unburned fuel creating a flammable gas mixture, eventually resulting a fireball that is commonly termed a backdraft.

White (2000) had put forward his own theory for this phenomena, he termed as high-pressure backdraft. According to his theory, he explained that the air entered through various opening on the structure causes excessive pressures to form within the building compared to outside of the building. Increasing speed of the wind eventually increase the pressure within the building. The high pressure formed within the building pushes against the wall of the building and the walls were to collapse. The resulting release of energy would be catastrophic.

2.3 THE BACKDRAFT PHENOMENON

Fire triangle or also known as combustion triangle, is the fundamental principle to understand how backdraft will occur. The triangle represents the three necessary components for most fire behaviors to occur: heat, fuel, and an oxidizing agent (usually oxygen). When all these three ingredients are present and are mixed in the right proportion or they react to each other, fires occur at this point.

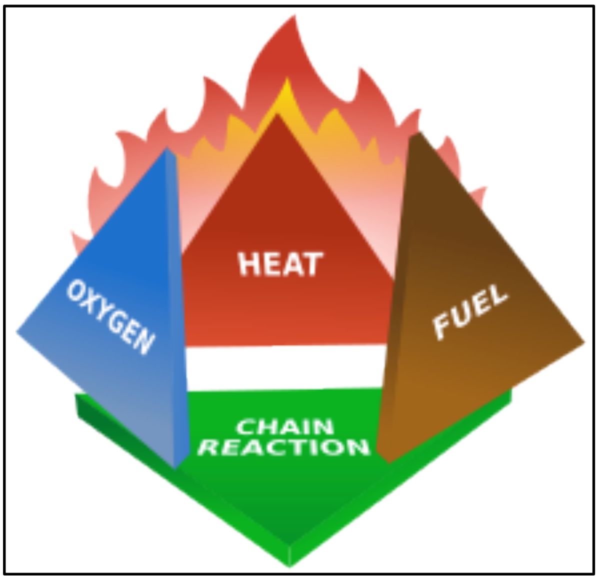


Figure 2.3: The Fire Triangle

Source: The Fire Triangle. [Online Image]. (No Date). Retrieved from https://en.wikipedia.org/wiki/Fire_triangle

In the case of backdraft, the oxidizer or the oxygen is missing in the fire triangle. Under limited ventilation, the fire does not produce smoke but the remaining and hot fuel continues to produce large amount of pyrolysis gases. In the event of reduced quantity of oxidizer and increased amount of pyrolysis gases, flammable mixture formed is brought to above the upper flammable limit (UFL) or upper explosive limit (UEL), which has a high potential of self-ignition with the condition of sudden introduction of oxygen by an opening.

As burning continues with time, heat buildup in the compartment, pyrolysis continues and the flaming combustion will exhaust while the room is filled with unburned pyrolysis products. In Fleischmann et al. (1994) experiment, they found that the mass fraction of unburned fuel that is higher than 10% is crucial to create the condition for a backdraft to occur. But later in his doctorial thesis (as cited in Lambert, 2013), he writes that the mass fraction of unburned fuel should be higher than 15%. This critical value for the mass fraction of unburned fuel for a backdraft to occur is then supported by Drysdale (1998).

At the point where an opening of the compartment is opened, i.e. a door or a window, the hot smoke escape through the opening while fresh and cool air will flow in to the compartment through the opening. The opposite flow of different densities of hot and cool air creates a current called gravity current.

Between these two layers of air, a flammable mixture is formed and when this flammable mixture meets an ignition source, the mixture is ignited and flame spreads towards the opening. Smoke and unburned pyrolysis are pushed outward towards the opening by the high pressure within the compartment, which then creates a higher rate of mixing of two flows resulting in creating a large quantity of flammable mixture. Ignition of gases outside the compartment creates a fireball that is typically associated with backdraft (Gojkvic, 2000).

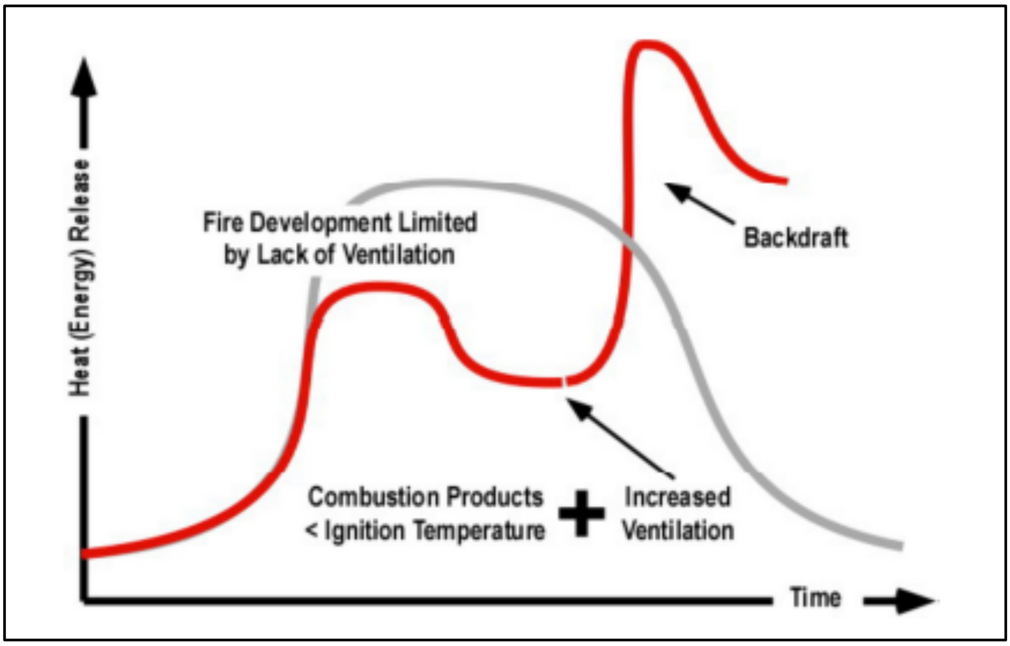


Figure 2.4: An under-ventilated fire can lead to backdraft when vented.

Source: Backdraft: fire science and fire fighting, a literature review. [Online Image]. (2013). Retrieved from http://www.cfbt-be.com/images/artikelen/LAMBERT_backdraft.pdf

A reduced scale experiments was done by Tuomisaari (1997) and he found out that no backdraft occurs when the door is opened too early as the amount of unburned pyrolysis products is not enough for a backdraft to occur. He concluded that keeping the enclosure airtight can reduce the risk of backdraft, however, in practice this may not be always possible.

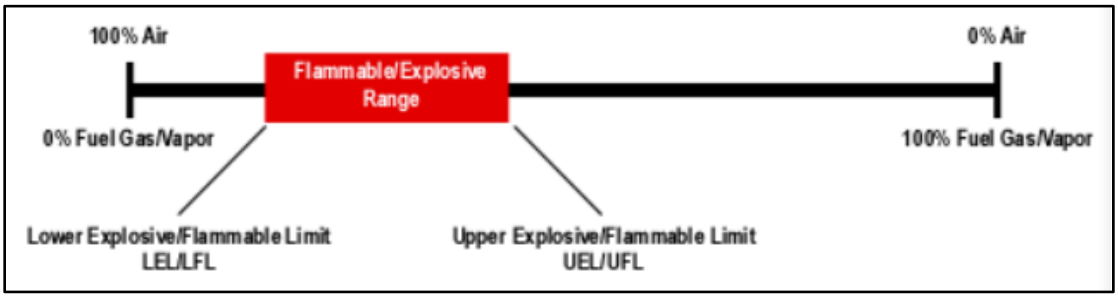


Figure 2.5: Explosive/Flammable Range

Source: Smoke Burns. [Online Image]. (No Date). Retrieved from http://www.cfbt-us.com/pdfs/SmokeBurns.pdf

In order for backdraft to occur, fuel and oxygen must be within the explosive or flammable range. Lower Explosive Limit or Flammable Limit (LEL/LFL) is the minimum concentration of fuel vapor in air to support burning, which means combustion will not occur if the concentration of fuel vapor is below this limit. Upper Explosive Limit or Flammable Limit (UEL/UFL) is the highest concentration of fuel vapor in air that causes fire. Above this limit, fire is vigorous and consumes oxygen at a higher rate causing the oxygen to be insufficient to support combustion. Flammable range lies between LEL/LFL and UEL/UFL.

To sum up, for a backdraft to occur, there are some conditions that are necessary to be met. The contributing factors are as below:

- Excessive amount of hot fuel remained in the compartment.
- High temperature to ignite the fuel.
- Low concentration of oxygen.
- The concentration of gas or vapor is above Upper Explosive Limit (UEL) and/or Upper Flammable Limit (UFL).
- Sudden introduction of oxygen, or in another word, increased ventilation.

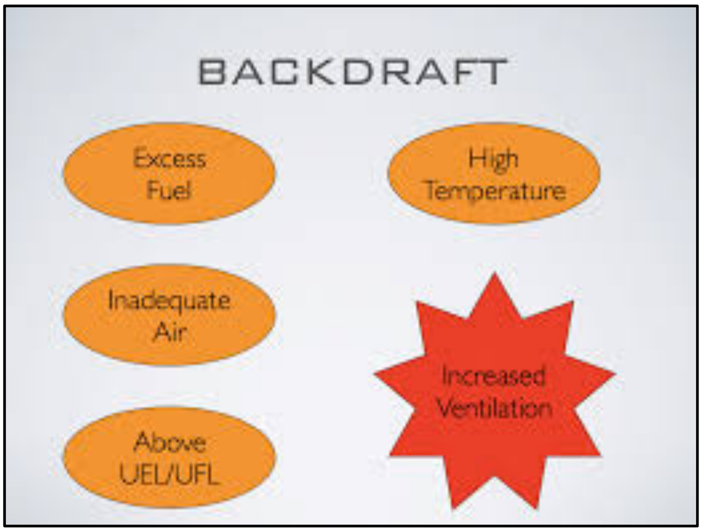


Figure 2.6: Contributing Factors of Backdraft.

Source: Backdraft. [Online Image]. (2012). Retrieved from http://firerescuesafety.blogspot.my/2012/03/backdraft.html

2.4 FLASHOVER

Occurrence of flashover is one of the extreme fire behaviors, which the rapid progression of the fire presents a noteworthy threat to both people and the building. Most of the definitions of the flashover concept are very much the same. By definition, a flashover can be explained as "the sudden involvement of a room or an area in flames from floor to ceiling, which is caused by thermal radiation feedback." (Flatley, 2005).

This radiation is able to raise all the contents in the compartment to their ignition temperature.

National Fire Protection Association (NFPA) (1995) defined flashover as "a transition phase in the development of a enclosure fire that the surfaces are exposed to thermal radiation, reaching ignition temperature nearly simultaneously and fire spread expeditiously throughout the compartment.

According to ISO 13943 (2008), flashover is defined as stage of fire transition to a state of total surface involvement in a fire of combustible materials within an enclosure.

Both definitions state that flashover is a transition period, which lies between the growth and fully developed stage. Flashover is categorized into two main types, namely, radiation induced flashover and ventilation-induced flashover. Contributing factors of flashover occurrence can be easily identified first by understanding the physics of flashover.

2.5 Phenomenon of Flashover

To further understand how a flashover can occur, stages of enclosure fire development will be discussed briefly. The unique characteristics of each stage affect the behavior of the fire differently. Compartment fire development is comprised of four stages: incipient, growth, fully developed and decay (refer Figure 2.7). For the case of flashover, it is not considered as one of the fire development stages but it is a rapid transition between the growth and fully developed stages.

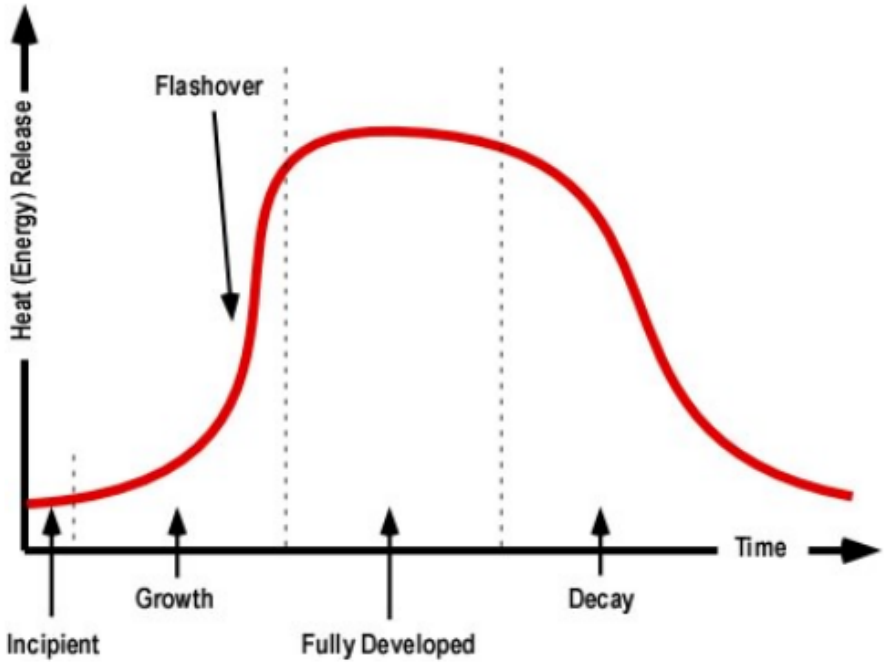


Figure 2.7: The Development of Enclosure Fire

Source: Fire Development in a Compartment – Part II. [Online Image]. (2005). Retrieved from http://www.firehouse.com/article/10508990/fire-development-in-a-compartment-part-ii

2.5.1 INCIPIENT STAGE

In this stage, the fire triangle is completed. All the essential elements for a fire to occur are present, which are: heat, fuel and oxygen. Fire burn freely with the requirements of 21% concentration of oxygen, sufficient amount of fuel is available and the ignition source is found in the compartment (Kraszewski, 1998). Once the development of incipient fire has started, the fire is known as fuel-controlled fire as the incipient fire is dependent on the characteristics and the configuration of the fuel involved. Fire continues, as the amount of oxygen is sufficient. Smoke and radiant heat generated from the fire is spread through convection and continues the process of pyrolysis. Transfer of energy increases the overall temperature in the compartment and the hot gases started to spread horizontally across the ceiling. Fire continues to grow more quickly if and only if the amount of oxygen is sufficient and at this point, the fire has moved beyond its incipient stage (Ed Hartin, n.d.).

2.5.2 GROWTH STAGE

When an incipient fire is increased to the point where the heat is started to transfer from the fire and the pyrolysis of adjacent fuel source by combustible products begins, the growth stage of fire development is started. However, in order for the fire to continue growing, adequate amount of oxygen within the compartment is important, as well as additional fuel is made available for burning (Ed Hartin, n.d.). As heat release rate from the fire increases, temperature of the compartment also increases at this stage.

2 layers of gas temperatures within the compartment are formed with a hot layer extending down from the ceiling and a cooler layer down towards the floor. Hot gases create a high pressure within the compartment and push down this layer of gas within the compartment and out through openings. Due to the lower pressure of cooler gases outside the compartment as compared to the high pressure of hot gases within the compartment, an inward movement of air is created. As fire continues to growth, the heat is transferred through radiation, replacing convention heat transfer method, which then increases heat flux at floor level.

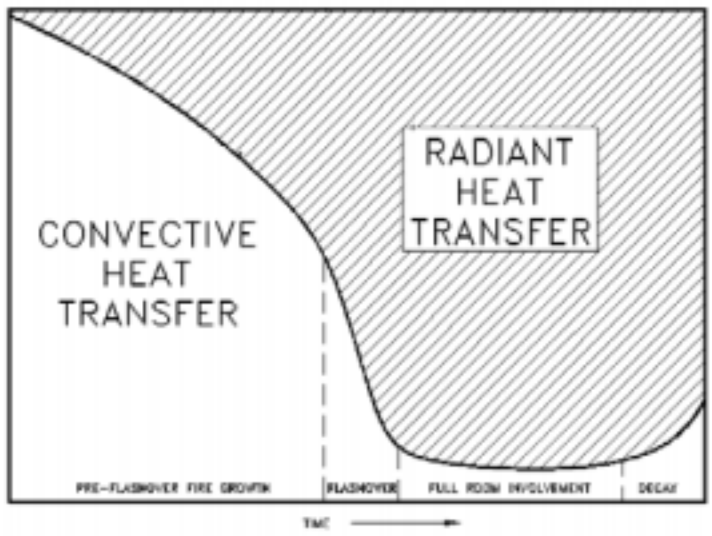


Figure 2.8: Relationship of Heat Transfer Mechanisms within a Compartment Fire.

