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An Experimental Study
of
Backdraught
using
Solid Fuels

Chia Lung (Farian) Wu

A thesis submitted for the degree of Doctor of
Philosophy

THE UNIVERSITY
of **EDINBURGH**

2019

An Experimental Study
of
Backdraught
using
Solid Fuels

by

Chia Lung (Farian) Wu

The thesis has been supervised by:

Dr Ricky Carvel

Dr Stephen Welch

Prof Albert Simeoni

Prof Dougal Drysdale

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Declaration

The work in this thesis has been completed solely by Chia Lung (Farian) Wu at the University of Edinburgh under the supervision of Dr Ricky Carvel and Dr Stephen Welch.

Full reference is given where other sources are used. This work has not been submitted for any other degree or professional qualification.

A handwritten signature in black ink, reading "Chia Lung Wu". The script is cursive and fluid, with the first name "Chia" and last name "Wu" clearly legible.

Chia Lung (Farian) Wu

May 2019

Abstract

Backdraught is one of fire phenomena that is yet to be fully understood. Previous researchers have tried to use gaseous fuel to investigate the mechanism of backdraught. Some results for this phenomenon have been proposed, including a minimum concentration value required to trigger backdraught. However, the value may not be able to widely be used as it was based on methane, which can be ignited at ambient temperature, as the fuel.

Backdraught can be deemed as an expression of a fire, it requires heat, oxygen, and fuel itself. Unlike a normal compartment fire, a starting point of this phenomenon must make the fire compartment become under-ventilated (less oxygen supply, even no oxygen supply). Then a sudden door/ window opening occurs, the incoming fresh air support the fire reignition. The opening introduces oxygen to allow backdraught to occur, which reflects the critical value of unburned smoke, as the fresh air will dilute the smoke; as to the effect of heat, there is still a lack of research about the role of the temperature inside fire compartments for the occurrence of backdraught. In previous research, electric sparks were commonly used as an ignition source, therefore, the heat required to trigger backdraught may not be an issue in their backdraught studies, but it is possible to generate backdraught without any ignition source present, in demonstrations of most firefighting training centres. Hence, the characteristics of backdraught may be different.

A series of experiments was conducted to investigate factors that influence the occurrence of backdraught and its behaviour. A new finding is that a 'critical temperature exists' before a backdraught can be triggered. Also, it was found that any temperature higher than the critical temperature can always trigger backdraught if the experimental fire experienced flashover before the door was closed. But this critical value varies with fuels used. For polypropylene (PP) and high-density polyethylene (HDPE), the critical temperatures are 350°C and 320°C, respectively. However, even with a temperature below the critical temperatures, a pilot spark still can trigger a backdraught, but generating a backdraught almost immediately.

Also, CO/CO₂ value and CO concentration are other factors governing the occurrence of backdraught, but the values change with temperature, and also if a pilot is present. If there is no extra ignition source, a CO concentration of at least 0.6% in the compartment, before the door is opened, is necessary for backdraft to occur without a pilot spark. When at temperatures slightly below the critical temperature for non-piloted backdraught, a CO concentration of above 2.8% and a pilot source are essential conditions for the occurrence of backdraft.

Backdraught always requires a time of the delay after the change of ventilation, it makes firefighters hard to know when a backdraught may occur in fire scenes. As known that the characteristics / behaviours of backdraught are not identical when the ignition sources are different. Therefore, the prediction of the delay time on the basis of the ignition sources is crucial as it affects the life safety of firefighters. There is no guarantee any type of ignition may

be in fire scenes, hence, both of non-piloted and piloted ignition source should be considered. Result shows that the delay time of backdraught can be predicted. For non-piloted ignition experiments, the stability of the hot gases in the fire compartment directly affects the time of the ignition of backdraught. In addition, a suitable condition is required for non-ignition backdraught, when the opening size and the volume of the compartment is known, the longest delay time of backdraught may be predicted. In general, when a pilot is present, a backdraught event will occur much faster.

This work demonstrates that when using solid fuel to generate backdraught, the result provides some new findings compared with the previous research. The experimental design was used to create a realistic fire condition that may suitable for backdraught to occur without any ignition apart from the hot smoke, although the study was limited to PP and HDPE fuels only. But, at least, it was found that both temperature and unburned smoke are essential for backdraught. It makes the future work on backdraught can have different views, which is that if the regime of the critical temperature diagram can be mapped out by investigating different fuels (or fuel combinations) by continuing the experimental procedure in the thesis. In the future, a safe working environment for firefighters when tackling a possible backdraught event may be able to be achieved.

Lay summary

With the development of technology, safety issues seem to be able to totally be avoided as many tools or equipment have been designed to reduce those risks. Every issue / risk can start to be solved; the most important thing is that we must know the mechanism of the risk then scientists / designers will try to design a way to cope with it.

An explosive fire phenomenon called backdraught troubles fire rescuers for a long time (a fire condition with explosive force when the ventilation of an under-ventilated fire is suddenly changed, usually by the opening of a door or window). Until now, the condition of triggering this special fire phenomenon is still yet to be understood in fire scenes. When a fire experienced a lack of oxygen supply condition, it will tend to smoulder (non-flaming fire) or even extinguishment. This phenomenon is like 'Schrödinger's cat', you will never know when you are opening the door, if the cat (fire) is dead or alive. If this cat (fire) is alive, firefighters who conduct the fire-rescuing may suffer from an explosive fire impact, then possibly may lose their lives.

The thesis conducts a series of experiments and investigating some factors (temperature, gas data) to observe the behaviour of the cat (fire), it may either to show up or die. A series of experiments have been done to judge the boundary of the line of the occurrence of backdraught. Also, it is found that from the research, a possible time in which the backdraught will be occurring, can be predicted to some extent.

Finally, a scientific research result can help fire authorities to rethink or to make some changes in fire-fighting tactics and operational practice, which may prevent firefighters from any tragedy caused by backdraught and should be able to be used for future research.

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Chapter 1. Introduction

1.1 Background

With progress of technology, modern buildings are built by using state of the art technology. The multiple functions not only make use of building with flexibilities but also make living easier in society. Either prescriptive fire regulations or performance-based design are used to minimise / reduce the possibility of a fire, also, both active firefighting methods, such as smoke detectors, sprinklers etc. and passive firefighting method, such as integrity of compartmentation, and higher fire resistance material are used to extend the Available Safe Egress Time (ASET) that allows safety evacuation of a fire.

Fire always can develop owing to wrong usage habits by residential occupants or electrical equipment not maintained regularly. History has even shown that buildings constructed in full compliance with the relevant codes have not performed well when fires do break out. Based on those reasons mentioned above, the use of space might not be well-protected. Stakeholders, including owners and the authorities concerned, can hardly assure the level of building's safety by existing safety regulations and codes.

Some of the buildings might not be safe enough because building owners commonly make changes without understanding the fire safety implications. Under this circumstance, fire can easily be triggered by insufficient protection. In order to keep people away from fires, firefighters always risk their lives to go into buildings. In rescue missions, a phenomenon so-called 'backdraught' is one of the dangerous conditions that firefighters do not want to encounter with because it often leads to serious tragedy. Backdraught normally occurs when a sudden opening is formed from firefighter opening or breaking of a window or a door. This phenomenon brings about explosions and sometimes can cause severe casualties, and most of the injured are firefighters, this may be the reason the film called "Backdraft (1991)" is often introduced to students of firefighter training courses/fire academy. Even if the backdraught in the film does not reflect real backdraught conditions, it still demonstrates the danger of this unpredictable fire phenomenon.

Research on fire has widely focused on burning characteristic of materials, severe fire conditions (wildfire, compartment fire), human behaviours in evacuation, and structure sustainability after a fire etc. Flashover and backdraught are severe fire conditions which lead to possible tragedies in fire scenes. However, research mainly focuses on the study of flashover, and have paid comparatively little attention to backdraught. In the survey of backdraught by Chitty (1994) [1] it was

mentioned that flashover has been the subject of many studies and a reasonable understanding of backdraught had yet to be developed, also the quantitative mechanisms of backdraught were still largely absent [2].

In theory, backdraught is hard to observe directly compared to flashover owing to the former always being related to a confined compartment fire scenario, and this leads to the unpredictability of nature of backdraught, it may be the reason why research on backdraught is considerably sparse.

Abovementioned makes researchers reluctant to conduct experiments on backdraught, life safety of firefighters can only be protected by any emergency response but not precaution measures as the time of backdraught occurrence is unknown. The definition of backdraught only exists in qualitative descriptions, an explosive fire condition with unpredictability.

Definitions of backdraught,

“Limited ventilation can lead to a fire in a compartment producing fire gases containing significant proportions of partial combustion products and unburnt pyrolysis products. If these accumulate then the admission of air when an opening is made to the compartment can lead to a sudden deflagration. This deflagration moving through the compartment and out of the opening is a backdraught [1].”

“Limited ventilation during an enclosure fire can lead to the production of large amounts of unburnt pyrolysis products. When an opening is suddenly introduced, the inflowing air forms a gravity current and begins to mix with the unburned pyrolysis products, creating a combustible mixture of gases in some part of the enclosure. Any ignition sources, such as a glowing ember, can ignite this combustible mixture. Resulting in an extremely rapid burning of gases/pyrolysis products forced out through the opening and causes a fireball outside the enclosure [2].”

“Backdraught is preceded by burning under conditions of very poor ventilation and is initiated by the sudden influx of air when a door opens or a window breaks [3].”

“Consider a fire in a closed compartment where only a minimal amount ventilation is provided by the leakage through the small cracks around windows, doors etc. As the fire heats up, these small openings permit the

expanding gases to exit, thus minimizing the pressure rise. A hot layer composed largely of combustion products descends around the fire causing some of the fuel produced to remain unburned. The unburned fuel and other combustion products accumulate forming a deep layer which has insufficient oxygen to support flaming. Somewhere in the room there remains a small flame or glowing ember. Suddenly, a new ventilation source is provided as a window breaks or a firefighter opens a door. The hot, fuel rich atmosphere in the compartment flows out the upper portion of the new opening. Simultaneously, cold, oxygen rich air rushes in the lower portion of the opening. This density driven flow is called a gravity current. A mixed layer forms between the outflowing hot gases and the cold air flowing in as a result of the shearing action. This mixed layer rides on the gravity current across the compartment..... In a fire compartment, the mixed current is within the flammable range and ignites when it reaches a flame or glowing ember. After ignition, a new flame propagates back through the mixed region..... This preceding flame burns through the mixed region between the entering gravity current and the exiting compartment gases. The preceding flame and its wake are extremely unstable and generate a rapidly propagating turbulent flame. The resulting expanding flame within the compartment drives some of the accumulated fuel out the door and consumes the fuel that has been forced out of the compartment ahead of the initial flame forming a dramatic fireball. This entire process: the accumulation of unburned gaseous fuel, the propagation of an oxygen rich gravity current creating a mixed region and carrying it to the ignition source, the ignition and propagation of an eventually turbulent explosion, collectively constitutes a backdraft [4]."

Every expert has its own understanding towards backdraught phenomenon, with diversity to some extent. However, it can still be seen that the generic required elements for backdraught to occur are "Limited ventilation, a large amount of unburned pyrolysis products, and a sudden influx of air (a sudden opening)". It seems that both stages of fire (even though 'underventilated' fire is often referred to a fire grows to the stage just before flashover) and temperature distributions inside fire scene are outside the scope of the definitions of backdraught, these two elements are directly to the quantity of unburned smoke in fire compartment, then contributes to that if a suitable condition (in flammable limits) is reached. It should be noted that the phrase "unburned smoke", used throughout this thesis, means

smoke which contains flammable gases, particles, aerosols, pyrolyzates, toxic species, etc. This is the source of gaseous fuel in a compartment, before a backdraught occurs

Thus, some questions are,

- How can it be determined whether there is an ignition source or not in a confined fire compartment?
- How much unburned pyrolysis products (i.e. fuel) is required?
- How much influx of fresh air is required?

Based on the fundamentals of fire science, a fire can only develop when there is sufficient “heat, oxygen, and fuel”. The first question which arouses our interest is what kind of role an ignition source plays to affect the onset of backdraught, also, in a real backdraught event, how can observers determine whether an ignition source exists? And do the physical properties of the occurrence of backdraught follow some characteristics observed in the previous backdraught research projects, or provide different behaviours for different types of ignition source; that is, is the behaviour of a backdraught ignited by a pilot source different to the behaviour of one ignited by non-piloted (ignited by the hot smoke rather than an extra pilot ignition source) ignition?

In addition, it seems that an ignition source can always be in the fire scene even if the fire has suffered a considerably long time of oxygen depletion. If this is true, a backdraught may occur in many fire scenes when the building is with limited ventilation.

In the very beginning of a fire, oxygen supply is normally enough to provide complete combustion, in this stage, the severity of the fire is determined by the quantity of the fuel, called a fuel-controlled fire. When the rate of burning is controlled by the rate at which air can flow into the compartment: such a fire is known as a ‘ventilation-controlled’ (or ‘ventilation limited’) fire [3]. The space will become oxygen starved, fresh air may only available at the bottom of the fire compartment. It is known that the longer the fire is, especially in “ventilation controlled” condition, the more unburned pyrolysis products will be produced, the reason is because the oxygen supply is not enough to sustain a complete oxidation process in fire burning. This part may be of the most importance because in a real fire scenario, firefighters must decide proper firefighting tactics based on whether a backdraught may occur or not.

From the previous experimental research, it was found that the critical factor of backdraught is the concentration of unburned pyrolysis gases. No apparent correlation between the temperature of fire compartment and the occurrence of backdraught has been established.

Backdraught, unlike in the film “Backdraft” when it occurs as a door is open, always requires a delay time to allow enough fresh air to a fire room, it is of importance if a correlation can be discovered to predict the delay time of backdraught.

At present, a clear challenge for firefighter / fire officers is that, there is no clear strategy to tackle a possible backdraught based on a variety of fire scenarios. If there is, only focus on a roughly qualitative description, like changes of colour of smoke, very thick smoke layer, “breathing-like” behaviour at the leakage of the fire compartment etc. The only way for firefighters to reduce the risk of backdraught, so far, is experience.

1.2 Aims of this research

The main aims of the research presented in this thesis is to discover the gaps in the current backdraught research, and investigate the fundamentals of the backdraught phenomenon, by using representative materials (commonly used material in residential space) as the fuel to conduct a series of backdraught experiments, then to have a thorough understanding of this phenomenon. Therefore, by using the research results, some critical factors relating to the onset of backdraught may be identified, then eventually present a quantifiable way to predict if a backdraught may occur or not.

To fulfil these aims, a series of goals need to be pursued,

- **Review of the backdraught research.** This part is the fundamental part of this thesis, by thorough understanding of the pros and cons of the previous research will allow the experimental design and apparatus used are suitable, therefore, any redundant design can be avoided.
- **Identification of the critical factors of backdraught.**
- **Development of a methodology for a future backdraught research using different materials.**

- **A preliminary approach for predicting the delay time of backdraught.**

1.3 Outline of chapters

This thesis contains nine chapters, starting from the outline of the thesis, experimental design to data analysis and conclusion. A brief description of these chapters, aside from the current introductory chapter, is presented below.

Chapter 2

Literature review

A literature review on backdraught research over the past two decades (from the 1990s), highlighting aspects of research that have been conducted and the critical understanding of backdraught has been known so far. It includes discussions on the current understanding of backdraught, some classification of the previous research, and also restrictions of applications.

From the literature review, outlining the limits of the understanding of backdraught research, it shows the gaps which are required to be filled in the backdraught research. Therefore, it provides a clear direction to conduct backdraught research for the thesis.

Chapter 3

Experimental design, blank testing and preliminary experiments

This chapter describes how to conduct preliminary tests using the experimental apparatus before installing any sort of equipment in the fire compartment. The reason is that most of related research used electrical / hot ignition sources to initiate/ trigger backdraught, which means only “pilot ignition” have been investigated, it is questionable if it is the same case in the experimental design of the research.

Any interference may affect if backdraught occurs, therefore, the first stage of research was to keep it simple, by only set the fire, control the time of closing and opening of the front door, to initial backdraught. A systematic analysis is presented to judge whether to install an ignition source or not, results showed that backdraught can be triggered without any ignition source and other heat source

apart from the fuel tray itself. To compare what ignition sources may affect the behaviour of backdraught, a few experiments were conducted to observe the location of ignition of backdraught, to find a suitable location to install an electrical spark to ignite the unburned gases.

Chapter 4

An experimental study on backdraught: The dependence on temperature [5]

Chapter 4 presents the results of a series of reduced scale experiments to investigate the temperature conditions leading to backdraught in the fire compartment. A systematic approach is presented from flammability limit theory, development of the design fire, neutral plane observation to investigate the phenomenon of backdraught. Results indicate that “temperature is one of the critical factors for backdraught occurrence”, “backdraught is not relevant to the occurrence of flashover”, “Extra ignition source increases the possibility of backdraught”. This chapter is based on:

C.L.Wu, R.Carvel, *An experimental study on backdraught: The dependence on temperature*, Fire Saf. J. 91 (2017) 320–326. doi:10.1016/j.firesaf.2017.04.003. This paper was presented at IAFSS 2017, Lund, Sweden.

Chapter 5

The influence of compartment temperature on backdraught dynamics

Following the previous chapter showing that temperature (a characteristic temperature used) is a critical factor to backdraught. To understand if a temperature distribution affects the backdraught dynamics by compared three TCs (the highest temperature, near the floor near the opening, near the top of the compartment). Results show that only the maximum temperature observed determining the onset of backdraught. In addition, it is shown that a long door closure and a lower room temperature leads to a longer delay time. This chapter is based on:

C. L., Wu, R., Carvel, *The influence of compartment temperature on backdraught dynamics*, Proceeding of the 11th Asia-Oceania Symposium on Fire Science and Technology, Taipei, Taiwan, 2018.

Chapter 6***Critical factors determining the onset of backdraught using solid fuels***

In chapter 6, two fuels, polypropylene (PP) and high-density polyethylene (HDPE), were used to investigate the critical factors that govern the occurrence of backdraught, with temperature and gas analysis. In parallel, a series of pyrolysis investigation have been conducted by using the fire propagation apparatus (FPA) and FTIR gas analysis.

Results show that both CO/CO₂ ratio and temperature (maximum temperature) are determining factors as to whether backdraught may occur. Also, it is found that the accumulation of CO (which indicates incomplete combustion) contributes to the change of the critical temperature, which indicates that the greater the quantity of CO is, the lower the temperature is needed to trigger backdraught. When the CO/ CO₂ > 0.08 (for the experiments closing the door after experiencing flashover), a backdraught occurred. This chapter is based on:

C.L., Wu, S., Santamaria, R., Carvel, *Critical factors determining the onset of backdraught using solid fuels*, submitted to Fire technology, 2018. (under review)

Chapter 7***Critical delay time to the onset of backdraught under different ignition scenarios***

This chapter discusses the possible approaches to predicting the delay time of backdraught based on the experimental design fire. Investigation on backdraught here was to discover how the maximum temperature affects the time of ignition of backdraught, at the same time; when a pilot spark is used as the ignition source to trigger backdraught, it requires a different calculation method compared to the method that can be used for the non-piloted backdraught events.

Results demonstrate that the higher the temperature, the shorter the delay time is. In the cases where backdraught was triggered after flashover, for both PP and HDPE, the correlation of the reciprocal of the delay time and the temperature is approximately constant, the only difference is the slopes of the linear relationships.

Chapter 8***Compartment size, opening geometry to the onset of backdraught- a novel approach and moving toward to practice.***

From previous chapters, it was found that the close to flashover, the longer delay of backdraught will be. It will be the worst scenario for firefighters when tackling this sort of fire emergencies. In Chapter 4, it was found that the “critical temperature” is about 350 °C for the experimental design fire to achieve backdraught condition. Here, a selected characteristic temperature, 370 °C, was used to decide when should start the door opening procedure. Sizes of the compartment, opening and type of ignition source (auto ignition & pilot ignition) were used as variations to investigate the impact on the delay time of backdraught and the behaviour of backdraught.

Results showed that the delay time of backdraught can be predicted, if the size of the opening, compartment, and source of ignition is known.

Chapter 9***Conclusions and further work***

The main conclusions of this thesis are highlighted, followed by a detailed summary of the developed work and extended findings. Also, limitations and recommendations for further work on the backdraught research are described.

1.4 References

- [1] R.Chitty, 5 / 1994 : A survey of backdraught - main report, Fire Research and Development Group, Home Office,1994.
- [2] G.E.Gorbett, R.Hopkins, The Current Knowledge & Training Regarding Backdraft , Flashover , and Other Rapid Fire Progression Phenomena, National Fire Protection Association World Fire Safety Conference, Boston, Massachusetts, 2007.
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- [4] C. M. Fleischmann, Z.Chen, Defining the difference between backdraft and smoke explosions, Procedia Engineering Vol. 62 (2013) 324-330.
- [5] C.L.Wu, R.Carvel, An experimental study on backdraught: The dependence on temperature, Fire Saf. J. 91 (2017) 320–326. doi:10.1016/j.firesaf.2017.04.003.

Chapter 2. A Review of Backdraught Research

Regarding the contribution of this chapter, I did most of the work for this chapter. Dr Carvel edited some of the content (especially sections 2.3 and 2.4.1) of the chapter to make the text more accessible to read through and also polished the words/ paragraphs to become more academic. Also, he redrew the figure of the mechanism of backdraught (**Figure 2.3.1**).

2.1 Introduction

Despite being feared by fire-fighters for many decades, and brought to popular attention by Ron Howard's motion picture "Backdraft" in the 1990s, backdraught remains one of the largely unresolved issues in the field of fire science [1]. Research has so far explained the mechanisms involved in backdraught, as will be discussed, but a rigorous definition of instances where backdraught can occur remains elusive.

Backdraught generally occurs in conditions where a compartment containing a fire has a very limited fresh air supply, and the fire becomes considerably ventilation-controlled or is extinguished. A backdraught may occur if there is a sudden supply of fresh air, e.g. due to a window or door opening or breaking, possibly due to the fire, or commonly due to the intervention of fire-fighters. Backdraught has led directly to fire-fighter injuries and fatalities; thus, it is essential to study backdraught in order to mitigate or avoid its effects in future fire-fighting interventions.

Fundamental research into backdraught has been ongoing sporadically since the early 1990s. Fleischmann et al. [2–4] originally conducted a series of experiments using a reduced-scale compartment with a methane burner as the fuel supply. They observed the propagating flame of backdraught, defined the mechanisms of the phenomenon, and identified the concentration of the unburned gases in the compartment as a critical factor determining the occurrence, or otherwise, of backdraught.

After a comment on some historical backdraught events, this paper will briefly present the generally accepted mechanism of backdraught and will then comprehensively discuss the research literature on the phenomenon, highlighting apparent gaps in our knowledge and proposing directions for future research.

2.2 Historical backdraught events

Backdraught is not a typical phenomenon that can be encountered in all fire scenes, to be more precise, it is rare. However, it is one fire phenomenon that firefighters do not want to face/ encounter when conducting fire rescue missions because it always results in severe fatalities and the ones who suffer most of the time, are firefighters only.

Chitty [1] mentioned that backdraught in large building spaces presents a special hazard to the firefighters because this explosive event may occur by suddenly door/ window opening, but backdraught events still led to firefighters dying or injured even when the fire compartments were comparatively small.

Table 2.2.1 shows some of the historical backdraught events.

Table 2.2.1 Backdraught events that caused fatalities of firefighters

Year	City / Country	Building type	Death toll of firefighters
1974	Kent / UK	Warehouse	2 fire fighters died and injured 4 others [1]
1994	New York City / USA	Apartment	2 firefighters died ¹
1996	Blaina/ South Wales/ UK	House	2 part-time firefighters died after rescuing a child from a house fire [32]
2001	New York City / USA	Hardware store	3 firefighters died and numerous injuries ²
2014	Taipei City/ Taiwan	Basement of a shoe shop	1 squad leader died, and 4 firefighters seriously injured ³
2015	Taoyuan / Taiwan	Bowling Alley	6 firefighters died ⁴

It can be seen that the casualties of backdraught events were mainly firefighters. It is because of the nature of backdraught, which need to rely on a sudden change of ventilation. When firefighters try to break the barriers of the compartment to extinguish the fire inside, this characteristic (sudden ventilation change required) always puts firefighters of risk.

This table is to demonstrate that firefighters are the most vulnerable groups in backdraught events. And even with the development of firefighting technology, there is still no way to prevent it from occurring or minimise the risk of it.

¹ Bukowski, R., "Modeling a Backdraft: The Fire at 62 Watts Street," NFPA Journal, pp. 85-89, November/December 1995.

²Source: <https://www.nytimes.com/2001/06/18/nyregion/three-firefighters-die-as-store-explodes-in-queens.html>

³Source: <https://tw.news.yahoo.com/%E5%8C%97%E5%B8%82%E7%81%AB%E8%AD%A6%E6%B6%88%E9%98%B2%E5%B0%8F%E9%9A%8A%E9%95%B7%E5%91%BD%E5%8D%B1-071438524.html>

⁴ Source: <http://news.ltn.com.tw/news/society/breakingnews/1210062>

It should be noted that this table does not include every backdraught event, which means it cannot conclude that there are no backdraught events that killed firefighter during 2001 to 2014. Also, it is a tip of the iceberg of backdraught events that occurred in the world. The purpose is to emphasize that firefighters are the major groups injured during backdraught.

2.3 Mechanism

Backdraught may occur when a door or window is opened to a compartment full of hot gases, allowing a flow of cooler air into the compartment. This condition generally occurs after a fire has been burning in a partially sealed room for some time, resulting in the build-up of heat and flammable products of incomplete combustion or pyrolysis. The various stages of backdraught are shown schematically in **Figure 2.3.1**.

Figure 2.3.1 – Schematic of the mechanism of backdraught: (a) a sealed or partially sealed compartment full of hot gases, (b) initial flow after the door is opened, (c) the gravity current flow, (d) turbulent mixing leads to creation of a potentially flammable gas mixture, (e) piloted or spontaneous ignition, and (f) rapid combustion of the mixed gases, leading to external fireball.

When a door or window is opened, the hot gases will tend to spill out of the upper part of the opening, and cold air will flow into the lower part of the opening, as shown in **Figure 2.3.1** (b) and (c). This flow of air has become known as a “gravity current” and is crucial in determining the occurrence and severity of a backdraught, as will be discussed. The opposed flow of the gravity current with respect to the hot gases drives the process of turbulent mixing, creating a zone of hot flammable gases, as shown in **Figure 2.3.1** (d). It should be noted that the turbulence is driven by velocity fluctuations caused by the large density difference between the compartment hot gases and the inflowing air, this enhanced velocity gradient generates shear flow, this unstable type of shear flow may contain a series of advancing lobes and clefts at the leading edge of the cold and hot air mixing. This phenomenon is like Kelvin–Helmholtz instability [19] which normally occur when there is a velocity difference across the interface between two fluids [35]. When there is a flow of hot gases in one direction (hot smoke), and a flow of cool gases (the fresh incoming air) under the hot gases in the opposite direction, turbulence occurs and turbulent mixing of the two layers inevitably happens, this phenomenon is typically observed in the mixing between the layers, near the location of the vent [36].

Ignition need not occur instantly. Indeed, the severity of a backdraught is often greater if there is more time for mixing of gases before ignition occurs. In situations where there is a fire source or pilot flame at the back of the compartment, as in **Figure 2.3.1** (e), it is often assumed that the time at which backdraught is initiated (delay time after opening the door) is due to the time taken by the gravity current to create the flammable mixture and drive it to the ignition source, assuming the gravity current shear interface, which generates a flammable mixing region, actually arrives at the ignition source [3]. If a significant volume of gases reach flammable conditions before ignition occurs, the resulting fireball, ejected through the opening, may be powerful and highly dangerous, see **Figure 2.3.1** (f).

However, if conditions are sufficiently hot, ignition may occur spontaneously, and a pilot source may not be needed. As this will occur as soon as any sufficiently hot flammable mixture is formed, the volume of flammable gases may be relatively small, and the resulting backdraught may be relatively weak.

It is clear from this brief description that the following factors all play a role in the occurrence and severity of a backdraught:

1. The gas composition in the compartment before the door is opened.

2. The temperature in the compartment before the door is opened.
3. The size, shape, and location of the opening.
4. The properties of the density-driven 'gravity current'.
5. The location and nature of the ignition source, if present.

All research to date has used fresh air at ambient temperature for the inflowing gas, so questions regarding vitiated air, or inflowing air at elevated temperatures, have not been addressed even though this may also have an effect on the occurrence or otherwise of backdraught.

In this review, each of the above elements will be considered in turn and the relevant research available in the literature will be discussed.

2.4 Literature review

The list of five items, above, may be in approximately chronological order during an actual backdraught event, however, this is not the order in which most of the research has been carried out, so when reviewing the available literature, it is best to begin with studies around the 'gravity current'.