Source: The Current Knowledge & Training Regarding Backdraft, Flashover, and Other Rapid Fire Progression Phenomena. [Online Image]. (2007). Retrieved from http://ssem.eku.edu/sites/ssem.eku.edu/files/gorbett_-_the_current_knowledge_training.pdf

2.5.3 TRANSITION STAGE - FLASHOVER

Flashover is not one of the stages in fire development but it is the sudden transition from growth stage to a fully developed fire, involving a rapid transition to a state of total surface involvement of all combustible material within the compartment (Ed Hartin, n.d.). During flashover, fire spreads rapidly throughout the space and burning gases are pushed out through the openings in the compartment at an ample velocity.

Flashover can either be fuel or ventilation controlled. Both flashovers are end with a fully involvement of compartment, but the initiating events make them different from each other.

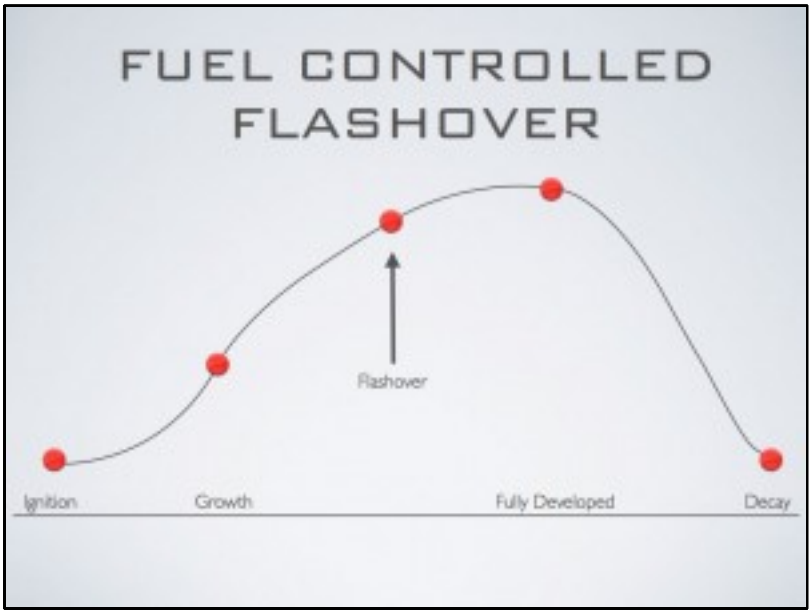


Figure 2.9: Fuel Controlled Flashover

Source: Modern Fire Behaviors; Stages of Fire Development. [Online Image]. (2014). Retrieved from http://firefightertoolbox.com/wp-content/uploads/2015/02/MFB-3.pdf

A fuel-controlled flashover is one of the traditional fire behavior, which the heat release rate and growth were primarily controlled by fuel. The amount of oxygen and fuel are enough to support the burning; additional fuel to sustain combustion after the event of flashover. Increased ventilation does not affect the fire development. This kind of fire is able to naturally grow and transition into a fully developed fire. During flashover, the temperature in the compartment rise rapidly, reaching 600°C. the radiated heat flux will increase as well.

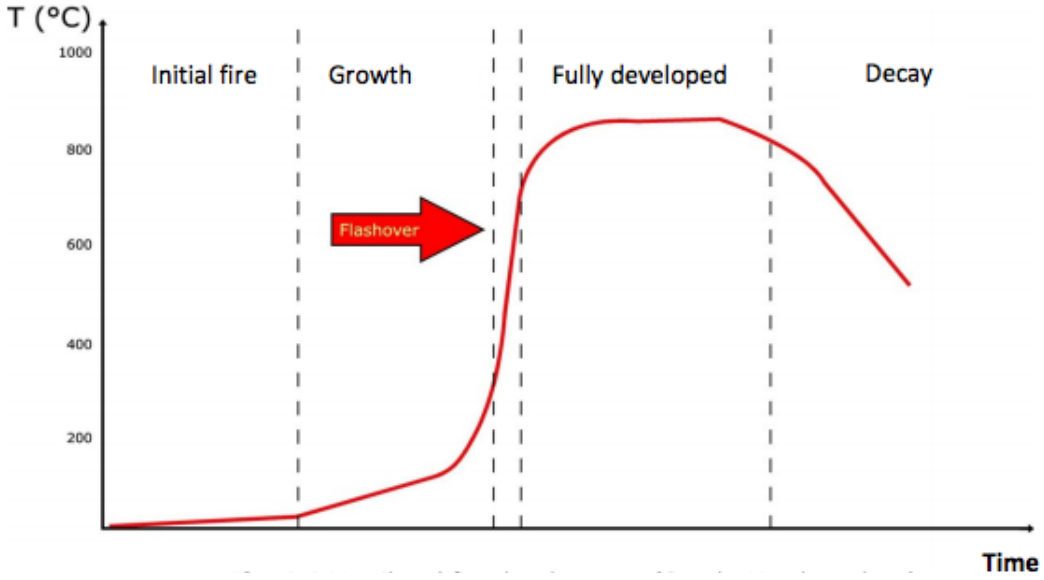


Figure 2.10: Ventilated Fire Development.

Source: The Most Familiar Form of Rapid Fire Progress: Flashover. [Online Image]. (2014). Retrieved from http://www.cfbt-be.com/images/artikelen/art_06_ENG.pdf

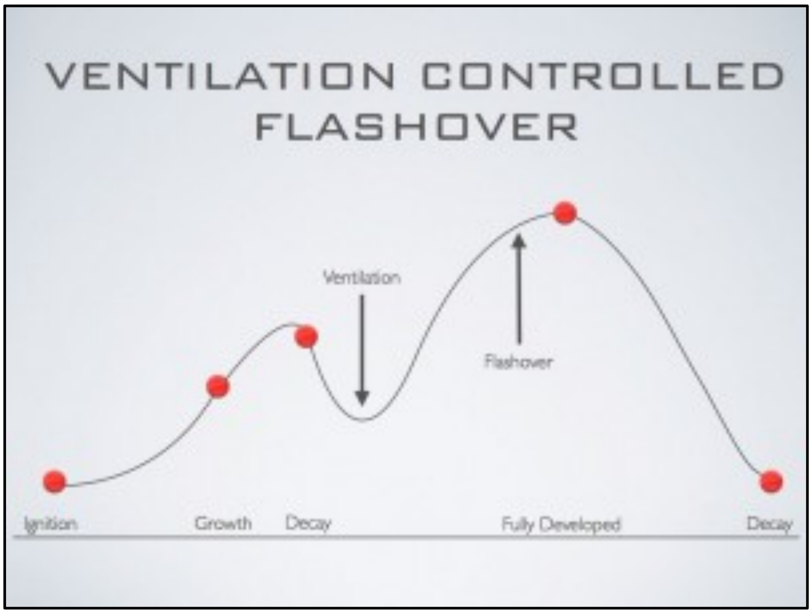


Figure 2.11: Ventilation Controlled Flashover

Source: Modern Fire Behaviors; Stages of Fire Development. [Online Image]. (2014). Retrieved from http://firefightertoolbox.com/wp-content/uploads/2015/02/MFB-3.pdf

Ventilation controlled flashover is quickly becoming common and it is known as a modern fire behavior, which the fires heat release rate and growth are controlled by the available oxygen. Both types of ventilation share a common feature that is the amount of fuel is adequate to drive the fire, meanwhile, the main difference between fuel and ventilation controlled flashover is there is an insufficient ventilation profile for ventilation controlled flashover. This type of flashover creates a much dangerous situation. Increased ventilation has an immediate and enormous effect on the fire development. In figure 2.12 the red line represents the flashover under ventilated condition and the fire will stop burning as a result of fuel and oxygen exhaustion. In contrary, the yellow line depicts the ventilation-induced flashover with temperature rises slowly at the beginning stage and eventually starts to decline. Combustibles in the compartment continue to paralyze with sufficient amount of heat, creating a high amount of flammable gaseous fuel. Creating an opening changes ventilation profile and this extra ventilation will in turn fan the fire. Smoke inside the compartment will ignite and the fire reaches a fully developed stage in a matter of second. The speed of occurrence of ventilation-induced flashover is determined by the amount of ventilation added.

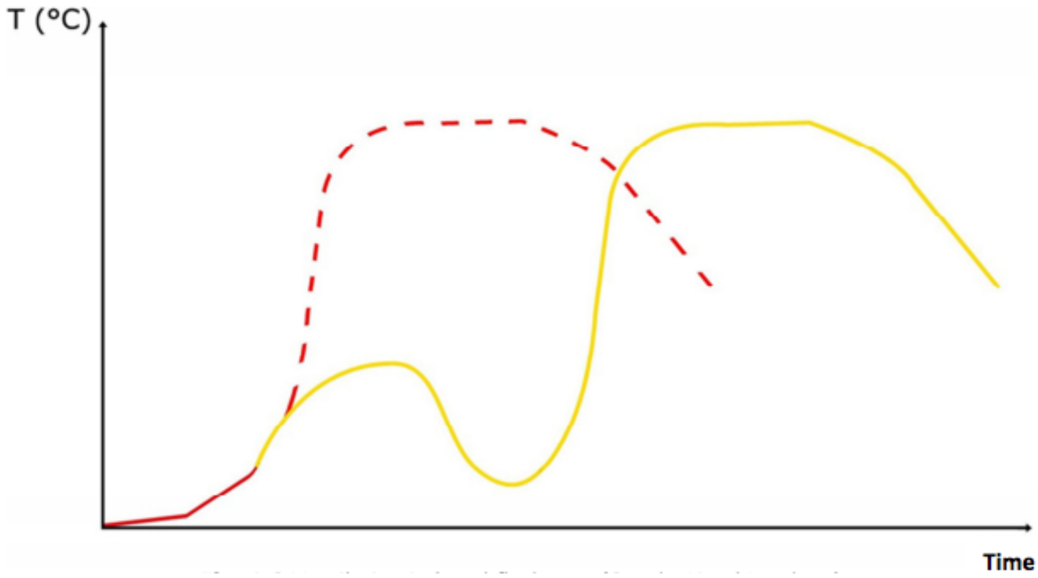
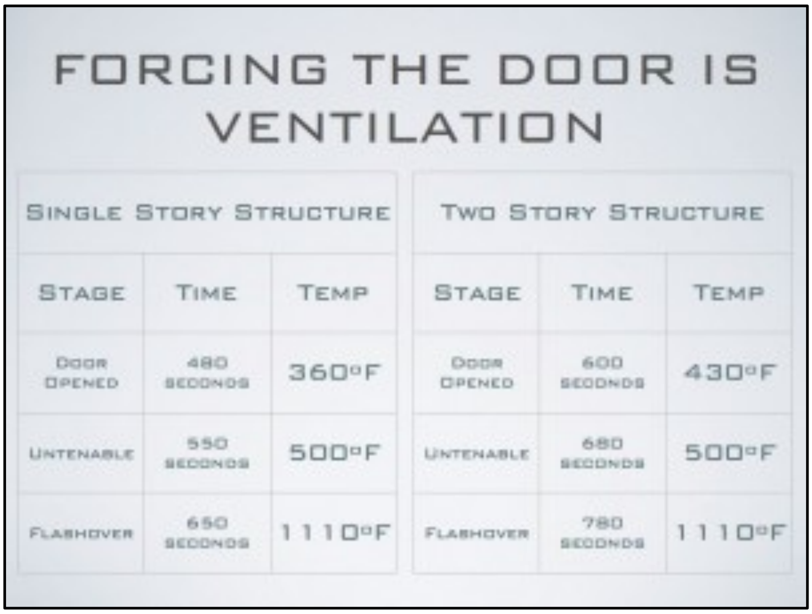


Figure 2.12: Ventilation Induced Flashover

Source: The Most Familiar Form of Rapid Fire Progress: Flashover. [Online Image]. (2014). Retrieved from http://www.cfbt-be.com/images/artikelen/art_06_ENG.pdf

A study entitled Impact of Ventilation on Fire Behavior in Legacy and Contemporary Residential Construction done by Underwriters Laboratory (UL) revealed that various types of buildings lead to different fire behaviors (as cited in CHRISFSW, 2011). UL burned different types of building in order to obtain information on how fire behaves over period of time. The results obtained are used as a benchmark to avoid being caught in ventilation controlled flashover (Figure 2.13).



Single Story Structure			Two Story Structure		
Stage	Time	Temp	Stage	Time	Temp
Door Opened	480 seconds	360°F	Door Opened	600 seconds	430°F
Untenable	550 seconds	500°F	Untenable	680 seconds	500°F
Flashover	650 seconds	1110°F	Flashover	780 seconds	1110°F

Figure 2.13: Types of building and the Fire Behaviors.

Source: Flashover. [Online Image]. (2011). Retrieved from
http://www.fireservicewarrior.com/2011/12/flashover/

Doubtlessly, from Figure 2.13, the conditions deteriorated and flashover took place roughly within two minutes after the door is opened, which acted as a source of oxygen. This timeframe is important as to predict the time of flashover occurrence that put us in a position to get seriously injured or killed.

Another important key of recognizing flashover and understanding the mechanism enable the prediction of probability of flashover can take place. Indicators of potential or impending flashover are listed as below:

Growth Stage	Radiation Induced Flashover *Fuel Controlled Burning Regime*	Ventilation Induced Flashover* Ventilation Controlled Burning Regime
Building	Flashover can occur in all types of buildings! Consider compartmentation, fuel type & configuration, vent profile, & thermal properties	Most fires beyond the incipient stage are vent controlled when the fire department arrives! High fire load with high heat of combustion increases risk of vent induced flashover
Smoke	Increasing volume, darkening color, & optical density, lowering level of the hot gas layer	Increasing volume, velocity, turbulence, darkening color, & optical density, low and lowering level of the hot gas layer
Air Track	Strong bi-directional air track (smoke out at the top & air in at the bottom), any air track that shows air movement, increasing velocity & turbulence	High velocity & turbulence, pulsing (in & out) air track (which may also be a backdraft indicator)
	Air track indicators are significantly influenced by the location and size of openings	
Heat	Pronounced heat signature from the exterior (thermal imaging camera), observation of pyrolysis, feeling increased temperature (may not provide sufficient warning)	Darkened windows, hot surfaces (doors & windows), high interior temperature
Flames	Flames at the ceiling level of the compartment & rollover (late indicator)	Ignition of fire gases escaping from the fire compartment, isolated flames in the hot gas layer (strong indicator of a vent controlled fire), rollover (late indicator)

Figure 2.14: Indicators of Potential Flashover.

Source: Fully Developed Fires: Key Fire Behavior Indicators. [Online Image]. (2011). Retrieved from http://cfbt-us.com/wordpress/?p=950

It is essential to remember that sufficient fuel and oxygen are the keys for a flashover to occur (Ed Hartin, n.d.). Initial objects that lack of sufficient energy or heat of combustion for ignition, and the heat release rate is not released quickly, flashover will not occur. Birk (as cited in Grimwood, Hartin, Mc Donough, and Raffel, 2005) models the fire development in a hotel room and he determined that closing the all the openings to prevent the room from reaching flashover. Insufficient ventilation causes the fire to enter the growth stage and not reach the peak heat release of a fully developed fire.

2.5.4 FULLY DEVELOPED

Energy release at this post-flashover stage is the greatest yet is limited under ventilation-controlled situation. The average gas temperature within a compartment during a full-developed fire ranges from 700° – 1200°C. Fire spread occurs when hot gases and flames extending from the involved compartment to other combustible materials, for example, furniture. The maximum rate of heat released is dependent on either available ventilation or quantity of fuel. Indicators of potential or impending flashover are listed as below:

Fully Developed Stage	Fuel Controlled Burning Regime	Ventilation Controlled Burning Regime
Building	*Fully developed compartment fires are generally ventilation controlled*	As with growth stage fires, size, construction, and fire load influence fire development. Heat release rate (HRR) in the fully developed stage is largely influenced by the ventilation profile. Increases in ventilation will result in increased HRR.
Smoke		Smoke will darken to darker gray, brown or black. Smoke color is influenced by both what is burning and ventilation (all organic fuels can produce black smoke under ventilation controlled conditions). Height of the hot gas layer is dependent on ventilation, but is likely to drop close to floor level in a fully developed fire.
Air Track		Air track is dependent on the ventilation profile. However, a fully developed fire will generally produce a strong, well defined air track. Velocity of smoke and air movement will be high and smoke discharge will generally be turbulent.
Heat		In this stage of fire development temperature will be at its highest. Intact windows are likely to be blackened and cracked Hot surfaces may be detected using a thermal imager or fire stream. High temperatures will be evident inside the structure, even a considerable distance from the involved compartment.
Flames		Flames will be extending from compartment openings (interior and/or exterior). Flames observed from the exterior may indicate the extent of involvement. Flames will be present throughout the compartment. Flaming combustion extending out of the compartment may be masked by smoke.

Figure 2.15: FBI – Fully Developed Fire.

Source: Fully Developed Fires: Key Fire Behavior Indicators. [Online Image]. (2011). Retrieved from http://cfbt-us.com/wordpress/?p=950

2.5.5 DECAY

Fire enters this stage when the available fuel is consumed or the oxygen amount is limited. At this stage, oxygen concentration to support combustion decreases followed by heat release rate. However, the temperature in decay stage may remain high for a period of time. There are two significant threats: first, the presence of non-flaming combustibles and second, potential for a backdraft when oxygen is reintroduced into the compartment. Figure 2.16 lists the fire behavior indicators for ventilation controlled decay stage.

Decay Stage	Fuel Controlled Burning Regime*	Ventilation Controlled Burning Regime
Building	Fires that enter decay based on fuel limitations often involve contents with limited mass, low heat of combustion, and/or low heat release rate.	Ventilation controlled conditions develop much more readily in highly compartmented and energy efficient buildings. High fire load and fuels with a high heat of combustion increase the potential for vent induced flashover or backdraft.
Smoke	Limited volume, light color, and limited thickness (optical density) and buoyancy. Smoke may or may not be visible from the exterior. Lack of a clearly defined hot gas layer on the interior. ***Note Similarity to Incipient Stage Indicators***	Inefficient combustion results in darkening smoke color and increased thickness (optical density) with the appearance of texture (like velvet). Color (alone) is not a reliable indicator of ventilation controlled decay (despite traditional use of yellow smoke as a backdraft indicator). Raising and lowering of the hot gas layer may be an indicator of extreme ventilation controlled conditions (and potential for backdraft)
Air Track	Air track indicators may be limited to slight smoke discharge from openings in the compartment of origin. Air track indicators may not be visible from the exterior. ***Note Similarity to Incipient Stage Indicators***	Air track is dependent on the ventilation profile. In the decay stage, smoke discharge may be turbulent (early) and less so as temperature decreases (this is really important!). A pulsing (in & out) is a strong indicator of potential for vent induced flashover or backdraft). Duration of pulsations can be quite long, making this a subtle indicator.
Heat	Temperature near ambient (even in the compartment of origin). ***Note Similarity to Incipient Stage Indicators***	As the fire enters the decay stage, temperature is high, but will drop, following heat release rate. While high temperatures have traditionally been considered a backdraft indicator, this is not necessarily the case.
Flames	Combustion is limited to objects near the point of origin. Limited flaming and surface combustion (smoldering).	Flaming combustion is reduced in the decay stage and may cease entirely. However, early in the decay stage flaming combustion may still occur despite low oxygen concentration (due to widened of flammable range at high temperature).

* Fuel controlled decay stage fires may involve a fire that had insufficient HRR to extend to other fuel packages and progress into the growth stage or these fires can involve structural failure and substantial loss of compartmentation. Indicators in this chart are based on the first case, fires limited to contents only.

Figure 2.16: FBI – Decay Stage.

Source: Decay Stage Fires: Key Fire Behavior Indicators. [Online Image]. (2011). Retrieved from http://cfbt-us.com/wordpress/?p=957

2.6 COMPARISON OF FUEL CONTROLLED FLASHOVER AND VENTILATION INDUCED FLASHOVER

In this section, the similarities and the differences of both kinds of flashover are identified and compared. A notable difference that distinguishes both flashovers is the source of the phenomenon. A ventilated fire development is required for a fuel controlled flashover to occur, meanwhile, ventilation induced flashover occurs in the limited-ventilation fire development. Walton and Thomas (1995) explain that, … in the case of fire in open, it is the local fuel concentration that controls the reaction … In ventilation-controlled enclosure fires, the air is deficient and it is then the oxygen concentration that controls the reaction." Figure 2.17 shows the graph of percentage (gaseous) fuel versus temperature.

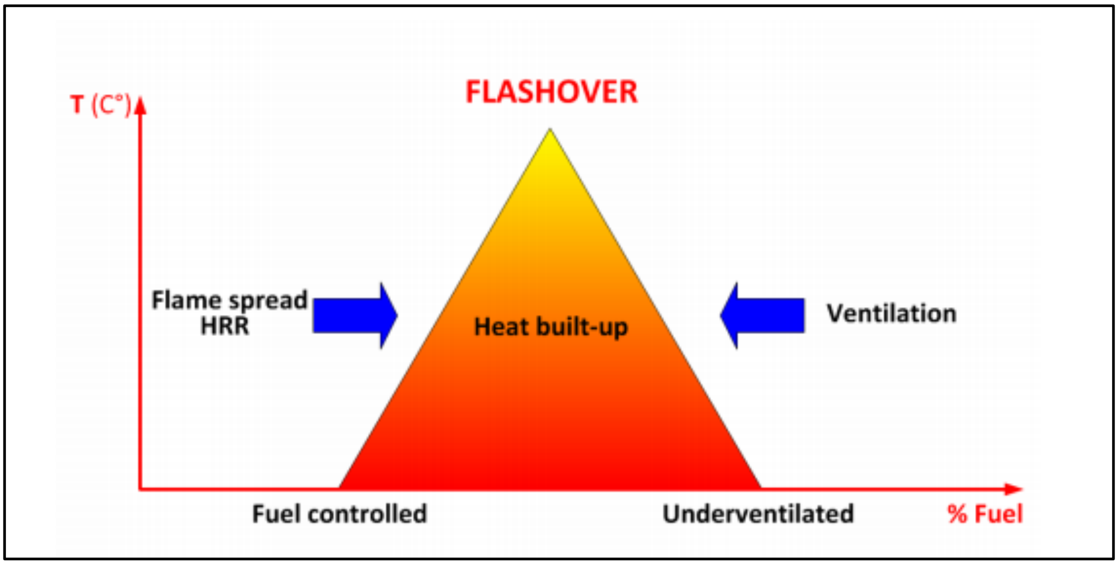


Figure 2.17: Graph of percentage of gaseous fuel versus temperature for both types of flashover.

Source: The Most Familiar Form of Rapid Fire Progression: Flashover. [Online Image]. (2014). Retrieved from http://www.cfbt-be.com/images/artikelen/art_06_ENG.pdf

Beginning of the graph indicates the fire is fuel controlled and limited to a certain surface area. The evolution of fire to flashover is determined by the material involved in the combustion process, parameters such as Heat Release Rate (HRR), the rate of energy released by the material and flame spread, the rate at which flames expand across fuel surfaces (Karel, 2014). Sufficient HRR and flame spread, as well as sufficient amount and sufficient energy is released, allow the flashover to happen.

As fire continues to growth, although sufficient fuel is available, but the air is lacking to support the combustion and this depicts the fire is under-ventilated. Fire will extinguish by itself; yet, fire development will again accelerate if the ventilation is increased. The temperature will rise and heat buildup again within the compartment. Flashover will only happen again if the heat built up in the compartment is high enough. The source of heat buildup is caused by the change in ventilation profile; therefore, the flashover is defined as ventilation induced flashover.

2.7 COMPARING BACKDRAFT AND FLASHOVER

Backdraft and flashover are two different phenomena that most people will confuse of. Backdraft is an explosive event that leads to a fireball; whereas flashover is the result of the sudden involvement of full room in flame (fuel-controlled flashover) or the continuation of fire development after an opening is introduced (ventilation-controlled flashover). The difference between backdraft and flashover is defined by Grimwood et al. (2005) as a “transient” event (backdraft) and a “step” event (flashover). It is important to remember that an under ventilated fire does not always lead to a backdraft, but flashover will occur often.

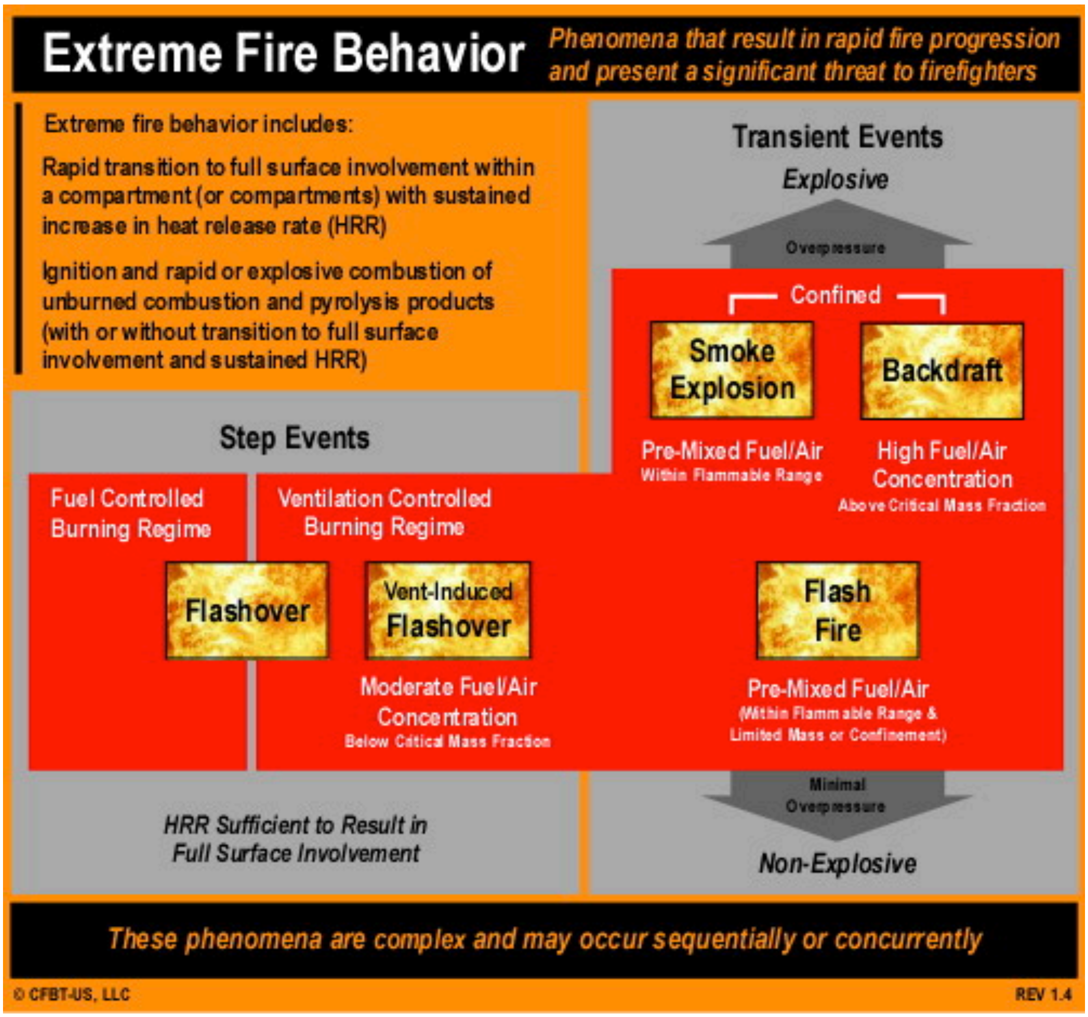


Figure 2.18: Extreme Fire Behavior Classification.

Source: Recent Extreme Fire Behavior. [Online Image]. (2010). Retrieved from http://cfbt-us.com/wordpress/?p=1046

Backdraft and flashover occur at different stages of fire development. Backdraft occurs only when there is smoke in a confined space, which is during the first decay stage of fire development. On the other hand, flashover occurs only in the growth stage of fire development and signals the end of the growth stage.

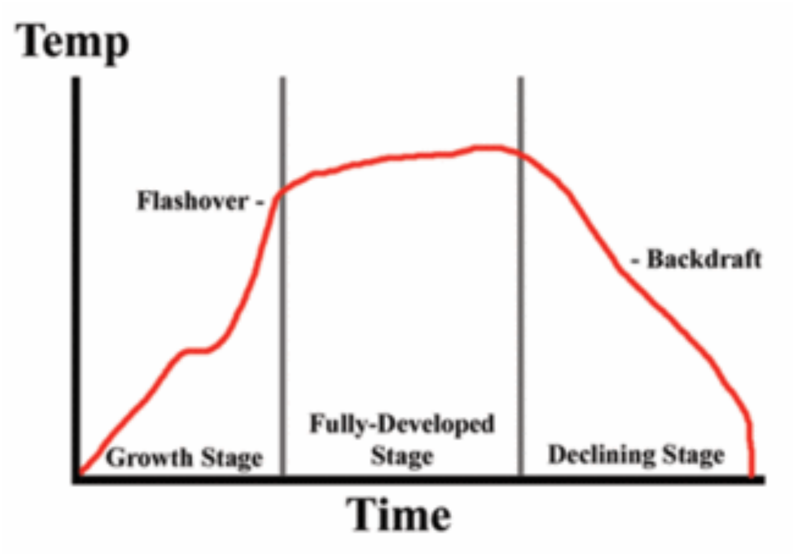


Figure 2.19: Backdraft and Flashover at Different Stages.

Source: Flashover and Backdraft: A Primer. [Online Image]. (2005). Retrieved from http://www.fireengineering.com/articles/2005/03/flashover-and-backdraft-a-primer.html

Contributing factors of a backdraft and a flashover are different. Backdraft is caused by sudden increased ventilation into a confined smoke filled compartment, whereas, a flashover is triggered by heat, which is re-radiated back into burning room and rises the content of the compartment to their auto-ignition temperature.

2.7.1 BACKFDRAT vs VENTILATION INDUCED FLASHOVER

As mentioned earlier, a fireball is associated with backdraft while ventilation induced flashover occurs only an opening of a compartment is created, in which an under-ventilated fire is burning. The development of fire is stopped if the fire has become ventilation controlled before flashover. However, the fire able to continue its development when an opening is made and oxygen becomes available again. Flashover will occur if and only if the ventilation does not limit the fire development in the first place (Lambert, 2013). The extra ventilation of the compartment triggers the flashover. Unlike normal flashover, the phenomenon is the result of a development from a fuel-controlled stage.

Figure 2.20 and Figure 2.21 show the rapid progression of the fire but backdraft is an explosive event while ventilation-induced flashover isn't. The key factor that differentiate a backdraft and a ventilation induced flashover is the heat release rate.

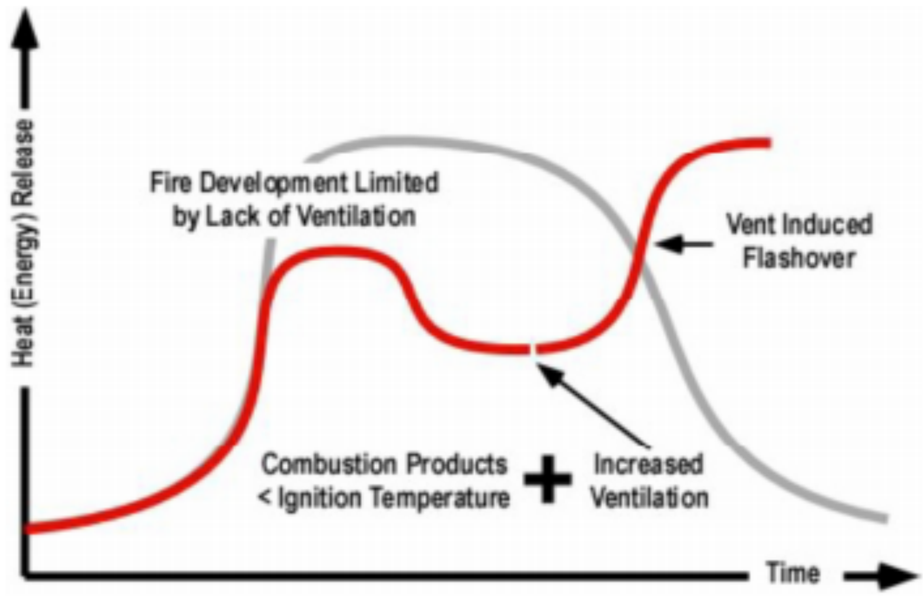


Figure 2.20: Heat Released by Ventilation induced Flashover.