2.4.1 Gravity current

Gravity current is a term used to describe the physical motion of gases or fluids, driven by density differences, and this physical movement represents stage 3 of a backdraught, as shown in **Figure 2.3.1** (c). Benjamin [5] defined the term in this manner: "A gravity current consists of a wedge of heavy fluid (e.g. salt water / cold air) intruding into an expanse of lighter fluid (fresh water / warm air)."

In a real backdraught scenario, air movements will be produced due to the differences in temperature and density of the hot gas in the compartment and the cool inflowing air. Gravity current is the technical term to describe the flow of one fluid into another, and researchers have adopted a variety of methods to investigate this phenomenon in the context of backdraught [2–4], [6-17].

Fleischmann and co-researchers have demonstrated that this physical phenomenon is a crucial factor in the development of a backdraught. Their experiments included reduced scale experiments, using salt water modelling, to

visualise and characterise the phenomena, and real fire experiments, to characterise the gas mixtures which can and can't lead to backdraught.

In the early 1990s, Fleischmann et al. [2] started their research to observe the gravity current experimentally in a reduced scale laboratory apparatus, which was 2.4m x 1.2m x 1.2 m. Two types of fuel, methane and propane, were used for the experiments. The opening was 1.2m x 0.4 m and centred on the short wall. Various data such as deflagration time, temperature rise and observations on the colours of flame were collected. 'Deflagration' is a term describing subsonic combustion propagating through a fuel/air mixture, driven by heat transfer. In confined space, such as a compartment, the rapid increase in temperature due to the deflagration will result in a significant overpressure leading to explosive effects. In Fleischmann's research, "the deflagration wave travel time", is the time from ignition until the leading edge of the wave passes through the opening of the fire compartment [2].

The experiments were carried out as follows: the gas burner was ignited and allowed to burn for a specified time period, with a specified flow rate, after the compartment was sealed, then the gas flow was switched off, but the spark ignitor remained active, a few seconds after this the vent was opened, allowing fresh air into the compartment. In some experiments a flammable mixture was generated by the gravity current and was ignited by the spark.

27 experiments were carried out in this test series, however, only some of the experiments using methane as the fuel resulted in backdraughts. In the experiments using propane, the density difference between the hot propane layer and cool inflowing air was minimal, thus the gravity current was not effective at mixing a cloud of flammable gas. The tests which successfully triggered backdraught had the following characteristics: a pre-burn time of around 180s (which is also described as the burner time, it means that the methane burner was shut off around 180s, details in [3]), with methane as the fuel, only one vent opened, and a 5 second delay between burner shut off and the opening of the vent.

Fleischmann et al. [3] in their "Exploratory Backdraft Experiments" utilised not only experimental testing but also a technique called "Salt Water modelling" to assist for the understanding of the mixture conditions in a backdraught. The layout of the real fire experiments was the same as their previous research in 1992. Both approaches were used to demonstrate the phenomenon of the mixture of

backdraught. Two different ventilation configurations were used, at the floor and the ceiling, the result indicated that no backdraught happened in the two-vent experiment.

Additionally, temperature histories also showed the thermal changes during the time as backdraught happening. Dancing flame, which occurs in under-ventilated fires [18], was observed, but not in all the successful backdraught experiments. Also, a computer program FIRE Simulation Technique (FIRST) was used to analyse the compartment conditions by predicting the histories of the upper-layer temperature, depth, and species concentrations, and compartment. They indicated that a gravity current needs to travel to an ignition source is required, for the occurrence of a backdraught.

In order to investigate the gravity current speed in backdraught experiment, Fleischmann et al. [19] conducted a series of salt water experiments with the size of 0.3m x 0.15m x 0.15 m and altered the geometry of the opening: full, slot, door, and window. (This salt water technique uses the chemical reaction based on acid-base neutralization to dye the liquids using pH indicator, such as phenolphthalein, which is a better indicator of the mixing within the gravity current [20]).

Gravity current traveling time can be calculated using the following equations,

$$\beta = \frac{(\rho_0 - \rho_1)}{\rho_1} \quad (1)$$

Where ρ_0 is the higher density fluid within the gravity current (fresh air from outside of fire compartment), ρ_1 is the lower density fluid (hot compartment ahead of the gravity current)

$$v^* = \frac{v}{\sqrt{\beta g h_1}} \quad (2)$$

Where v^* is the nondimensional velocity (also described as the velocity of the compartment fluid approaching the gravity current (the gravity current velocity) [19]), v is the speed of leading edge of gravity current, g is 9.8 m/s², h_1 is the height of compartment.

$$v = \frac{L}{t_{in}} \quad (3)$$

Where t_{in} is the time required for the leading edge of the gravity current to reach the wall opposite the opening, L is the length of the compartment.

v^* only depends on the opening geometry, and the average values for full, slot, door, and window opening are 0.44, 0.32, 0.35, 0.22, respectively [19].

It was suggested that this salt-water model could predict the time of ignition for a backdraught with similar compartment and opening geometries. Based on salt-water experiments it may help to understand how long the gravity current reaches the rear wall of fire compartment by adjusting opening geometries (including sizes, orientations).

Fleischmann et al. [3] tested this method compared with a series of fire experiments, it was found that some ignition delay time of tests were much larger than the gravity current time, but in general, it provided some evidence that the delay time of backdraught was close to the gravity current time.

Before their application, salt water approach had been applied to simulate many fire problems such as corridor smoke flow, ship board fires and compartment fires. The result of physical analysis (both quantitatively and qualitatively) was similar to a naturally occurring gravity current even though the scale was comparatively small.

Figure 2.4.1 .Salt water experiment. (Fleischmann & McGrattan [19])

Jia et al. [3] tried to predict the fire propagation in enclosure fires, so a Computational Fluid Dynamics (CFD) (called CFDS-FLOW3D) was used for

modelling a simple solid fuel combustion model, two scenarios were considered involving opened and closed compartment, and they concluded that this model is able to qualitatively describe both flashover and backdraught.

In order to clarify the mixing that occurs in a gravity current, Fleischmann & McGrattan [7] compared among 2D-simulation with salt water model, and conducted backdraught experiments. Two different door openings, a full open-end wall and a 1/3 open slot, centred on the end wall, were used both in the salt water experiment and the numerical simulation. The 2-D numerical simulation shows good agreement compared with the compartment gravity current for both the fully open and 1/3 open condition. Over all, the transit time results and velocity measurements for the computations compared favourably with the experiments.

To demonstrate possible explosive backdraught events to firefighters, Gojkovic [8] designed full scale backdraught experiments and the container used was based on the same layout of the experiments conducted by Fleischmann et al.[2–4]. The container and apparatus were laid outside, and the size was 5.5m×2.2m×2.2m, natural gas was the fuel used in this research. Temperature histories, gas concentrations were collected as well.

CFD models were carried out to investigate the behaviour of the gravity current. Gojkovic noted that the time to achieve ignition should be dependent of the gas concentration inside the container, therefore, higher gas concentrations require more fresh air in order to reach the flammable condition. The testing result showed that there was no problem producing backdraught as there was enough fuel in the test. The behaviour of the gravity current is dependent on ventilation condition, therefore, wind, opening geometry and the temperature of the gases can affect the behaviour of the gravity current prior to backdraught. Regarding the role of gas concentration, the author admitted that “the results from this device are not very good though.”

Weng et al. [9] used a numerical model, so called Large Eddy Simulation (LES) in Fire Dynamic Simulator (FDS), to investigate the fluid structure of the gravity current, also to predict the ignition time of backdraught using eight different opening geometries. A non-dimensional velocity (see Equation (2)) was used for predicting the transit time required for the leading edge of the gravity current to reach the wall opposite the opening. The hot gas temperatures were set from 400K

to 900K (within an interval of 100K), and the ambient temperature kept the same at 300K.

From the result of the non-dimensional velocity, they concluded that the required time for a backdraught with a vertical opening is shorter than with a horizontal opening of the same opening area and location of the centre. In addition, the non-dimensional velocity they created, only depends on the different geometries used.

Yang et al.[10] knew that the flame spread in a backdraught is difficult to simulate because it involves the non-premixed and premixed flame spread under a ventilation-controlled condition. Therefore, numerical models including a sub-grid scale laminar flamelet model and a partially premixed model were imbedded in FDS 3.0 to simulate backdraught. Gravity currents were modelled in this research, but the majority of the study focused on the flame spread after backdraught is triggered.

To quantitatively describe salt water modelling, Yao and Marshall [11] visualised salt water experiments via Planar Laser Induced Fluorescence (PLIF), and they also mentioned that salt water dispersion closely simulates the dispersion of hot exhaust gases (smoke) in a fire plume.

Horvat et al.[12] in their “Numerical and experimental investigation of backdraught” paper describe full scale experiments (the same experimental setup as Gojkovic [8]) and compare the result using a CFD model, Ansys CFX-5.7.1 software, the Detached Eddy Simulation (DES) to model turbulent behaviour.

The simulation includes the gravity current, spreading of flame in the enclosure, the external fireball, and the subsequent decay. The results show that the that the simulated temperatures obtain good agreement with the experiments, however, the calculated ignition time was slightly shorter than the average ignition time observed in their full- scale experiments. Also, the numerical simulations slightly over predict the flame front speed.

Guigay [13] in his doctoral thesis, mentioned that there has been very little description of the gas dynamics and the mixing between opening and ignition, so he tried to fill the gap using Particle Image Velocimetry (PIV) to improve knowledge of the flow-mixing phenomenon involved in the first period of a backdraught, before the reigniting of fuel gases in the enclosure, which can be understood as gravity current movement.

He created a reduced-scale compartment ($0.55\text{m} \times 0.50\text{m} \times 0.41\text{m}$) and put inert gas inside, using fan to heat the space. Based on theory, the gravity current appears only when two different densities of gas or liquid meeting together. In this study, difference of temperature was used to establish the suitable condition for gravity current. By applying PIV as a visualization tool, Guigay considered the result can be used for the calibration and validation of the sub grid turbulence model used in numerical models.

Ferraris et al. [16] simulated backdraught phenomenon using LES for the reduced scale test conducted by Weng & Fan [25]. Some factors, such as species concentrations, total mass outflow and inflow rates, maximum pressure, and likelihood of the occurrence of the fireball outside the container were regarded as reasonable. The authors concluded that water mist can reduce the likelihood of an external fireball because it reduces the laminar burning velocity (the rate at which a flame propagates into a quiescent mixture is referred to as the laminar burning velocity [33]) and also it dilutes the combustible gases in the fire compartment. It should be noted that the term 'water mist' used in this paper was not a water mist system using high pressure nozzles, rather, the water here was a typical sprinkler design.

The gravity current was used for predicting ignition time, also they concluded that the time to ignition is directly influenced by the vent opening area, vertical openings (from the floor to the ceiling) are more likely to generate strong gravity current resulting in a larger flammable volume in a shorter ignition time. If the door/opening is small, the ignition time will be delayed because of the restricted inflow of fresh air. In terms of fireball outside the container, they considered that it is strongly influenced by the size and location of the opening.

Guigay et al. [14] continued the research by Horvat et al. [12]. They used classical hydraulics and a transient numerical simulation using the ANSYS CFX computational fluid dynamics (CFD) code to further understand the gravity current prior to a possible backdraught condition. They compared with the velocity fields predicted by Ansys CFX when simulating Gojkovic's experiments and found that the result compared well with previously published data.

Guigay et al. [15] in order to better the knowledge of gravity current (flow-mixing phenomena, "gravity wave" in this paper) for the first period of a backdraught, a specific device (PIV) and experimental procedure were developed

to understand the movement of flow during the growth of a backdraught. The instantaneous velocity changes at the time of door opening were studied. In their research, there was no real fire, instead, the tests were conducted with heated inert gases, and the layout of experimental apparatus (including PIV technique) was the same as previously used by Guigay [13].

Moreover, the application of FDS shows that the characteristics of the vortices observed in experiments seem well reproduced by the code (only convective velocities). In this paper, a chain of time-resolved PIV (TR-PIV) was used because the typical PIV technique was unable to faithfully demonstrate the gravity current, this makes it is possible to quantify the evolution of the size and speed characteristic of the vortices of the experiments.

Figure 2.4.2 PIV technique. (Guigay et al. [15])

Different opening geometries were investigated and the unsteady gravity current movement when a sudden change of the ventilation occurred was observed. They observed deceleration of the gravity current, which means that the mixing is weak and the residence time was relatively long, when the opening was low. This means the time required for the gravity current to reach the rear wall is longer for low openings. However, when the configuration changed to the middle opening, the gravity wave was accelerated by the descent of the dense fluid (the fresh cold air), resulting in the more intense vortices and the residence time of two fluids (hot and cold gas) is longer. In other words, when the opening is nearer the floor, the gravity current needs more time to reach the rear wall.

Most et al. [17] follow the design of Guigay et al.[15], using a time-resolved PIV technique was used to predict the probability for potential local ignition and backdraught development. After the validation in an inert environment, their conservative variables which came from assuming ignition conditions will provide the gas mixing rate, the local mixture fraction.

To conclude, gravity current of cold air and hot gas has given fire researchers much attention when tackling backdraught issue. The research evolution of this phenomenon in fire safety engineering is from experimental (including salt water approach, laboratory-sized testing) to numerical, and apply the state-of-the-art technique to get a better understanding of this density driven phenomenon.

Even though restrictions exist in PIV, some research used numerical approach (FDS) to compare the PIV result, in general, it can be concluded that the physics of the phenomena is consistent between the CFD model and experiments.

2.4.2 Research concerning the size, shape, and location of the opening

The opening size is another issue in backdraught studies to investigate how the opening affect the characteristics of backdraught. As backdraught is explosive, the compartment sizes for backdraught research must be not too large, otherwise, it may be difficult to control the risk that may occur when trying to generate backdraught. However, this does not mean that it is impossible to conduct full scale backdraught tests, as some full-scale tests are imperative to get better understanding of this phenomenon. The true thing is that there is not a backdraught event at the same size as the lab size testing in fire scenes.

Scaling is a common issue in fire research as it is sometimes unable to describe a phenomenon using small-scale tests. However, as mentioned above, the fundamental knowledge is required beforehand, which means that unless it

Figure 2.4.3 Sketch of Backdraught Experiment in Fleischmann's Research

has been known well regarding the mechanism of this phenomenon, otherwise, safety is the priority. Also, the size of the compartment does not influence the occurrence of backdraught [21].

Fleischmann et al. [2–4]) used an opening which was $1.2\text{m} \times 0.4\text{m}$ in a compartment which was $2.4\text{m} \times 1.2\text{m} \times 1.2\text{m}$ (see **Figure 2.4.3**). The opening size was one third of the short wall.

Later, Weng & Fan [22] used $1.2\text{ m} \times 0.6\text{ m} \times 0.6\text{ m}$ size compartment, followed the one third opening size idea of Fleischmann; the $0.2\text{ m} \times 0.6\text{ m}$ opening was positioned in the middle of the end wall.

In order to get more understanding whether opening geometries affect backdraught or not, eight different geometries were designed [23], see **Figure 2.4.4**.

Figure 2.4.4 Eight opening geometries in Weng and Fan's Research [23]

Mass fraction of unburned gases were analysed. They found the critical values to trigger backdraught range from 7.0% to 9.8%. Three of the result were lower than eight percent, which were 7.0%, 7.1%, 7.7%, respectively. Relevance of these three is that the opening location is near the top of the compartment, two of them were on the roof and one was at one third height near the ceiling. Moreover, the critical value of unburned gas mass fraction on the top slot, middle slot and lower slot were 7.1%, 8.5%, and 9.0%, respectively. In conclusion, the higher the opening is, the lower mass fraction of unburned methane is needed to trigger backdraught.

To explain the research result above, it can be related to the fuel they used in the experiments and the products after burning. One flammable fuel is methane.

Methane (CH_4), based on its natural characteristic, is lighter than air. CO, which is also lighter than air, is another flammable material, and it is produced when a fire experiences incomplete combustion due to an insufficient oxygen supply. Because methane is the fuel in these tests, and still leaked into the fire compartment during the time of the door closure, it occupied the majority amount before the occurrence of backdraught. Thus, when mixing with air, most of the unburned gases were most likely to be methane, which will float above air and gather in the upper layer of the compartment.

It can be explained that the upper opening made fresh air directly contact to methane and CO, and the movement path of the gravity current would be different from the observation of Fleischmann [4], where air probably quickly went down lower layer owing to its heavier density. This makes an opening next to the top of the compartment become more dangerous in methane cases due to the concentration of unburned methane. It is worth noting that the unburned gases in this study were hydrocarbons, carbon monoxide was investigated and flammable but not included in the group of the unburned gases.

In terms of location of opening, most of these openings were placed against the wall or ceiling opposite the gas burner / fuel source. Fleischmann et al. [4] mentioned that the experimental design could be used for observing how gravity current reaches the ignition source and how flame comes out of the compartment.

2.4.3 Research concerning the location and nature of the ignition source, if present

From the previous research, most of the backdraught related tests have set up the ignition source and the fuel container near the rear wall. However, the location of an ignition source can affect the occurrence and properties of backdraught, especially for those backdraughts which require a pilot source. Initiation of a backdraught would require the zone of mixed gases in between the flammability limits to actually extend to the location of the ignition source. The ignition source must also be able to provide the minimum ignition energy (MIE) required to ignite the mixture. Different locations of ignition sources can affect the delay time of backdraught, as the time of gas mixing (hot smoke and cold air) and transport to the location of the ignition source may be different.

So far, only a few research studies have investigated the location of ignition source, i.e. in most of the research regarding backdraught, the location of the fuel was fixed. In addition, the location of the igniters was mostly above or near the fuel.

Wu et al. [24] tried to change the location of the piloted ignition source and the result shows that when the ignition source is far away from the centre of the fire compartment, it is easier for a backdraught to occur. When a mixture of inner (hot unburned gases) and outer gases (fresh air) is created, a suitable gas concentration for a backdraught may be created, the condition required from the previous backdraught research (most studies) is that there should be an ignition source present.

The severity of a backdraught will be influenced by the location of the ignition source. The nearer the ignition source is to the opening, the less severe the fire ball will be or less likely to bring out backdraught. One possible explanation is that there is only a very short time available to lower the concentration of flammable gases to within flammability limits near the ignition source to create backdraught. The external fireball is formed as the result of the burnt gases expanding and forcing the unburnt fuel inside and air ahead of the advancing flame front, out through the vent [3]. It should be noted that the lower flammability limit reduces with increasing temperature. That is, a mixture that may not be flammable at ambient temperature may become flammable if the temperature is high enough. Also the limits vary significantly with initial temperature, more discussion please see Chapter 4 (section 4.1). Very small amount of energy is sufficient to ignite flammable mixtures, and the ignition requires a spark with energy above the MIE, this minimum energy varies with the gas mixtures, lower than MIE, no mixture can be ignited [33]. To better the understanding or support the hypothesis above, it still requires more investigation in future research.

2.4.4 Research concerning the gas composition in the compartment before the door is opened

The chemical reaction is one of the important parts of combustion, which determines if a combustion process can continue or not. A compartment needs to provide enough fuel, oxygen, and heat, to meet the requirements of combustion. In a possible backdraught condition, even in an oxygen-starved situation (under-ventilated), the oxygen will become enough as the opening procedure has been

done. That is, if any fire source is provided, and there will be a backdraught occurring because the fire source provides the essential energy initiating fire / explosion.

A predictor for backdraught is that the flammable gas inside must be higher than a specific concentration, this is one of the critical conditions for backdraught. Other critical conditions include temperature and flammability limits, as will be discussed in later chapters. Components of a typical compartment fire are sophisticated, varying with materials, and the flammability behaviour of clouds of mixed pyrolysis gases can be extremely complex. To simplify this problem, most backdraught research used single fuel, and the majority use methane (see **Table 2.4.1**). Also, fire sources, such as electrical sparks, were provided to ignite the flammable fuel for most of the backdraught research.

Table 2.4.1 Types of fuel in Backdraught experiments

Fuel type / Year/ Authors	Scientific name
<i>Gas / 1994 / Fleishmann et al.</i>	Methane (CH ₄)
<i>Gas / 1995 / Bolliger</i>	Methane (CH ₄)
<i>Gas / 2000 / Gojkovic</i>	Natural gas (CH ₄)
<i>Gas / 2002 2003 / Weng and Fan</i>	Methane (CH ₄)
<i>Gas / 2011/ Wu et al.</i>	LPG
<i>Gas / 2013/ Tsai and Chiu</i>	Methane (CH ₄)
<i>Liquid /1999/ Gottuk et al.</i>	Diesel
<i>Liquid /2011/ Mao et al.</i>	n-heptane (C ₇ H ₁₆)
<i>Liquid /2011/ Chen et al.</i>	n-heptane (C ₇ H ₁₆)
<i>Solid /2011/ Chen et al.</i>	Wood
<i>Solid / 2013/ Tsai and Chiu</i>	Polyurethane Foam

It can be seen that gaseous fuels were used for the majority of the previous backdraught research, different gases will affect the dynamics of the gravity current due to differences in their densities. For instance, gases like methane (0.7 kg/m³ at 0°C) are lighter than air at ambient and elevated temperatures, so will naturally rise above the gravity current of inflowing fresh air, irrespective of temperature. Other fuels, such as propane (the main component of LPG; 2 kg/m³ at 0°C) are heavier than air at ambient temperatures and will require considerably elevated temperatures to allow the gravity current dynamic to occur. The following section will discuss the representative backdraught research projects, categorised by the type of fuel used.

2.4.4.1 Gaseous Fuel

In order to obtain more information about backdraught phenomenon, Fleischmann et al. [4] designed a series of reduced scale experiments, to investigate this explosive fire phenomenon (burning with an explosive force [3]). An important conclusion was given by the result which indicates that unburned fuel mass fraction greater than 10% is necessary for a backdraught to occur. If firefighters open a door or window, it will introduce fresh air into the fire compartment and lead to backdraught if the flammable gas is more than 10%. Compared to qualitative characteristics, this quantitative result provides an initial understanding of the determining factor to backdraught occurrence, but relates only to methane fuel.

Bolliger [21], in his research, tried to determine the effects of scale. A full residential-scale compartment, with the size was 5.4m×2.2m×2.2m, was built to compare the experimental result obtained from Fleischmann [4]. Several types of data were collected, including flow rates, gas concentrations (CH_4 , O_2 , CO_2), temperature histories and pressure changes.

From the experimental result, it was concluded that the experimental scale has no obvious effect on observation of backdraught, in addition, the required unburned gas (hydrocarbons) must be higher than 15 % (mass fraction). Also, because the experimental apparatus was laid outside, the most uncontrollable variable was the ambient wind condition, which makes a substantial effect on the results.

To demonstrate possible explosive force of backdraught to firefighters, Gojkovic [8] designed full-scale backdraught experiments and the container used was based on the layout of the experiments conducted by Fleischmann et al.[2–4]. The fire compartment and experimental apparatus were laid outdoors, and the size was 5.5m×2.2m×2.2m. A total of 13 experiments were conducted, 8 of the experiments resulted in backdraught. Measurement including gas concentration (CH_4 , O_2 , CO_2), histories and change of temperature and pressure were made.

The testing results showed that there was no problem to trigger backdraught as long as there was enough fuel. However, the measured data cannot provide a good explanation about quantitative analysis, and may have a large margin of error. For instance, the author mentioned that some of the results are not very reasonable, for instance, the gas measurements show that the oxygen

concentration will be as low as 3 % when the flame went out, in his opinion, a value of 12 % would seem more appropriate. Also, Gojkovic says that the fuel for backdraught experiments must be “normal”, such as wood and plastic products that may be used in our ordinary lives.

Later, Weng et al.[22,23,25,26] conducted half scale (compared to Fleischmann’s experiment) which had a similar result that unburned fuel mass fraction need to be greater than 9.8% to produce backdraught.

In the studies, Weng et al. managed to discover the critical factors to the occurrence of backdraught. Probes were set to obtain the values of carbon monoxide, carbon dioxide and oxygen during testing. Weng and Fan compared unburned fuel with backdraught, and they found while Y_{HC}^5 is higher than 9.8% (critical value) in the compartment, backdraught will occur.

Also, Weng et al. considered that the mass fractions of oxygen, carbon dioxide and carbon monoxide, upper temperature, lower temperature and layer height, opening flow mass are not the key parameters determining the occurrence of backdraught. Only one opening geometry was used in this study.

Weng et al. continued analysing critical values from different geometries [23] in the same small-scale compartment. Eight different geometries of opening were used, and the critical values of unburned fuels ranged from 7.1% to 9.8%, thus,

Figure 2.4.5 Sketch of Backdraught Experiment in Weng and Fan's Research

⁵ $Y_{HC} = \frac{m_{CH_4}}{m_{total}} \cdot \frac{4}{11} Y_{CO_2} - \frac{4}{7} Y_{CO}$, Where m_{CH_4} was the total fuel mass which served as fuels in the compartment and m_{total} was the total gas mass. Y_{HC} , Y_{CO_2} , Y_{CO} were the mass fractions of unburned fuel (methane), carbon dioxide, and carbon monoxide, respectively.

they concluded that 9.8% is the critical mass fraction of unburned fuel for backdraught, this part has been discussed in 2.4.2.

Propane (C_3H_8) is heavier than air. It has been used once in backdraught research [4]. In this study, the researchers both used methane and propane as fuels in same experimental configuration, however, no backdraught occurred in propane cases, only methane led to backdraught.

LPG is another sort of material has been used to investigate backdraught phenomenon. In the research, Wu et al. [24] changed the ventilation geometry in a very quick manner to investigate the sudden change of ventilation on the behaviour of backdraught. Also, the effect of the ventilation conditions, ignition location was discussed.

Their conclusion is that the smaller the opening is, the further of the ignition position is from the centre of the compartment and the larger the mass flux of gas leakage is, the more easily backdraught occurs.

2.4.4.2 Liquid Fuel

Gottuk et al. [28] designed full scale experiments in a confined space (the US Navy fire test ship in Mobile, Alabama) , and diesel was used as the fuel. To study the development and mitigation of backdraught, CO, O₂, CO₂, pressure, and temperature histories were collected. They concluded that the fuel mass fraction is the key parameter for backdraught development, no backdraught was produced with a mass fraction below 15%, backdraught events only occurred when the mass fraction was above 16%. So, a conclusion is that the critical fuel mass fraction for the development of diesel fuel backdraught is 16% for fully vitiated conditions.

In addition, the injection of water spray into the fire compartment is an effective mitigating tactic which was able to completely prevent backdraught by diluting the atmosphere.

Mao et al. [29] investigated backdraught phenomenon in tunnel fires by using liquid n-Heptane C_7H_{16} (95% pure) which may represent unleaded petrol. A 1/8 scale tunnel was created to conduct the tests.

Critical gas concentrations for the occurrence of backdraught were also found in the research. The critical value of the mass fraction of unburnt fuel for the single tube configuration with natural ventilation was 8.78%.

2.4.4.3 Solid Fuel

Some backdraught researchers have suggested that to get a better understanding of backdraught, more realistic fuels must be selected for further studies [4] [8] [22]. This does not mean that they (solid fuels) can be burned directly, only gaseous fuels can be ignited as backdraught. Enough heat or energy is essential for the physical transformation to pyrolyse or vaporise the fuel.

Pyrolysis is the decomposition of solid materials into lighter (often gaseous) components, sometimes leaving a char residue, under the action of heating. Pyrolysis processes vary from material to material, but all require a minimum (critical) external heat flux. Pyrolysis is faster at higher temperatures and with higher external heat fluxes. The external heat may come from flames, hot surfaces, or other energy sources. If produced in sufficient quantities, pyrolysis gases, when mixed with air, may form a flammable mixture. This implies that the heat flux will determine if whether or not a flammable mixture is generated.

If the generated gases are within the flammability limits and at a sufficiently high temperature, the unburned fuel vapours may ignite spontaneously. It should be noted that the required heat flux will be higher for spontaneous ignition than for piloted ignition [33].

Chen et al. [30] designed a small-scale compartment, 0.68m×0.42m×0.42m, conducting backdraught by using n-heptane and wood. The mean volume fraction was calculated 9.3%. Therefore, it was considered to be very close to the result, 10% of unburned fuel mass fractions, given by Fleischmann [4]. Temperature, NO_x, O₂, CO, CO₂ and hydrocarbons, and delay time of backdraught were also analysed during the tests.

Tsai & Chiu [31] designed full scale backdraught experiments which used an loveseat, which is made by polyurethane (PU) foam, as the fuel. The compartment size was 5.9m×2.35m×2.4m and was located outside, in an open space. In the testing, a simulated living room was created.

The observed gas components in the experiments of the backdraught of related research are listed as follows, see **Table 2.4.2**.