Source: Backdraft: fire science and firefighting, a literature review. [Online Image]. (2013). Retrieved from http://www.cfbt-be.com/images/artikelen/LAMBERT_backdraft.pdf

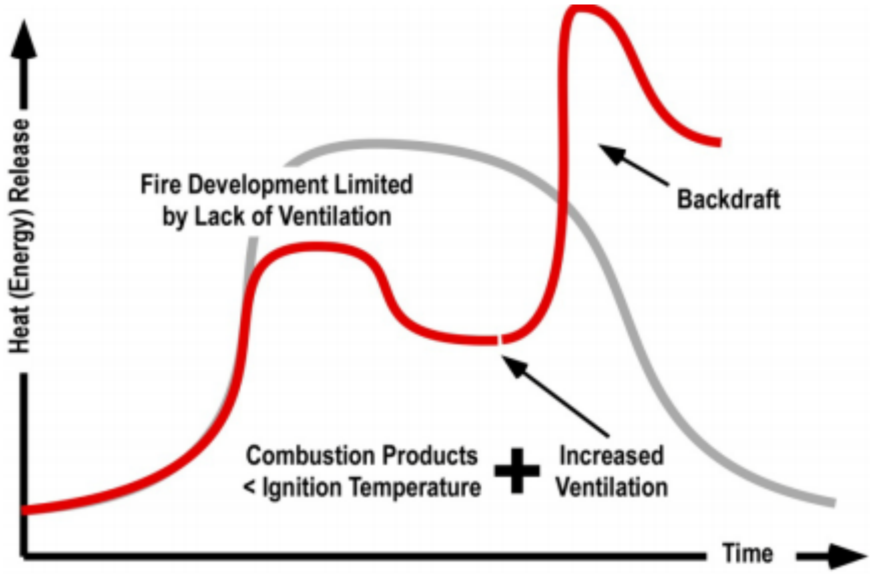


Figure 2.21: Heat Released by Backdraft

Source: Extreme Fire Behavior: Understanding the Hazard. [Online Image]. (No Date). Retrieved from http://cfbt-us.com/pdfs/ExtremeFireBehavior_v2.pdf

A grey zone is claimed to be existed between the two curves (Gojkvic, 2000; E Hartin, 2010). Hartin (2010) considered the two phenomena as limit states. It is difficult to determine what kind of phenomenon that has been occurred and this is due to the grey zone.

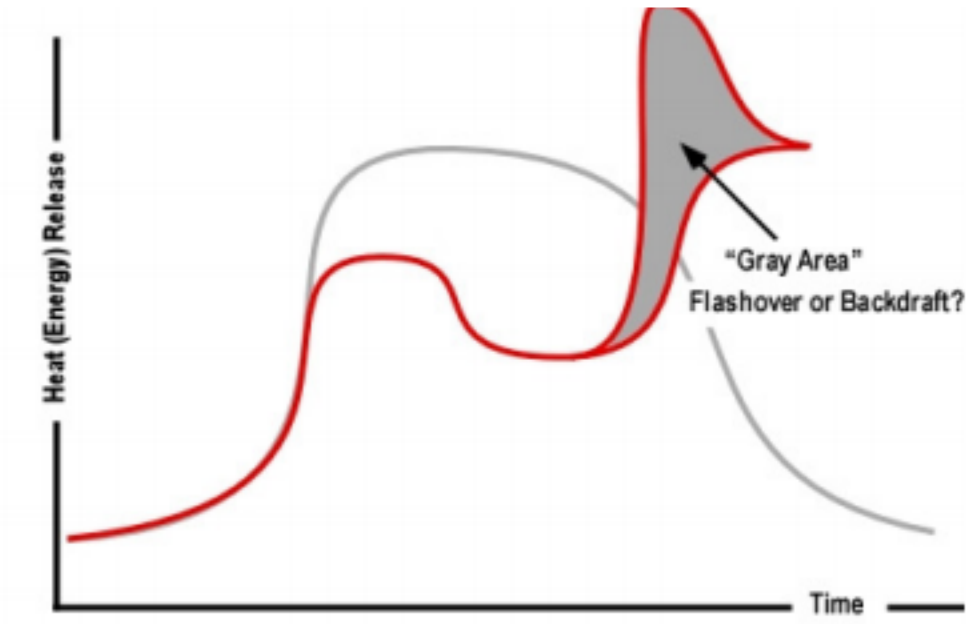


Figure 2.22: The Grey Area.

Source: Recent extreme Fire Behanior . [Online Image]. (2013). Retrieved from http://cfbt-us.com/wordpress/?p=1046

2.8 VENTILATION CONTROLLED FIRE HAZARD

Numerous fire service publications and training manuals have documented the dangerous consequences of ventilation-controlled fire; nevertheless, little research has been done in the area of ventilation-controlled fire, particularly backdraft (Fleischmann et. al., n.d.). A comparison between the decline of the numbers of structural fires and the decline of the number of fire death at structure fires shows that both declines are interrelated, in other words, the drop in firefighters death may have been a result of the reduction in numbers of fires (Fahy, 2002). Deaths due to traumatic injuries while firefighters operating inside the structures were increased over the period of the study. Nearly all of these fatalities inside structure fires were the outcome of smoke inhalation or asphyxiation, burns, or internal trauma (Fahy, 2002). The death rate for the major causes of these traumatic injuries were presented in Figure 2.23. In this section, the hazards presented by ventilation-controlled fire are discussed in contemplation of reducing the fatality or injuries caused by ventilation-controlled fire.

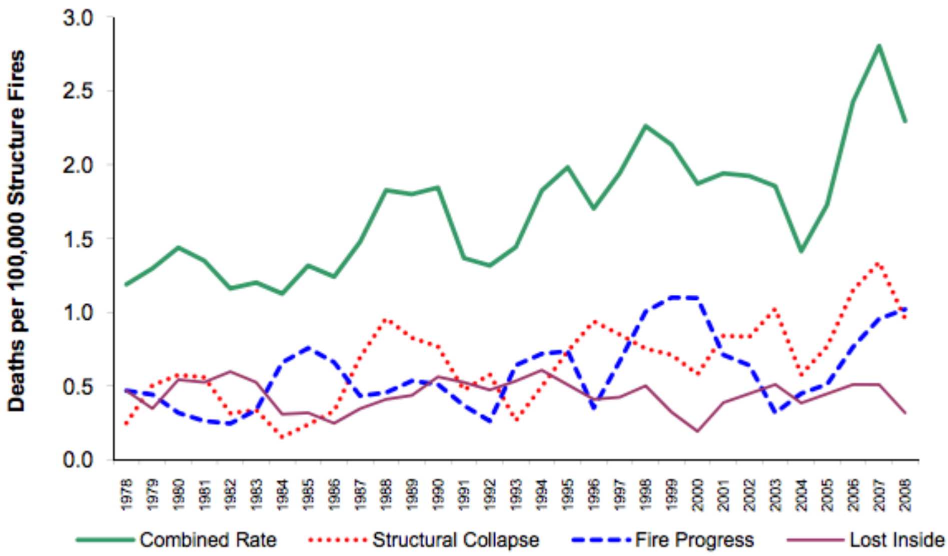


Figure 2.23: Death Rates for the Three Major Causes of Fatal Injuries from 1977 - 2009.

Source: U.S Fire Service Fatalities in Structural Fires, 1977 - 2009. (2010).

One of the dominant hazards posed by ventilation-controlled fires is the increased potential of releasing huge amount of toxicants. It is commonly reported that most fire victims die from smoke inhalation, or smoke inhalation and subsequent burns (as cited in Abdulaziz & Aljumaiah, 2012). The fundamental description and classification of the impaired effects of exposure to toxic smoke and heat in fire is done by Purser (2002):

1. Vision impairment resulting from obscuring smoke and painful caused by irritant smoke and heat on eyes.
2. Respiratory tract pain and breathing difficulties caused by inhalation of irritant and hot smoke.
3. Lung inflammation

4. Unconsciousness due to inhalation of toxic gases
5. Skin burns or hyperthermia.

Asphyxiate gases are gases that reduce or prevent oxygen uptake in cells that leads to unconsciousness and death. The common asphyxiate gases produced during a ventilation-controlled fire are Carbon Monoxide (CO) and Hydrogen Cyanide (HCN). In spite of that, it is crucial to consider that low oxygen levels and high carbon dioxide level in a fire environment significantly enhance the effects of asphyxiate gases (Abdulaziz & Aljumaiah, 2012).

The leading cause of death from fire gases is carbon monoxide, which its effect on human has been long recognized (as cited in (Abdulaziz & Aljumaiah, 2012). Carbon monoxide is the primary product of inefficient combustion; therefore, concentration of carbon monoxide found across all under ventilated fire is high. Carbon monoxide inhaled will combine with hemoglobin to form carboxyhaemoglobin (COHb), which eventually causes reduction in oxygen uptake in human body. Once COHb concentration reaches 30% to 40% in human body, incapacitation and loss of consciousness is predicted to happen (Abdulaziz & Aljumaiah, 2012). Another fatal toxic gas that is emitted during a under-ventilated fire is hydrogen cyanide (HCN). Comparing to CO, HCN is the product of inefficient combustion of fuel containing nitrogen. Although HCN is not as commonly produced as CO in compartment fires, yet, its toxicity is 25 times higher than CO, making it one of the component of fire toxicity hazards in compartment fires (Abdulaziz & Aljumaiah, 2012).

Apart from toxic gases generated under ventilation fires produce excess pyrolysis products and flammable gases that present in the form of smoke that poses a significant hazards to firefighters. As reported in Fahy's research (2002), 24 fatal cases out of 78 cases of firefighters death while operating inside a structural fires were due to the rapid progress of the fire, backdraft or flashover.

Figure 2.24: Fire Triangle: Fuel Rich.

Source: Smoke Burns [Online Image]. (No Date). Retrieved from http://www.cfbt-us.com/pdfs/SmokeBurns.pdf

Referring to the fuel-rich fire triangle, the heat of the fire is producing more fuel vapor than the fire can consume, also, incomplete combustion due to the restriction of oxygen produces flammable gases such as carbon monoxide. When a compartment fire is ventilation control, any changes to the ventilation profile will cause the fire development to increase and the fire spreads to the readily available fuel present in smoke. This leads to the life-threatening extreme fire behavior phenomenon that has a high potential of lives claiming for firefighters and building occupants: ventilation induced flashover or backdraft.

Two scenarios of which firefighters must be fully aware are:

Scenario 1

Combustion gases are not escaping after the door is opened for fire that is still burning within a compartment, incoming air will mix with the gases and form an explosive mixture. Auto ignition will occur and flame will spread back into the compartment together with fresh air that results in rapid-fire growth.

Scenario 2

Fire in the compartment has almost died out can create a more dangerous situation. There is a high potential for ignition of explosive mixture due to the entry made by firefighters by disturbing and exposing an ignition source. Total flame engulfment may occur and this is defined as a "delayed backdraft" (Generic Risk Assessment: Flashover, Backdraught and Fire Gas Ignitions, 2009).

In the nutshell, there are distinct differences between backdraft and flashover that must be recognized:

1. Backdraft is an explosive event that leads to a fireball; whereas flashover is the result of the sudden involvement of full room in flame (fuel-controlled flashover) or the continuation of fire development after an opening is introduced (ventilation-controlled flashover).
2. Backdraft and flashover occur at different stages of fire development
3. Backdraft is caused by sudden increased ventilation into a confined smoke filled compartment, whereas, a flashover is triggered by heat, which is re-radiated back into burning room and rises the content of the compartment to their auto-ignition temperature.

After recognizing the differences between backdraft and flashover, as well as their physics of occurrence, hazards presented, especially ventilation-controlled fire, can be identified. Regrettably, firefighters are unaware by the sudden increase in fire intensity and by the moment of rapid-fire progression, firefighters rarely stand a chance of surviving. Consequently, conducting research on backdraft is essential to understand the physics and knowledge of backdraft as well as to perform safer intervention in future

2.9 SUMMARY

In addition of providing foundations for this research, this chapter covers a spectrum of topics relevant to this work. Firstly, a short background, and an overview on definitions made by previous researchers were discussed. This was followed by the physics of fire development that comprised of four stages, namely, incipient stage, growth stage, fully developed and lastly, decay stage. Next, comparison between fuel-controlled flashover and ventilation-induced flashover, as well as the comparison between backdraft and ventilation-induced flashover, enhanced by several researcher's findings (Walton and Thomas, 1995; Gojkvic, 2000; Grimwood et al., 2005; E Hartin, 2010 & Lambert, 2013; Karel, 2014). The final section of this chapter reports on hazards presented by ventilation-controlled fires, mostly affecting the human aspects.

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

This chapter discusses the methodology used in this research and explains how the methodology is applied in this research study. To gain an understanding of the critical condition in determining the occurrence of backdraft fire, a meta-synthesis of two different methods in identifying the critical mass fraction of unburned fuel in the compartment was performed. This research was conducted based on the methodology as it plays an important role in guiding and implementing the research accordingly. The details of the methodology are illustrated and explained in this chapter.

3.2 RESEARCH DESIGN

This research study is designed to be a qualitative research synthesis using meta-analysis approach. According to Turner (1997), a meta analysis is an analysis of the results of original data from multiple studies. The inductive nature of meta-analysis allows us to reduce, compare, and translate interpretive studies, either published or unpublished, as a way of synthesizing knowledge.

Readers of research, policymakers and other interested parties benefit from synthesis of multiple research studies performed by meta analysis as results and usable findings are provided in a single research paper instead of numerous studies that repeat the same subjects. Qualitative meta-analysis does not use statistical methods, but it tries to understand and analyze the meaning of a collection of studies through descriptive narratives (Mike Weed, 2005). New knowledge is gained by comparing different studies across a specific subject area and forming connections, which is not seen in the individual studies. It also aims to formulate useful information about findings and to contribute to existing research by formulating connections among a variety of studies.

From this research design, comprehensive and historical information related to backdraft phenomenon can be obtained with lesser biases as there were some researches conducted by different researchers. However, the information obtained from this type of research design might be incomplete and it is time consuming. The idea of meta analysis is to find patterns of results that may not come to light through one study or even the review of dozen studies (Glass, 1976). In short, Meta analysis able to provide an increased power, precision improvement, to answer questions by several studies and opportunity to solve controversies associated from conflicting claims.

3.3 RESEARCH PROCESS AND PROCEDURE

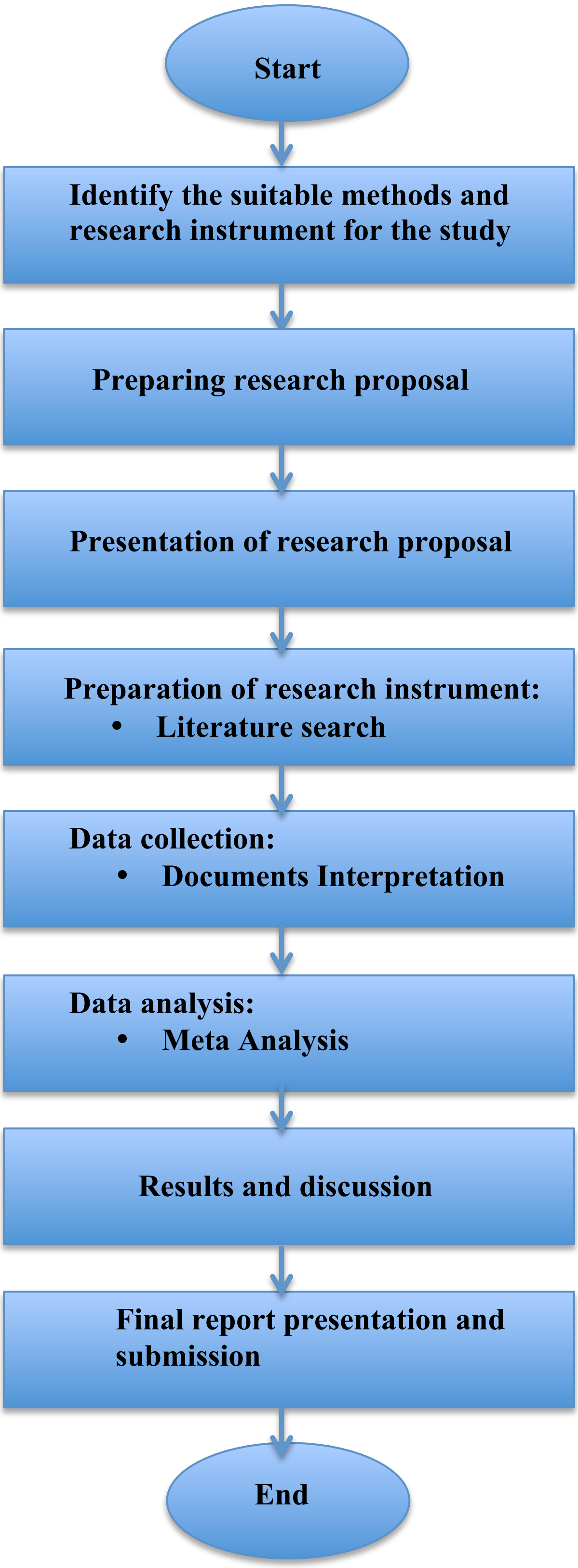


Figure 3.1: Research Process and Procedure

3.4 META SYNTHESIS

When conducting qualitative meta synthesis, basic criteria for the retrieval of data need to be included in the study. Research questions and the phenomenon being studies are the scope for the search. In this research, only researches that conducted experimental test to identify the critical condition in the compartment in order to allow backdraft to take place and used liquid fuel as the source of fuel are included in meta analysis. This ensures the integrity of the synthesis of different studies included.