Table 2.4.2 Gas concentrations before opening in backdraught testing

Fuel type	Year	Authors	Approximate values (in volume fraction)			
			O ₂	CO	CO ₂	HC
Gas	1994	Fleischmann et al. [4]	0.03-0.09	0.002-0.01	0.022-0.05	0.156-0.298
Gas	1995	Bolliger [21]	0.053-0.067		0.026-0.038	0.192-0.411
Gas	2000	Gojkovic [8]	0.05		0.011	
Gas	2003	Weng and Fan [22,23,25,26]	0.11-0.12	0.001-0.008	0.013-0.017	0.186-0.334
Liquid	1999	Gottuk et al. [28]	0.005-0.05	0.04-0.05	0.105-0.13	
Liquid	2011	Mao et al. [29]	0.140-0.162	0.0001-0.0003	0.023-0.026	0.04-0.14
Liquid	2011	Chen et al. [30]	0.051-0.099	0.007-0.015	0.063-0.11	0.025-0.043
Solid	2011	Chen et al. [30]	0.084-0.112	0.008-0.033	0.045-0.072	0.087-0.164
Solid	2013	Tsai and Chiu [31]	0.143			

Previous research projects have been stated investigation results regarding gas concentrations using different units, i.e. mass fractions and volume fractions, which leads to the results are not comparable. For instance, 10% mass fraction $\approx$ 15.6% volume fraction on the top right of the Table. For consistent interpretation, all the gas components have been converted into volume fractions. For those experiments using methane, the volume fractions have been directly obtained from the mass fractions of O₂, CO, CO₂, and HC (CH₄) in Fleischmann's and Weng's experiments, calculated in a range of the minimum and maximum values of methane in the experiments using the suggested chemical formula [34]. As no CO data was obtained in Bolliger's research, the CO/ CO₂ ratios are in a range of 0.1-0.3 in Fleischmann's and Weng's experiment, therefore, the CO/ CO₂ is assumed to be 0.2 (i.e. combustion efficiency = 0.8). As for Mao et al.'s [29] research, the unburned fuel was determined by C₇H₁₆. Hence, O₂, CO, CO₂, and HC (C₇H₁₆) are obtained using the same procedure.

In **Table 2.4.2**, it shows that the none of oxygen, carbon monoxide, or carbon dioxide concentrations provides useful information to describe the critical conditions for backdraught to occur. But this does not mean the contribution of carbon monoxide gases to the occurrence of backdraught can be neglected, it requires more scientific research to support or deny it.

The range of the O₂ shows that backdraught can be triggered even if the oxygen concentration is as high as 14%, which means that an under-ventilated

condition may not be required, when the level of the oxygen depletion to 14%, backdraught is ready to happen if an ignition source exists.

In summary, an unburned fuel mass fraction which is higher than 10% (that is, 15.6% in volume fraction, see **Table 2.4.2**) is the critical factor for the occurrence of backdraught when the fuel is methane. If the fuel changes to C_7H_{16} , the volume fraction must be higher than 4%. As to solid fuel, Chen et al. [30] concluded that the required volume fraction (total hydrocarbons) $>9.3\%$ is the critical factor for backdraught to occur. So far, apart from the research aforementioned, there is no research result showing conclusively how much unburned gaseous fuel is required for the occurrence of a backdraught to support the conclusion given by Chen [30].

Methane is the fuel used most broadly in backdraught studies, one of the reasons is that methane is lighter than air and has known flammability limits. Gojkovic [8] mentioned that those physical qualities (natural gas) are similar to products of pyrolysis, and it is easy to control the amount of the fuel release during experiments.

Gas analysis is a common task in backdraught experiments. In research studies, gas probes were used to obtain concentration of gases, and observed subjects focus on carbon dioxide, oxygen, carbon monoxide, and hydrocarbons. But not only those gases have been investigated, observations for nitrogen, volatilized n-heptane, and NO_x have also been conducted [29,30].

2.4.5 Research concerning the temperature in the compartment before the door is opened

Before the occurrence of backdraught, a temperature decrease was generally observed in backdraught research, as the door was being shut to mimic a real under-ventilated fire scenario before triggering backdraught. According to the past backdraught experimental studies, the lowest temperatures before backdraught occurring were different, changing with different fuel types, see in **Table 2.4.3**.

Table 2.4.3 Critical temperature among different type of fuel in Backdraught Experiments (before backdraught)

Fuel type	Year	Authors	Scientific name	Approximately Temperature (unit, K)	
				Upper layer	Lower Layer
Gas	1993	<i>Fleischmann et al.</i> [3-4]	Methane (CH_4)	344-570	330-475
	1994				422-485

				(averaged compartment temperature)	
Gas	1995	Bolliger [21]	Methane (CH ₄)	312-433	302-324
Gas	2000	Gojkovic [8]	Methane (CH ₄)	373	353
Gas	2003	Weng and Fan [22,23,25,26]	Methane (CH ₄)	375-402	326-353
Gas	2011	Wu et al. [24]	LPG	320	310
Gas	2013	Tsai and Chiu [31]	Methane (CH ₄)	321	315
Liquid	1999	Gottuk et al. [28]	Diesel	553-693*	
Liquid	2011	Mao et al. [29]	n-heptane (C ₇ H ₁₆)	330-340	300-310
Liquid	2011	Chen et al. [30]	n-heptane (C ₇ H ₁₆)	700-758*	
Solid	2011	Chen et al. [30]	Wood	523-553*	
Solid	2013	Tsai and Chiu [31]	Polyurethane Foam	533	473

In **Table 2.4.3**, it can be seen that the temperature records changed from different experiments. In terms of experiments using gaseous fuels, the temperatures before backdraught for either methane or LPG were below 570K. In addition, most of them were only about 350K, no matter upper layer or lower layer temperature. But it should be noted that the value of the temperature varies with gas flow rate in Fleischmann's experiments

Unlike experiments using gaseous fuel, those experiments which used liquid fuel had a wider range of temperature, from 300K to 758K. Even if using the same fuel (n-Heptane) for backdraught research (Mao et al. [29] and Chen et al. [30]), results showed extremely different temperatures before backdraught when the compartments of the experimental design were not the same.

Figure 2.4.6 Typical temperature graphs for the methane case when backdraft occurs. (Fleischmann et al. [4] (left); Gojkovic [8] (right))

One factor is whether a man-made ignition source exists. Heptane easy to vaporise and ignite at room temperature. In Mao's research, an electrically heated

* not given this is upper or lower temperature

metal resistance wire was used as the ignition source to ignite the unburned fuel at about 323K (50°C); however, no ignition source (apart from the warm smoke) was provided in the fire compartment in Chen's research. This shows the difference between non-piloted and piloted backdraught events; a higher temperature is required for those backdraughts without a spark used as the ignition source.

Solid fuels, wood and polyurethane, have also been used in backdraught experiments. The temperature range when using wood fuel was from 423K to 553K, while for Polyurethane, the temperature range was from 473K to 553K. According to Chen's research, the temperature continued to increase in the closed compartment because of the wood smouldering during the time of door closure, while in Tsai's research, the temperature gradually decreased from 773 K to about 500K. Different experimental protocols were used by Chen and Tsai, hence, the observed temperature just before backdraught varies considerably between these series.

Pressure change is definite in backdraught process owing to its explosive characteristic. Measured pressure values will change if different experimental condition exists. For instance, leakage vent was set in several experiments ([2–4], [21]), this pressure relief apparatus can prevent pressure from increasing to an extremely high level, which avoids damaging the adjacent areas or hurting people nearby; on the other hand, it will fail to simulate a well-sealed compartment, as such modern energy saving houses. However, two scenarios are both possible in real fire scenes.

2.5 Discussion

Methane (CH₄), as most popular fuel in backdraught experiments, has the lowest average temperature for both upper layer and lower layer. The lowest observed temperature which triggered backdraught was about 312K (39°C), near room temperature. But if the fuels are diesel, wood or polyurethane, it seems a higher temperature is required before backdraught.

Even though related experiment studies have been collected in this chapter, we still cannot make conclusion that gas fuel need lower temperatures to allow backdraught, because there is no standardised testing procedure for backdraught

prediction. The opening time and premix burning time were different in every previous experimental testing. The only thing that can be concluded is that temperature before a backdraught will vary with different sorts of fuel in a fire. But it still a long way to discover if a regular pattern exists or, a correlation can be found among the factors (i.e., temperature, gas concentrations, etc.)

When referring to fuels used for backdraught research, researchers must make sure the use of the materials before conducting experiments. For instance, natural gas represented methane in the previous studies. In fact, natural gas a mixture of hydrocarbon gases which consists primarily of methane, even if the purity of natural gas is very close to 100% methane. If the original fuel was pure methane, it will not bias the result and change the mass fraction of hydrocarbons. So, fire scientists should make sure what sort of fuel they will use before conducting any experimental testing. Furthermore, a typical fire scenario should be selected. This gaseous man-made fire scene is unlike a real compartment fire, one reason is that in a real fire, the combustible material will not leak at a very steady rate, it is dependent on the ambient conditions, such as heat transfer (conduction, convection, and radiation). In addition, methane is very easy to diffuse if there is a very tiny leakage in the compartment, if the tests do not make the compartment well-sealed, the results of the gas concentration may be unstable even the rest of the experimental design is kept the same.

Mass fraction of unburned gases is a key factor to the occurrence of backdraught. Both Fleischmann et al.[4] and Weng & Fan [22] had the same statement that over 10% of unburned gases mass fraction is essential for a backdraught. But when it comes to flammability limits, 10% mass fraction of methane is higher than 15 % of volume concentration in the previous research studies (see **Table 2.4.2**), which is the UFL of methane, which implies the need for a backdraught is higher than the flammability limits of methane. One possible reason to explain this is that the gas detectors were put very close to the ceiling, however, the combustion (backdraught) started at the height approximately in the middle of the compartment (depending on the location where they ignite the fuel).

In shipboard experiments, Gottuk et al.[28] assumed the fuel used to be $C_{10}H_{19}$. In fact, the common diesel fuel is a mixture of hydrocarbons, ranging approximately from $C_{10}H_{20}$ to $C_{15}H_{28}$. When researchers try to simplify the chemical formula, the most realistic one ($C_{12}H_{23}$; commonly used) might be the optimal selection.

In relevant research studies, mass fractions were calculated using simple chemical formula, thermal pyrolysis was not considered. Simplicity is always good to start the initial investigation, but results may be limited to the experimental fire itself. Therefore, to make use of the result to predict a backdraught event seems not even possible as the boundary conditions may totally different. In addition, gas concentrations were probably not representative. Some of the obtained data, such as CO, were nearly zero percent. Sometimes it may be incorrect if unreliable data is used, hence, more investigation of gas compositions is essential.

Based on the previous experience on backdraught research and flammability regime theory in fire science, a clear definition of backdraught for two different conditions (with and without extra ignition sources) are given:

Non-piloted ignition backdraught.

After a well-developed fire experiences a time of door closure, if the door is suddenly opened, any local temperature above a required critical temperature for backdraught and accumulation of unburned smoke, with a suitable mixture of cold air entrainment and hot smoke, result in a fast expanding fire spread and leads to an external explosive fireball.'

Piloted-ignition backdraught.

After a well-developed fire experiences a time of door closure, if the door is suddenly opened, accumulation of unburned smoke, when the interface of the cold air entrainment and hot smoke reaches a pilot spark, fast flame spreads along the interface and leads to an external explosive fireball.' In some events, fire re-ignition occurs without external fireball; this is not considered to be backdraught.

To conclude, researchers have tried to use varies fuels to describe and investigate the critical factors for the occurrence of backdraught, not only gas fuels, but also liquid and solid fuels. The generic conclusion is that the unburned fuels in the gas phase are the determining factor for backdraught.

2.5.1 Temperature

The range of temperatures was different when using varies fuels in the previous backdraught research. A high temperature was not required, for instance, the

range was about 312K to 570K in the upper layer of the fire compartment when using gaseous fuels in successful backdraught events.

Experiments used liquid materials as the fuel, such as n-heptane, the observed temperatures prior to backdraught were between 330K and 758K. As to solid fuels, experiments that used solid fuels resulted in different temperature range, depending on what types of fuel was used, the range was 393K to 783K in wood, while in polyurethane, and it increased to 873K to 1173K.

From the above, it can be seen that the temperature required to initiate backdraught is generally lower when using gaseous material compared to liquid and solid fuels. The reason for this is that the gases like methane can be ignited at room temperature while the liquid and solid fuels require a thermal pyrolysis process to produce the flammable vapours required for backdraught.

In fact, the temperature of the fire compartment will change with materials also the duration of the burning time before door closing, every material has its properties which will affect the peak of the temperature, and therefore, we cannot conclude that there is no chance to create a backdraught because of the observed temperature is lower than the result of the previous backdraught research, further research and investigation on this phenomenon are needed.

2.5.2 Gravity current analysis and its application

Chitty [1] mentioned that “the time delay for the gravity current to cross an enclosure and for a flammable mixture to coincide with an ignition source may extend to minutes for very large spaces.”, that is, fire fighters possibly risk their lives when entering a large compartment. Therefore, gravity current delay time obtained from reduced scale experiments might not reflect to a real delay time of backdraught, results from those experiments are very likely shorter than a real delay time of gravity current. If fire brigades adopt those research data to design their tactics to backdraught, firefighters may suffer risks from uncertain occurrence of backdraught when recurring a modern, complex building.

2.5.3 Salt water and PIV method

Salt water and PIV technique can provide a visualized image of gravity current. Both are based on density differences of two liquids or gases. In a real backdraught

situation, unburned gases can be formed by gases, water, and soot and so on. Even though this can be assumed that it becomes stable status before the door opening, it still needs more experimental and numerical studies to prove the reliability. Also, Chitty [1] pointed out the salt water approach will need to be extended to include ignition and combustion. What the components in a real fire, or under-ventilated fire will be, and what the possible proportions of different gas components are, can be useful for predicting the occurrence of backdraught more accurately.

For visualization, the traditional salt water approach needs to dye the liquids using a pH indicator, such as phenolphthalein. This approach is to use a chemical reaction (the colour change) to observe the mixing process of two different liquids (different density). In terms of a qualitative aspect, it can give nice visual effect, however, this method will not be able to provide direct information compared to a fire scene because the temperature distributions inside the fire compartment are not always well-stirred.

PIV technique now have been used to investigate the temperature difference inside and outside of the heated experimental space. Nowadays, there is fast tomography in supporting PIV, the observation of gas movement (after the change the ventilation condition) will become more continuous. But again, in a real fire scene, the temperatures in every location change over time, even if the fire becomes a non-flaming combustion. It makes the observational result from this technique is still hard to faithfully represent a real fire condition.

2.6 Conclusion and future work

The previous research demonstrates what a backdraught looks like, and the mechanisms of it, restriction of the ventilation conditions, burning status, and mixture of hot and cold gases. Even though fire scientists have tried to understand more about backdraught phenomenon, it has been shown that only the big picture of backdraught, i.e. the theoretical basis and general understanding of the backdraft phenomenon, has been understood. However, the quantitative mechanisms of the backdraft phenomenon are still largely absent [32].

Unburned fuel mass fraction seems to be the most useful factor in backdraught research over the past twenty years, and research result has validated the result

given by Fleischmann, largely using the same fuel, methane. But how those result can be used to establish a standard for fire rescue procedure to reduce the possible casualties for firefighters, has still long way to go. In addition, they only adopted one of the possible fire conditions using man-made ignitors to ignite the fire, in some cases, backdraught may be triggered by the temperature inside the compartment (hot smoke itself) in the fire scene.

If removing one part of the basic fire triangles (heat, fuel, and oxygen), it is not possible for any form of fire to happen. The oxygen can be related to the flammable limits of the fuel, described as fuel mass fraction in most of the research. At the same time, temperature in the compartment can be described as the given energy to initiate the combustion process, if a minimum energy is given, then the concentration of the unburned gases matters, but what if the temperature inside the compartment is not high enough, the temperature inside of the fire space may dominate the occurrence, or not, of backdraught.

Researchers have designed experiments using different type of fuels to create backdraught and explaining the observations. It is concluded that 10 % of the unburned gases is the requirement for a backdraught to be initiated, and many used the flammability diagram as a tool to analyse the mixture of air and fuel, this concentration value can also vary with the geometry of the opening, locations of gas sampling etc. But it should be kept in mind that pyrolysates in the fire compartment will change according to the ventilation conditions, this means that if the composition of the mixture is unknown, researchers need to discover the concentrations of the possible pyrolysis products in different fire scenarios.

Methane is the most popular fuel in backdraught research, therefore, if there is a methane manufacturing plant on fire, the information can be given to fire brigades using the previous research findings. However, this condition is unlikely to happen as most of the fires are residential fires, it makes the previous research projects exist many restrictions in practice. Moreover, it is not possible to use a single type of compartment to represent most of the fire that is ventilation restricted. Several factors, such as geometry of the ventilation and compartment, type and location of the fuel, and the insulation of the compartment boundaries, may affect the result. The difficulty in the related research is that there are too many variables that need to be compared at the same time.

The question remaining is, how can this research push the scientific understanding of backdraught forward? So, there are crucial things to be solved and developed specifically:

- *There is no a clear approach to tell if a backdraught is going to happen or not in a fire scene, even if there is, this is only limited to methane fuel.*
- *What the elements of Fire Triangle play a role for the occurrence of backdraught, does Fuel, Oxygen, Heat affect the occurrence of backdraught, or only unburned fuel (this was popular in the previous research)? Can firefighters/rescuers use those factors above to control or prevent a backdraught from occurring?*
- *To investigate backdraught and to develop a guideline for the firefighters to cope with a possible backdraught event.*

Therefore, the thesis focuses on these three questions, and more discussion and experimental results can be seen in the following chapters.

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Chapter 3. Experimental design, blank testing and preliminary experiments

3.1 Introduction

This chapter describes the details of the experimental design in this thesis, and the way the experiments were conducted. In the literature review chapter, it can be seen that there is a rough consensus about the mechanism of backdraught, from experienced researchers on backdraught. But there is not a systematic research on backdraught using realistic fuels that may be used in our daily lives so far, such as solid plastics, wood etc. Some of the researchers have tried to investigate backdraught using solid fuels, but these studies have been mainly focused on the outcome of the backdraught itself. The caused analysis of the backdraught was outside their research.

From the point of view of fire rescuers, backdraught is not always triggered in fire scenes. Rescuers may have different understandings of backdraught. Even if “suitable” conditions occur, it is still difficult for a firefighter to judge if there is a backdraught going to occur.

Flashover, from anecdotal evidence/ understanding, seems crucial to the occurrence of backdraught, but it seems that there is no scientific basis for this. Owing to the lack of information with regard to the backdraught phenomenon in fire research, the first and most important part of this study is to successfully create it without any interference by instrumentation (i.e. thermocouples, gas sampling, etc.), thereafter this research protocol will conduct a series of experiments creating backdraught investigating any possible characteristics of backdraught in different fire source conditions, which is useful to understand the reasons why a backdraught may occur in a real fire scenario.

Stages of this chapter includes

- I. Experiment design to generate backdraught.
- II. Preliminary experimental testing without pilot source.
- III. Preliminary experimental testing with pilot source.

3.2 Aims and objectives

The first task is to successfully create backdraught by trying different amounts of fuel to make sure this research is viable, because there are no specific clues or procedures from the previous research projects showing how backdraught is

initiated using solid fuels. In the first stage of backdraught experiments, in this testing, adjustable openings were used for creating backdraught successfully and the behaviour of backdraught under different ventilation conditions was observed. By doing so, the possibilities of backdraught have been obtained. At the same time, fuels that have been used are generally not reusable, therefore, the suitable quantity of fuel was examined to avoid wastage, and to be able to be cost-effective for the research.

Different from the most backdraught research, this research uses solid fuel, instead of gaseous fuels. Polypropylene (PP) was selected to be the main fuel used for the whole thesis. PP is one of the common materials in plastic production. Many household facilities or equipment rely on this sort of material (plastics); therefore, it will be more representative of reality than gaseous fuel. Also, to aid the ignition process, a small quantity of n-Heptane (C_7H_{16}) was used as an accelerant to start and sustain the burning process. By following the experimental process and design mentioned above, a real fire in a typical compartment can be replicated with some credibility.

3.3 Layout of experimental compartment

From the literature review (Chapter 2), it is found that both Fleischmann et al [1,2] and Weng & Fan [3,4] have used the same ratio of length, width, and height for the fire compartment for their backdraught research. It was thought good to use the same ratio as in their research, so it should be easy to compare the results. The location of the burner is different, it was installed with a 10 cm distance from the rear wall rather than directly touching the rear wall. This was to prevent the electric spark (ignition source) coming into contact with the fire during the experiment. Some different results may be observed. In addition, backdraught is commonly occurring with explosive force [2], so to make sure everyone / every equipment in the fire lab is safe, it is essential to conduct experiments in a safe manner. Luckily, it has been demonstrated that the occurrence of backdraught (including the general nature) is independent on the scale of the compartment [5]. Therefore, a small-scale fire compartment (0.8 m×0.4m ×0.4 m, this size fits the

width of the experimental bench) was designed and built for the backdraught research, at a laboratory scale, see **Figure 3.3.1**.

Figure 3.3.1 Sketch of the backdraught testing compartment

The size of an opening may vary during fire rescue missions as a door / window may break by either sudden pressure release, owing to the temperature increase, or fire rescuing by firefighters. So, three movable baffles were designed to adjust the opening orientations and sizes, therefore, it will be possible to investigate the effect of the size and of the opening shape.

To be able to conduct a series of experiments, the materials adopted were expanded vermiculite boards, for which the maximum working temperature is 1,100 °C. This ensures the box can be used for several experimental testings. Because when the fire reaches the flashover condition, the highest temperature is not likely to increase much beyond 1000°C. As the material is an insulating material, outside the compartment, the temperature is only few degrees higher than the room temperature during fire experiments. Most of the heat is kept inside the compartment. This characteristic can also be used to simulate energy saving houses in real fire conditions, but it should be noted that this is not a completely sealed compartment, which may allow hot gases to dissipate from the edge of the front opening. The layout of the fire compartment can be seen in **Figure 3.3.2**.

A steel fuel tray with 0.2 m×0.2m×0.05m was positioned 0.1m distance from the rear wall (opposite to the location of the opening) of the compartment. This design allows the ability to change the compartment size (width) by installing parallel vermiculite boards. To control the opening, a sliding door is used to seal and open the compartment during testing, this ensures people working around the

adjacent area are safe and stay to the side of the compartment when the door is open and are well out of the way of any ejected flames.

Figure 3.3.2 Compartment of the experiment (front view)

Outside the compartment, aluminium frames are used to support and protect the compartment if a sudden explosion occurs during the test. To sum up, it has been designed that the door at the front of the compartment provides the only path for energy release when a backdraught occurs.

3.4 Creating backdraught- experimental procedure and results

3.4.1 Experimental procedure

Factors that affect the occurrence of backdraught are not well-understood, but it is well-known that before a backdraught can be triggered, the fire compartment should only have a limited /confined ventilation condition. In general, to trigger this phenomenon, a change of ventilation condition is required, therefore, a “switching procedure” which restricts and introduces fresh air is required for all experiments in this research.

The procedure of preliminary experimental design of this research is described as follows,

- 1) Ignite fuel and put the fuel tray to a specified location.
- 2) Once the fire clearly develops to flashover and becomes a fully developed fire, then close the door to restrict the ventilation of the compartment. Wait for a while, then re-open the door again (the

size of the opening is adjustable) to investigate if this manner can trigger a backdraught.

- 3) A few seconds after backdraught happens, fully open the door to allow fresh air in to increase the ventilation, and let fire grow to flashover again.
- 4) If the fire rekindles, wait until the fire evolves to flashover conditions again. Then follow procedure 2, to test if another backdraught is possible.
- 5) Finally, to finish the experimental procedure, completely open the door until the remnant (if there is any) of the fuel is consumed (if the fire is re-ignited) and allow the compartment to cool to ambient temperature.

In this project the way to judge if the fire has achieved flashover is by observing external flaming at the opening. There is no heat flux gauge inside the fire compartment, it cannot directly apply to the research here. Every experiment has its uncertainty, a suitable way is to adopt a qualitative approach using external flaming as the indicator of flashover. It means that the fire has experienced “the transition from a localized fire to the general conflagration within the compartment (the definition used in [6])”. This definition applies throughout the whole thesis.

It should be noted that this experimental protocol was designed to create possible conditions for backdraught. In reality, backdraught conditions are achieved after a large fire becomes starved of oxygen, this may be due to the fire consuming all available oxygen in a space, or it may be due to door closures or structural collapses blocking ventilation pathways. It is conceivable that such blocking of ventilation pathways could occur after flashover has occurred, although (as will be shown) the fire growing to flashover is not a necessary condition for backdraught.

In this research a ‘door closing’ procedure was used. Therefore, it may not directly reflect the ‘real’ backdraught condition of a fire consuming all available oxygen, but it does provide a repeatable and consistent experimental test protocol.

To sum up, this procedure is used to test,

- Whether the fuel selected is sufficient to achieve flashover.

- Whether the experimental fire can achieve the conditions that a backdraught requires.

3.4.2 Experimental results

3.4.2.1 Selection of Quantity of Fuel

The first experimental setup was to test if a backdraught could be triggered without any extra energy supply, which means that the heat source is limited to the temperature elevated by the development of the fire itself. To avoid any hot source which could provide heat/ energy to interfere with the occurrence of backdraught, there are no other materials used inside the box, except for the fuel tray, namely, inside the fire chamber, only the fuel and the steel fuel tray exists.

For simplicity, a ratio of 2:1 (2 g of PP to 1 ml of n-Heptane; it is acknowledged that this is not a true ratio, as the units are different, but it is unnecessary to convert these two units to be the same as the mixture is simply a convenience in experimental preparation; the heptane functioned only as an accelerant and burned up before the compartment door was closed in all tests) was found to be the best ratio in which the plastic pellets (PP) can be soaked in the accelerant liquid (n-Heptane), the height of n-Heptane reaches approximately to the surface of the solid fuel pellets.

Three combinations of fuels were tested,

Table 3.4.1 Quantities of fuel

Combination	PP ((C ₃ H ₆) _n)	n-Heptane (C ₇ H ₁₆)	Flashover
Type A	200 g	100 ml	No
Type B	300 g	150 ml	Yes
Type C	400 g	200 ml	Yes

In **Table 3.4.1**, it was observed that both type B and C can reach the stage of flashover. In general, type C required a considerable time to consume all the fuel as the fuel load is larger than type B. Also, it is found that after reaching flashover, about 2 minutes of burning remain for type B. To be cost-effective, type B was selected to be the fire load used for the experimental fire.

It should be noted that some gas/ smoke leakage was observed at the edge of the joints of the vermiculite boards owing to heat expansion during experiments. Fire cement was used to prevent leakage to minimize the uncertainties for the next/following experiment.

3.4.2.2 Preliminary backdraught results

At this stage, the experiments aimed to trigger flashover first before investigating any door closing procedure. Unlike most of the previous backdraught research, this is based on a real fire development to mimic a real fire scenario before a door / window opening, instead of injecting flammable gases, then igniting these by a fuel burner/ electric spark. This might be able to create more realistic fire conditions that reflect a real possible backdraught event.

As a ventilation change is one of the critical steps to allow mixing of fresh air to dilute the smoke concentration in the fire space to have suitable conditions for backdraught to occur, it is of interest to investigate how the location of the opening plays a role in the occurrence of this phenomenon. The rate of the mixing process will be determined by the temperature inside the fire compartment as the fluid mechanism changes with the density difference influenced by hot and cool temperature from the inside and outside temperature during experiments. Also, the energy balance becomes more stable with a longer door closure as the temperature difference among layers tends to be smaller, the mixing process between the hot smoke and cold air (outside the compartment) may become less vigorous. Hence, experimental trials of three types of opening were investigated to obtain the initial results, these allow us to know whether backdraught can be produced with different opening locations, and observe the different characteristics of backdraught.

Of course, changing the opening size is also crucial to test if the opening factor affects the behaviour of backdraught, but this is not the purpose of this chapter, for details see Chapter 8.

Three types of opening location were tested, upper, middle and lower part of the front opening, see **Figure 3.4.1**.

Figure 3.4.1 Opening geometries

When the opening is positioned at the top of the door, backdraught was not observed after the opening procedure. The other two openings, middle and lower, could trigger backdraught. During the experiments, a trial had been tried to control the open geometries by adjusting the horizontal baffles. It was found that the proportion of opening (at least 1/9 of the full opening area (full opening: 400mm x 400mm), did not affect the occurrence of backdraught. Although backdraught can be triggered with different opening sizes, the results show that the behaviour of

Figure 3.4.2 Backdraughts under different opening locations (1/3 of each horizontal baffle)

propagation of backdraught is not identical, which indicates that the locations of the opening can be one of the useful factors to test the behaviour of backdraught, see **Figure 3.4.2**.

In **Figure 3.4.2**, the development of backdraught can be observed from video clips. Theoretically, an ignition spot should be able to provide the initial energy needed to start the whole process of backdraught. However, because the insulation vermiculite boards are not transparent, it was not easy to observe the development of backdraught from the side of the fire compartment. Also, if putting a camera in the compartment, black particles/ soot (hot unburned smoke) would hinder the vision of cameras during the time of door closure, hence, it is not suitable to install cameras inside the chamber. Luckily, observation of the whole process of backdraught can be obtained if the camera is directly positioned in front of the central line of the compartment if the two upper baffles at the opening are kept in place. Hence, in the thesis, all experiments of change the size of the opening will be observed to have a better understanding of backdraught by using video recordings.

It should be noted that the fuel tray (PP and n-Heptane) is the only object in the compartment during this initial testing (no other measuring apparatus installed). Thermocouples were not used in the compartment in this stage, and backdraught was still able to occur, which means that backdraught does not require any other heat source apart from the hot fire compartment, therefore, this type of backdraught can be described as a backdraught driven by non-piloted ignition if compared with most of the related backdraught research. It means that it is critical to compare the difference between non-piloted and piloted (used for most of the previous research) backdraught phenomenon as it is generally unknown what type of ignition is present in a real backdraught condition.

It was found that it is difficult to achieve a flashover using a small amount of fuel when the ventilation / opening is near the upper part of the compartment. The heat and smoke dissipate during experiments, thus it is difficult to retain enough energy to achieve flashover efficiently. Therefore it requires a longer time to have a suitable condition to enhance the possibility of backdraught. Thus, in general in this project, the opening is only designed at 1/3 height near the bottom at the front opening, with other two baffles kept in place. This means that the ventilation conditions of experiments before the door was closed were fixed.

3.4.2.3 Thermocouple installation

It is unclear when a backdraught may occur, and there is no a specific clue in the literature review. In order to investigate at which stages of fire can provide suitable conditions for backdraught to occur, there is a need to build up an environment which allows the experimental fire to experience four stages, including incipient, growth, fully-developed, and decay stages.

At the same time, the experimental design must be cost-effective, as producing too much waste after each test is not acceptable, an unburned fuel is not useful for the analysis, it only produces unnecessary waste. Also, if there is some unburned fuel left, this may have been melted by the fire and the ambient heat, so the structure of the pellets may have changed. This result would influence the next experiments even if the total amount of fuel is kept the same weight before experimenting. This problem has been sloved in the previous section, the suitable fuel combination was decided to be “300 grams PP, 150 ml n-Heptane.”

The core idea of this thesis is that “**Simple is good**” because there is a lack of fundamental knowledge on backdraught using solid materials. As it is known that the unburned smoke is one of the critical factors for the occurrence of backdraught, to investigate if temperature can be one of the factors required for backdraught to occur. For this purpose, the initial investigation focus was on temperatures, other measurements will be considered in later chapters. Therefore, temperature was selected to be the first variable to investigate the correlation with the occurrence of backdraught.

As the first aim is to investigate if temperature can be correlated with the onset of backdraught, the only measuring instrument used inside the fire compartment was thermocouples.

Figure 3.4.3 Sketch of the backdraught testing compartment with TCs

7 Thermocouple trees (TCT) in total were used and designed for the temperature measurements in this research (24 type K thermocouples in total). TCT 5-2 and 5-1 were positioned on the centreline of the compartment, at 0.4 and 0.6 m from the back wall of the compartment. On these trees, there are TCs fixed at 0.0, 0.1, 0.2, 0.3, and 0.4 m below the ceiling. All the TCs are installed in the gas phase in the fire compartment, not touching the surface of the vermiculite boards. TCT 3-3 and 3-4 were positioned on either side of TCT 5-2, halfway between the centreline of the compartment and the wall. Similarly, TCT 3-1 and 3-2 were positioned on either side of TCT 5-1. Trees 3-1, 3-2, 3-3 & 3-4 had TCs at 0.1, 0.2 and 0.3 m below the ceiling. TCT 2 is positioned in line with TCT 3-4 and 3-2, not on the centreline, as this is near the location of the fire. This TC tree only has TCs at 0.1 and 0.3 m, details see **Figure 3.4.3**.

Figure 3.4.4 demonstrates the typical temperature history during the experiment, not every TC was used in this figure, instead, using three lines show the average temperature at 10 cm, 20 cm and 30 cm from the bottom of the compartment, in yellow, black, and red, respectively. It is found that the temperature did not always increase with the development of the fire, followed by a cool down period (4 to 6 minutes). Then the temperature continued to increase in a stable manner, from 7 to 12 minutes. About 16 mins after burning, the fire extinguished because of running out of fuel. The peak in temperature at 4 minutes may be attributed to burnout of the heptane, more discussion can be seen in section 3.4.2.4.

Figure 3.4.4 Typical temperature profile of the design fire

Above the fuel tray, no TC was installed because it was generally observed that the ignition of unburned smoke (from the preliminary testing) always started somewhere above the fuel tray before generating a backdraught, the temperature of this area is the highest inside the fire compartment to provide energy for backdraught to occur, none of the observed backdraught events started its ignition from the hot surface of the fuel. Thus, the space above the fuel tray was kept unoccupied, hence, there was no other specific object present to function as the heat source to backdraught, except the accumulated hot smoke.

3.4.2.4 Design fire

In section 3.4.2.1, the fire load of the experimental fire was selected, 300 grams PP and 150 ml n-heptane. As the stages of fire relating to the occurrence of

backdraught have not yet been researched by fire researchers, it is one of the aspects which this research would like to investigate.

In order to understand the changing temperature of the fire, temperature data were used to investigate the value changes before flashover and after the fire extinction. Three repeat tests were conducted, from the ignition of fire to the fire extinguishment with no periods of door closure, **Figure 3.4.4** shows the general temperature trend of these tests.

In **Figure 3.4.4**, it shows the whole temperature history of the experimental design fire, from ignition, growth, flashover (approximately at 15 minutes after fire ignition), then following a fire extinction. It is observed that the temperature data did not gradually increase, about 4 minutes after ignition, most of the temperature values dropped, this is not a typical observation result of a fire growth. This implies the growth of the fire around the time suffered from some strange influence from unknown reasons, the fire did not maintain its combustion status. Seeking for the possible reason, a fire experiment using only n-Heptane as the fuel was conducted to understand how temperature changes.

Figure 3.4.5 Temperature profiles of the burning of n-Heptane. TC-1003 is at 0.3 m above the bottom of fire compartment on TCT 2 (the TC tree near the fuel tray); TC-1022, 1023 and 1024 are at 0.1, 0.2 and 0.3 m above the bottom of fire compartment on TCT 5-2 (The TC tree located at the centre of the compartment)

In **Figure 3.4.5**, only TCs near the fuel tray is used to depict the temperature change in pure heptane fuel fire as this experiment was conducted to

discover/prove if the cooldown condition in **Figure 3.4.4** was because of the depletion of heptane. Stable increase in temperature was found in the first 30 seconds, then becomes very fluctuating, the highest temperature reached about 650°C. All the values of TCs in **Figure 3.4.4** dramatically decrease at the time of 3 minutes burning, this indicates that the fuel (150ml) was running out in three minutes. So, comparing **Figure 3.4.4** and **Figure 3.4.5**, it seems that the n-Heptane plays an important role to the experimental fire for the first few minutes, to assist the unburned PP to melt, providing energy to change the material structure from solid phase. After this period of time, the PP fuel dominates the rest of the whole fire growth of the experiments. The cooldown period (about 4 to 6 minutes) in **Figure 3.4.4** is due to the burnout of the n-Heptane, this makes the fire unstable as most of the fuel was still not ready to burn (solid pellets still needing to melt). Later, the fire only relied on some liquefied PP or PP vapour to continue the combustion process by the obtained energy (beyond the required activation energy) or radiant feedback from the flame or hot smoke near the fuel tray. It may provide a reasonable explanation for the unusual decrease of temperature of the early stage of the fire, however, how the fire behaves at the first few minutes is not the primary interest of this research project. It should be noted that the main point of this test was only to demonstrate how fast the heptane burns off, the observed temperature data will not need to be used further. The depth of the pellets (including the liquified and solid pellets) influences the rate of burning. If the PP fuel occupies the full area of the fuel tray, the burning continues at a steady rate. However, if the PP becomes localised in only parts of the tray, the fire becomes localised, and this results in fire decaying towards extinguishment.

3.4.2.5 Installation of spark apparatus

The experimental design of non-piloted ignition for backdraught research has been done. But in a real fire scene, it should keep in mind that there may exist some smouldering material, electric short circuit, or flaming embers which can provide energy for a fire to restart the combustion process, then triggering a backdraught. Therefore, it is essential to understand how a man-made heat source affects the possibility of backdraught and what the differences of the behaviour of backdraught triggered by non-piloted and piloted ignition sources are.

Before conducting a series of experiments to investigate the differences of ignition source to backdraught, an electric spark should be installed properly. The difficulty is where the spark apparatus should be attached, a wrong location is chosen, it may lead to no backdraught occurrence. So, by checking the video of the non-pilot ignition experiments conducted, it is found that all initiating point of the backdraught start from somewhere above the fuel tray, see **Figure 3.4.6**. It provides a clear clue that a heat source installed nearby this place may trigger a backdraught, and the location of the ignition source is similar to that used in the previous backdraught research [2][3][7].

However, it should be noted that in a real fire scene, heat sources can be anywhere inside the compartment, here, this part is used to compare with the related backdraught research and to reduce the chance of failure to trigger backdraught. It is found that a backdraught can successfully be triggered with the spark, for details see the next chapter.

Figure 3.4.6 The beginning of backdraught (w/o spark); observation of two experiments from different angles, a visual demonstration of the ignition of backdraught (not including the whole process of backdraught)

Figure 3.4.7 Spark apparatus for backdraught experiments; left: the spark units for igniting unburned smoke; right: the whole electric spark apparatus.

The spark apparatus consists of electrodes and a control panel, the used electrodes are the typical type used for gas stoves, see **Figure 3.4.7**. The exact

location of the spark apparatus can be seen in **Figure 3.4.8**, details will be discussed in the following chapters.

Figure 3.4.8 Sketch of the small-scale backdraught compartment (with TCs and Spark apparatus)

3.5 Conclusion

This chapter describes the preliminary design and the initial testing before conducting the main series of experiments for further investigations on the backdraught phenomenon.

The next chapters will discuss details of experiments investigating temperature, gas aspects and the behaviours of backdraught using different ignition sources; also, the correlation between the delay time of backdraught at different openings locations and sizes will be investigated.

3.6 References

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Chapter 4. An experimental study on backdraught: The dependence on temperature

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Regarding to the contribution of this chapter, I did the most work for the article, including the experimental design, conducting experiments, data analysis and the paper writing up. Dr Carvel edited some contents of the paper to make the text more accessible to read through, also he polished the words/ paragraphs to become more academic.

Compared to the previous backdraught research literatures, this paper, perhaps for the first time, tried to use the value of the temperature to predict the occurrence of backdraught. Also, it demonstrated that the different characteristics of backdraught when the ignition sources are not the same.

The only difference between this chapter and the published paper is the renumbering of the figures, plus minor text change.

Summary

This chapter presents the results of a series of reduced scale experiments to investigate the temperature conditions leading to backdraught in a fire compartment (0.8 m×0.4m×0.4 m), using solid polypropylene pellets as the fuel. The factors of primary interest are the pre-burn time, before the fire becomes oxygen limited, the duration of door closure, and the temperature distribution in the compartment. It is shown that the temperature inside the compartment is crucial for the occurrence of backdraught. Above 350 °C, backdraught by non-piloted ignition is possible.

If a pilot spark is present, backdraught may occur at temperatures down to 300 °C. It is shown that backdraught conditions can be achieved in the early stages of a fire as long as a suitable temperature is reached, at considerably lower temperatures than those generated during flashover. Further investigation on gas concentration is essential to understand the chemistry of backdraught combustion.

4.1 Introduction

Despite being well known for several decades, backdraught remains one of the largely unresolved issues in fire science [1]. Research has demonstrated the mechanisms involved in backdraught, but a rigorous definition of instances where backdraught can occur is still elusive. This phenomenon generally occurs in conditions where a compartment containing a fire has a very limited fresh air supply, and the fire is considerably ventilation-controlled or extinguished. A backdraught may occur if there is a sudden supply of fresh air, e.g. due to a window or door opening or breaking, possibly due to the fire, or commonly due to the intervention of fire-fighters. Backdraught has led directly to fire-fighter injuries and fatalities, thus it is essential to study backdraught in order to mitigate or avoid its effects in future fire-fighting interventions.

Fundamental research into backdraught started in the 1990s. In the pioneering research into this field, Fleischmann et al. [2-4] conducted a series of experiments using a reduced-scale chamber (2.4m x 1.2m x 1.2m). A methane burner was used as the fuel supply. They observed the propagating flame of backdraught, and identified the concentration of the unburned gases in the compartment as a critical

factor leading to backdraught; they observed that a mass fraction of 10% unburned fuel in the compartment is required in order to have a backdraught. Later studies by Weng and Fan [5-7], using an apparatus half the size of Fleischmann's (1.2m x 0.6m x 0.6m), produced similar results, with 9.8% of the unburned gas being the identified criterion. Both these studies suggest that the concentration of flammable gases is an import factor with regard to the occurrence of backdraught, when methane is the primary fuel used.

When a door is opened to a compartment full of hot gases, the hot gases will tend to spill out of the upper part of the opening, and cold air will flow into the lower part of the opening. This flow of air is known as a "gravity current" and is crucial in determining the occurrence and severity of a backdraught.

The gravity current has been extensively observed and studied [2-4, 8-18]. The opposed flow of the gravity current with respect to the hot gases drives the process of the mixing of the hot flammable gases with the fresh air. In situations where there is a fire source or pilot flame at the back of the compartment, it is often assumed that the time at which backdraught is initiated (delay time after opening the door) is due to the time taken by the gravity current to create the flammable mixture and drive it to the ignition source. This characteristic time required for backdraught normally involves the mixing of the hot gases from inside the compartment with the cold air from outside the fire compartment. The density (temperature) difference affects the time of mixing, the pyrolysis process of the hot compartment is also a factor to influence the delay time of the backdraught, as will be discussed in chapters 7 and 8.

Our current understanding of backdraught suggests the gravity current and the concentration of unburned gases are the crucial factors. The former may be able to predict the time when a backdraught will occur, the latter is used as the determining factor for the possibility of backdraught occurrence. However, the gravity current travelling time related to backdraught was based on the tests using an artificial ignition source, such as an electric spark, but in real life, not every backdraught fire has such an ignition source. Another possibility is auto-ignition leading to backdraught. This involves various physical and chemical processes beyond questions of gas concentration. Current knowledge is considerably limited by the fact that the majority of backdraught studies have used methane gas as fuel, and very few real backdraught incidents involve this fuel.

In a typical backdraught scenario, the atmosphere in the compartment, before the door is opened, consists of a mixture of pyrolysis gases and vitiated air at elevated temperature, generally above the upper flammability limit of the fuel-air mixture [19]. This initial set of conditions is represented conceptually by points A or A' in **Figure 4.1.1**. Opening the door allows cooler air into the compartment, resulting in both a decrease in gas temperature and the mixture being diluted with fresh air to form a flammable mixture, denoted by points B or C in Fig. 1. If the resulting mixture is sufficiently hot, auto-ignition can occur. If the resulting mixture is cooler, the flammable mixture will ignite only if an ignition source is present, or if the flammable mixture moves to where an ignition source is found.

Figure 4.1.1 Flammability limits change with temperature.
(Adapted from Zabetakis [20])

Previous research is somewhat limited by the fact that methane-air mixtures are flammable at ambient temperatures (and below) so the dependence of pilot-ignited backdraught on temperature has not been adequately investigated. More realistic fuels must be selected for further studies [4][6][10]. This limitation is one of the drivers of the study described here.

This project aims to discover if there is a critical temperature for backdraught, using a fuel other than methane. Furthermore, this project aims to ‘map out’ the conditions of temperature and gas mixture under which backdraught does and does not occur. This paper describes experiments using polypropylene fuel, other fuels will be considered and published in the future.

4.2 Experimental setup and procedure

Most of the experimental research to date has been carried out at the laboratory scale, to minimise the risks due to explosive effects, and also because it has already been demonstrated that the general nature of backdraught is not depended on the scale of the compartment [21].

Figure 4.2.1 Test compartment

In the present study, a small scale fire compartment ($0.8\text{m} \times 0.4\text{m} \times 0.4\text{m}$) was designed and built for backdraught research, see **Figure 4.2.1** and **Figure 4.2.2**. It is instrumented with 7 thermocouple trees (24 type K thermocouples in total). TCT 5-2 and TCT 5-1 are positioned on the centreline of the compartment, at 0.4 and 0.6 m from the back wall of the compartment. On these trees, there are TCs fixed at 0, 0.1, 0.2, 0.3, and 0.4 m below the ceiling. TCT 3-3 and 3-4 are positioned on either side of TCT 5-2, halfway between the centreline of the compartment and the wall. Similarly, TCT 3-1 and 3-2 are positioned on either side of TCT 5-1. TCT 3-1, 2, 3 & 4 have TCs at 0.1, 0.2 and 0.3 m below the ceiling. TCT 2 is positioned in line with TCT 3-4 and 3-2, not on the centreline, as this is the location of the fire, it only has TCs at 0.1 and 0.3 m. The fuel bed is contained in a steel tray, which is $0.2\text{m} \times 0.2\text{m} \times 0.05\text{m}$, and was positioned 10 cm from the rear wall. The compartment was constructed out of two-layers of expanded insulating vermiculate boards, for which the maximum working temperature is $1,100\text{ }^{\circ}\text{C}$. An electric spark apparatus was installed on the rear wall for some tests investigating

the role of an ignition source. The influence of the position of the pilot spark has not yet been assessed; this will be investigated and reported in the future.

Figure 4.2.2 Spark apparatus (side view)

There are three removable baffles which may be positioned across the opening of the compartment, to investigate the effects of opening size. In all the experiments described here, the upper two baffles were kept in place, such that the opening was fixed at 0.13m x 0.4m wide. Other door opening sizes and configurations will be tested in the future, and the findings will be published elsewhere. A sliding outer door is used to seal and open the compartment, this ensures that the experimenter is safely to the side of the compartment when the door is opened, and is well out of the way of any ejected flames.

4.2.1 Design fire

In order to simulate a realistic backdraught phenomenon, a solid fuel was used as a fire source. To date, there has been no research investigating the relationship between the stage of fire development when the fire becomes oxygen starved, and the propensity for backdraught. This research uses the duration of burning before door closure as the controlling factor to investigate the conditions leading to backdraught.

Figure 4.2.3 Free burn of the design fire

For the experiments described here, this was plastic pellets (Polypropylene, PP). To aid ignition and repeatability, a small quantity of n-Heptane (C_7H_{16}) was used as the accelerator to start the burning process. Initial tests were carried out to identify the optimum fuel load for these experiments. It was determined that 300g of PP with 150 ml of n-Heptane was sufficient to achieve flashover conditions in the compartment (after about 13 minutes, from ambient initial conditions), and that all the liquid accelerant was consumed in the first 5 minutes of burning. From about 7 to 12 minutes after ignition, the heat release rate of the fire is quasi-steady and the temperature in the compartment rises in a steady and highly repeatable manner. During this time, the only fuel present is PP, so the primary focus of our research concerns what happens when the door is closed during this time-window, is kept closed for a variable period of time, and then opened again.

Figure 4.2.4 Development of the design fire

Figure 4.2.3 shows the temperature evolution in the compartment in ‘free burn’ conditions, that is, the door is never closed. The zone marked A is the ‘steady burning’ phase of primary interest to us, the zone marked B is the rapid growth

period leading to flashover, and the zone marked C is a fully developed fire, followed by burnout.

Throughout zone A the fire behaved in a very consistent manner, with a clearly defined upper smoke layer and smoke spilling out of the upper part of the opening, with a steady neutral plane, see **Figure 4.2.4**. When the fire transitioned from zone A to zone B, the neutral plane descended rapidly, indicating that the heat release rate of the fire increased considerably. At this stage, the fire becomes oxygen limited, that is to say ventilation-controlled.

Experiments have shown that backdraught may occur after closing and opening the door in any of the stages mentioned above, but the resulting backdraughts exhibit considerable variation in the apparent strength of the backdraught. Having identified the 'steady' burning zone, experiments were carried out at various times within these zones. Three different times for door closures were studied in detail; 6.5 min after ignition (just before the steady state), 12 min (at the end of the steady state), and after observing flames emerging from the compartment opening (that is, flashover). The temperature curves for tests with these door closing times, without subsequent reopening (hence, no backdraught) are shown in **Figure 4.2.5**.

For clarity, five of the TCs were used to visualise the temperature increase during burning and the decrease after closing the door. The maximum temperature is the top TC on TCT 2, above the fire source, shown in red; the green and purple graphs represent the TCs at mid-height in the compartment on TCT 5-2 and TCT 5-1, respectively; the grey and blue graphs represent the lower TCs on TCT 5-2 and TCT 5-1, respectively; TCT 5-2 is near the middle of the compartment and TCT 5-1 is near the opening.

In each of these three fire scenarios, the temperature declined in a consistent and repeatable manner during a period of about 8 minutes after the door being closed. As the box is well insulated, the temperatures remain relatively high for many minutes after closing the door.

Figure 4.2.5 Temperature histories (close the door at (a) 6.5min, (b) 12min, and (c) after flashover)

The aim of these experiments was to characterise the temperature conditions in the compartment after the door had been closed, for different initial temperatures at the time of door closure. For example, the range of temperatures in the compartment are between 150 and 300°C less than 2 min after closing the door at 6.5 min, but it takes over 4 min to cool to these temperatures if the door was closed at 12 min, and over 6 min to cool to these temperatures if the door was closed at flashover. It is highly likely that the mix of fire gases in the compartment will be substantially different in each of the three scenarios described here, but the temperature distribution in the compartment is largely the same. Thus, by comparing such tests, this shows the trends in the temperature dependence of backdraught, independent of questions of gas concentration / composition.

The aim of this research is to discover if there is a “critical temperature” for backdraught, therefore experiments were carried out by opening the door at different temperatures in order to map out the temperature dependence of backdraught

4.3 Result and discussion

90 experiments have been carried out to date. Experiments 1 to 63 were carried out with no pilot spark, while experiments 64 to 90 had an electrical spark present to ignite any flammable vapours. **Figure 4.3.1** presents a typical temperature plot for a test that did exhibit backdraught.

Figure 4.3.1 Typical temperature variations with time

4.3.1 Testing for backdraught with no pilot spark

63 experiments have been completed in this series. Initial experiments showed a repeatable temperature decline and variation after the door was closed, with thermocouple TC1003 (10cm from the ceiling) consistently exhibiting the highest temperature in the compartment. For simplicity, TC1003 was used to monitor the temperatures in the compartment and identify the time at which the door would be opened again in each test. When quoting the temperature recorded by TC1003, it should be borne in mind that the other TCs in the compartment covered a distribution of temperatures down to about 100-150°C cooler than TC1003.

All the experimental results are summarised in **Figure 4.3.2**. Each data point corresponds to one experiment, where the time (horizontal) axis indicates the time after ignition at which the door was closed, and the temperature (vertical) axis indicates the temperature of TC1003 at which the door was opened. It should be noted that the duration of door closure is not explicitly represented here. ‘Stacks’ of data points, as shown, represent experiments with the same time of door closing, and a range of durations of door closure, with the longest periods of door closure corresponding to the lower temperatures, at the bottom of the ‘stack’.

The solid triangles in **Figure 4.3.2** represent experiments where backdraught occurred, and the unfilled triangles indicate no backdraught occurring.

Figure 4.3.2 Results of backdraught testing

It should be noted that it is almost impossible to control flashover condition to occur at the same time after ignition, but the time of reaching flashover was about 16 minutes; for better comparison among burning times, for those experiments that experienced flashover, this was fixed at 16 mins on the x-axis.

Three zones, alpha (α), beta (β), and gamma (γ), represent backdraught without an extra ignition source, backdraught events triggered by a pilot spark, and the fire re-ignition zone. In this figure, the different maximum temperature seems to play a role to divide the experimental result into these three zones. At a lower temperature condition (for instance, the observed maximum temperature was about 300°C in those tests experienced flashover before the door closing) an extra ignition source apart from the heat of the compartment will result in backdraught or re-ignition, but this depends on both temperature and the stage of the fire. It should be noted that backdraught did not occur in any instance where the door was closed before 9 min after ignition, even at elevated temperatures (above 360°C). Backdraught was consistently observed in all experiments with more than 9.5 min of burning and when TC 1003 (30 cm above the bottom of the tray on TCT 2) was over 350°C. From the free burn tests, it is known that the steady state burning of this fire is between 7 min to 12 min, that is to say, backdraught can only be triggered just after the middle of the period of steady state burning.

4.3.2 Testing for backdraught with a pilot spark present

Another part of this research is to use an electrical spark to trigger backdraught, simulating any sort of the possible conditions in a real fire. The solid squares in **Figure 4.3.2** represent experiments where backdraught occurred, and the unfilled squares indicate no backdraught occurring. In a number of experiments, the pilot spark re-ignited the fire, after the door was opened, but without the violence and fireball of a backdraught, these instances are represented by circles in **Figure 4.3.2**.

It is clear that the presence of a pilot spark does allow the ignition of a backdraught at temperatures considerably lower than the auto-ignition limit, in these tests down to 300°C. However, backdraught only occurs for later times of door closure (corresponding to higher initial temperature conditions at the time of door closure).

The experiments where there was re-ignition of the fuel pan, but without backdraught, suggests that under these conditions, the gas mixture inside the compartment was not generally a mixture of fuel gas and vitiated air, above the upper flammability limit. It would appear that a hot zone, in the vicinity of the fuel pan, was the only location where a potentially flammable gas mixture was to be found.

In the experiments where backdraught was not observed, the thickness of smoke layer was broadly the same of that during successful backdraught experiments. In order to determine if there was a potentially flammable mixture under these circumstances, a pilot flame was held near the edges of the closed door. As the door seal is not perfect, there is always a small leakage of gas around the door. Even in instances where backdraught did not occur, at lower temperatures, it was commonly found that the gases leaking out did form a flammable mixture when mixing with air, see **Figure 4.3.3**. Thus it is clear that in these cases, the occurrence (or otherwise) of backdraught is not merely dependent on the existence of a gas mixture above the upper flammability limit.

Figure 4.3.3 Testing leaked gases

In summary, backdraught can occur in a range of temperature conditions, which do not need the fire to grow to flashover. For PP fuel at least, if the temperature is above about 350°C, and the fire has been established for sufficiently long (in this case, more than 9 mins) there is significant risk of backdraught, even in the absence of a pilot flame. “Zone α ” (as denoted in **Figure 4.3.2**) represents a set of dangerous conditions for fire-fighters, as any door opening could lead to spontaneous backdraught.

It should be noted that the 350°C identified here as a critical condition is close to the literature value of 370°C for auto-ignition of PP, however, it is perhaps significantly below this limit, and it should be noted that the 350°C represents the highest observed temperature in the box, while the average temperature is considerably lower. It would appear that this is not merely an instance of a gaseous fuel reaching auto-ignition temperature. It is likely that there is more complex chemistry going on in the gas phase; this will be the subject of future study and future publications.

Figure 4.3.4 The electric spark ignites the unburned gases

4.3.3 Characteristics of backdraught – with and without electric spark

Having identified that TC1003 being 350°C is critical for backdraught, a comparison with the development of backdraught in three different cases, see experiments 35, 76 and 86. These cases are very representative to compare the higher or lower temperature in the fire compartment with and without extra ignition source.

In **Figure 4.3.5**, it can be seen that experiment 35, characterised by a temperature of 347°C, which auto-ignited 6s after opening the door, creates the flame propagation immediately, however, in the piloted-ignition experiments 76 and 86 (characterised by temperatures of 329°C and 369°C, respectively), the a puff of smoke and fire gases was pushed out of the doorway first then, following ignition inside, the flame spread rapidly through the flammable gases both inside and outside the compartment. Even though the temperature in experiment 86 was high enough for auto-ignition, it appears that the spark ignited the backdraught earlier than if it had auto-ignited, exhibiting the same sequence of events as the cooler experiment 76. Thus it is clear that the spark plays a very important role,

even in conditions that could auto-ignite. The puff of smoke before backdraught is not generally observed in the absence of a pilot spark.

Figure 4.3.5 Development of backdraught (front view), from at the beginning of igniting backdraught to develop to become an extended external fireball. Left, expt. 35 (347°C; w/o spark); middle, expt. 76 (329°C; with spark); right, expt. 86 (369°C; with spark) (Each image is one video frame after the preceding image, with a frame rate of 29 fps.)

4.3.4 Auto-ignition point & fire point

From the experimental results, it can be concluded that there is an auto ignition temperature, effectively a fire point for backdraught. This implies that a backdraught requires a suitable temperature distribution inside the fire compartment, which means the heat should be retained for the whole procedure of backdraught; the mixing stage driven by gravity current will help generate a

flammable mixture, but the occurrence (or not) of backdraught is dependent on the temperature distribution. This is the reason why there was always a longer time delay for the occurrence of backdraught in non-piloted ignition experiments. If the fire room cannot meet the requirement, only localised fire will occur, the increased pressure pushes the gases out of the compartment, and restarting the diffusion flame combustion.