3.5 RESEARCH INSTRUMENT

The research instrument for this research study is experimental-based research articles and journals that were conducted to characterize the condition in the compartment prior to backdraft occurrence. Different methods of identifying the critical mass fraction of unburned fuel for comparison are:

1. Calculation based on chemical reaction equation (W.G. Weng, & W.C. Fan, 2003)
2. Flame ionization detector (C.M. Fleischmann, P.J. Pagni, & R.B. Williamson, 1994)

3.5.1 ETHICAL CONSIDERATION

The interpretation of the findings is based on data reported in the original studies. For all the me-syntheses the use of academic "search engines" such as Science Direct will be used to find the articles and journals. A list of keywords used for the searches includes: Backdraft, Critical Conditions, Experimental Research, Compartment Fires, and Opening Geometries.

Since this study is a qualitative analysis, which involves content and interpretative analysis of different research papers, therefore, careful consideration and selection are important after a large number of studies have assembled in order to select the right information. There are several factors that need to be considered in this type of research method, including the authenticity of the authorship, credibility of the documents, representativeness of the documents, and lastly, the meaning of the documents.

3.6 DATA COLLECTION

The data collection method for this research study is to search high quality, peer-reviewed research journals that are related to compartment condition that determine backdraft occurrence. The research journals should cover one of the following areas:

- The compartment condition prior to backdraft occurrence.
- The effects of ventilation on the fire behavior in a compartment.

This provides a method of purposeful and meaningful sampling of all the possible research journals and this is a way to set a boundary for the study.

3.6.1 HOMOGENEITY

A meta analysis combined the data from several studies across the same subjects. Several studies can be combined together if and only if they reach nearly the same conclusion (Frans Gieles, 1999).

3.6.1.1 INCLUSION CRITERIA

Studies with similar objectives, conducted experimental test are included in this meta analysis. Only flammable liquid fuel is included. The key parameter that determines the occurrence of backdraft is the mass fraction of unburned fuel in the compartment.

3.6.1.2 EXCLUSION CRITERIA

Researches that were conducted based on mathematical model in predicting the backdraft occurrence are excluded for meta-analysis. Solid fuel as source of fuel for the researches did not qualify for the Meta analysis.

3.6.2 SELECTION OF STUDIES

In the interest of conducting a meta analysis, important preliminary steps that are searching and selection of studies have to be carried out. 11 studies were met the primary criteria of including the essential conditions in formation of backdraft fire. Of these studies, seven (63.6 %) did not qualify for the meta analysis as they focuses on mathematical model in predicting the occurrence of the backdraft, the fuels used in their study are different and the information was not sufficient enough to compare and to conclude the critical conditions for the backdraft to occur. Therefore, of the four studies retained for the meta analysis, preliminary readings of the studies were undertaken, details about the experiment conducted were extracted and tabulated. The basic details about the studies are shown in Table 3.1. They are listed in order of publication. Of the four studies included were published in professional journals (36.4%). Table 3.1 provides the detailed information on the studies included in this research.

Table 3.1: Detailed information included in the meta analysis.

Author(s) Year of Publication Country where the study took place	Title	Objective	Data Collection	Main findings
C.M. Fleischmann et. al. 1994 Canada	Quantitative backdraft experiments	To quantify the backdraft including opening gas flow velocities and compartment pressures.	Half scale experimental tests.	The mass fraction of unburned fuel of more than 10% is necessary for a backdraft to occur. As the hydrocarbons concentration increases, the compartment overpressure increases and the backdraft becomes more severe.
W.G. Weng et. al. 2003	Experimental study of backdraft in a compartment with openings of different geometries.	To characterize conditions in the compartment before backdraft to identify the key parameters. To study the effects of the inlet geometries for any critical values for backdraft. To quantify the severity of deflagration.	Reduced scale experimental tests	Mass fraction of total hydrocarbons is the key parameter in determining the occurrence of backdraft. As the mass fraction of total hydrocarbons increases, the over-pressure in the compartment also increases, and the backdraft becomes more severe. The critical values of the mass fraction of total hydrocarbons determining the occurrence of a backdraft vary with inlets of different geometries.

Table 3.1: Continued

W.G. Weng et. al. 2003 China	Critical condition of backdraft in compartment fires: a reduced-scale experimental study.	To characterize the conditions in the compartment prior to backdraft to seek for the key parameters. To quantify the severity of the deflagration.	Reduced scale experimental test series	The key parameter determining the occurrence of backdraft is the mass fraction of unburned fuel. When the mass fraction of unburned fuel in compartment exceeds a critical value, i.e. 98% backdraft will take place.
J.X. Wu et. al. 2011 China	Experimental research on gas fire backdraft phenomenon。	To identify the effect of different ventilation conditions, the ignition locations, and the gas velocities in the inlet on the occurrence of backdraft fire. To quantify the effect of backdraft by measuring the temperature of the compartment.	Reduced scale experimental test	The ventilation condition is the key parameter determining the occurrence of backdraft fire, followed by the ignition position, and the leakage rate. The smaller the opening, the ignition position is further away from the center of the compartment and the larger the gas leak speed, the more easily backdraft is produced.

3.7 DATA ANALYSIS

Data analysis in this content is the process of systematically applying analytical and logical reasoning to examine and to evaluate data, which support in forming some sort of finding or conclusion. Data analysis includes an interpretation of the researches included; and a comparison of the results obtained by different methods. Qualitative meta-analysis aims to address the research questions focusing on previous studies that had been conducted on backdraft occurrence.

In Chapter 4 Results and Discussion, each of the factors that contribute to the occurrence of backdraft was analyzed. The data is the result of the research journals, and was then analyzed and is presented as a descriptive narrative that describes how the factors contribute to backdraft occurrence.

3.7.1 MASS FRACTION OF UNBURNED FUEL

In this research, only flammable liquid fuel is included. The key parameter that determines the occurrence of backdraft is the mass fraction of unburned fuel in the compartment. In order to characterize the compartment conditions that contribute to the formation of backdraft fire, gas concentration were measured and recorded. The gas concentrations measured were oxygen, carbon dioxide and carbon monoxide and these were done by using probes in the experiments.

The mass fraction for unburned fuel (methane) was calculated based on a chemical reaction equation and also can be obtained through the use of flame ionization detector. For the calculation of mass fraction for unburned fuel, assumptions were necessary as to analyze the mass fraction of unburned fuel are as follow:

- The upper layer of the compartment was well stirred.
- The overall reaction was

$$CH_4 + a(O_2 + 3.77\,N_2) + bH_2O \rightarrow cCO_2 + dCO + eH_2O + fN_2 + gCH_4 \quad (1)$$

The mass fraction of unburned fuel can be calculated by using the following equation:

$$Yf = \frac{M\,CH4}{M\,total} - \frac{4}{11}\,Y\,CO2 - \frac{4}{7}\,Y\,CO \quad (2)$$

Where,

M CH4 = total fuel mass flows into the compartment

M total = total gas mass in the compartment

Yf, Y CO2 and Y CO = mass fraction of unburned fuel, carbon dioxide and carbon monoxide.

3.7.2 SIZE AND LOCATION OF THE COMPARTMENT OPENINGS

Video data were captured using Samsung S6000 digital camera that has 30 frames per second to measure the size of the fireball that burn outside the compartment. The openings were made by using the Bolt system, which allows in change opening with different geometries as shown in Figure 3.2. The sizes of the compartment opening are changed from:

1. 0.05m to 0.25m
2. 0.25m to 0.5m
3. 0.5m to 0.75m

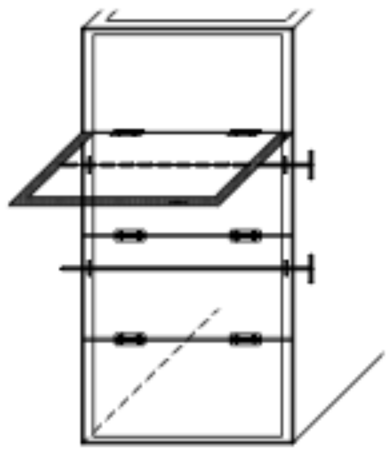


Figure 3.2: Sketch of window structure.

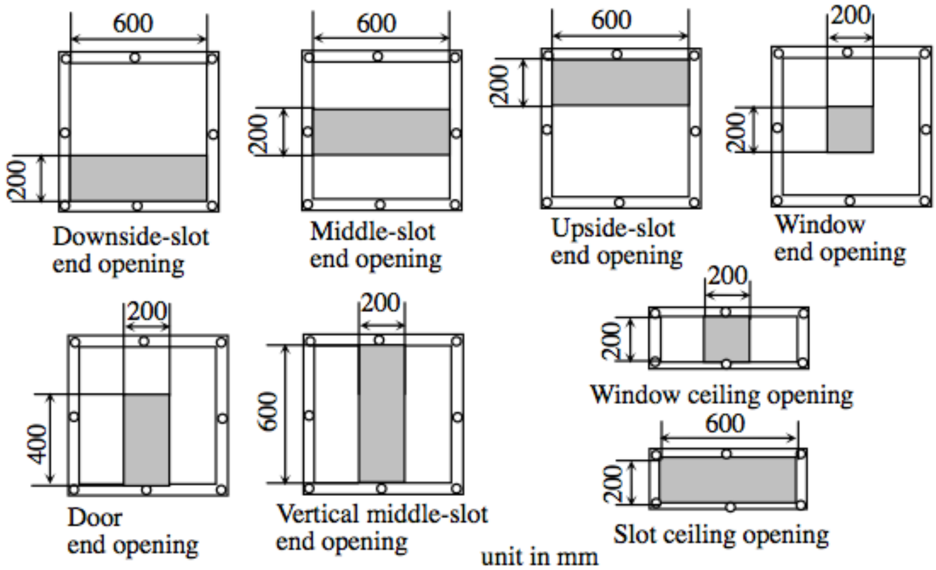


Figure 3.3: Different location of openings for the reduced-scale compartment

3.7.3 LOCATION OF THE IGNITION SOURCE

Three different locations of ignition source are located at the rectangular compartment vertical axis symmetry, as shown in Figure 3.4. To facilitate the discussion for the effect of location of the ignition source, they are called ignition position A, ignition position B and ignition position C respectively.

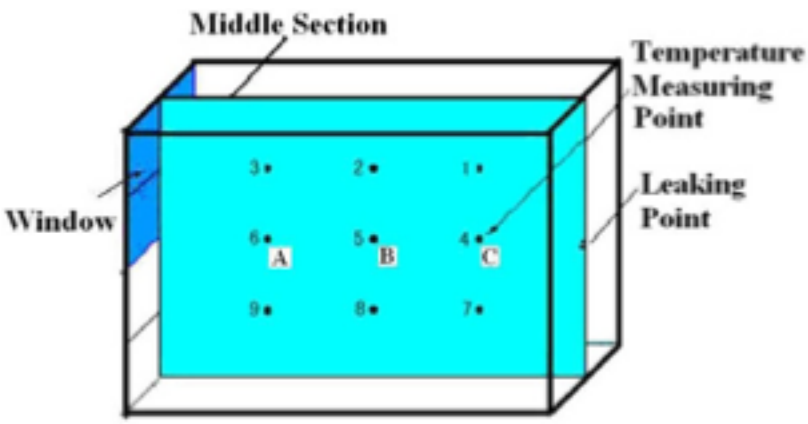


Figure 3.4: Model of reduced-scale compartment showing the location of ignition source.

3.7.4 COMPARTMENT PRESSURE

The compartment pressure was recorded using an electronic pressure transducer that calibrated within the range of -150 Pa to 300 Pa. the pressure pot was mounted in the wall opposite the observation window.

3.9 LIMITATION OF STUDY

Fire behavior is dynamic and it keeps changing due to the changes of interaction between factors in fire environment, especially for compartment fire. Such changes include geometries of houses, synthetic fuel loads and construction material. Each of these changes may not significantly change the effect of fire behavior in a compartment; yet, the all-encompassing effect of these changes has greatly affected the fire behavior.

In this research, due to the limitation of experimental funding and the faulty condition of Fire Detection & Suppression Simulator (Model FDSS-CI), only meta analysis was conducted. However, the difficulty of obtaining the raw data for each of the study also limits this research to use the results of each study included in meta analysis. Fire behaviors in this study correspond to fire scenarios encountered for easily vaporized liquid fuel. Hence, with the hope that further studies on extreme fire behaviors are needed to investigate the influences of other type of combustibles on the fire behaviors, i.e. solid waste.

External factors that also may influence the fire behavior in a compartment such as home geometry, content or furniture in a compartment, different construction materials are not taken into account in this experiment. Thus, the accuracy of the findings is still to be discussed in the future research by focusing and including other external variables with the aim of improving the quality of prediction in backdraft occurrence.

3.9 SUMMARY

This chapter discusses the methodology that was used to predict the temperature distribution during fuel and ventilation controlled flashover and to compare the critical conditions that are necessary for these two types of fire to occur from different studies. Firstly, the framework of the overall study is proposed. Secondly, the details of research design and instrument were discussed followed by the Meta analysis were discussed to conduct this research. Finally, the results obtained are used to explain later in the next chapter.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter presents the findings on four experimental studies, which were conducted with the intended outcome of identifying the critical condition in the compartment for the occurrence of backdraft. The data for this research study is obtained from research journals from a search of Science Direct database. The analysis compares the results obtained from different method conducted by two different groups of researchers that shared the common objective, which is to identify the critical mass fraction of unburned fuel in the compartment in determining backdraft occurrence.

4.2 A GENERAL DESCRIPTION OF COMBUSTION

The interactions between the flames, fuels, and the surrounding can be strongly nonlinearly affecting the behavior and the development of fire. Explanation using compartment fire growth starting with the incipient phase leading into the growth phase that will then transit into flashover, then into the fully developed phase and ends in the decay phase was used to discuss the development of compartment fires. This explanation allows us to obtain useful terminology of each of the phases and also a whole picture of the fire development from the starting point until the end point. The area of interest in an enclosure fire mainly focuses on mass fluxes and heat fluxes to and from the fuel to the surrounding.

Combustion is defined as a heat producing chemical reaction in which fuel combines with oxygen (CFBT-US, n.d.). Fire triangle model, as shown in Figure 4.1, is used to explain the basic process of combustion. This model provides a framework to understand combustion and is useful to understand the changes in compartment fire development and causes of extreme fire behavior phenomena, i.e. backdraft. Formation of fire is possible only with the presence of these three elements and their interaction with each other and the surrounding. In compartment fire, flammable mixture of solid, gas, and vapor are the products under limited ventilation of fuel combustion.

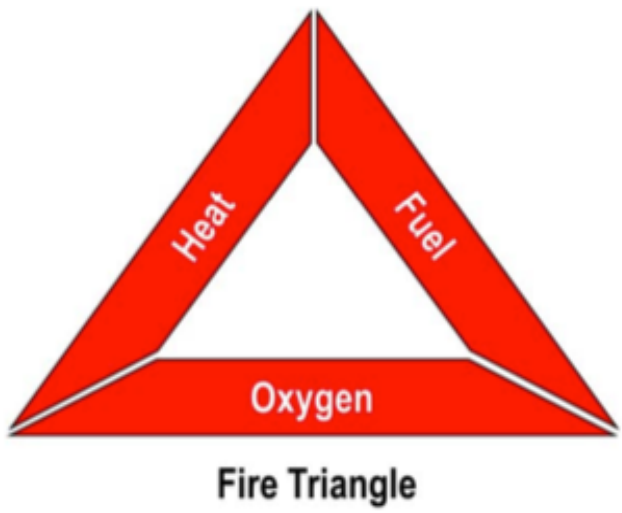


Figure 4.1: The fire triangle.