4.3.5 The relationship of backdraught delay time and gravity current

So far there is a consideration about the occurrence (or not) of backdraught, but no discussion on the delay between opening the door and the actual occurrence of the backdraught. In general, backdraught occurred much more rapidly in the presence of a pilot spark than without. In general, and perhaps counter-intuitively, the backdraught delay time was also longer, the later into the fire development the door was closed.

The average backdraught delay for piloted experiments in the steady burning period (i.e. zone A in **Figure 4.2.3**) was only 1 second. As conditions tended towards flashover (i.e. zone B in **Figure 4.2.3**) the average delay was 2.7s, while for experiments where the door was closed after flashover (i.e. zone C in **Figure 4.2.3**) the average delay was 3.2s. The corresponding average delay times for the non-piloted ignition tests were 5.1, 7.5 and 7.2, respectively.

According to Fleischmann et al.[3], the velocity of the gravity current can be estimated using the following equation,

$$u = \frac{1}{3} \sqrt{\frac{\Delta\rho}{\rho}} gh, \quad (1)$$

where u is the speed of the leading edge of gravity current, $\Delta\rho$ is the initial density difference across the opening, ρ is the compartment density, h is the compartment height, and g is 9.8 m/s^2 .

The temperature of the fire compartment before opening in all the experiments varied from around 200°C to 500°C , meanwhile the ambient temperature in the lab varied between 15°C and 27°C . Therefore, the range of possible gravity current velocities can easily be calculated, and hence the time taken for the gravity current to traverse the experimental compartment. In all cases studied here, the transit

time was between 1.1s and 3.26s. It should be noted that the gravity current transit times and backdraught delay times would be much longer at real scale than in these laboratory scale experiments. Froude modelling considerations suggest that timescale varies with the square root of the length scale, so in a compartment that is 2.8m high (that is, 7 times larger), the timescales would be about 2.6 times greater.

Only the piloted ignition tests, carried out in the steady burning phase of the fire have ignition delay times as short as this transit time.

In all other instances, piloted or otherwise, the backdraught delay time is at least 2.5 times longer than the gravity current travel time, which means if only using the time of gravity current, an underprediction of the occurrence time of backdraught may be made. The implication of this is that, except in the case of particularly hot, piloted tests, the gravity current is not the crucial factor controlling the time to backdraught, only to provide enough fresh air (oxygen) supply. In addition, the leading edge of gravity current may not be immediately flammable. Meanwhile, the location of the ignition source may also affect the result.

4.4 Conclusions and future work

From our experiments it is clear that backdraught can happen in an underventilated compartment, as long as the temperature remains sufficiently high, but not all stages of fire becoming underventilated can lead to backdraught. From these experiments, backdraught only occurs in instances where the fire has become well established into its steady burning regime (the steady burning of the experimental fire starts from 7 mins to 12 mins after ignition, and backdraught can only be triggered at least experienced around 9 to 10 mins burning time before the door closure, see **Figure 4.3.2**). The time of door closure is another key factor for backdraught because this is related to the reduction in temperature. Due to heat losses, the longer the door remains closed, the smaller the probability of producing backdraught conditions will be.

This research has identified two zones of backdraught, zone α and β , as shown in **Figure 4.4.1**. The bounds of these regions have been identified experimentally, and work is ongoing to better quantify the conditions which will (or won't) lead to

backdraught along these bounds. Points A, B, C and D represent different boundary condition for different fire scenarios during the test. A is the minimum required pre-burned time for the smallest backdraught to occur. The curve from A to B shows the temperature decrease during the cooling period by the closure of the door. Point B demonstrates the minimum required temperature in the first observed backdraught event (the maximum temperature in the fire compartment), it is observed that with the pre-burn time was longer then the need for point A, when the maximum temperature before the door opening was higher than 350 °C, a backdraught was always observed.

If no additional ignition source is present, zone α represents the conditions leading to backdraught, but if any ignition sources, other than the initial fire itself, are present, the dangerous area will include both zones α and β . However, the critical temperatures are not identical if there is a spark present. Point C shows the required temperature at which the burning transitions from fuel-controlled to ventilation-controlled (approximate 12 min after burning).

That is, these two zones show whether the investigated backdraught events required an extra spark to be triggered.

With regard to the ignition source, a compartment with a sufficiently high temperature distribution does not require an additional ignition source for backdraught to occur, and there is a well-defined minimum temperature for a non-piloted ignition backdraught, which is 350°C, if PP is used as the fuel. This temperature may well vary with fuel type, and experiments with different fuels are intended for future study.

**Figure 4.4.1 Temperature hot zones for backdraught.
Temperature data from TC1003**

When an ignition source is present, backdraught can be initiated at temperatures down to 300°C, although longer pre-burn times appear necessary at this limit. Point C to D demonstrates the change of the required temperature for backdraught, about 25°C decrease. As above mentioned, The required temperature changes with the stages of the experimental fire before the door closing. Again, this limit may be highly fuel specific.

Even though a backdraught is very complex, and involves not only fire physics but also combustion chemistry, this research suggests that it is possible to predict and avoid backdraught by using temperature data. From the previous research results and this research, has explained that both of “the concentration of unburned gases” and “compartment temperature” are the critical factors for the occurrence of backdraught.

Further research needs to be done to adequately map out and understand all the parameters that define the “backdraught boundary”, the line on **Figure 4.4.1** connecting points A, B, C and D.

4.5 References

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Chapter 5. The influence of compartment temperature on backdraught dynamics

The content of this chapter was published as ‘The influence of compartment temperature on backdraught dynamics’ as part of the proceedings of the 11th Asia-Oceania Symposium on Fire Science and Technology, Taipei, Taiwan, October 2018.

Regarding to the contribution of this chapter, I did the most work of the article, including the experimental design, conducting experiments, data analysis and the paper writing up. Dr Carvel edited some content of the paper to make the text more accessible to read through and also polished the words/ paragraphs to become more academic.

Compared to the previous chapter, this chapter discusses temperature data at different locations of the fire compartment (Near the bottom, above the fuel container, and near the ceiling). It shows that only the TC above the fuel tray (TC-1003) provides useful information to predict if backdraught may occur. In addition, this location of the ignition of backdraught observed is closed to TC-1003, which means that a specific value of temperature, 350 °C, is representative. In this chapter, the plots (run number and temperature) were used to demonstrate even if there is no indication showing which stage the fire was at when it became starved of oxygen, it is still possible to predict backdraught by using temperature data, which indicates the importance of the observed highest temperature value.

The only differences between this chapter and the conference paper are the renumbering of the figures and some minor text corrections.

Summary

Backdraught is an unpredictable and dangerous fire phenomenon, particularly for fire-fighters during search, rescue and fire-fighting activities. Most previous research into backdraught has used methane as fuel, leaving many questions unanswered. A series of reduced scale backdraught experiments have been carried out using solid polypropylene as a fuel source, and conclusions have been drawn correlating the compartment temperatures to the onset of backdraught.

It is found that when the maximum temperature in the compartment is above 350°C when the door is opened, a backdraught can occur by non-piloted ignition, no ignition source is required. However, no correlations could be identified with temperatures near the door or near the floor. It was also found that there is a correlation between compartment temperature and backdraught delay time, with cooler compartment temperatures leading to longer delays.

5.1 Introduction

In a fire scene, flashover and backdraught are perhaps the top two fire conditions that fire-fighters do not want to encounter. The former generally creating a rapid temperature increase due to most of the materials being ignited at the same time, this is a fuel-dependent phenomenon, if there is not enough fuel, then flashover cannot occur. Many research studies have quantified and explored indicators for the onset of flashover, such as heat flux, temperature, external flaming etc.[1], fire-fighters are routinely trained to look for the signs of an impending flashover. However, backdraught has only been sporadically researched even though identifying the conditions leading up to the onset of this fire phenomenon is equally necessary to ensure the safety of fire-rescuers.

In theory, a backdraught can only occur when there is a hot, fuel-rich fire compartment with a limited air supply, this shortage of oxygen supply will constrain the fire to become smouldering or extinguished. If a sudden opening occurs, such as a window breaking by the fire or a door being opened by fire-fighters, the mixing of the hot gases from inside fire compartment with cooler fresh air from outside may create a flammable gas mixture. If an ignition source is present, the gas

ignites, typically resulting in an explosive fireball projected through the opening, a potentially fatal occurrence if fire fighters are near the opening.

Unlike most fire phenomena, the majority of backdraught casualties are firefighters because backdraught usually occurs late in the fire timeline, and is triggered when doors or windows are opened, which fire-fighters need to do as part of their search and rescue activities. 20 years ago, Fleischmann et al. [2]–[4] started their pioneering backdraught research, using a lab-scale chamber (2.4×1.2×1.2m). This research established a fundamental understanding of this phenomenon, and concluded that a critical amount of “unburned gases” is the main factor controlling the onset of backdraught. Later on, Weng and Fan [5]–[7] conducted similar experiments at half the scale of Fleischmann’s to investigate how the opening geometry influences the critical gas concentrations, and made some conclusions regarding water mist as a mitigating tactic. All the above studies were based on experiments using methane as fuel. Methane is not a typical fuel in compartment fires.

Basic fire chemistry tells us that a fire requires three things: heat, fuel and oxygen, the classic fire triangle. Fires involving most fuels cannot occur if one of the elements is missing. It is expected that variations in temperature will influence the onset of backdraught, but such variations cannot be observed in tests using methane, a fuel that is readily ignited at room temperature. The research described here seeks to investigate the dependence on temperature, using fuels other than methane; solid fuels are much more realistic.

Backdraught, when it occurs, does not occur at the instant the door is opened. There is a delay during which the gases within the compartment mix with the inflowing air. Due to buoyancy, the cooler air flows under the hot compartment gases, in a so called “gravity current/ gravity wave”. This has been studied in some depth [8]–[10], but the conclusions regarding the backdraught delay time are still lacking. Also, previous research has generally focused on piloted ignition of backdraught, using an electric spark to initiate the backdraught. In reality, particularly when temperatures are elevated, backdraught may occur spontaneously by non-piloted ignition. This has not been widely studied before, so this study investigated backdraught without any ignition source apart from the hot fire compartment.

This research aims to identify the thermal conditions crucial to the occurrence of backdraught using solid fuels, and also investigate the factors influencing the delay time of backdraught. Once such factors are understood, a strategic fire-fighting tactic approach can be developed.

5.2 Experimental setup and procedure

5.2.1 Experimental setup

A small-scale fire compartment ($0.8 \times 0.4 \times 0.4$ m) was designed for this project, the same size ratio as Fleischmann's, but one third the size. The size of compartment does not affect if backdraught will occur or not [11]. The compartment used is as the same as the fire chamber in chapter 3, please see **Figure 5.2.1** (the same as **Figure 3.4.3**), the positions of thermocouple trees are described in chapter 3, so there is no need to repeat the description. Two-layers of expanded insulating vermiculite boards are used to reduce heat losses; the working temperature of this material can be up to 1100°C .

There are three removable baffles which may be positioned across the opening of the compartment, to investigate the effects of opening size. In all the experiments described here, the upper two baffles were kept in place, such that the opening was fixed at $0.13\text{ m} \times 0.4\text{ m}$ wide, investigation on backdraught with different opening sizes will be discussed in chapter 8.

Figure 5.2.1 Diagram showing the locations and dimensions of the thermocouples, fuel tray and door opening.

A sliding outer door is used to seal and open the compartment, this ensures that the experimenter is safely to the side of the compartment when the door is opened.

5.2.2 Experimental procedure

In this project, backdraught was investigated based on different pre-burning times, before door closure, this provides a range of different thermal distributions in the fire compartment. In each test, 300 g of polypropylene (PP) pellets were used as fuel, with 150 ml of n-heptane (C_7H_{16}) used as an accelerant. It was found that this quantity of n-heptane was consumed thoroughly in the first 5 min of burning, so it is assumed that the quantity of heptane is negligible at the time of door closure in all tests. In the tests where backdraught did not occur, it was always found that there was still unburned fuel in the fuel tray at the end of the test, which means the lack of backdraught was not due to insufficient fuel in the test.

Figure 5.2.2 Non-piloted ignition of backdraught (3 consecutive video stills at 0.034 intervals)

Figure 5.2.2 shows that backdraught is typically observed to start (by non-piloted ignition) at a location above the fuel container. Backdraught, as can be seen, initiated at the intersection of the clean air and hot smoke.

A typical temperature history profile is shown in **Figure 5.2.3**. It shows all temperature data in the fire compartment; this figure is only to show the time of the rate of temperature change and the general trend of temperature increase, see Chapter 4 for more detail. Here the door was closed at 14 min. After closure it is clear that the fire was rapidly smothered and all locations within the compartment tended towards similar values, indicating that the compartment gases are quite well mixed, and not particularly stratified, with only about 50°C variation between the hottest and coolest locations. During the period of door closure the compartment cools down slowly. In this instance, after waiting approximately 240 seconds, the door was opened. After a few seconds of delay, backdraught occurred.

Figure 5.2.3 Typical temperature history in backdraught testing

Backdraught experiments were tested with different pre-burning times, ranging from 7 min after ignition to just after flashover (at about 14 minutes), and for different door closure times. The opening time in each test was established on the basis of the compartment temperature at the time of opening. Initial experiments showed that fire growth to flashover before door closure is not necessary to attain backdraught conditions [12]. The conditions inside the chamber when the door is closed, at different stages of the fire, have a considerable influence over the properties of the resulting backdraught, see **Figure 5.2.4**.

It can be observed that the earlier the door is closed, the less intense the fireball will be (judged from the size of the fire ball only). From observation, when the door was closed earlier than 12 min, the neutral plane of the smoke was stable, staying at the same height. After 12 minutes, the temperature dramatically increased, the smoke layer became thicker, and the neutral plane dropped dramatically [12]. This is consistent with the observed changes in temperature after 12 minutes, see **Figure 5.2.5**.

Figure 5.2.4 Backdraught tests with different pre-burning times before the door was closed

Figure 5.2.5 Temperature in the compartment at different heights, for various times of burning

Figure 5.2.5 shows that the temperature variation increases steadily from 6 min to 12 min, for TCs at different heights. The highest temperature is the TC installed at 30 cm from the bottom of the compartment, with an approximately 20°C increase every 2 minutes. It is not surprising that the temperature accelerated after 12 min, at this time, it was observed the smoke layer gradually decreased owing to the fire transited to ventilation-controlled.

5.3 Result and discussion

5.3.1 Temperature distribution

A series of 64 experiments was carried, with 35 of the tests leading to backdraught. All the observed temperature used the maximum temperature among TCs, the temperature data for the time of door opening are presented in **Figure 5.3.1**, **Figure 5.3.2**, and **Figure 5.3.3**. These tests had various burning times before door closing, ranging from 7 min after ignition to after flashover. In tests 1 to 34 (indicated using triangle markers), the door was closed while the fire was in the steady growth phase, between 7 and 12 minutes after ignition (in the steady state burning regime). Here, the smoke layer height remained approximately constant and the temperature increased in a steady manner). Tests 35 and 36 (square markers) were just before just before the onset of flashover. In the rest of tests (diamond markers), the door was closed after the fire had transitioned to flashover. From these results it is possible to identify the thermal conditions required, at the time of door opening, for backdraught to occur.

Figure 5.3.1 Temperature (near the floor, near the door) with or w/o backdraught

Instead of comparing all the 24 TCs in the compartment, 3 TCs were chosen for analysis: the TC with the highest temperature (TC-1003, 10 cm from the ceiling on TCT 2), one near the floor near the opening (TC-1031, the bottom one on TCT 5-1) and one near the top of the compartment (TC-1025, the top one on TCT 5-2).

In **Figure 5.3.1**, it can be seen that the temperature near the opening has no clear correlation with the onset of backdraught. It can be seen that all tests above 300°C at this location lead to backdraught, but this is only evident in tests where the door was closed after flashover. At lower temperatures, no correlation is apparent; for example, in test 8 the temperature was only 200°C, yet backdraught was observed, however in test 30 the temperature was 270°C and no backdraught was observed.

Figure 5.3.2 shows the observed temperature at the time of door opening at TC (TC-1025) near the ceiling, in the middle of the fire compartment. Once again there is no clear correlation between temperature and the onset of backdraughts. Backdraught occurred at temperatures ranging between 150°C to 390°C, yet other tests exhibited no backdraught at temperatures ranging from 120°C to over 300°C.

Figure 5.3.2 Temperature (near the ceiling, in the middle of the compartment) with or w/o backdraught

However, there appears to be more of a correlation between temperature and onset of backdraught when TC-1003 is used. In all tests this TC showed the highest temperatures, both as the fire grew and during the period of door closure; it is located 30cm above the edge of fuel tray. **Figure 5.3.3** shows that, except for tests 1 to 7, where the door was closed very early and the period of door closure was very short, there appears to be a critical temperature of about 350°C determining whether backdraught would occur or not. In the first 7 tests it appears likely that the shorter pre-burn time meant that the box was relatively cool, so pyrolysis may have been slow or not occurring, and the relatively short closure

times meant that there was insufficient time to accumulate a critical quantity of flammable gases.

In summary, it has been observed that the temperature at some locations in the compartment has no apparent correlation with the onset of backdraught. However, for the tested scenario at least, it is possible to use the compartment maximum temperature at the time of door opening to predict whether or not backdraught will occur. On the basis of these observations a “critical temperature of 350°C” is required for backdraught to occur.

Figure 5.3.3 Temperature (maximum) with or w/o backdraught

5.3.2 Delay time of backdraught- with the relationship to temperature

When a fire-fighter opens a door during search and rescue operations, they do not know if a backdraught will occur. When ‘nothing’ happens after the door is opened, there is still a great uncertainty as to whether backdraught will occur or not, as there is always a delay before a backdraught. In this research, backdraught delay times, which were measured by using video cameras, with an accuracy of 1/29th of a second, were compared with compartment temperatures. **Figure 5.3.4** shows the data for backdraught delay time vs compartment maximum temperature, for fires which grew to flashover before door closure. In these tests, the

backdraught delay time varied between 3 and 12 s, and there is an observable trend in the data, with hotter temperatures leading to faster backdraughts.

Figure 5.3.4 Delay time of backdraught after door opening

It should be noted that backdraught delay times in real compartments will be considerably longer due to scale [12]. Previous research suggested that the backdraught delay time was linked to the time taken by the gravity current to reach the back of the compartment [13], however this observation was made from experiments using a spark-igniter at the back of the compartment. In our apparatus, the gravity current only requires 3 s to reach the back wall, so it is clear that other factors must be contributing to the delay time.

When the temperature was close to the critical temperature for backdraught, 350°C in these tests, the delay time was consistently about 9 to 10 s. In these tests with the long delay times, the compartment door had been closed for more than four minutes. In general, the longer the time of closure, the lower the temperature will be and the longer the delay time will be. Thus, if the highest temperature inside the compartment is known and information about the duration of door closure is also known, it should be able to approximately predict the delay time for backdraught. However, it should be noted that the compartment used for this project was small and a detailed analysis correlating this to a full sized room has yet to be carried out.

5.4 Conclusion and future work

In this research, a series of reduced scale compartment fire tests has been carried out to investigate the driving force governing the occurrence of backdraught, using solid PP fuel. It has been demonstrated that the temperature distribution in the compartment is not correlated with the onset of backdraught, but a critical maximum temperature of about 350°C, at the time of door opening, has been observed to determine the onset of backdraught, above this value, a backdraught will be triggered (but it should be noted that this observation was made using only PP as fuel, other fuels might result in different results). This, perhaps, would be useful information for firefighters with Infrared Thermographers (Infrared Cameras), who may be able to assess temperatures and predict (with some uncertainty) whether backdraught is likely or unlikely.

If the fire has longer development before the door is closed, a more violent fireball will be generated because of accumulated unburned flammable gases. While flashover is not required to bring a compartment to backdraught conditions, fires which have transitioned to flashover before door closure have an increased possibility of backdraught due to a hotter compartment. It has been shown that if the compartment door is closed before the neutral plane of the fire begins to drop (that is, well before flashover), backdraught still can be triggered.

A range of delay times for backdraught was obtained. The observed trend is that a longer door closure time and a lower compartment temperature leads to a longer delay time. Infrared Cameras may be used by fire-fighters to predict whether backdraught is likely to occur, although there is considerable uncertainty here.

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Chapter 6. Critical factors determining the onset of backdraught using solid fuels

The content of this chapter has been submitted to Fire Technology with the name of 'Critical factors determining the onset of backdraught using solid fuels.' Currently the article is under review. To fulfil the spelling requirement of this journal, the word backdraught is replaced by 'backdraft' this chapter only.

Regarding the contribution of this chapter, apart from the experiments in the FPA, I did most of the work, including the experimental design, conducting experiments, data analysis and the paper writing up. Simon Santamaria, who is also a PhD student at the University of Edinburgh, conducted the FPA experiments and its data analysis (with FTIR), also the writing of related paragraphs. Dr Carvel edited some content of the paper to make the text more accessible to read through and also polished the words/ paragraphs to become more academic.

Compared to the previous chapters, this chapter focuses on the chemical components to the occurrence of backdraught in the fire compartment, also, conducting FPA tests in parallel, to investigate possible evolved gases in an under-ventilated fire condition.

The only differences between this chapter and the submitted paper are the renumbering of the figures and some minor text edits. In addition, as this is a submitted paper, the final published paper may be modified.

Summary

A reduced scale series of compartment fire tests have been carried out to investigate the critical factors governing the onset of the phenomenon of backdraft, using polypropylene and high density polyethylene samples as fuel. It is established that there are critical temperatures for non-piloted ignition of the pyrolysis gases leading to backdraft which vary with fuel properties.

In parallel with these tests, a series of pyrolysis investigations have been carried out using the fire propagation apparatus, with FTIR gas analysis, to mimic a possible condition for different burning status during the period of door closure and try to compare the observed data from these two experimental approaches (reduced scale and FPA (with FTIR) experiments). A correlation between the evolved pyrolysis gases and the onset of backdraft is proposed. The crucial factors determining whether backdraft occurs or not are the maximum temperature, and the CO/CO₂ ratio in the compartment prior to opening the door.

It should be noted that the critical temperature for backdraft is dependent on the pyrolysis chemistry of the fuels present, i.e., it is material-dependent, which means it is not possible to generalize a critical temperature for backdraft that could be of use by brigades in fire and rescue interventions. Future investigation of a range of solid fuels will enable the variations with different materials to be mapped out, revealing the possible critical temperature range.

6.1 Introduction

Backdraft (or 'backdraught' if the British spelling is preferred) is a fire phenomenon which typically occurs late in the development of a fire and is usually triggered due to the interventions of fire-fighters, often with fatal consequences. It remains one of the primary unresolved issues in fire science [1].

A backdraft can only occur when there is a hot, fuel-rich fire compartment with a limited air supply, such that the fire becomes highly ventilation-limited or is extinguished, possibly with residual smoldering or hot spots remaining [2]. If a door or window is opened or breaks, the inflowing air mixes with the hot, fuel-rich compartment gases, creating a flammable gas mixture. If the mixture is above non-piloted ignition temperature, or if some pilot source is present, the gas ignites,

typically resulting in a fireball driven through the opening, with potentially fatal consequences for those outside the compartment. Backdraft is not instantaneous however, and there is often a significant delay between the opening of the door and the onset of the backdraft, the delay can be as long as several minutes.

There has been sporadic research into backdraft and related phenomena over the past two decades or so, but many questions remain unresolved or have only been answered approximately.

Fleischmann et al.[3–5] pioneered backdraft research in the early 1990s, using a lab-scale chamber ($2.4 \times 1.2 \times 1.2$ m) with a methane burner to test and observe backdraft development. They observed the ‘gravity current’ flow, the delay time, and deduced factors crucial to the occurrence of backdraft. They concluded that 10% of unburned fuel in the compartment gases was the critical concentration to allow backdraft.

Subsequently, Weng and Fan [6–8] conducted a series of backdraft tests using an apparatus half the size of Fleischmann’s, but with the same geometry. They also found the concentration of unburned methane is a key parameter in determining the occurrence of backdraft, and found that the critical value varied with the location of the inlet; for some locations, a gas concentration as low as 7% could result in a backdraft [7].

The ‘gravity current’ observed by Fleischmann has been the subject of most backdraft research to date [3,6,9–15]. When the door between a hot compartment and a cooler external atmosphere is opened, the buoyancy differential means that hot gases from the compartment will spill out the top of the opening, and a flow of cooler air will flow in through the bottom of the opening, under the hot gases. This phenomenon has been labelled the ‘gravity current’. The rate of gravity current flow is largely dependent on the temperature difference between the two fluids; a higher temperature and density difference between the two gas mixtures will lead to a fast flow situation, with strong turbulent mixing. Provided there is sufficient fuel in the hot gas and sufficient oxygen in the cooler gas, this turbulent mixing will rapidly create a cloud of flammable gas. If this gas is ignited, the resulting deflagration is described as a backdraft [2].

The mixing process is not instantaneous. It is commonly assumed that the delay time between door opening and backdraft occurring is the same as the time

taken by the gravity current to travel to the rear wall of the compartment. Thus, prediction of the delay time can be made if the geometry of the compartment and the density difference between the gases is known. This reasoning assumes that the backdraft is triggered by a pilot source at the rear of the compartment, as in Fleischmann's and Weng & Fan's experiments. This, of course, may not correspond to reality in many backdraft situations.

To date, most experimental and modelling studies of backdraft have used methane as the fuel source, and while the conclusions regarding the crucial conditions for backdraft have often been expressed in general terms, these conclusions are strongly limited by the fuel used. In reality, backdraft events occur in compartments filled with complex mixtures of partially burnt products of pyrolysis from solid fuels such as wood, plastics and foams. Such pyrolysis gases have a range of flammability limits, and may only be flammable at elevated temperatures. Methane, on the other hand, is flammable at ambient temperature, so any dependence on temperature of the onset of backdraft in real situations cannot have been observed, and has not been defined using methane. This limitation of the literature studies is the primary motivation for the study presented here.

Previous research has generally focused on piloted ignition of backdraft, with the pilot flame or spark generally being positioned at the other end of the compartment from the opened door. Observations made about the delay time between opening the door and the onset of backdraft have therefore been largely related to compartment geometry. Non-piloted ignition of backdraft has not been widely studied. To address this deficiency in the literature, both piloted and non-piloted ignition conditions have been investigated in this study.

This research aims to identify critical temperatures and flammable gas concentrations for backdraft relating to different solid fuels, for both non-piloted ignition and piloted ignition backdraft events. Furthermore, this study aims to map out these critical conditions for backdraft, providing a robust method for predicting whether the onset of backdraft is possible in a given scenario.

6.2 Experimental setup and procedure

6.2.1 Experimental apparatus

Previous research has shown that the occurrence of backdraught is not dependent on the size of compartment used [16], therefore these studies may be carried out at laboratory scale. This not only enables a greater number of experiments to be carried out, but also reduces the risks inherent in the experiments to manageable levels.

Figure 6.2.1 Diagram showing the locations and dimensions of the thermocouples, fuel tray, electrical spark, electric balance and door opening.

A small-scale fire compartment ($0.8\text{m} \times 0.4\text{m} \times 0.4\text{m}$) was designed and built for backdraught research, see **Figure 6.2.1** and **Figure 6.2.2**.

Figure 6.2.2 Sketch of the experimental apparatus used

Locations of TCs and materials of the fire compartment has been demonstrated in previous chapters. A repeat of the description of the setup is not required here. An electric spark apparatus was installed on the rear wall for the tests investigating piloted ignition.

Three removable baffles were used to allow the incoming air to flow into the compartment via the bottom part of the opening (0.13 m height $\times$ 0.4 m wide). A sliding outer door is used to seal and open the compartment, this ensures that the experimenter is safely to the side of the compartment when the door is opened, and is well out of the way of any ejected flames. An electric balance manufactured by Mettler Toledo (model: MS4002SDR) with 0.1 g readability was used to measure the mass loss during testing.

A portable gas analyser (model 7911) manufactured by Crestline Instruments was used to characterise the gas for a few seconds before opening the door in several of the tests. The apparatus was calibrated with accuracies of $\pm 1\%$, $\pm 3\%$, and $\pm 3\%$ (relative accuracy) for O_2 , CO and CO_2 , respectively. Also, the measuring ranges for the accuracies above are 0 to 25%, 0 to 10%, 0 to 16% respectively. Before each test, operating the gas analyser about for 4 minutes to make sure the observed O_2 at ambient was about 20.9 % for calibration according to the product manual. The gas sampling tube was installed in line with TC 3-1 and 3-3 for some tests investigating the gas composition immediately before backdraught, 20 cm distance to the rear wall, the sampling location is at 15 cm distance to the bottom of the fire compartment, close to the ignition point of backdraught. In these tests, a gas sample with a flow rate of 1 litre/min, was extracted in the 8 to 10 second period before opening the door. The reason for this very short sampling time was to limit the influence of the sampling procedure on the compartment fire dynamics; a longer sampling duration would significantly change the conditions in the compartment and therefore influence the outcomes. In these tests, the sampled gases extracted less than 0.013% of the total volume of the compartment. In practice, a shorter sample duration could not be used as the gas analyser required a few seconds of sampling to reach a stable reading.