4.3 A SUMMARY DISCUSSION OF FIRE GROWTH IN AN ENCLOSURE

Compartment fire can develop in different ways, depending on the compartment geometry, the ventilation profile and the fuel type, amount, as well as the surface area. Three important elements (heat, fuel and oxygen) and their interaction with each other and the surrounding are required in allowing fire to start and to develop. According to International Fire Service Training Association (IFSTA), there are four stages of a fire, mainly incipient, growth, fully developed and decay. General description of the fire phenomena that may occur during the development of a compartment fire is as below:

Incipient:

This is the first stage, where heat, oxygen and fuel source interact and combine with each other resulting in fire. This is also known as "ignition" and is represented by a small fire that has no significant negative effect on the environment in the compartment. After ignition, the fire grows and produces increasing amount of heat energy that is caused by the spread of flame. The enclosure of the compartment has no effect on the fire in the early stage because the development of an incipient fire is mainly dependent on the amount and the type of fuel in the compartment, also known as fuel-controlled fire. Air in the compartment is sufficient to support the fire development.

As burning continues, radiant heat warms adjacent fuel and initiate the process of pyrolysis. Besides releasing heat energy, toxic and nontoxic gases and solids are produced. A plume of hot gases and flame rises from the fire and mixes with cooler air in the compartment. Hotter and less dense mass will rise upwards due to the difference in density, or buoyancy. The buoyant flow is referred as a fire plume. When the total mass flow in the plume increases, this causes the plume to reach the ceiling. At this point, the compartment is divided into two distinct layers: (1) a hot upper layer (near the ceiling) consisting of a mixture of combustion products, and (2) a cold lower layer consisting of air. As plume reaches near the ceiling, hot gases start to spread horizontally across ceiling, and the layer of hot gases becomes more obvious. At this point, the fire has moved beyond its incipient phase and with adequate oxygen concentration, the fire will grow more quickly into growth stage.

Growth:

As fire continues to grow, the rate of energy released will continue increase with adequate oxygen concentration. Hot layer extends down from the ceiling and increases in temperature; the heat is transferred by radiation and convection from the hot gas layer to the ceiling and walls that are in contact with the hot gases. Besides heat transfer through radiation and convection, the hot gas layers also radiated to the interior surface of the compartment and its contents. This leads to an increase in burning rate of the fuel and heats up other fuel packages in the compartment.

Pressure increases as the volume and temperature of hot gas layer increases. High pressure in hot gas layer causes it to push down within the compartment and out through the openings. The lower pressure in cool gas layer results in inward movement of air from outside the compartment. The interface of the hot and cool gas layers is known as the neutral plane, where these two layers meet through the opening and the pressure is neutral.

Fire continues through spread of flame or by ignition of other fuel package in the compartment, with a very rapid increase in energy release rates. Flames bend and begins to extend horizontally when it reaches the ceiling. Pyrolysis products and flammable byproducts of incomplete combustion in the hot gas layer will ignite and support this horizontally extension of the flame. This phenomenon is known as rollover and it is an indicator of impending flashover.

The rapid and sudden transition of the fire leads to **flashover**, a transition to a state of total surface involvement of all combustible materials in the compartment, and this transition is destructive and deadly. At this point, the temperature in the compartment reaches 500 °C to 600 °C, the burning gases will accelerate out from the openings at a substantial velocity. However, flashover will not always occur. The two key parameters in affecting the occurrence of flashover are: (1) sufficient amount of fuel to develop flashover conditions, and (2) sufficient ventilation profile to reach flashover. If the ventilation is not enough to reach flashover, the fire may enter the growth stage and not reaching the peak heat release of a fully developed fire.

Fully developed:

At this stage, the energy release at its greatest, flame extends out through the opening and the entire combustible fuel package in the compartment is involved in the fire. Fire continues as long as there is sufficient amount of fuel and oxygen. Unburned gases accumulated at the ceiling level and burned when they leave the compartment, which results in flames showing from windows or doors.

Decay:

As burning continues, the available fuel is consumed, the heat release rate will decrease and fire now becomes fuel-controlled stage from ventilation-controlled stage. However, even though the heat release rate is decreasing, the pyrolysis may continue at a high rate that causes the accumulation of unburned gases in the compartment. If any opening is made at this point, the hot gases flow out through the top of the opening and cold fresh air will flow in through the lower part of the opening to the compartment. The in and out movement of cool fresh air and hot gases may leads to a secondary deadly fire growth, i.e. **backdraft**.

Backdraft:

As a worst case, the movement of fresh air into the compartment and hot gases escape from the compartment causes the mixing of air with the unburned pyrolysis products from the under-ventilated fire. Any ignition sources can ignite the resulting flammable mixture and leads to an explosive or rapid burning of gases, reaching high temperature. Backdraft last for a very short time and usually be followed by a secondary flashover, and again leading to a fully developed compartment fire.

Figure 4.2 shows that red line representing the fire development curve of a fuel-controlled fire, while black line representing the fire development curve of a ventilation-controlled fire. From the graph, when the fire runs out of oxygen and becomes ventilation-limited, the compartment temperature starts to decrease (position 2) as the fire is in the decay stage. At this point, the volume of existing hot fire gases starts to decrease, which results in the decreased of compartment pressure. The lower compartment pressure causes the movement of fresh air outside the compartment being drawn into the compartment through any openings. Due to the insufficient of oxygen to support the burning, the compartment may be full of hot unburned fire gases. Any increased in ventilation at this point (position 3) will cause the fire to quickly transition into fully developed fire, this phenomenon is known as backdraft (position 4).

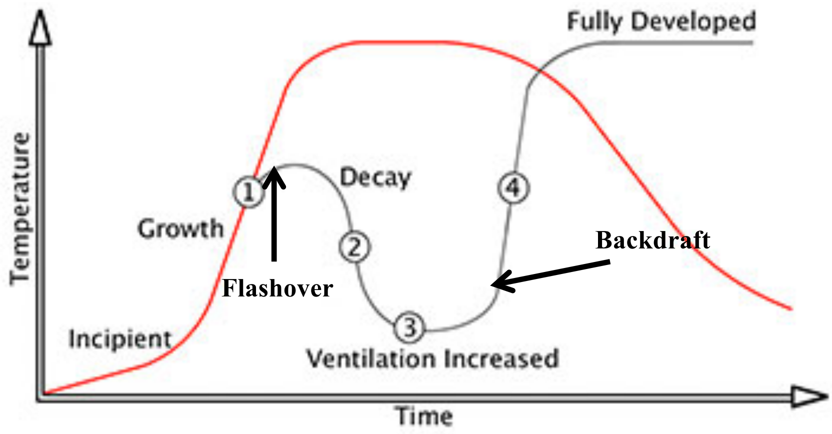


Figure 4.2: Compartment fire development in term of gas temperature.

4.4 MASS FRACTION OF UNBURNED FUEL

The mass fraction of unburned fuel in the compartment can be obtained through the calculation based on a chemical reaction equation (refer Section 3.7.1, equation (1) and (2)) or with the use of flame ionization detector.

4.4.1 CALCULATION OF MASS FRACTION OF UNBURNED FUEL BASED ON CHEMICAL REACTION EQUATION

Table 4.1 shows the summary of results of backdraft experiments in a reduced-scale compartment. Test 7 and Test 8 shows the occurrence of backdraft. From the table, it shows that backdraft took place in the compartment when the mass fraction of unburned fuel in the compartment at mass fractions of unburned fuel of 9.94 % and 12.24 %. 9.94 % of unburned fuel in the compartment leads to occurrence of fireball with length of 0.62 m, while 12.24 % of unburned fuel leads to occurrence of fireball with length of 0.93 m. This shows that the higher the mass fraction of unburned fuel in the compartment, the compartment overpressure and the size of fireball increase.

Table 4.1: Summary of results of backdraft experiments in a reduced-scale compartment.

Run Number	Fuel Flow rate (10^{-3} kg/s)	Species Concentration (%)				Fireball (m)
		YO2	YCO2	YCO	Yf	
1	0.2340	14.6	0.5	0.32	5.73	0
2	0.2385	13.5	0.2	0.40	6.72	0
3	0.1553	14.5	0.3	0.25	7.15	0
4	0.2399	13.6	1.0	0.38	7.29	0
5	0.1606	14.3	0.7	0.23	8.86	0
6	0.1589	14.4	0.4	0.45	9.76	0
7	0.2389	14.5	0.2	0.30	9.94	0.62
8	0.1583	14.6	2.1	0.12	12.24	0.93

The mass fraction of unburned fuel needs to exceed a critical value; only then, backdraft will take place. Compartment overpressure increases along with the increased in mass fraction of unburned fuel, resulting in more severe backdraft. There is a need for the mass fraction of unburned fuel to be equal or more than 9.94 % for a backdraft to occur as shown in Figure 4.3. When the mass fraction of unburned fuel is less than 9.94 %, the flame speed is slow and the compartment overpressure is lesser, backdraft will not occur. In short, in order for a backdraft to occur, enough unburned fuel have to be released in the compartment.

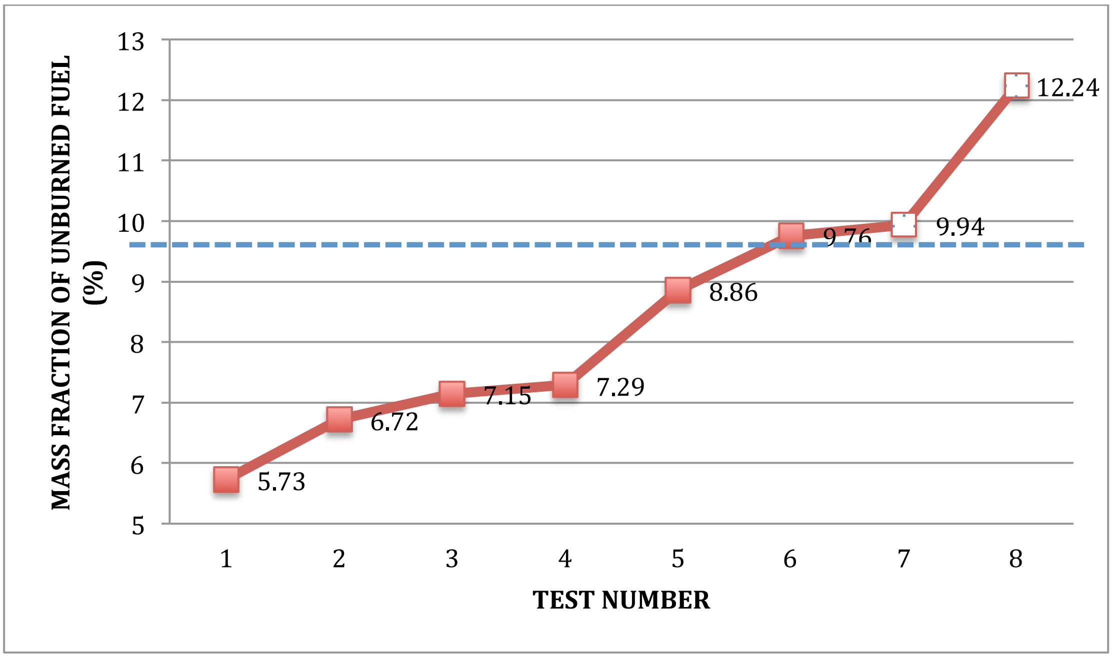


Figure 4.3: Mass fraction of unburned fuel determining backdraft occurrence. Solid symbols representing the non-occurrence of backdraft. Hollow symbols representing the occurrence of backdraft. Dashed line is the estimated critical value of mass fraction of unburned fuel in determining the backdraft occurrence.

A standard flammability diagram is illustrated, in Figure 4.4, to show that the mass fraction of unburned fuel is the key parameter in determining the occurrence of backdraft. The flammability diagram consists of three axes representing the mass fraction of unburned fuel, oxygen and nitrogen.

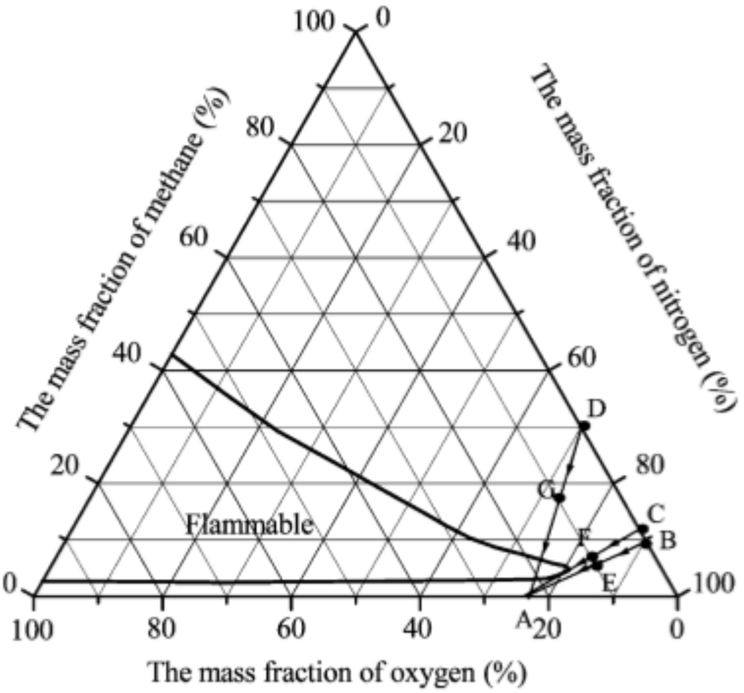


Figure 4.4: Flammability diagram.

Source: Weng, W. G., & Fan, W. C. (2003). Critical condition of backdraft in compartment fires: A reduced-scale experimental study. *Journal of Loss Prevention in the Process Industries*, *16*(1), 19–26. http://doi.org/10.1016/S0950-4230(02)00088-8

The figure shows that all mixtures are flammable, which means explosive. The intersection point between the dashed line and the flammability envelope represents the lower flammable limit (LFL) and upper flammable limit (UFL).

A fire compartment that is depleted of oxygen (i.e. points along the nitrogen axis), the fire is extinguished. However, the space is rich with fuel due to insufficient oxygen in the compartment or incomplete combustion.

Line B-A shows the varying mixture composition that will be created if an opening was made by allowing fresh air to enter the compartment and mix with the composition, but, since line B-A does not intersect with flammability envelope, a flammable mixture will not be created and thus, no backdraft will occur.

Line C-A is at a tangent to the flammability envelope, which means this is the minimum mass fraction of unburned fuel needed to create a flammable mixture once mixed with air. Any mass fraction of unburned fuel greater than Point C will result in the formation of flammable mixture after mixed with fresh air (i.e. Point G and Point F). However, the mass fraction of unburned fuel of different liquid fuel is different. This is because different fuels have different flammability, different LEL and different UEL and can be explained by their respective flammability diagrams.

4.4.2 FLAME IONIZATION DETECTOR IN MEASURING THE MASS FRACTION OF UNBURNED FUEL

Table 4.2 shows the summary of results of backdraft experiments in a reduced-scale compartment. All tests show the occurrence of backdraft, except Test 5. From the table, it shows that backdraft took place in the compartment when the mass fraction of unburned fuel in the compartment at mass fractions of unburned fuel of more then 10 % is necessary for 70 kW fuel flow. The 70 kW fuel flow produces an excellent backdraft with size of fireball of 4 m. However, 72 kW fuel flow produces 10 % of unburned fuel in the compartment unable to trigger backdraft. In another word, the results presented here indicate that the concentration of unburned fuel in the compartment must more than 10 % in order to trigger backdraft. This is because when the concentration of unburned fuel is less than 10 %, the flame spread is slow, and the compartment overpressure is low, and it is more difficult for a backdraft to take place. The compartment overpressure increases along with the increase of concentration of unburned fuel, hence, resulting in more severe backdraft.

Table 4.2: Summary of results of backdraft experiments in a reduced-scale compartment.