6.2.2 Experimental procedure

In this project, different solid fuels have been used to investigate the relationship between the onset of backdraught with material type. Here this

research presents results for polypropylene (PP) and high-density polyethylene (HDPE) fuels. Future research will involve other fuels including wood.

The conditions for backdraft can be achieved after a fire has become well established, but it has already been demonstrated that fire growth to flashover is not required [17]. Flashover, when it occurred, was identified during these tests by a rapid increase in burning rate, a significant increase in temperature, and external plume burning. In these experiments, the fire was initiated using a small quantity (150 ml) of n-heptane (C_6H_{16}) to accelerate the fire, this liquid fuel was consumed in the first five minutes of each test, so it is assumed that negligible quantities of n-heptane remained in the fuel during the periods of door closure, which were generally initiated more than 7 minutes after ignition, as will be described.

In tests using PP fuel, 300 g of pellets were used as fuel, in the square fuel tray. If the door was left open, this quantity of fuel exhibited a 'steady burning' phase from about 7 minutes to 12 minutes after ignition, followed by a rapid growth to flashover between 12 and 14 minutes after ignition and the fuel began to run out about 16 minutes after ignition. The steady burning phase is characterised by a gradual and consistent increase in temperature of all thermocouples in the compartment. **Figure 6.2.3** shows a photograph of the PP fuel in the tray.

Figure 6.2.3 The PP fuel in the fuel tray

In tests using HDPE fuel, which has a similar heat of combustion to PP [18], about 300g of short strips of the material (see **Figure 6.2.4**) were used as fuel, in the same pan as used for the PP experiments. The HDPE fuel load generally took longer to become established but exhibited a steady burning phase from about 13

to 18 minutes after ignition, growing to flashover after about 20 to 22 minutes after ignition.

Figure 6.2.4 Photograph of one of the HDPE fuel strips

In each test, the temperatures within the compartment were monitored and the door was closed at the temperature of interest, which varied from test to test, as will be discussed. This rapidly led to an oxygen-starved fire in the compartment and flaming ceased. Without the fire to maintain the heat balance, the box and the gases in it began to cool. During this phase the temperatures were monitored closely, and the door was opened once the gas cooled to the temperature to be investigated; again, this varied from test to test. Following this there was usually a short delay (as discussed below), followed by one of three things:

1. a backdraught event (sudden ignition of compartment gases resulting in a significant fireball emerging from the compartment opening),
2. a reignition event (sudden ignition of compartment gases within the compartment, and pool fire re-established, but no significant external flaming or fireball), or
3. no reignition or backdraught.

The primary objective of this research is to identify the minimum set of conditions (temperature, gas concentrations, etc.) required to allow the establishment of a backdraught.

Temperatures were generally monitored using one specific thermocouple in the upper part of the compartment. This reference thermocouple consistently showed the highest temperature reading in all tests, both when the door was open and when it was closed. In all discussion of temperature that follows it should be remembered that the temperature quoted is characteristic of the highest

temperatures found in the box, and is not an average or characteristic temperature within the box.

In every experiment that resulted in no reignition, the fuel pan was found to contain significant quantity of residual fuel, so it may be assumed that the lack of reignition or backdraught in these tests was due to factors other than availability of fuel.

Figure 6.2.5 shows the temperature variations in the apparatus during a typical test with PP fuel. In this instance, the door was closed at 14 minutes, just after the compartment transitioned to flashover. The door was kept closed for 4 minutes, and then opened. A backdraught occurred after a 10.5 second delay.

Figure 6.2.5 Temperature variations during a typical test with PP fuel, door closed after flashover, pilot spark was not used. Plots show maximum recorded compartment temperature, average compartment temperature and minimum recorded compartment temperature.

Figure 6.2.6 shows the temperature variations in the apparatus during a typical test with HDPE fuel. In this instance, the door was closed at 18 minutes, just after the compartment transitioned to flashover. The door was kept closed for 7.5 minutes, and then opened. A backdraught occurred after a 29.7 second delay in this instance.

It is clear from **Figure 6.2.5** and **Figure 6.2.6** that the temperature gradients in the compartment are considerably reduced when the door is closed. In most experiments, the temperature difference between the highest recorded temperature and the lowest recorded temperature in the compartment, just before the door is opened, was about 50 °C.

Figure 6.2.6 Temperature variations during a typical test with HDPE fuel, door closed after flashover, pilot spark was not used. Plots show maximum recorded compartment temperature, average compartment temperature and minimum recorded compartment temperature.

Attempts have been made to try and obtain accurate mass loss data for the fuel tray in the period between door closure and door opening. Unfortunately, to date, it has not been possible to obtain sufficient acceptable data, or to distinguish between burning and pyrolysis following flame-out.

There are two possible reasons: One is because there was no ventilation during the time of the door closure. The continued pyrolysis process may press the supporting holder of the fuel tray, so it makes the reading of the weight was extremely unstable, and it was very different from a typical compartment fire. The other reason is that the design of the apparatus of weight measurement. It is unable to weight the mass loss by installing electric scale or balance under the box, the result showed the total weight did not change even if it has been a while after fire burning. The reason is that the scale / balance weight the box and the trapped smoke inside. To solve this issue, it is necessary to weigh the fuel tray only, using

an external balance, with a rod penetrating the compartment, supporting the fuel tray inside.

To restrict loss of the compartment gases through the penetrations, the hole for the rod was kept very small (the radius of the hole is only about 0.2 cm larger than the rod). When conducting the opening and closing procedure, the vibrations of the box made the rod come in contact with the compartment, which rendered the mass loss data unusable. A better way would be to design a larger scale testing box in future research.

The most reliable data obtained so far, for door closures at around flashover for either fuel, show that the PP fuel tray lost 28.8 g in mass during a 257 s door closure, and the HDPE fuel tray lost 65.4 g during a 446 s closure. This shows a higher average mass loss rate per second for HDPE compared to PP, approximately 0.15 g/s compared to 0.11 g/s, respectively. It should be noted that as the temperature in the compartment is gradually diminishing when the door is closed, it is assumed that the pyrolysis rate will also diminish across this time, so it is unwise to infer anything from average mass loss rates, particularly when comparing tests with different door closure times.

Also, the effect of geometry on gas concentrations was investigated. Three experimental series with different compartment sizes (narrower compartments, varied by adjusting the position of the internal walls) were investigated to further understand gas concentrations during tests. The purpose of these tests was to observe CO and CO₂ gas species variations before door opening, with the same location of the gas tube, and if the changes can be correlated to the occurrence or not of backdraft.

A series of 64 experiments using PP fuel and 8 experiments using HDPE fuel have been carried out to map out the conditions under which backdraft may occur, both in the presence and absence of a pilot spark. These tests were to investigate the influence of temperature on backdraft occurrence. Following this, 33 experiments were conducted with gas analysis. The results are presented below.

6.2.3 Pyrolysis gas analysis

Once the compartment door is closed, the fire will rapidly use up much of the remaining oxygen in the apparatus and will then burn out. Following flame-out, the

compartment remains hot and the fuel pool will continue to pyrolyze for some time, provided the compartment remains hot enough. In order to understand the chemistry which may lead to backdraft conditions it is essential to know what the products of pyrolysis are.

It is not possible to adequately characterise these pyrolysis gases in situ, during a backdraft experiment, so a series of pyrolysis experiments have been carried out using the fire propagation apparatus (FPA) [18] at reduced oxygen levels, together with a Fourier transform infrared spectroscopy (FTIR) system [19], to determine what the likely products of pyrolysis are.

The FPA was used to expose all samples tested to a constant incident radiation of 50 kW/m². The mass of each sample was recorded before testing and the test was terminated once the sample had completely pyrolyzed. Pyrolysis was studied at three oxygen concentrations: 13%, 9% and 0% (100% N₂ environment), these scenario selections are based on the observed data of the gas analyser in reduced scale experiments. A pilot flame was not used, and ignition was not observed in any of the experiments.

In each test, the plastic material (PP in pellets, HDPE in thin strips, as in the backdraft experiments) was placed in a sample holder measuring 85 × 85 × 20 mm, and the initial mass of each sample was about 40 g. The duration of exposure varied between experiments, as the objective was to ensure complete pyrolysis. The tests varied between 420 and 510 seconds.

A quartz tube was used to enclose the pyrolysis chamber in the FPA. A nominal inlet flow of reduced oxygen air of 100 L/min was kept constant before and during each test. The FTIR probe was positioned near the top of the quartz tube, 900 mm above the sample surface. In each experiment, the concentration of 11 chemical signatures was estimated with the FTIR. In each test it became clear that there appear to be four primary pyrolysis product families (in terms of maximum concentrations and ratio with other species), but that these are different for PP and HDPE. **Table 6.2.1** shows all measured species and highlights the primary gases identified for PP and HDPE.

Table 6.2.1 Dominant species generated per material

Species	PP	HDPE
<i>Water Vapour</i> H_2O	-	-
<i>Carbon Dioxide</i> CO_2	-	-
<i>Carbon Monoxide</i> CO	-	X
<i>Methane</i> CH_4	-	X
<i>Ethylene</i> C_2H_4	-	-
<i>Ethane</i> C_2H_6	-	X
<i>Propane</i> C_3H_8	-	-
<i>Butane</i> C_4H_{10}	X	-
<i>Pentane</i> C_5H_{12}	X	-
<i>Hexane</i> C_6H_{14}	X	X
<i>Benzene</i> C_6H_6	X	-

It should be noted that the FTIR system does not identify specific chemicals, but rather identifies modes of bending of chemical bonds and structures characteristic of the chemicals named. For example, when 'Benzene' is identified by the FTIR system, the pyrolysis products might not actually contain benzene, but will certainly contain some compounds with aromatic ring structures, like benzene. For simplicity in the analysis that follows, however, this research will use the various named chemicals as shorthand for the family of chemicals which may represent.

6.2.3.1 HDPE pyrolysis

Figure 6.2.7 shows the concentration of carbon monoxide, methane, ethane and hexane for the pyrolysis of HDPE in hypoxic atmospheres. In each test, following a period of 200 seconds after the start of the exposure where the generation of gases was comparatively low, the material degraded rapidly, and the concentration of flammable gases increased sharply. The concentration of CO gas is higher for higher oxygen concentrations and diminishes with diminishing oxygen; there appears to be an equivalent trend for the other three primary gases, although this is less apparent. Of course, the dominant species, carbon monoxide, requires oxygen for its formation, but the reducing trend in the other gases is less explicable. It would appear that the presence of oxygen assists the process of fragmentation of the polymer to shorter chain hydrocarbons. Aside from carbon monoxide, the dominant pyrolysis product appears to be hexane, with lighter hydrocarbons also being produced.

Figure 6.2.7 Pyrolysis products from HDPE samples. Left: 13% O₂, Centre: 9% O₂ and Right: 0% O₂. (Note: The methane plot on the graph on the right is almost entirely hidden behind the ethane plot)

6.2.3.2 Polypropylene pyrolysis

Figure 6.2.8 shows the concentrations of the hexane, benzene, butane and pentane families during pyrolysis of PP. For all cases, the concentration of pentane is the highest, followed by hexane. The maximum concentration of these two gases

is much lower at the highest oxygen level, showing that partial oxidation may be occurring with this amount of oxygen present. Aromatic hydrocarbons are also produced, but these are at a lower level and will be discounted in the discussion that follows. Under the controlled conditions of the FPA, the highest concentrations of the four primary gases were attained for the 9% O₂ test.

It should be noted that the maximum concentrations are an order of magnitude higher than those for HDPE, which has a direct impact on the attainment of concentrations of these gases sufficient to generate a potentially flammable mixture in an enclosed chamber.

Figure 6.2.8 Pyrolysis products from polypropylene samples. Left: 13% O₂, Centre: 9% O₂ and Right: 0% O₂.

6.3 Results

6.3.1 Polypropylene

6.3.1.1 Temperature factor

64 experiments have been carried out using PP fuel. No backdraft was observed in 29 of these tests. **Figure 6.3.1** shows which tests resulted in backdraft (solid markers) and which tests did not (empty markers). All the observed temperature used the maximum temperature (not an average compartment temperature) among TCs, the location of this TC is the closest to the starting point of backdraft (not every backdraft occurs at exactly the same location among

tests, but the locations are always similar; it always appears somewhere above the fuel tray). For more discussion on the values of the TCs, please see Chapter 4. In tests 1 to 34 (triangular markers), the door was closed while the fire was in its steady burning phase, in tests 35 and 36 (square markers), just before the onset of flashover, while in tests 37 to 64 (diamond markers), the door was closed after the compartment had transitioned to flashover. The temperature plotted here indicates the maximum recorded temperature in the compartment at the time the door was reopened, it should be noted that the used temperature only relates to the mixture before it is ignited.

It is clear that in all tests where the temperature was above 400°C, backdraught occurred. Likewise, it is clear that in all tests when the temperature had dropped below 330°C, no backdraught or reignition occurred. The focus of our investigation therefore lies between these limits. In test numbers 1, 3, 6 and 7, which had door opening temperatures above 350°C, yet had no backdraught, the temperature at the time of door closure was relatively low, and the duration of closure was relatively short. It is supposed that the relatively cool box and the short duration of closure meant that insufficient pyrolysis gases accumulated in these tests and no flammable mixture could be generated.

It is clear that there is a critical temperature, close to 350°C, above which backdraught generally does occur and below which backdraught generally does not occur. No instances of backdraught in the absence of a pilot spark were

Figure 6.3.1 Temperature at time of door opening for tests using PP fuel, indicating backdraught and non-backdraft events.

observed below 350°C. Further analysis of the data reveal that the instances of backdraught triggered between 330°C and 350°C all featured a high temperature before door closure, a relatively long duration of door closure, and the presence of a pilot spark. These results are discussed in more detail in [17].

6.3.1.2 Gas concentrations

From previous section, it is shown that temperature is one of the crucial factors in determining the onset of backdraft. A temperature close to 350 °C seems to be a critical value when PP is used as fuel. It is of interest to investigate other measurable factors to explore the other necessary conditions for backdraft to occur.

In well ventilated conditions, most hydrocarbon fires tend towards complete combustion, generating primarily water vapor and carbon dioxide as products, as follows:

When there is insufficient air, that is, in ventilation controlled fire conditions, complete combustion cannot occur and carbon monoxide will be one of the products:

where $p = q + 2r$; when $n + \frac{1}{4}m > p > \frac{1}{2}n + \frac{1}{4}m$, neglecting soot production.

(Note, it is highly unlikely that burning can be sustained as q tends towards zero and r tends towards n , except at highly elevated temperatures; production of only CO and H₂O is thermodynamically unfavourable.)

It is hypothesized that the relative quantities of CO and CO₂ could provide information about the amount of underventilated burning during the time of door closure, and this might be correlated with the onset or otherwise of backdraft.

Figure 6.3.2 shows the relevant experimental data for CO/CO₂ ratio immediately prior to door opening. Experiments with backdraft occurrence are shown using solid black markers, re-ignition without fireball is shown in grey, and those tests did not result in backdraft or reignition are shown using empty markers. Both pilot

and non-piloted ignition conditions were tested, and are indicated using diamonds and triangle markers, respectively.

Figure 6.3.2 CO/CO₂ ratio to the maximum temperature

In terms of non-piloted ignition experiments (consider only the triangles in **Figure 6.3.2**), it is clear that when the maximum temperature was above 350°C and the CO/CO₂ ratio was higher than 0.4, backdraft occurred. However, an implication is that temperature is not the only factor leading to backdraft. A boundary line in red provide the information about backdraft condition (occurrence of backdraft or fire extinguishment), above the red line, backdraft will be triggered. The three dashed lines in **Figure 6.3.2** indicate the apparent boundaries between backdraft and non-backdraft events. None of the tests with less than 0.08 (CO/CO₂) resulted in backdraft, even with a similar temperature and gas concentrations to the one next to it, see the data at point A in **Figure 6.3.2**. When the temperature dropped to about 360°C, a new boundary appears to be located between 0.22 to 0.27, see the data near point B. At 350°C, it can be seen the boundary condition changes again to 0.27 to 0.4, see point C. It implies that the suitable conditions for onset of backdraft vary with a combination of burning status and the temperature conditions inside the fire compartment.

A boundary line in blue divides the experimental result (using a spark as the ignition source) into two part. The right is the backdraft region, and the left shows no backdraft was triggered, see **Figure 6.3.2**. Considering only the diamond markers, that is, when a pilot spark was present, either backdraft (black markers) or fire re-ignition (grey markers) always occurred in these tests. It is observed that

when CO/CO_2 was above 0.35, backdraft occurs, lower than this value, the spark can only ignite the unburned smoke and re-ignite the fuel tray only, with no obvious fireball indicating backdraft. It should be noted that even with an extremely long time of door closure with lower temperature about 200°C , a re-ignition is still possible, for details see [17]. It should also be noted that there were only three instances of backdraft observed in this test series, so it is hard to define the boundary between backdraft and non-backdraft events with any confidence. Further research will be required. It should be noted that all tests experienced at least 25 seconds door closure in this part to make sure the fire has been extinguished (there is no extra oxygen to continue flaming (gas phase oxidation), but there should still have pyrolysis, melting processes, etc.). In those experiments closing the door at the early stage of the fire, the temperature of the room was not uniformly warm. A considerable temperature difference exists between the hotter and the colder layer of the fire compartment. Also, the fire had not developed to under-ventilated fire as the neutral plane was kept the same, did not drop yet. When those tests experienced the door closing, this condition makes the temperature drop fast, a short time (about 30 seconds) of the door closing was the controlling method to have a higher temperature above 370°C , but at the same time, generating a lower CO/CO_2 ratio. As the fire conditions were not the same, controlling both temperature and the gas component is not possible at the same time. This figure only faithfully presents all the observation during the tests.

Measurements of the CO/CO_2 ratio provide useful information on the burning conditions, a higher value implies a relatively oxygen starved situation. CO_2 does not assist fire combustion, quite the opposite, but CO is flammable and may contribute to the tendency towards backdraft. Further research is required, but it appears that CO measurements may provide a means to predict if a possible backdraft is coming.

In **Figure 6.3.3**, it can be observed that there is similar boundary between backdraft and non-backdraft events, as in **Figure 6.3.2**. The markers in **Figure 6.3.3** have the same meanings as in **Figure 6.3.2**.

Figure 6.3.3 CO concentration to the maximum temperature

When the CO is below about 0.6% (by volume) backdraft is not observed, irrespective of temperature. At temperatures below 350°C, backdraft only occurs in the presence of a pilot spark and when there is more than 2.8% CO (by volume). Between these conditions, there is an apparent boundary (indicated by the line from A-C on **Figure 6.3.3**) between backdraft and non-backdraft events which varies with both temperature and CO concentration.

It should be noted that one test with a pilot spark, which sits significantly above the apparent boundary did not result in backdraft, but only in a reignition. It should be stressed that any correlation drawn on the basis of only temperature and CO concentration is only an indicator of the likelihood of backdraft occurrence, not an absolute predictor.

The detected value of CO was obtained around the time of the door opening (10 seconds before the opening procedure). Gas sampling was conducted for a short time. But from the knowledge of fire science, it should produce more CO when the burning lasts longer as the fire tends to become a ventilation-controlled fire, the burning condition transit from complete to incomplete combustion. Production of CO during the period of door closure will initially have been due to underventilated burning of the fuel as the oxygen in the compartment was used up, followed by pyrolysis of the fuel in low oxygen conditions after the fire had

extinguished. It has not been possible in this research to identify when the fire reached extinction conditions, or to quantify pyrolysis after that, so the quantity of CO used here as an indicator for backdraft must be understood to be due to both processes, but the relative importance of each has yet to be determined.

6.3.2 HDPE

A shorter series of 8 tests were carried out using the HDPE fuel. In each instance, the fire was allowed to grow to flashover (by observing if an external flame exists when backdraught occurred) conditions before the door was closed.

Door opening temperatures from 400°C down to 300°C were tested with no pilot spark. **Figure 6.3.4** shows that backdraft was observed in all tests with door opening temperatures above 320°C, while backdraft did not occur below this limit.

Figure 6.3.4 Temperature at time of door opening for tests using HDPE fuel, indicating backdraft and non-backdraft events

In terms of CO/CO₂ and CO to the maximum temperature inside the fire compartment, see **Figure 6.3.5** and **Figure 6.3.6**. It is found that only temperature plays the role of determining if a backdraft occurs. A lower temperature generally results in a smaller ratio of CO/CO₂. Possible reasons for explaining this is that the fire compartment experienced a considerable door closure at the lower temperatures, and the compartment is not well-sealed, some CO and CO₂ may have been released through the leakage of the compartment. However, this does

not affect the occurrence of backdraft if the maximum temperature is higher than 320°C

Figure 6.3.5 CO/CO₂ ratio to the maximum temperature (HDPE)

Figure 6.3.6 CO concentration to the maximum temperature (HDPE)

6.4 Discussion

The tests have clearly identified that the critical temperature in allowing the onset of backdraft by non-piloted ignition varies between PP and HDPE. For PP,

the limit is about 350°C, while for HDPE it is about 320°C. This is explained by consideration of the pyrolysis gas signatures, described above. The largest component of the pyrolysis gases in the case of PP is pentane, with hexane being the second most abundant flammable gas present. For HDPE, the pyrolysis gas (in low oxygen conditions, where CO is not produced) is predominantly hexane.

The non-piloted ignition temperatures for stoichiometric mixtures of pentane and hexane gases in air are 260 and 215°C, respectively [20]. For gas mixtures closer to the upper flammability limit a higher non-piloted ignition temperature would be expected, but the authors would expect the limit for pentane to remain higher than that for hexane. Thus, it is to be expected that a mixture of pentane and hexane would exhibit a higher non-piloted ignition temperature, close to the upper flammability limit, than a mixture that is predominantly hexane. This is consistent with the trend observed in the tests described above.

This means that the critical temperature for backdraft is dependent on the pyrolysis chemistry of the fuels present. Unfortunately, this means that it is impossible to generalize a critical temperature for backdraft that could be of use by brigades in fire and rescue interventions. Future investigation of a range of solid fuels will enable the variations with different materials to be mapped out.

As discussed above, when a spark is present backdraft may be triggered at temperatures up to 20°C lower than the critical temperature for backdraft by non-piloted ignition. However, in this temperature range backdrafts with fireball were sometimes observed, while re-ignition events were also sometimes observed. Similarly, when the door was closed early in the steady burning period, re-ignition rather than a typical backdraft was occasionally observed, even for door opening temperatures above 350°C.

A series of tests were carried out using PP fuel along the identified 'backdraft boundary', with and without the pilot spark active, using the gas analyzer to try to identify the characteristics of compartment gases which would lead to backdraft. Without any ignition source (non-piloted ignition), backdraft can only occur when the CO/CO₂ ratio is above 8%, temperature required is higher, but when the temperature to 350°C, the CO/CO₂ ranges from about 30% to 40%, see **Figure 6.3.2.**

Table 6.4.1 Gas analysis along the ‘backdraught boundary’ for PP fuel (with pilot spark)

Pre-burn time (min)	Duration of closure (s)	Characteristic Temperature (°C)	CO ₂ %	CO%	O ₂ %	CO/CO ₂ ratio	Backdraft
9	52	368	6.40	0.80	8.89	0.12	No
11	124	337	6.92	1.79	7.07	0.26	No
12	95	366	6.81	1.86	6.66	0.27	No
12	148	338.79	7.41	2.57	5.70	0.35	No
12	78	383.91	2.19	0.57	11.89	0.26	No
13	234	341.11	8.13	3.34	3.51	0.41	Yes
F.O.	382	329.63	6.94	3.16	1.69	0.46	Yes
F.O.	474	316.67	7.60	2.72	2.33	0.36	Yes

With the spark active, in all the tests, backdraft occurred, however, shows different behavior. Therefore, the gas analyzer was used for trying to identify the characteristics of gases which would lead to re-ignition, which is a considerably less violent and dangerous fire phenomenon. **Table 6.4.1** and **Figure 6.3.2** show the findings, correlated with the CO/CO₂ ratio. It is clear that in the all range of testing, backdraft always occurred, but only when the CO/CO₂ ratio is above 35%, backdraft with fire ball can occur, below this limit, led to fuel re-ignition. For additional data, not presented in Table 6.4.1, see Appendix B.

As demonstrated above, CO is not a significant product of the pyrolysis of PP, even in relatively high oxygen conditions, thus the high CO/CO₂ ratio suggests that the duration of the period of underventilated burning may have some control over the onset of backdraft or otherwise. At the same time, CO concentration provides a similar trend to CO/CO₂ ratio, which shows that the non-piloted ignition temperature varies with the accumulated CO. This suggests that the non-piloted ignition temperature of backdraft in fires does not have a constant value, which is to be expected from established flammability limit theory [19].

6.5 Future work

Future research needs to focus on the underventilated burning phase, investigate extinction, pyrolysis during the time of door closure, and map out a more detailed picture of the gas composition at the time of door opening.

A greater range of solid fuels, for example woods and common rigid foams, also need to be investigated to establish a greater understanding of backdraft in the real world.

There also remain many unanswered questions about the backdraft delay time, the location and size of the opening and mitigating measures which may be employed by the fire brigades. Work on these topics is ongoing.

6.6 Conclusion

A reduced scale series of compartment fire tests have been carried out to investigate the critical factors governing the onset of the phenomenon of backdraft, using solid polymeric materials as fuel.

It has been established that there is a critical temperature for non-piloted ignition of the pyrolysis gases leading to backdraft which varies with fuel properties. When fire has developed to near flashover conditions before door closing, for polypropylene fuel, the critical temperature is 350°C, for polyethylene fuel, the critical temperature is about 320°C.

These temperatures are consistent with the gases evolved in a parallel investigation of the pyrolysis products from the two polymers considered, carried out in the fire propagation apparatus, under reduced oxygen conditions, and analyzed using FTIR spectroscopy.

An investigation into gas properties along the boundary between backdraft and non-backdraft outcomes revealed that a CO concentration of at least 0.6% in the compartment, before the door was opened, was necessary for backdraft to occur without a pilot spark. At higher CO concentrations, backdraft may occur at slightly lower temperatures. At temperatures slightly below the critical temperature for non-piloted ignition of backdraft, a CO concentration of above 2.8% and a pilot source are essential conditions for the occurrence of backdraft.

6.7 References

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Chapter 7. Critical delay time to the onset of backdraught under different ignition scenarios

Summary

A reduced scale series of compartment fire tests have been carried out to investigate the delay time of backdraught under different scenarios, such as non-piloted ignition and piloted ignition⁶, on various fire stages using polypropylene and high-density polyethylene as fuels. The intention of this chapter is to investigate the possible delay time of backdraught under various fire conditions before opening the door of compartment. Both piloted and non-piloted backdraught are compared, and different fuels (PP and HDPE) have been used to investigate if this delay time is fuel-specific or is a general principle that can be used irrespective of fuel. Mass loss rate and the change of temperature during the time of the door closure were used to investigate the possible conditions to influence the delay time.

Results are compared with the empirical theory of backdraught delay time. It is found that the delay time of backdraught varies with the type of ignition source, this time delay presents a correlation to the temperature inside compartment but

⁶ It is found that the term “non-piloted” ignition is more appropriate than “auto-ignition” (the term used in the previous published paper) to describe the backdraught triggered without the spark apparatus installed because it is difficult to judge if there are small ignition sources existing during the time of the door closure. The following chapters will use “non-piloted backdraught” to describe the events that did not use the spark apparatus to generate backdraught. Even though this change in terminology cannot be imposed on already published works, the wording of previous chapters has been updated to reflect this, which makes the whole thesis coherent.

varies with fuels, and is highly related to the temperature distributions / stability in the fire compartment. A longer time of door closure, result in a longer time delay.

The 'gravity current' can only be used to predict the delay time in tests with an extra ignition source, with a few underestimations, under these conditions, the time delay only depends on the distance from the opening to the spark, the temperature, and the opening configurations.

7.1 Introduction

A backdraught can only occur in conditions when there is a hot, fuel-rich fire compartment with limited ventilation with not enough oxygen to provide complete combustion, the fire becomes under-ventilated or is almost extinguished, possibly with smouldering or hot embers remaining. If a sudden opening is triggered, such as a door or window is opened or breaks, introducing a flow of cold fresh air into fire compartment, a flammable gas mixture is created. When there is a suitable ignition source present, either being above auto-ignition temperature or having a hot spark, the gas mixture ignites, typically resulting in a fireball which travels through the opening, causing potential casualties as the consequence.

There has been sporadic research into backdraught and related phenomena over the past two decades, but many questions remain unresolved or have only been answered approximately. For a firefighter, the time when backdraught may occur is a critical issue because in most of the cases when backdraught occurred, this was a rescue mission. However, there has been no systematic research systematically discuss on this. Such research as there is, mainly used methane as fuel [1].

Fleischmann et al.[2–5] started the pioneering backdraught research 20 years ago, attempting to explore the backdraught phenomenon, and this included the critical factors for the onset of backdraught, and the delay time predicted both experimentally and numerically. Following this, a series of research focused on the formation of backdraught and tried to evaluate fire-fighting tactics on backdraught [6–14].

The 'gravity current', which is often considered as the driving force behind backdraught, was observed by Fleischmann, and has been the most widely

researched subject to date. A gravity current can be briefly described as the flow of one fluid into another caused by a difference in density [15], this phenomenon is typically linked to the time when backdraught will occur after the door is opened.

Most researchers have tried to use different simulation methods to investigate the gravity current in connection to the occurrence of backdraught. However, the applications in the simulation were mainly based on the backdraught events using methane as the fuel, whether this can be widely used to predict the backdraught using realistic fuels it is still unsure. Hence, more experiments should be carried on contributing to numerical modelling, then the numerical model can be well-established. Such experiments are still lacking.

This research aims to identify the range of delay time of backdraught relating to different solid fuels, for both non-piloted ignition and piloted ignition backdraught events. Furthermore, this study aims to provide an applicable approach which may be used to modify the current firefighting tactics on the basis of the experimental and theoretical results, to minimise the risk to firefighters when fighting compartment fires.

7.2 Traditional ignition classifications - piloted and non-piloted ignition applied to backdraught

Ignition of a flammable gas can commonly be classified into two types, non-piloted ignition and piloted ignition. The major difference between these is whether an external ignition source is needed apart from the hot fire compartment itself. No ignition is possible without a suitable environment of heat, oxygen, and fuel, based on fire triangle theory. In addition, chemical chain reaction is needed to sustain a longer fire spread or propagation. Normally, piloted ignition temperature is found to be lower than that required for non-piloted (auto) ignition temperature of a combustible material. Except for the auto-ignition region, a tiny ignition source which is above the minimum energy required should always ignite flammable mixtures when these exist between lower and upper flammability limits (LFL, UFL) [16]. These limits vary with temperature. This suggests that if the temperature

inside the compartment is lower than a certain value these will be no fire risk even if a huge ignition source is present.

Figure 7.2.1 Variation of induction period with temperature for stoichiometric fuel/air mixtures [17]

Figure 7.2.2 Left, scheme for spontaneous ignition of a combustible solid [17]; right, scheme for non-piloted ignition of a backdraught

Non-piloted ignition of fuel/air mixtures normally requires an “induction period (τ)” before ignition occurs [17], and this delay sometimes can be found to be of

the order of 1 second or more, if the temperature cannot reach auto-ignition temperature, the induction time will be infinite, see **Figure 7.2.1**. As to a spontaneous ignition, consider a combustible solid for as shown on the left of **Figure 7.2.2**, this requires energy and materials that are exposed to this energy, volatiles at high temperature and a suitable condition (a period for induction) [17]. Both needs a time before achieving ignition, the former can only require approximately 1 second, whereas for the latter even at a temperature which near its critical (auto-ignition) temperature, the spontaneous ignition within a combustible porous solid (bulk solid, such as milk powder) needs more than one hour (some require several days) to be ignited as the self-heating process of these materials are slow [17], see **Figure 7.2.2** left.

A typical formation of backdraught is like the fire triangle concept but essentially follows a different mechanism. In the previous chapters, it has been demonstrated that the compartment should have experienced at least the steady state burning stage of fire development (the closer to flashover, the easier a backdraught is, but this is not a necessary condition [1]). In **Figure 7.2.2** (right), it shows related elements of development of backdraught, it includes a driven force due to density difference (gravity current). The gravity current is used to accelerate the mixture of hot and cold gases, with the unburned fuel, to achieve a well-mixed condition, which plays a similar role as the 'suitable conditions', with a corresponding period of induction. When a fire source presents, either an electric spark or a high temperature (above the auto-ignition temperature), backdraught occurs [1].

Figure 7.2.2 provides flowcharts for fire and backdraught. Both schemes involve energy to activate an ignition of a fire or a possible backdraught; an auto ignition temperature for a material for a fire, or a critical temperature for a backdraught are required [1]. To date, the suitable conditions of backdraught (apart from the critical unburned gases) has not been well-investigated, so an investigation on the possible delay time is essential as this concerns the safety of firefighters in their day to day work.

For the backdraught phenomenon, the induction period, unlike a typical fire combustion (for either non-piloted or piloted ignition), is the delay time of gas mixing. It has been observed that there is a time delay before a real backdraught occurs, some researchers have tried to describe the reason, however, these

mainly focus on qualitative descriptions [18]. A time of induction has been sometimes described as the time of gravity current reaching the rear wall of fire compartment [15]. I.e. gravity current, driven by density difference of gases to generate a suitable condition for backdraught, determines the delay, so the induction period is linked to the delay of backdraught after a sudden door opening [15].

Most previous backdraught research relied on an ignition source, in fact, compared to a real fire backdraught scenario, there may be two types of backdraught. It cannot make sure that there is always one type of ignition source, heat from either the ambient hot smoke or an electrical spark is possible. In a fire scene, uncertainties exist. However, it does not mean that anticipation of an occurrence of backdraught is not possible. To understand the difference, in Chapter 4, a series of reduced scale backdraught experiments using an electric spark and a hot fire compartment as the ignition sources have been conducted. This revealed that the behaviours of the fire propagations are not the same, the spark can help to generate a backdraught at a lower temperature inside the compartment, i.e. lower than the critical temperature required for non-piloted backdraught events. A delay time of backdraught was also observed and appeared to vary with the ignition sources.

Backdraught can be described as a transformation of typical fire combustion. It occurs under restricted ventilation conditions (almost no fresh air) before door opening. In most cases, backdraught does not occur immediately at the time of door opening or window breaking. A driving force to mix the hot and cold gases is essential, i.e. gravity current. The speed of the gravity current mixing relies on the density difference, a higher temperature inside tends to lead to a shorter time for the front of the gravity current to reach the rear wall of the compartment, see [1].

Based on previous research [1] [3] and observation of fire training centre backdraught demonstrations, in terms of qualitative analysis, classification of backdraught and the required elements are:

- Non-piloted ignition backdraught (see **Figure 7.2.2** right)
 1. Gas mixture: gravity current created by the gas density difference which allows the cold and hot gases to be well-mixed. This takes a

long time. In a fire training shipping container, sometimes it takes up to 40 seconds delay after door opening⁷.

2. Critical temperature: sufficiently high temperature, hot spot is enough. A compartment with high temperature is not required. Take polypropylene (PP) for instance, a temperature above 350°C in fire compartment is enough (for details see Chapter 5), but the value may change with materials.
 3. Enough unburned gases: fire has developed to a steady burning regime; flashover condition is not essential.
- Piloted ignition backdraught
1. Gas mixture: gravity current created by gas density difference, and quicker than those backdraughts which do not have extra hot source, backdraught ignition occurs.
 2. Critical temperature: sufficiently high-temperature hot point but lower than of that needed for non-piloted ignition cases. Although any ignition sources can ignite the unburned fuels inside the fire compartment, a warmer fire compartment is required. Otherwise, this may only lead to fire re-ignition instead of backdraught occurring.
 3. Enough unburned gases: fire has developed to a steady burning regime; flashover condition is not essential.

To summarise, if a door is closed at the time near or after the fire has developed to flashover, assumed the leakage is small to ignore, like modern buildings for energy saving [17], a backdraught may occur. Only two elements related to backdraught, which are 'hot ignition source' and 'gas mixture'. As it is generally impossible to be sure if there is ember or smouldering before door opening, two types of backdraught should be taken into considerations as both are possible, if the room temperature is still sufficiently high, the most important issue is how long until a backdraught will occur?

Until now, there is not a robust method for estimating this delay time, yet this directly impacts on life safety for fire rescuers, as backdraught always occurs at some time after firefighters have opened a fire compartment when conducting fire rescue missions, an over pressure environment of a sudden backdraught may result in difficulties for firefighters escaping from the fire scene, most of the time,

⁷ Video clip observation on YouTube, https://www.youtube.com/watch?v=Et_Y_kZXoQQ

firefighters may be trapped inside or killed. If there is a trend of the delay time, a new tactic for fire fighters could be established. Even though Fleischmann et al. [15] demonstrated time of backdraught can be predicted by gravity current travelling time, their experiments were based on the use of methane fuel, not a typical fuel in fire scenes, also, backdraught in their tests was always piloted. It still needs to be validated the ability of predicting a backdraught using realistic fuels in buildings [4].

Therefore, this chapter aims to investigate the delay time of backdraught using solid fuels based on two different ignition source scenarios, trying to fill the scientific gap.

7.3 Theoretical ignition time of backdraught

To estimate the time delay of backdraught, Fleischmann et al. [15] started a series test with salt-water approach, by changing the concentration of salt water, density also changes (1.003 to 1.101 kg/m³) (for detail see 2.4.1), this can be used to simulate smoke and air mixing during the time of door opening in a fire scene, because densities are direct related to temperature (assuming perfect fluids).

It seems that this model can provide reasonable predictions of the delay time of backdraught, however, it should be noted that methane (CH₄) was used as fuel, so it still need to test if it can be used for a real backdraught scenario. Also, an electrical spark was used as the ignition source in Fleischmann's experiments, an investigation is essential to discover the delay trends if there is no ignition source, such research on the induction period of non-piloted backdraught is still lacking.

7.4 Fire stages with backdraught

The occurrence of backdraught, like in the film of 'backdraft', is unpredictable. It can be triggered at any time when a change of ventilation occurs. (even though some of the fire scenes in the film were scientifically wrong). When a firefighter performs a fire rescue mission, perhaps he/she may know whether the fire has

experienced flashover or not or only at the very early stage of the fire. But it is unknown when, or if, a possible backdraught may occur.

As discussed in Chapter 2, experimental research on backdraught, largely, has not taken fire stages into consideration. For instance, the majority of research projects used gas fuels [3,4,19–23] or liquid materials [18][24] for a specific time of burning and installed an ignition source near the rear wall of the fire compartment. This was a good start to investigate the backdraught phenomenon.

To understand in which fire stages backdraught can occur is crucial for fire authorities to design a proper firefighting tactics. Backdraught is not a typical phenomenon for every fire, so to make sure backdraught will occur, even in fire training centres, fire demonstrators always allow fire to develop to flashover then conduct the door closing procedure. However, this makes a misunderstanding that backdraught can only occur after flashover, if backdraught can be triggered before flashover or in the early stages of fire, it may lead to firefighters at risk when fire rescuing. But, backdraught can happen at early stage of fire as long as the fire was in the steady state burning regime, this means that the hot compartment can provide a suitable environment for pyrolysis, and allows the accumulation of unburned gases into the flammable region [1].

To understand which stages of fire can provide a suitable environment for backdraught, it is essential to study the delay time at different pre-burning times. So that a proper range of estimation may be provided for the fire service. This is one of the aims of this chapter.

7.5 Experimental setup and procedure

7.5.1 Experimental setup

Given that the scale of compartment does not affect the occurrence or behaviour of backdraught [25], a reduced size of fire compartment ($0.8 \times 0.4 \times 0.4$ m) was designed for the whole thesis, the same size ratio as Fleischman's [3], but one third of the size. In this chapter, the aim is to discuss the delay time in different stages of the experimental fires, also how ignition sources may influence the delay time. No modification has been made to the fire compartment, therefore, there is no need to repeat the details of the experimental design here.

There are three removable baffles which may be positioned across the opening of the compartment, to investigate the effects of opening size. In all the experiments described here, the upper two baffles were kept in place, such that the opening was fixed at 0.13 m × 0.4 m wide. Other door opening sizes and configurations will be tested and discussed in the next chapter.

7.5.2 Experimental procedure

In this project, different solid fuels have been used to investigate the relationship between the onset of backdraught with material type, and to determine if the delay time of backdraught is similar when all variables are fixed except fuel. Therefore, results for polypropylene (PP) and high density polyethylene (HDPE) fuels are presented, which may represent plastic products common in our houses.

As aforementioned, the baseline conditions for backdraught to occur require only that a fire has become well established[1], but the conditions of the fire may affect the delay time. A series experiments was designed to observe the changes on the basis of burning time (from ignition to the door is closed).

The fire was initiated using a small quantity (150 ml) of n-heptane (C_7H_{16}) to accelerate the fire, this liquid fuel was consumed in the first five minutes of each test, so it is assumed that negligible quantities of n-heptane remained in the fuel during the periods of door closure, which were generally initiated more than 7 minutes after ignition.

**Figure 7.5.1 The PP fuel
in the fuel tray**

In tests using PP fuel, 300 g of pellets were used as fuel, in the square fuel tray, see **Figure 7.5.1**. If the door was left open, this fire exhibited a ‘steady burning’ phase from about 7 to 12 minutes after ignition, followed by a rapid growth to flashover between 12 and 14 minutes after ignition, and the fuel began to run out about 16 minutes after ignition. The (steady burning) phase is characterised by a gradual and consistent increase in temperature of all thermocouples in the compartment, about 20 °C/min. However, when the fire became oxygen-starved (under-ventilated), the temperature increase rate rose to about 100 °C/min.

In the tests using HDPE fuel, which has a similar heat of combustion to PP, about 300g of short strips of the material (2cm x 10cm) were used as fuel, see **Figure 7.5.2**, in the same pan. The HDPE fuel load generally took longer to become established but exhibited a steady burning phase from about 13 to 18 minutes after ignition, growing to flashover at about 20 to 22 minutes after ignition.

Figure 7.5.2
Photograph of one of
the HDPE fuel strips

The highest temperature was monitored to identify if it was above the critical temperature of backdraught (see Chapter 4), and this reference thermocouple consistently showed the highest temperature reading in all tests, both when the door was open and after it was closed [1].

An electric spark was used for the ignition source. Because of the fact that there is about a 4 second delay between initiating the spark device and the actual spark occurring, a timer was used to make sure that the spark was active before

introducing the opening procedure in every test. This was also confirmed by listening for the sound of the spark (it is obvious to hear the sound even though there are two layers of vermiculite boards separated the inner and the outer space). In addition, a camera (29 frames per second) was put in front of the front door with 0.8 m distance, monitored frame by frame, monitoring the time of door opening. To minimise the uncertainties of the time of the door opening, it was decided that the door was considered fully opened when the edge of the door moved to the edge of the full opening (the moved door touched the inner side of the insulating boards in the compartment).

Two types of ignition source are compared in this chapter, but before data analysis, there is a need to define the conditions of every test, which includes:

- Non-piloted ignition
 1. a backdraught event (sudden ignition of compartment gases resulting in a significant fireball emerging from the compartment opening),
 2. no reignition or backdraught.
- Piloted ignition
 1. a backdraught event (sudden ignition of compartment gases resulting in a significant fireball emerging from the compartment opening),
 2. a reignition event (sudden ignition of compartment gases within the compartment, and pool fire re-established, but no significant external flaming or fireball)
 3. no reignition or backdraught.

Reignition events only happened in the tests with a spark. The primary objective of this chapter is not to identify the conditions required to allow the establishment of a backdraught. Rather to investigate the time delay of backdraught/ re-ignition. The result of this chapter may be useful for both fire regulation officers and onsite firefighters. During fire-fighting, doors will be opened. This chapter will help inform fire-fighters when backdraught events are unlikely, and how long backdraught delays could be, depending on the fire conditions.

In every experiment that resulted in no reignition or backdraught, it was found that there was remaining unburned fuel in the fuel tray (The fuel was still in liquid form at the time of the door just opening, but gradually became solid again with the cooling of temperature). That is to say, the extinguishment of the experiment was not due to the availability of fuel, but due to other factors.

Figure 7.5.3 Temperature variations during a typical test with PP fuel, door closed after near flashover, w/o spark. Plots show maximum-recorded compartment temperature, average compartment temperature and minimum recorded compartment temperature.

Figure 7.5.3 demonstrates the typical temperature variations of this experimental design. The three curves represent the maximum, averaged, and the lowest temperature during the test. It can be seen that there is a sudden drop of temperature at 7 minutes after burning (especially for the maximum temperature), this has been investigated, and is due to the depletion of heptane. From 7 to 12 minutes there is a stable temperature increase, with a similar slope for these three temperature values. From video observation, the smoke neutral plane was kept the same height, which implies the fire was not yet ventilation restricted. The fire was allowed to free burn until 14 minutes, then the door was shut for 2 minutes. The temperature begins to decrease. When the maximum temperature in the compartment reduced to 350°C, the door was opened, and a few seconds later, backdraught occurred.

In every backdraught experiment in the previous chapters, it was observed that there always was a delay, none of them led to backdraught immediately. As shown

earlier, flashover is not essential for backdraught to occur but a period burning of about 10 minutes is required before door closure for this fire [1].

In Table 7.5.1, all the experiments experienced backdraught, five separated groups are used to indicate different fire conditions and fuels. Only backdraught or reignition were recorded in this series, those which failed to lead to backdraught or reignition are beyond the interest here and will be discussed in other chapters. A series experiments using PP fuel and HDPE have been carried out to map out the conditions of delay time, test scheme details can be seen in Chapter 4.

Table 7.5.1 Test number on different fire conditions and fuels

	Before flashover	After flashover
Non-piloted (PP)	27 tests	22 tests
Non-piloted (HDPE)		6 tests
Piloted ignition (PP)	21 tests	12 tests

7.6 Result

7.6.1 Testing for backdraught with no pilot spark

7.6.1.1 Delay time of backdraught with door closure

A total 49 tests with backdraught outcome are analysed here. Backdraught could be triggered at a time of door closing from less than 40 seconds to more than 5 minutes, which implies that even if there was no air supply after the door was shut for a considerably long time in the small fire compartment, a backdraught is still able to occur, see **Figure 7.6.1**.

In **Figure 7.6.1**, the delay time of backdraught is related to the time of the door closure; the longer the closure, the delay time will generally last longer. Delay time ranges from about 2 to 12 seconds and depends on the time of closure. Some uncertainty does exist in this figure, however, it demonstrates a general trend in non-piloted ignition backdraught events. A correlation between time of closure and delay time of backdraught is obtained, even before the stage of the fire before door opening is considered (many experiments in this figure had not yet experienced flashover).

This relationship may be useful for firefighters as for most of the time it is not easy to know a temperature distribution in a fire compartment without a door breaking or opening. At the same time, it would still be needed to check if the highest temperature in the compartment is higher than the critical temperature required for backdraught to occur. But it should be noted that the experimental compartment was about 1/8 of a full-scale room, the theoretical delay time of backdraught may last longer, more discussion of this is in section 7.7.2.

Figure 7.6.1 Duration of closure vs. delay time of backdraught

7.6.1.2 Delay time of backdraught with temperature

In this section, two test series are discussed. PP was used to test all the possibility of backdraught across a range of burning times before the door was opened, from 10 minutes of burning to after flashover. A short series of tests using HDPE was also used to compare the different delay times of other materials as most real fire backdraughts are observed after the fire had developed to the fully-development stage. Door opening temperatures ranging from 440°C to 340°C were tested with no flashover and no pilot spark.

All the temperatures quoted in this study (except section 7.5.2) refer to the maximum temperature in the compartment at the time of the door opening.

Figure 7.6.2 shows that the delay time varies with the temperature at the time of door opening. Also, it shows the delay times for various pre-burn times (including 10, 11, 12, 13, and 14 minutes of burning before the door closing). Tests which experienced flashover were not included in this figure, these will be discussed later.

seconds of the door closure was required to diminish the temperature to the similar value.

The experiments with a longer delay time, in general, had experienced a longer time of door closure, which means that the hot smoke in the fire compartment tended to become more stable. This can be observed in the temperature data from different layers and different locations, the temperature difference between layers (different heights of thermocouples) became less with longer times door closure. Hence, a longer waiting time for backdraught would be expected.

When considering the tests after flashover, the result showed that the time needed for backdraught were in the range of 3 to 12 seconds using PP (diamond markers), as to HDPE, the range was from 1.6 to 30 seconds (star marker), see **Figure 7.6.3**.

In **Figure 7.6.3** the solid diamonds represent tests with PP, the rest used HDPE as the fuel. For both fuels, when the temperature (TC-1003) was higher, the less delay time of backdraught was generally observed.

Figure 7.6.3 Delay time of backdraught of different temperature w/o spark (post-flashover), using PP and HDPE as fuel

Tests that used HDPE as fuel show a different behaviour, the delay time of backdraught was about 2.8 seconds when the temperature were higher than 350 °C, but when temperature decreased 20°C and 30°C (compared with 350°C), the delay time considerably increased, The HDPE had a different outcome from the

PP. The sample with lower temperatures exhibited much longer time for backdraught to occur.

7.6.2 Testing for backdraught with pilot spark

Here, the aim is to discover what a role of a spark ignition source plays for backdraught occurring. Three groups of tests were conducted at different burning times, zone A (10 to 12 minutes), zone B (13 to 14 minutes), and zone C (after flashover) [1], see **Figure 7.6.4**.

Figure 7.6.4 Delay time with spark and compared with theoretical delay time (using PP as fuel)

The time of closure in this research project were in the range of 52 to 1649 seconds, but the delay times were extremely similar. For example, from the temperature decreased at the time of door closing to 270°C, the fire compartment had experienced 13.5 minutes temperature cool down, the delay time was about 2 seconds. As two layers of vermiculite boards were used, it took more than 27 minutes to decrease the temperature to about 212 °C.

In **Figure 7.6.4**, it can be seen that the delay time of backdraught did not change significantly with stages of the fire, but only with temperature. Largely, the lower temperature showed a longer time delay, but only with a slight difference. As Fleischmann's experiments relied on a spark to ignite backdraught, therefore, the empirical theory given by salt water for the delay time of backdraught may be used.

To compare with the theoretically expected value of Fleischmann et al. [15], the geometry of the opening should be taken into consideration, as the normalised velocity will be different for different geometries of the opening. This can be used to predict the possible traveling time of the gravity current from the opening to the rear wall of the fire compartment.

The opening geometry for this research was the shape of a slot, and the normalised velocity in Fleischmann et al.'s research was 0.32 [15]. The curve of the expected delay time can be seen in the left curve in **Figure 7.6.4**. However, this model slightly underestimates the delay time. When the value for the geometry of a window is taken, giving a normalised velocity of 0.22, the curve fits well with the experimental results (see the right curve in the same figure).

It should be noted that all temperatures quoted are the maxima observed in each test, using TC-1003. This is not the average compartment temperature or even a characteristic temperature. In the early stages of the fire, or when there has been a short duration of door closure, the temperature gradient is large and makes the smoke movement in the fire compartment very fast and unstable. Using this temperature may underestimate the delay time of backdraught because the average temperature is always lower than the highest temperature.

7.7 Discussion

7.7.1 Tests without pilot spark

The tests have clearly identified the delay times before a backdraught, triggered by both non-piloted and piloted ignition. In practice, if the time of door closure is known, a possible backdraught delay time can be predicted, there is no need to know which stages the fire was in before door closure.

A clear trend is that the delay is dependent on how hot the fire compartment is. The highest temperature (30cm above the fuel tray) was used to decide when a door should be opened in each experiment. For example, when the door was opened at 350°C, the delay ranged from 4 to 10.5 seconds, the longer delays corresponding to longer pre-burn times, see **Figure 7.6.2**. The lowest temperature in the compartment for the cases with 10 minutes pre-burning time could be lower than 150°C. As the fire developed towards under-ventilated status (lower neutral

plane, more than 12 minutes into the fire), the temperature difference between the hottest and coldest parts of the compartment reduced to only about 100 °C. This instability (or non-uniformity of density) of hot smoke leads to a quicker mixing of hot and inflowing cold gases because the smoke in the fire compartment was not well-stirred, the steeper density gradient increases the mixing process.

The chance of backdraught increases after the fire has grown to flashover because of the accumulation of unburned gases before door closure. The test results show that there are clear correlations between the delay time and temperature for both PP and HDPE fuels, see **Figure 7.7.1**.

Figure 7.7.1 Correlation between reciprocal delay time of backdraught and temperature (PP (diamond markers) and HDPE (crosses markers))

In **Figure 7.7.1**, the linear relationship can provide the information for when a backdraught will occur for a given temperature for a specific material. The value range for the X-axis is not the same for these two materials; the ranges are 0.08 to 0.36 for PP and 0.03 to 0.6 for HDPE. The shortest delay time of backdraught is not limited to the maximum values (x-axis) in **Figure 7.7.1** but was very close for PP, the reason is that the time of door closure for the highest temperature of PP was only 32 seconds, uncertainties may appear as the fire may still not extinguished if the time of door closure is too short. No experiment with a short period of the door closure using HDPE was conducted; the shortest time of door closure for the HDPE tests was 209s. Experiments with shorter door closure time were not required as the delay time when using HDPE was almost constant (1.5

seconds), similar to the time of the gravity current travelling to the rear wall of the compartment; even when the time of closure was more than 200 seconds.

As for HDPE, the time delay only exhibited a small difference when the temperature was higher than approximately 350 °C, with a tiny range from 1.6 to 2.6 seconds, even with a wider range of time of door closure, from 209 to 328 seconds. In **Figure 7.6.3**, it shows that different materials tend towards different lowest delay times at higher temperatures, about 3 seconds for PP and 2 seconds for HDPE. The delay times for PP are consistently about 50% longer than those of HDPE.

Also, trends of these two materials appear to have different intercepts on the y-axis, 287°C for PP and 312 °C for HDPE. However, these lines can never be extrapolated to cut the y-axis because the lowest point in each case represents the “critical temperature” for non-piloted ignition of these two materials. Below these points, backdraught is not possible without an extra ignition source. However, it should be noted that the times shown in this figure are only applicable for this specific experimental compartment; a larger compartment would lead to a longer time delay for backdraught.

7.7.2 Tests with pilot spark

The test series has shown that a pilot spark can considerably shorten the backdraught delay time, for instance, when the door was closed after flashover, there was about 10 seconds delay after the door re-opening when no pilot was used, but when the spark was on, the delay time was only about 2 seconds, regardless of the stage of the fire before the door was closed.

This shows a similar trend to the empirical theory proposed by Fleischmann et al., the delay time of backdraught only varies with temperature, geometry of the opening and distance between the opening and the location of spark. It is no surprise that the delay times, in general, were similar irrespective of which stage the fire was at when the door was closed.

The empirical theory appears to slightly underestimate the experimental values. A possible reason for this is that although a similar opening geometry (slot) was used, the location of the slot was different in their research compared to this research. In Fleischman’s experiment, the opening was set at the middle height of

the side, in the experiments in this project the opening was near the bottom. Therefore, the flow/mixing characteristics are not the same.

However, this still demonstrates an acceptable result; a further investigation of parameters involved may provide more accuracy. In addition, it implies that piloted backdraught does not necessarily require a well-mixed mixture condition between the unburned smoke and incoming fresh air. For instance, the combustion can be triggered by any ignition source when the interface of the hot smoke and cold fresh air arrives at the location of the spark apparatus in this experimental fire compartment.

The experimental finding is, of course, only based on a single lab size backdraught experiment ($0.8 \times 0.4 \times 0.4$ m), if this was extrapolated to a full-scale compartment (say $4 \times 2 \times 2$ m), it would make a huge difference to the delay time of backdraught (assume the temperature distribution of each layer is the same as the compartment used in this thesis). Still, even in a large compartment, the time required for backdraught with an extra ignition source is still considerably quicker than the time required for non-piloted ignition backdraughts in the experimental fire of this research, see **Figure 7.7.2**.

Figure 7.7.2 Theoretical delay time of backdraught, PP as fuel (left: $0.8 \times 0.4 \times 0.4$ m; right: full $4 \times 2 \times 2$ m)

The black curve is the same as the black curve shown in **Figure 7.6.4**, generated using the empirical equation of Fleischmann's equation [3] for the gravity current time (obtaining the velocity of the gravity current, then divided by the distance of the door to the rear wall of the compartment, i.e. distance/velocity).

The dashed red curve was generated according to the same equation, only enlarging the distance from 0.8m to 4m.

In the gas phase, there is no need to have a temperature higher than the 'critical temperature' inside the fire compartment. An unexpected burst of energy, like a short circuit on the route of the gravity current flow path, may lead to backdraught. Unlike the typical backdraught abovementioned, this backdraught would start at the point at which the ignition source was located and would ignite the unburned smoke, then propagate the fire to the outside of the room. Well-mixed combustion is not required, although there must be some degree of pre-mixing before ignition. Only an ignition source (any form of energy supply, really), on the edge of the hot and cold gases, is needed.

7.8 Involved factors to the occurrence of backdraught: Temperature, ignition source and mixture conditions

In section 7.7.1, it was demonstrated that the delay time of backdraught may be predicted if knowing what kind of materials are in the fire compartment. Also, it shows there appears to be a linear correction between delay time and temperature. Thus, it would be of interest to investigate what was actually happening during the time of the door closure in the experiments.