Test Number	Fuel Flow (kW)	Species Concentration (%)				Fireball (m)
		YO2	YCO2	YCO	Yf	
1	68	0.12	0.003	0.04	0.22	4
2	69	0.12	0.003	0.04	0.19	4
3	70	0.12	0.002	0.04	0.22	4
4	71	0.11	0.003	0.04	0.20	4
5	72	0.09	0.005	0.07	0.10	0
6	72	0.11	0.004	0.06	0.12	2
7	72	0.11	0.003	0.05	0.16	3
8	73	0.12	0.003	0.04	0.19	4

4.4.3 COMPARISON OF DIFFERENT METHODS IN IDENTIFYING THE CRITICAL MASS FRACTION OF UNBURNED FUEL IN DETERMINING BACKDRAFT OCCURRENCE.

It is clear that despite of the methods used to identify the critical mass fraction of unburned fuel in the compartment to allow backdraft to take place, the critical value for the mass fraction of unburned fuel must be equal to or more than 10 %. The mass fraction of unburned fuel is the key parameters in determining backdraft occurrence, in which 98 % backdraft will occur if exceed the critical value.

The peak pressure and the mass fraction of unburned fuel are interrelated. The peak pressure and the size of the fireball increase with the increase of mass fraction of unburned fuel, resulting in a more severe backdraft. Hence, the greater the mass fraction of unburned fuel, the greater the intensity of backdraft.

In order to quantify the severity of backdraft, Table 4.3 shows the summary data of the mass fraction of unburned fuel and the peak pressure in the compartment.

Table 4.3: Summary data of the mass fraction of unburned fuel (calculation based on chemical reaction) and the peak pressure in the compartment.

Mass Fraction of Unburned Fuel (%)	**Peak Pressure**
5.73	0.66
6.72	0.97
7.15	1.01
7.29	1.26
8.86	1.46
9.76	2.74
9.94	4.31
12.24	7.79

From Figure 4.5, it can be clearly seen that the mass fraction of unburned fuel (Yf) increases with the increase in fuel flow. When the fuel flow rate is high, Yf in the compartment is high, eventually, it is easier to contribute to the occurrence of backdraft. However, from Figure 4.6, the Yf does not show the increasing trend along with the increase in fuel flow. Yf increased from 69 kW fuel flow to 70 kW fuel flow, and decreased to 71kW fuel flow, further decreased to 72 kW fuel flow. The possible reason behind is that an opening was made too early at this fuel flow, causing lesser-unburned fuel is produced in the compartment. As there is no enough of unburned fuel remained in the compartment, and thus, no backdraft takes place. Steady increase in Yf at fuel flow of 72 kW to 73 kW. The fuzzy trend of concentration of oxygen, carbon dioxide and carbon monoxide shows that they do not contribute to determine the occurrence of the backdraft.

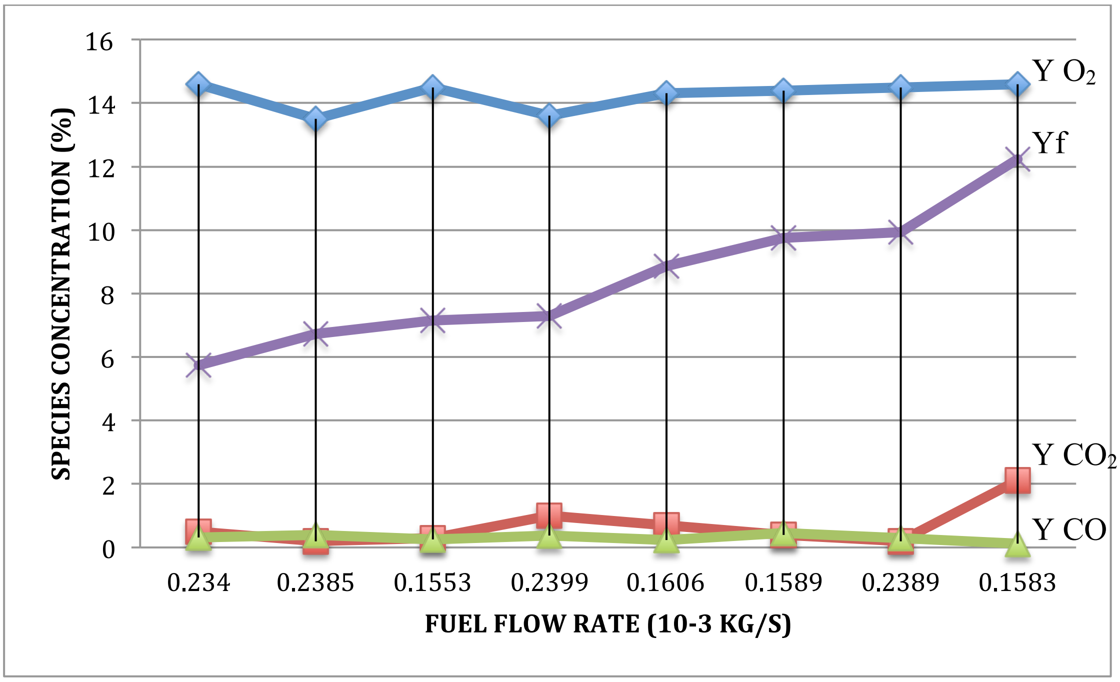


Figure 4.5: The relationship between species concentration and fuel flow rate.

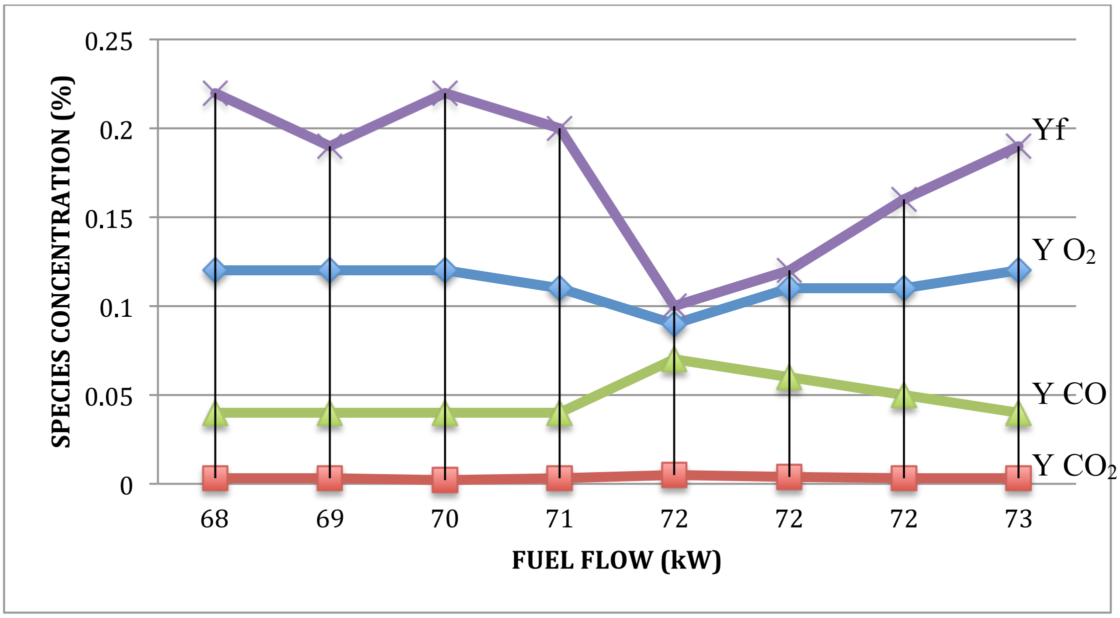


Figure 4.6: The relationship between species concentration and fuel flow.

The relationship between the mass fraction of unburned fuel and peak pressure in the compartment is shown in the Figure 4.7. From the graph, it shows that when the mass fraction of unburned fuel increases, the peak pressure in the compartment increases. In another word, the greater the mass fraction of unburned fuel, the greater the intensity of backdraft.

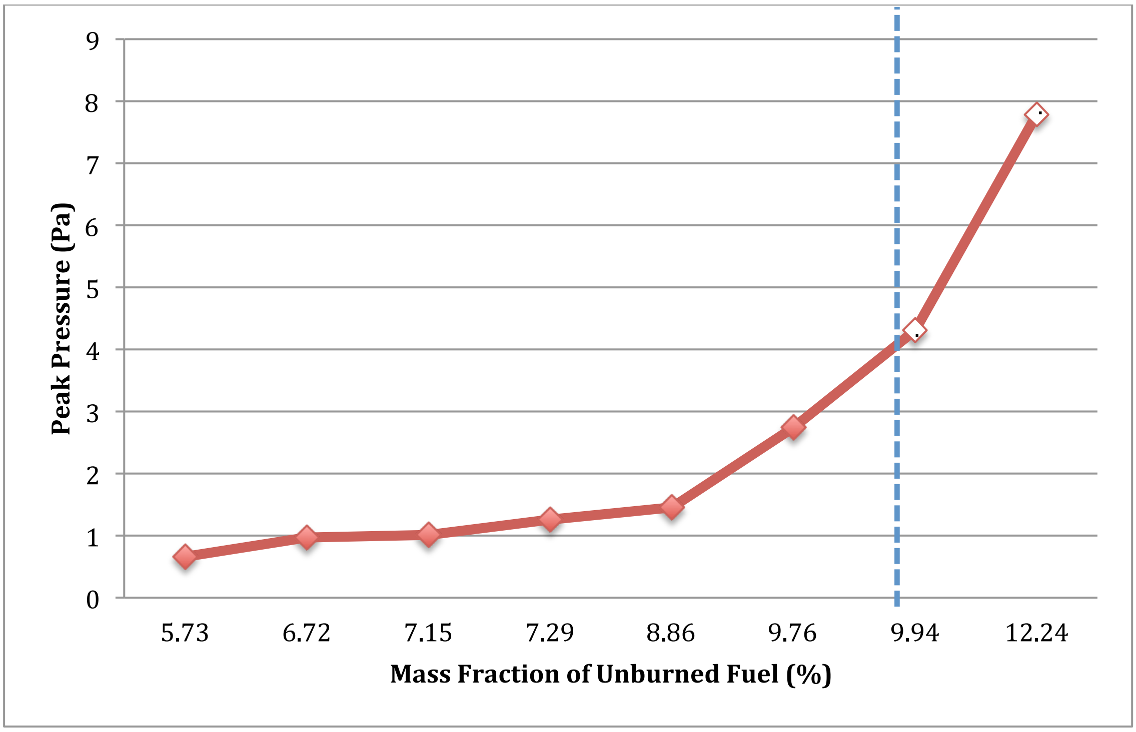


Figure 4.7: The relationship between the mass fraction of unburned fuel and the peak pressure in the compartment. Hollow symbols representing the occurrence of backdraft. Dashed line is the estimated critical value of mass fraction of unburned fuel in determining the backdraft occurrence.

4.5 SIZE AND LOCATION OF THE COMPARTMENT OPENINGS

From Figure 4.8, the window openings are changing in different geometries:

1. From 0.05 m to 0.25 m
2. From 0.25 m to 0.5 m
3. From 0.5 m to 0.75 m

It is clearly shown from Figure 4.8 that backdraft phenomenon is obvious when the window openings change from 0.05 m to 0.25 m or from 0.25 m to 0.50 m; meanwhile, there is no backdraft when the window opening is changed from 0.50 m to 0.75 m. The reason behind is that during the initial large window opening, the primary combustion is sufficient, which means the fire is under fuel-controlled, oxygen is sufficient to support the fire growth, the limiting factor is the amount of fuel. One of the condition for a backdraft to occur is the fire must be oxygen-exhaust with sufficient amount of unburned fuel in the compartment, so there is no backdraft occurrence for a large window opening. In the meantime, when the window opening changed from 0.05 m to 0.25 m or changed from 0.25 m to 0.50 m, the primary combustion produces a significant amount of incomplete combustion products. In another word, the fire changes from fuel-controlled to ventilation-controlled. When fresh air enters through the opening, second combustion takes place and temperature rise significantly. So, it can be concluded that it is easier for a backdraft to occur in a compartment with a small opening change than in a compartment with a large opening change.

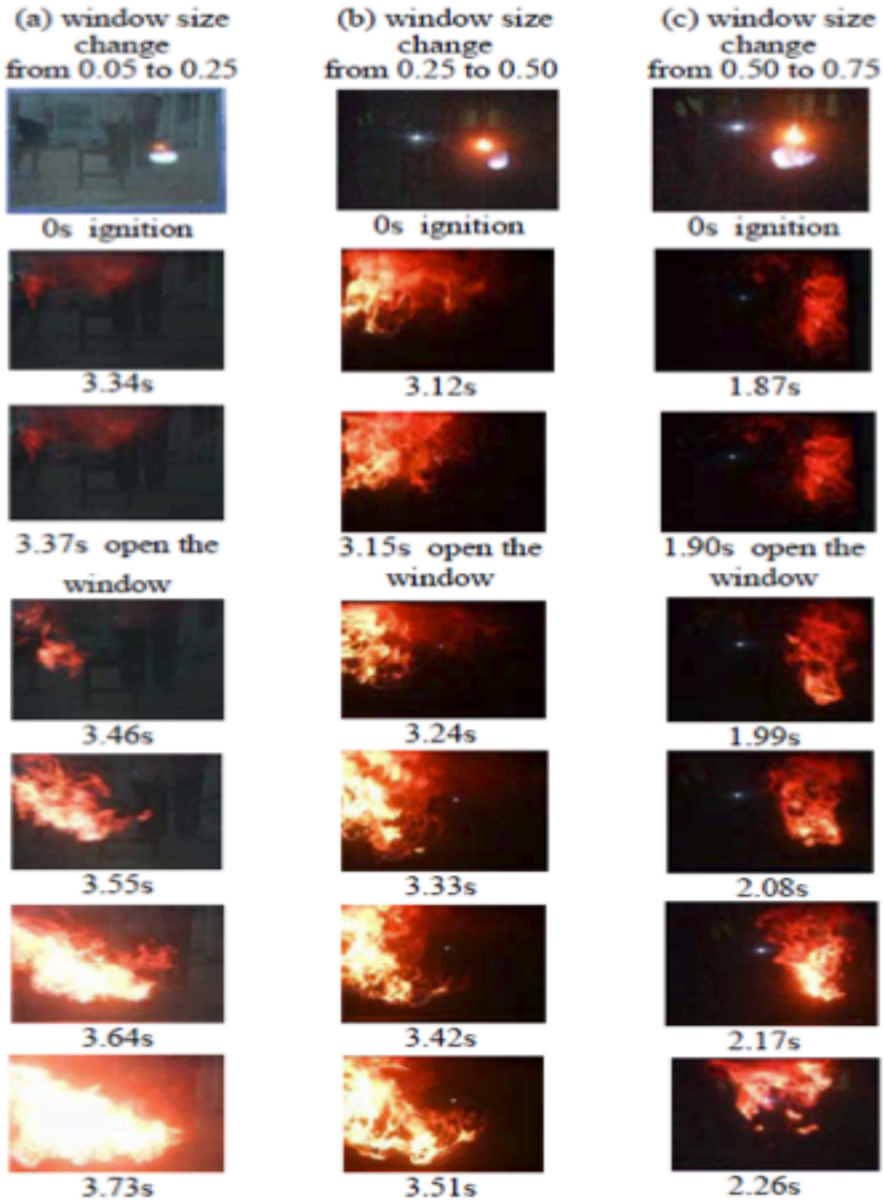


Figure 4.8: Influence of different openings on backdraft.

The behavior of compartment fire is dependent on the openings available of the compartment. Once burning is started, the fire needs enough oxygen concentration for continued development. In compartments with limited openings, which are closed or very small opening areas, the fire soon becomes oxygen-limited and may self-extinguish or burns at a slow rate depending on the availability of oxygen. During the growth stage, before the fire becomes ventilation-controlled, the openings act as an exhaust for the hot gases to escape from the compartment, and this leads to slower fire growth as thermal feedback is released into the atmosphere. However, the geometry of the openings becomes an important parameter affecting the fire growth when the fire is under ventilation-controlled. The size and type of the opening will result in different flow pattern and this will have a major influence of the movements of the smoke (unburned fuel) and air.

4.5.1 THE RELATIONSHIP BETWEEN DIFFERENT TYPE OF OPENING LOCATION AND THE MASS FRACTION OF UNBURNED FUEL IN THE COMPARTMENT

Figure 4.9 shows that the mass fraction of unburned fuel determining the occurrence of backdraft in a reduced-scale compartment with different location of and type of openings. Different type of the openings and its location will affect the critical values of the mass fraction of unburned fuel. Table 4.4 shows the estimated critical values of the mass fraction of total hydrocarbons determining the occurrence of backdraft for eight different type of openings. The results showed that the higher the location of the center of the openings, the lower the critical value of the mass fraction of unburned fuel, the more difficult for a backdraft to occur. Also, it is difficult for a backdraft to occur in a compartment with a large opening than with a small opening, as the critical value for the large opening is lower than the small opening.

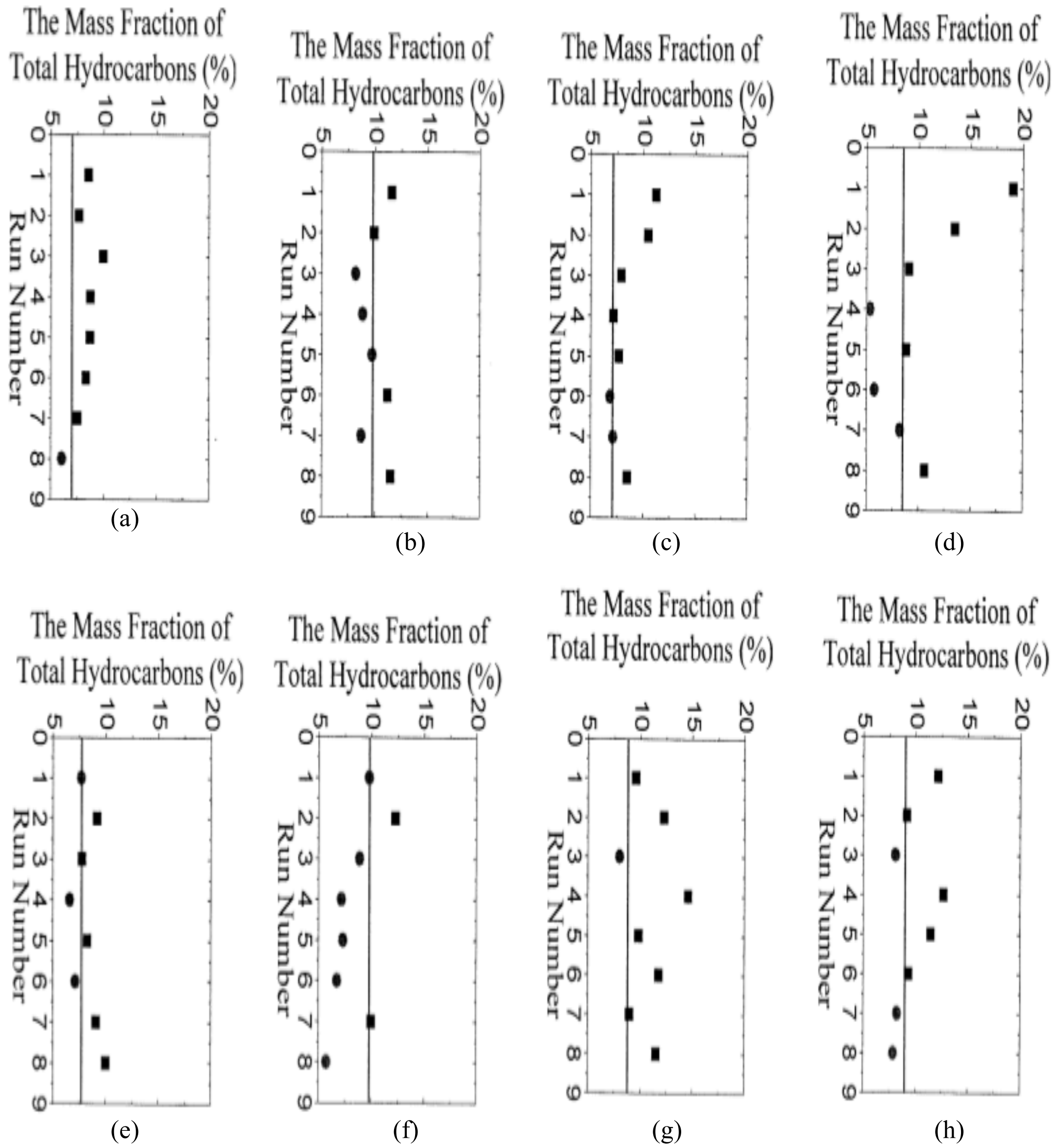


Figure 4.9: The mass fraction of total hydrocarbon determining the occurrence (■) and non-occurrence (●) of backdraft with (a) slotted opening in the middle of end wall, (b) slotted opening at the bottom of end wall, (c) slotted opening at the top of end wall, (d) door in end wall, (e) window in end wall, (f) slotted vertical opening in end wall, (g) slot opening in ceiling, and (h) window in ceiling. The lines (-) indicate the estimated critical values of occurrence of backdraft.

Table 4.4: The estimated critical values of the mass fraction of total hydrocarbons determining the occurrence of backdraft for eight different types of openings.

Openings	Critical values (%)
Slotted opening in the middle of end wall	8.5
Slotted opening at the bottom of end wall	9.0
Slotted opening at the top of end wall	7.1
Door in the end wall	8.8
Window in the end wall	9.8
Slotted vertical opening in end wall	9.8
Slotted opening in ceiling	7.0
Window in ceiling	7.7

4.6 LOCATION OF THE IGNITION SOURCE

The locations of ignition source are different: ignition position A, ignition position B and ignition position C (refer Section 3.7.3) as shown in Figure 4.10. The change of window opening is kept constant that is from 0.05 m to 0.25 m, in which the backdraft phenomenon is the most obvious. It is clearly shown from the Figure 4.10 that both ignition position A and ignition position C are easier to allow backdraft to occur in the compartment than ignition position B. While ignition position C is the easiest among three locations.

Ignition position C is the furthest position away from the window opening. When the fire is started at ignition position C, the flame spread fasts to the window, making the bottom part under the window a “combustion dead corner”, resulting in accumulation of significant amount of unburned fuel or incomplete combustion products under the window. When an opening is made, a gravity flow of cool fresh air enters the compartment and reaches ignition source, premixed fuel and air is ignited, resulting in an increased rate of combustion, increased velocity and turbulence, and thus, secondary combustion takes place immediately, i.e. backdraft. Hence, the further away the ignition source from the openings of the compartment, the easier for the backdraft to occur.

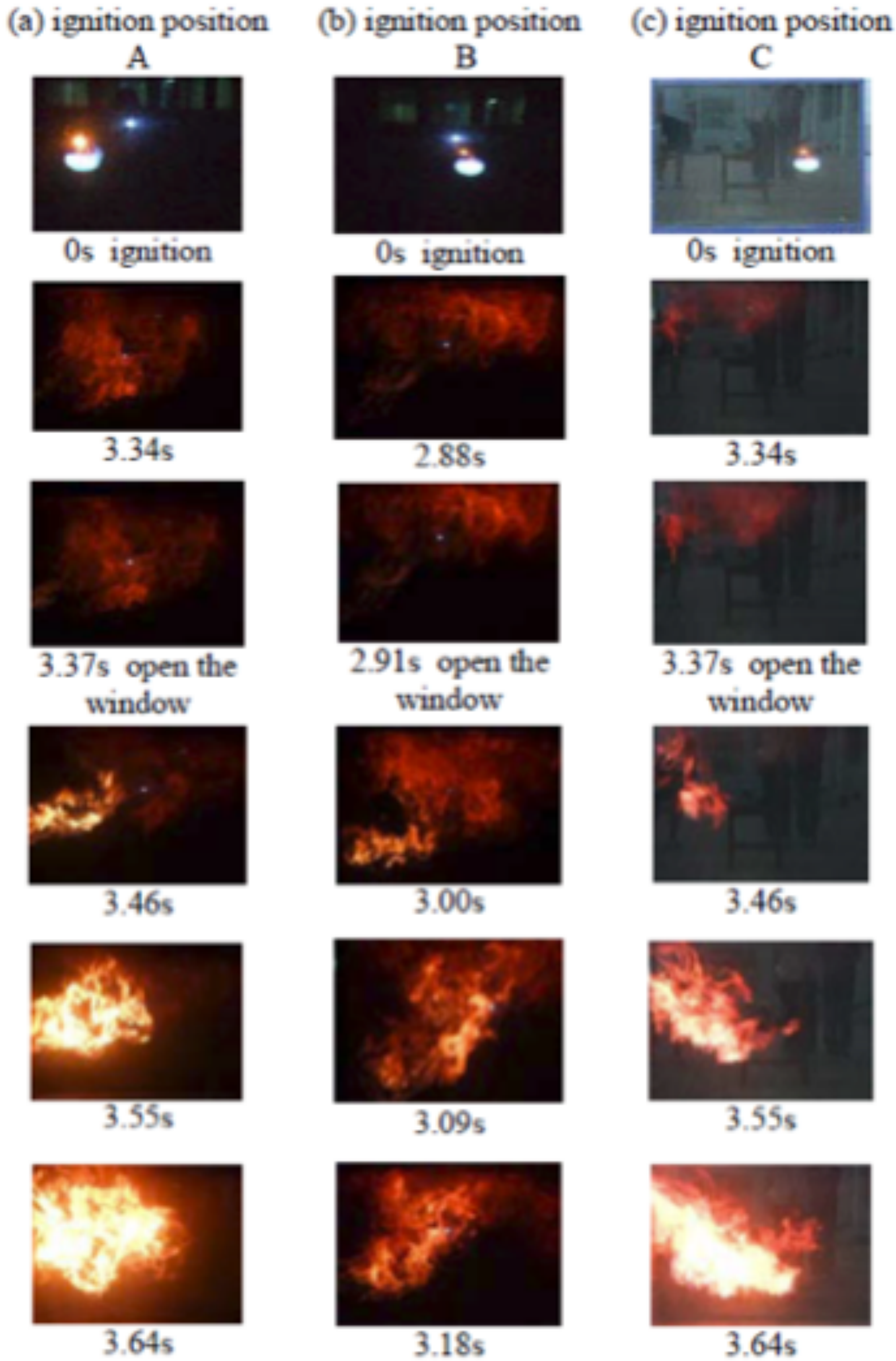


Figure 4.10: Influences of different ignition location on backdraft occurrence.

Figure 4.11 shows the influence of ignition location. Ignition inside a compartment expels a mass of unburned fuel and subsequently ignites outside the compartment.

Figure 4.11: Influence of ignition location.

Source: Reading the Fire: Building Factors. [Online Image]. (2009). Retrieved from http://cfbt-us.com/wordpress/?tag=backdraft&paged=2

In short, all the four researches retained for meta analysis have shown that in order for a backdraft to occur, the factors can be divided into two main categories: (1) factors related to the compartment itself, and (2) factor related to the fuel. These factors including:

- Mass fraction of unburned fuel remained in the compartment, which must exceed a certain critical value. Different liquid fuels will have different critical value of mass fraction of unburned fuel according to their flammability diagram.
- The size and location of the compartment openings, which also affect the mass fraction of unburned fuel, resulting in different flow pattern of air and movement of the smoke.
- The location of the ignition source, which is further away the ignition source from the openings of the compartment, the easier for the backdraft to occur.

4.7 SUMMARY

The first part of this chapter covers the general description of combustion and a summary discussion of fire growth in an enclosure to facilitate our understanding on how the condition in the compartment leads to backdraft occurrence. This was followed by the analysis of each factor that contribute to backdraft occurrence.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 INTRODUCTION

In this chapter, the findings of the research will be concluded based on results and discussion obtained and analyzed throughout the research. The conclusion was made based on the experimental studies conducted and supported by past researches. The recommendations suggested in this chapter will be useful and be helpful for future research in fire safety field as a whole to understand more thoroughly of modern fire development.

5.2 CONCLUSION

Rapid-fire progression poses a significant threat to firefighters during structural firefighting. The behavior of compartment fires today has changed from a traditional fire behavior to a modern fire behavior. Unfortunately, in the field of fire safety, lack of available and organized scientific information and lack of sustained research in backdraft contributed to the lack of awareness and knowledge regarding its behavior and the causation factors among both firefighters and civilians. If firefighters do not have a high level of situational awareness towards modern fire behavior, it is difficult to develop an understanding in fire dynamics and to make a correct decision on fire grounding activities. During this thesis work, meta analysis of past researches were carried out with the aim of studying the critical elements that contribute to the occurrence of backdraft fire.

From chapter 4, it shows that under-ventilated compartment fires can lead to deadly and dangerous fire phenomena, for example, flashover and backdraft. If an under ventilated fire is situated before flashover takes place, then the amount of air is not enough to support and progress the fire into flashover. However, if flashover occurs and the fire has moved into its decay stage with high heat release rate, high amount of unburned fuel and it's thirst of oxygen, and therefore, there is a high possibility for a secondary combustion to take place, i.e. backdraft.

However, backdraft does not always occur. The occurrence of backdraft needs to meet some critical conditions, which are:

- Under-ventilated compartment, which the fire changes from fuel-controlled at the initial stage of the combustion to ventilation-controlled in which the fuel is not the limiting factors but the amount of oxygen is the limiting factor.
- Mass fraction of unburned fuel that exceeds a certain critical value, which also depending on the geometry and type of opening as well as the type of fuel used.
- A sudden introduction oxygen, or in other words, increased ventilation, which allows fresh oxygen to enter the compartment, creating a gravity current and subsequently mixing with unburned hot gases, and thus, creating a flammable mixture.
- Presence of ignition source.

The findings of this thesis have successfully addressed the objectives outlined in Section 1.5 and have answered the hypothesis formulated in Section 1.6.

5.3 RECOMMENDATION

In this research, it is obvious that the proliferation of plastics in modern furnishing and energy-sufficient constructions have created a new paradigm in fire grounding activities against modern compartment fire. It is important to understand the modern fire behavior, and more importantly, to translate the knowledge into firefighting tactics that firefighter all over the world could use during fire grounding activities. Limited amount of research has been done so far and yet, they are still received very little attention. Hence, a number of potential areas of improvement for future research emerged.

A full-scaled experiment should be conducted as the previous studies on backdraft fire were conducted in reduced-scale experiment in a reduced-scaled compartment. Different compartment size has a great influence on the modern fire development.

Future research on backdraft occurrence should focus on using more realistic fuels such as solid fuels, i.e. wood and plastics. Experiments conducted by past researchers used liquid fuels as the source of fuel in their experiments, W.G. Weng et.al (2003) and C.M. Fleishmann et. al. (1994) used methane while J.X. Wu et. al. (2011) used liquefied petroleum gas (LPG). This would be an interesting research topic as the realistic fuel loads behave differently; the fire behavior as well as the firefighting tactics will be different.

Future research on backdraft occurrence should concentrate on more realistic ignition source. In reality, the ignition source can be flames, carbon-based materials, or hot surfaces in the compartment and most of the ignition source for backdraft is still not well understood. In experiments conducted, very powerful ignition sources are used. Hence, when conducting and evaluating future research, the link with reality should be made. More research into this item can enhance the understanding of this phenomenon. Past researchers used several ignition sources in their experiments.

These include:

a. Electrically heated metal wire with 1200W power in experiments of W.G. Weng et. al (2003).
b. Candle as the ignition source in experiments conducted by J.X. Wu et. al (2011). J.X. Wu, claimed that candle as the ignition source for their experiments able to ensure the reliability of ignition in reality.
c. A spark igniter as ignition source in experiments conducted by C.M. Fleischmann et. al. (1994).

Future research should consider the effect of atmospheric condition on backdraft occurrence. An important factor in this aspect is the wind. Wind has an effect on the outcome of backdraft occurrence. This is because the change in wind velocity or direction changes the pressure distribution over the surfaces of a building. For extreme cases, wind able to seal a window opening, limiting the exit of fire gases. Only when an opening is made on the low-pressure side of the compartment, the fire gases can exit the compartment and eventually ignite when exiting.

The nature of building and the materials used for construction are changing. The level of insulation and air-tightness are increasing as well. These have an influence on the fire behavior. Future research should consider on these factors and investigate the influence of these factors on the occurrence of backdraft.

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APPENDIX A

GANTT CHART OF FINAL YEAR PROJECT I & II

ACTIVITIES	SEMESTER 2 2015/2016				SEMESTER 1 2016/2017			
	FEB	MAR	APRIL	MAY	SEPT	OCT	NOV	DEC
CHAPTER 1								
CHAPTER 2								
CHAPTER 3								
CHEMICAL REQUISITION FORM			24/4					
PARTIAL RESEARCH THESIS SUBMISSION				13/5				
PROPOSAL PRESENTATION				24/5				
DATA COLLECTION								
PREPARATION FOR FYP II AND RESEARCH WORK								
DATA ANALYSIS								
PREPARATION OF THESIS								
SUBMISSION OF REPORT								
FINAL PRESENTATION								