Previous research [1], chapter 4, shows the different characteristics of backdraught on the basis of different ignition sources. In general, if a compartment has no ignition source (apart from the hot room temperature itself), the delay time of backdraught is more extended than in scenarios where there is a spark, ember or similar ignition source.

Also, when there is an ignition source, the delay time of backdraught occurring is approximately equal to the travelling time of the interface between the lower and higher density gases (hot smoke and cold fresh air) travelling to the place where the spark is installed. The time delay is dependent on the gravity current time only, the time of pre-burning (before the door was closed) has no influence on how long the delay time will be.

The maximum temperature is one of the factors which influences the time of backdraught occurrence. It is observed that the higher the maximum temperature

(T_{max}) is, the quicker backdraught is. In addition, a linear relationship appears to exist between the square root of temperature difference across the room and the delay time (by reciprocal form, s^{-1}), see **Figure 7.8.1**.

Figure 7.8.1 Correlation between reciprocal delay time of backdraught and temperature

The equations for these two materials are:

- $y = 0.7062x + 1$ for PP, and
- $y = 0.1959x + 1$ for HDPE

The data analysis yielded trendlines which crossed the y axis very close to $y = 1$. Given this, it was thought best to force these trendlines to cut the y axis at exactly $y = 1$, for clarity, thus the R^2 values are slightly different to those in **Figure 7.7.1**.

Therefore, $(Normalised\ temperature - 1) \times t_{travel} \cong const.$, where T_{max} is the highest observed temperature, T_a is the room temperature, assuming 293 K (20 °C) for all the experiments, t_{travel} is the delay time of backdraught.

The result provides (a) a predictable approach to justify the delay time in certain regions, and also implies (b) the delay time is directly related to the time of door closure, as the value of normalised temperature decreases with a longer door closure.

If revisiting the delay time and compare with the time of door closure, two different trends are evident; one where the delay time does not vary with door closure time, and the other where there is a linear trend with increasing delay time with increase of door closure time, see **Figure 7.8.2**. If extrapolating the linear 'stage II' trend to the origin, the junction dividing these clustered groups appears to be about 100s of door closure.

Figure 7.8.2 General temperature change (maximum (red), minimum (green) and averaged (black) value by 24 TCs)

In general, at the time of door closure there is a huge temperature distribution in the compartment (350 °C difference or even more between the highest and lowest observed temperature), this difference decreases with time. After about 100s the temperature difference in the compartment is lower than 50°C. This appears to correspond with the time at which the temperature changes in the compartment have converged to the same rate of decay, see **Figure 7.8.3**. It seems that a rapid heat transfer mixing process occurs immediately after the time of door closing. As the door is closed during the time of gas mixing, a way to understand the stability of the hot smoke is to observe the maximum, minimum and average temperature change versus time.

In **Figure 7.8.3**, it can be seen that at the beginning of the closure (about 16.2 min), the temperatures suddenly changed dramatically but in different ways. The TC with minimum temperature (TC-1031) in the compartment exhibited a rising temperature immediately after the door closure. The reason is that this TC is low in the compartment and in the inflowing air, so the temperature is generally lower than the rest of the TCs. Therefore, when the door is closed, the inflowing (cool) air is blocked and its temperature is heated up by the hot gases in the fire compartment. The temperature of TC-1031 increased for approximately 1 min before it started to decrease.

Figure 7.8.3 Backdraught delay time vs time of door closure (after flashover, PP as the fuel)

The average temperature in the compartment dropped more than $10\text{ }^{\circ}\text{C}/\text{sec}$ immediately after door closure because there was no air to sustain the combustion (i.e. under-ventilated combustion) due to door closure. It can be seen that 100 seconds (approximately) after door closure, there is a boundary between stage I and II in **Figure 7.8.3**, it is found that around the same period of door closing (100 seconds), the temperature change rates converged to become almost identical, which means after that time the smoke inside any location was only losing heat through the insulating boards to outside; all internal heat transfer processes had reached a steady state. Also, all the three values converged to about $1\text{ }^{\circ}\text{C}/\text{sec}$ (releasing energy) in stage I, it provides an evidence showing that a dramatic mixing of gases happened during this time, but that the mixing was largely complete before stage II. In stage II, the temperature change rates continue to slow down, e.g. 4 minutes after door closing, the average speed of temperature change was nearly constant at about $0.25\text{ }^{\circ}\text{C}/\text{sec}$. This suggests that a longer time of door closure leads to more stable conditions.

Figure 7.8.4 Fuel mass changes with time of door closure

As to the mass loss, in **Figure 7.8.4**, it is observed the mass loss in stage I was approximately 25 g (8 % of the total PP), reducing to 8 g mass loss in stage II, suggesting slow thermal decomposition. It shows that even though there was not enough fresh air to sustain burning, the retained heat still provides energy for the pyrolysis decomposition during long door closures; longer door closures lead to more pyrolysis products in the compartment atmosphere.

Based on the aforementioned investigation, a qualitative description of possible conditions of the confined fire compartment during the period of door closure can be summarised as below,

Stage I: Mixing period. In this stage, the fire transitions from a ventilation-controlled state to a completely sealed condition (probably still some smoke leaking from the edge of the front door). The temperature distribution presents huge thermal instability, and the higher temperature gases exhibit higher velocities. This enhances the gas mixing in the whole compartment. Although there is heat loss through the walls, ceiling and floor to outside of the compartment, the changes of the heat and gas mixing in the compartment dominates this stage. In addition, incomplete combustion will continue until the useful oxygen is consumed, and pyrolysis processes will continue, which makes the smoke layer become fuel rich, containing an accumulation of unburned flammable smoke (which may contain particles, aerosols, pyrolyzates, toxic species, etc.) dropping below the location of the neutral plane during the time of door closure because of the pyrolysis processes during the time of the door closure, see **Figure 7.8.5**.

Figure 7.8.5 Mixing of gases (stage I)

Stage II: Stable period. After some time, there is a transition period. The smoke becomes more stable because of the fire has gone out, however, there is still some pyrolysis of the fuel, albeit at a slower speed. If neglecting the leakage, the smoke layer will become thicker and richer in fuel. In this stage, the gas flow almost keeps constant because the driving force of the flow is the temperature difference (density difference) across the height and this is diminishing. The smoke may stratify slightly, groups of similar temperature gas particles tend to accumulate at the same height and continue to release heat to the adjacent areas, heat loss dominates this stage, releasing energy through the fire compartment to ambient space, see **Figure 7.8.6**.

Figure 7.8.6 Stable period of smoke mixture (stage II)

These different stages (stage I, II) can provide the explanations why the delay time seems considerably different on the basis of the initial fire condition (same fuel load, location, and reaching flashover, with external flaming) before door closure. A short time of door closing can trigger a quick response backdraught event if the temperature is above the temperature required (i.e. for PP, about 350 °C), the instability of temperature distributions inside leads to a rapid gas mixing. And if the compartment has experienced a longer time of door closure, e.g. more than 4 minutes, the delay time of backdraught will be three times longer (**Figure 7.8.3**). This demonstrates that a proper mixing of fresh air and hot smoke is required to make a backdraught occur. Also, when the compartment has

experienced an extremely long time of door closure, it may lead to a smoke stratification as the temperature gradient driven mixing slows down.

It is crucial if a correlation can be discovered to predict the delay time of backdraught. If a pilot spark is present, the time is almost the same. However, in non-piloted ignition backdraught conditions, the correlation would need to consider the thermal gradients at the time of closing, the fuel pyrolysis process (different for each fuel) which affects the smoke flow conditions, and the mixing conditions. Each of these needs further exploration. Therefore, the delay time can only rely for now on the empirical correlation investigated in the experimental fire.

7.9 Conclusion and future work

This chapter compared different scenarios of fire backdraught, to discover how the fuel, fire stage, and presence of an ignition source affect the delay time after door opening when a backdraught is going to happen.

If the time of door closure is known, a possible backdraught delay time can be predicted, as a linear correlation exists between delay time and door closure, see **Figure 7.7.1**.

A backdraught, which includes complex physical and chemical reactions, is not as the same as regular fuel burning. In general, a higher temperature can lead to a quicker backdraught occurrence, for both ignition source, non-piloted or piloted ignition.

The delay time is observed for all backdraught or reignition results, meaning that this kind of ignition requires a time of 'induction', for instance, the formation of a suitable mixture. For the tests conducted after flashover had occurred, the delay time can be correlated well to the observed temperature.

In **Figure 7.7.1**, it can be seen that these two materials demonstrate different results, but both exhibit clear linear relationships for delay time of backdraught with temperature. This varies with the fuel properties, but for fires with the same fuel, which have already transitioned to flashover, the delay time of backdraught can be calculated if the highest temperature in the fire compartment is known.

To conclude,

- **Fire environments for non-piloted ignition and piloted ignition are different.** Non-piloted ignition requires a longer time to reach a condition that allows a backdraught to occur, which means longer delay times for backdraught. For piloted scenarios, if the gravity current reaches the pilot, a backdraught will be initiated instantly.
- **A prediction of delay time of backdraught is possible.** In a compartment fire with no extra ignition source apart from hot environment, the delay time can be derived from information about the highest temperature, the duration of pre-burning and the nature of the fuel. On the other hand, if a pilot is present, the time to backdraught can be obtained based on Fleischmann's empirical correlation. A well-mixed condition is not required, it only depends on the highest temperature, the opening configurations, and the distance between the opening and the spark.

It should be noted that all the conclusions above were based on lab scale tests using PP and HDPE only, a small-scale salt-water experiment can help to identify a suitable value for the normalised velocity for both numerical studies (modelling) and experimental research.

The delay time increased with the extended time of door closing. In a fire scene, a longer time delay causes more backdraught risk to fire-fighters. Extreme care should be taken when the compartment temperature is close to the 'critical temperature'.

As the compartment geometries in real fires may be unknown, it would be of interest to investigate if a relationship exists between the sizes of opening, and the compartment geometries under the same burning conditions before the door is closed, and it is one of the aims of this research. This will be discussed in the next chapter.

Future research needs to focus on materials that are commonly used to establish a database where a reasonable region of time delay can be provided for the use of the fire service. In addition, it is essential to test if the delay time of backdraught for pilot ignition is independent of materials, a generic approach may be built up to describe the safety waiting time before fire intervention.

7.10 References

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Chapter 8. Compartment size, opening geometry, and the onset of backdraught

Summary

From previous chapters, it was found that the closer the initial fire gets to flashover, before the door is closed, the longer the delay time of backdraught, after the door is opened. This will be the worst scenario for firefighters when tackling fire emergencies. As shown previously, the “critical temperature” is about 350 °C for the experimental fire to achieve backdraught conditions. In these tests, a selected characteristic temperature, 370 °C, was used to determine the time of door opening.

The size of the compartment, the opening size, and the type of ignition source (non-piloted ignition or piloted ignition) were varied to investigate the impact of these factors on the delay time of backdraught and the behaviour of the backdraught. Results show that the delay time of backdraught can be predicted, if the size of the opening, the compartment, and the source of ignition are known.

Also, it is found that the delay time of backdraught is related to the opening size of the compartment. Furthermore, whether an extra ignition source exists inside contributes to different types of backdraught; a suitable mixture is required for non-piloted ignition backdraught; while for backdraught with a pilot spark, the time needed is simply the gravity current travel time to the ignition source. The former relies on a volumetric relationship, while the latter relies on a distance relationship.

8.1 Introduction

In a fire scene, firefighters are the people who conduct the fire rescues when residents need to escape from buildings. To ensure their safety, firefighting strategies and tactics are provided in guidelines by the authorities concerned, then commanders apply it to tackle the fire. However, a possible backdraught condition using realistic fuels has never been described quantitatively due to lack of relevant scientific data. This means firefighters always need to rely on their own experience or their training to judge if a backdraught may occur.

Fleischmann et al. [1] started their pioneering research on backdraught two decades ago to observe the behaviour of backdraught. Weng and Fan [2][3] followed up the research on backdraught using methane as the fuel, and conducted a series of reduced scale ($1.2 \times 0.6 \times 0.6\text{m}$) backdraught tests to provide more information on the backdraught phenomenon and compared this with Fleischmann's findings. It was found that 9.8% of unburned fuel, is one of the critical factors for the occurrence of backdraught, this is close to Fleischmann's conclusion, even though they used half of the compartment size compared to Fleischmann's, but it should be noted that the values also changed with opening geometries [4]. Therefore, it is not easy to apply these findings to a normal fire scene, as critical gas concentrations will change with location. Also, the studies used methane, which is not a common material/ fuel found in fire scenes.

In fact, firefighters are always forced to enter fire scenes unless conditions that are described as dangerous in the firefighting guidelines are identified. Because there is a lack of full understanding of backdraught, only qualitative descriptions exist to provide guidance for them. As shown in the previous chapter, there is always a time delay for backdraught after the door/ window opens. Fire-fighters' knowledge of this delay time may reduce the possibility of tragedy caused by backdraught. Also Fleischmann et al. [5] found it is related to the gravity current travelling to the heat source near the opposite part of the opening, a driving force to mix cold and hot gases. If a sudden backdraught occurs, firefighters may probably be trapped or die as they may have already entered fire compartment to tackle with the fire.

A crucial issue is how to predict the time delay before backdraught occurs. Previous research [6–13] has focused on numerical studies of backdraught, to predict the formation of backdraught, the time delay, and provided estimations on

the basis of methane fuel and an electric spark as the ignition source. Methane is commonly used in backdraught research, as it provides an understandable mechanism of backdraught, but is still not applicable to real fires because of the ignitable nature of methane at room temperature. Realistic materials need to be used to broaden our understanding of backdraught [3].

In chapter 4 of this thesis, solid polypropylene was used as the fuel, which is more like materials used in buildings, and temperature was identified as one of the critical factors that affect the occurrence of backdraught. In addition, the presence of an ignition source changes the behaviour of backdraught; it can occur at lower temperatures than those required for non-piloted ignition backdraught. Also, the closer to flashover conditions the fire gets before it becomes starved of oxygen, the more likely it is that a backdraught could occur if the maximum temperature is above the critical temperature, and there will be a longer waiting time before the backdraught occurs. So, this condition may be the worst scenario for the experimental fire before door opening.

Given that there has been no systematic research on the delay time of backdraught using solids fuel to date, it is essential to carry out research on backdraught delay time using a quantitative approach.

This chapter aims to investigate the delay time in relation to the opening geometry, compartment size, and types of ignition sources, to show how the impacts are on various fire scenarios.

8.2 Experimental design and procedure

8.2.1 Setup of the fire compartment

In this research, the compartment is based on the same ratio of Fleischmann's [2][5], but smaller, as the occurrence of backdraught is not dependent on the scale of the fire compartment [14]. There is no need to repeat the apparatus description of the fire compartment in this chapter. This section only discusses the reasons and purpose of the differences from the original experimental design used in this part of the study.

The purpose of this chapter is to discover how the compartment size and opening size influence the delay time of backdraught, based on tests with and without ignition sources. In order to reduce the cost, a new fire compartment with a smaller size was not required. An easy way to change the volume of the chamber is by installing insulation boards inside the compartment, thereby changing its width.

Figure 8.2.1 demonstrates that the TC trees were installed vertically, which means that if there was to be a horizontal compartmentation, a reinstallation of the TCs from the sidewalls of the compartment would have been needed. Thus, for convenience, these tests only installed boards attached to the sidewalls, and the effect of the changes of the height of the chamber is outside the scope of this thesis. Further experimental investigation of this will be discussed in the future.

Figure 8.2.1 Locations of TC trees in unmodified compartment. Left, top view; right, front view

8.2.2 Geometries of compartment

Three sizes of compartment have been used to investigate the influence of width on the behaviour of backdraught as well the delay time. The way to shorten the width of the compartment is to put one more layer of vermiculite boards (25mm) (working temperature 1,100 °C) on each side wall, 2 more layers layer of vermiculite boards (25mm×2) and one layer of a non-combustible board (FireFree Sandiboard 850, working temperature 1,000 °C) (22mm) to achieve the new compartmentation, see **Figure 8.2.2**.

Figure 8.2.2 Compartment sizes of experiments

Figure 8.2.3 Testing opening geometries with different compartment sizes (1/3 opening height)

Some of the experiments were designed with a limited opening, this is used to observe if there is a limitation of opening sizes required to trigger a backdraught. The variation of opening sizes is shown in **Figure 8.2.3**.

Figure 8.2.4 Testing opening geometries (2/3 opening height)

The largest opening area in the research was about 0.053 m^2 . The aspect ratios are 0.4m (width) $\times$ 0.13 m (height) and 0.2m (width) $\times$ 0.26 m (height) for the single and double height of the opening, respectively. This can be seen in **Figure 8.2.3** and **Figure 8.2.4**, both are on the left side of the figures. A series of experiments using a double height opening were conducted to observe the behaviour of backdraught in these. This is to compare the delay time, behaviour of backdraught if the opening area is similar but the shape is different, see **Figure 8.2.4**.

8.2.3 Experimental procedure

The aim of this research is to understand the delay time of backdraught under a severe fire scenario. As mentioned above, the longest delay time occurs in the cases which have experienced flashover and waited for 4 minutes or more before opening the door. This was about 10 seconds in average in the $0.8 \text{ m} \times 0.4 \text{ m} \times 0.4 \text{ m}$ fire compartment. If a similar fire happened in a typical fire compartment (at least 5 times larger than this one), firefighters who are not aware of it may be faced with a backdraught, and they may be trapped in the fire scene because of a longer delay time expected before it occurs, see discussions in Chapters 2 and 7.

The main object of this part of the research is to identify the delay time of backdraught in various conditions (compartment geometries, opening sizes, and ignition sources).

To simulate a typical backdraught condition, a solid fuel was used as the fire source. Following the previous research, 300 g of PP with 150 ml of n-Heptane was sufficient to develop the fire to flashover, for details see Chapter 4 [15]. The difference here is the sizes of the compartment and the door opening.

To make sure backdraught is going to occur in the testing, two important criteria include,

- a. **Develop the fire to flashover condition.** It has been found that backdraught does not require the occurrence of flashover, but is more likely to happen following flashover [15] as this is related to a ventilation-controlled fire condition, this allows more accumulation of unburned gases due to lack of oxygen to complete the burning process.
- b. **A certain temperature required.** It may also be described as the 'non-piloted ignition temperature' for backdraught. The energy source plays a role in initiating backdraught, especially for an environment without an extra ignition source. This temperature is about 350 °C for PP, see chapter 4 [15]. The smoke composition of the compartment space is not like a pure material or a compound, on the contrary, it is very complicated. It may include many organic compounds, as discussed in chapter 6. It should be noted that the driving force to initiate backdraught can be either a specific temperature or a localised high temperature. However, there is no robust evidence yet to prove which one is the driving energy for backdraught to occur, more investigation / experiments will be required.

In terms of the definition of backdraught, it is taken to be observing fast flames emerging from the opening [16]. The reason is that in our experiments, different ignition sources show different behaviour/ characteristics of backdraught.

For those experiments without a spark apparatus as the ignition source, to judge if there is a backdraught is very intuitive, only need to observe the opening of the compartment to see whether a visible (an external) flame comes through the opening or not. There are only two results, backdraught or fire extinction (no backdraught).

However, a pilot spark changes the behaviour of the system. This can be seen in chapter 4, **Figure 4.3.5**. In some of our experiments, the spark reignited the unburned smoke then ignited the fuel in the fuel container without an external fireball being observed. From video observation, the fuel re-ignition did not generate a sudden or quick pressure release; so, there was no visible external flame through the front opening. Hence, this type of the result cannot be called a backdraught, so the term of fire re-ignition is used to describe it.

In this research, the judgment only relies on a qualitative method, in future research, it would be useful to test the minimum pressure (the boundary) required to classify whether it is backdraught or re-ignition, i.e. explore the boundary line between backdraught or fire re-ignition.

As to temperature, one TC (TC-1003) always gave the maximum temperature among the 24 TCs, and was used to monitor the temperature. To reduce the variables in these experiments, 370 °C was selected as the characteristic temperature for all these tests.

Also, to make sure the door is open to the correct location, a marker used by either red pen or black tape was used to help identify the position because the sliding door slides to the side of the compartment. It is dangerous and inconvenient if checking the location in front of the door.

8.3 Results

In total, 43 experiments were conducted to investigate backdraught delay time under different opening geometries, compartment sizes and types of ignition source. TC-1003 was used as an indicator to determine when to open the door (the maximum temperature among TCs) with a range of $370 \pm 3^\circ\text{C}$. The overall test results can be seen in **Figure 8.3.1**, including those tests led to fire extinguishment. In **Figure 8.3.1**, triangles mean those experiments without the spark, diamonds represent experiments with the spark as the extra ignition source; experiments with a double opening height are shown in squares. Empty / half transparent markers show that the experiments did reignite but without a sudden explosive fireball (which means a puff of smoke emerged, followed by fire reignition).

Those tests which did not result in either backdraught or fire re-ignition were tests when the opening height was only 1/3 of the total height of the compartment, and those with the smallest opening compared to the rest of the experiments. Even under the same conditions (experienced flashover condition before the door closing, the similar temperature (TC-1003), about 370 °C) to control to open the door, when the ratio A_o (the opening size, m^2)/ V_c (the compartment size, m^3) was less than 0.05, the fire extinguished. As for experiments with the double height of opening, even when the ratio A_o/V_c was much lower than 0.05, backdraught was

Figure 8.3.1 Opening size to compartment volume vs delay time of backdraught

still observed, this suggests that the height of the opening influences the delay time and whether backdraught will be initiated.

In general, the smaller the opening, the longer the waiting time of backdraught; the larger the opening, the quicker a backdraught can be triggered. It is clear that the diamonds (spark ignition) are consistently below the triangles (no spark); the squares do not correlate with the groups aforementioned (i.e. the diamonds and triangles). Hence, some analysis will need carried out to identify different trends among these different sets of data.

It is tried to use reciprocal time of backdraught with correlation to the Ao/V_c to see if clear trends appear, see **Figure 8.3.2**. Clear linear trends are evident in experiments without the extra spark (i.e. Figure 8.3.2 (a) and (c)), for both different heights of opening. But there is no trend observed when the extra ignition source is present, see **Figure 8.3.2** (b), which implies there is some other relationship in this case between delay and geometry that is not volumetric.

It should be noted that the full opening in different compartment sizes results in a similar delay time, about 2 second, but shows as a wide range of 3 data points (see the red circle) in the figure; this shows some uncertainties because of the delay time was too short and the time was determined by video observation (see Chapter 7 for the specific method of obtaining the period of the delay time), future experiments in a larger scale may be useful to improve the uncertainty here. More analysis will be conducted in the following sections.

Figure 8.3.2 Opening size to compartment volume vs reciprocal delay time of backdraught (a) w/o spark (1/3 opening height) ; (b) with spark (1/3 opening height); (c) w/o spark (2/3 opening height)

8.4 Discussion

8.4.1 Testing with no pilot spark (1/3 and 2/3 height of opening, near the bottom)

28 experiments were conducted in 3 compartment sizes and opening sizes, the part of this research focused on investigating if there is a correlation between the opening size, compartment volume to the time of backdraught delay. This research investigated the ratio between opening size (m^2) to volume of compartment (m^3), i.e. A_o/V_c .

Figure 8.3.1 shows that when the opening size is above $0.01 (m^2)$, or $A_o/V_c > 0.08$, the delay time increases as the size of the opening decreases. The occurrence of backdraught is not related to compartment geometries in the experimental fire. Even if with a narrower compartment layout, a backdraught still can be triggered, there is no need to fix a certain/ specific aspect ratio. Also, when the value dropped to about 0.05 or less, a backdraught was unable to occur, four repeated experiments showed the same result. Between 0.05 to $0.08 (A_o/V_c)$, it was observed that there was in general smoke puffing out of the fire compartment, with about 0.5 sec at least delay, before a backdraught occurring it may be that a localised ignition occurred first, is pressurised the ambient thick hot smoke, then a proper flammable mixture was obtained to complete backdraught process, smaller than this ratio, the fire is extinguished. This result implies that a limiting/ critical flow of the air into the compartment, resulting in fire extinguishment rather than initiating backdraught.

As to the ignition time of backdraught, see **Figure 8.4.1**. It can be seen that it presents a linear correlation between $\frac{A_o}{v_c}$ and the reciprocal delay time of backdraught (s^{-1}), which means $\frac{A_o t_d}{V_c} \approx const \approx 3$, even though this is only valid

when $\frac{A_o}{v_c} > 0.05$. The result provides considerable credibility, the R-square fit is 0.9283.

Figure 8.4.1 Opening size to compartment volume vs reciprocal delay time of backdraught. (w/o spark; with trend line)

The linear trend observed suggests that non-piloted backdraught is related to the volume of the compartment, which means that a specific ratio between the incoming air and the overall volume of the fire chamber is required to initiate backdraught. To allow the discussion equipped with more physical meaning, the following description is used to analyse the possible incoming air during the time of the door opening, with some assumptions.

Here, the air flow rate ($\dot{M}$) through a window opening can be determined by [17],

$$\dot{M} = A_o V_f \quad (1)$$

where A_o is the minimum cross-section area of the flow through the opening, i.e. the opening size, V_f is the velocity of the flow.

Also, the velocity of the outflow in a fire room can be estimated using the following equation [18],

$$u_u = \sqrt{2g \frac{\Delta \rho}{\rho} y} \quad (2)$$

where u_u is the outflow velocity, $\Delta \rho$ is the initial density difference across the opening, ρ is the compartment density, y is distance above the neutral plane (total height of the opening minus the height of the smoke natural plane), and g is 9.8 m/s².

In this research, no probe was used to measure the velocity change during the time between the door opening and backdraught occurring. Theoretically, the velocity of the inflow of fresh air changes with the density of the smoke in the fire compartment, and the smoke layer will decrease with the time of the door opening, so the longer the door is opened, the thinner smoke layer will become. Measurement of velocity here would be complicated and would not necessarily yield useful information.

Hence, to simplify the analysis, this research only investigates the temperature difference between inside and outside the fire compartment, and only one thermocouple (the one used to describe the critical temperature required in previous chapters, TC-1003) was used as characteristic (about 30 °C above the average temperature, see Chapter 7). Uncertainty always exists. Even though, owing to the nature of fire, it there was some variation in the burning conditions, it can be assumed that the temperature distribution was similar for every test, as all had experienced flashover. Therefore, the velocity of the air flow may be assumed to be only related to the temperature difference, neglecting the thermal gradient (in fact, the temperature decreased, but less than 10 K in average (24 TCs)) during the time of gas mixture before backdraught, the velocity here can be taken to be approximately constant, and according to the ideal gas law

$$pM = \rho KT \quad (3)$$

Although pressure differences also exist (either positive or negative, depending on the location above or below the smoke neutral plane), the height of the neutral plane will be not the same with different periods of the time of the door opening. In general, there is almost no change (slightly decrease) for the neutral plane observed from video clips (the camera installed in front the fire compartment), from the time of the door opening to the occurrence of backdraught. Therefore, the small difference of the height of the neutral height can be neglected. So, if the pressure is almost the same, then $pT \cong \text{const.}$, therefore equation (2) can be expressed as,

$$u_u = \sqrt{2g \frac{\Delta T}{T_a} y} \quad (4)$$

where T_a is the ambient temperature (outside the fire compartment), ΔT means the difference between the average temperature inside the compartment and T_a , and y is the distance above the neutral plane.

The mass flow can be expressed as [18],

$$\dot{m}_u = \frac{2}{3} C b \sqrt{2g \frac{\Delta T}{T_a}} (h_v - h_n)^{3/2} \quad (5)$$

where C is the flow coefficient, is normally 0.68 used for buoyant flows, b is the width of the vent, h_n is the height of neutral plane, h_v is the height of the vent.

The total mass influx from the air can be expressed as,

$$M_{total} = \dot{m}_{air} \cdot t_d \quad (6)$$

where t_d is the duration of the inflow, i.e. the delay time of backdraught.

Then the total mass influx from the air (during the time of mixing) becomes according to equation (1),

$$M_{total} = A_o V_f \cdot t_d = \dot{m}_{air} \cdot t_d \quad (7)$$

If the fire compartment keeps the same condition (the same maximum temperature, experienced flashover like the experimental fire in this chapter) in different fires before the door opening, the mass influx from the air can be regarded as constant, only relevant to the dimensions of the opening. In addition, if/ assuming a non-piloted ignition backdraught requires a specific mixture to occur, then $A_o t_d$ should be a fixed value, as the height during the experiments were kept the same, or an equivalent to a ratio of the fire compartment (the volume of the fire compartment, V_c) should be the same, i.e. $\frac{A_o t_d}{V_c} = const$, which supports the finding mentioned above.

However, It should be noted that the effective opening area of the door is not the total area of the door, the effective opening area (A_{eff} , allowing incoming fresh air) of experiments (tests experienced flashover before the door closing). Based on video observation (see **Figure 8.4.2**), is about 75% and 60% of the opening, for 1/3 and 2/3 opening height experiments, respectively, i.e. $A_{eff} \cong \frac{3}{4} A_o$ or $\frac{3}{5} A_o$.

Figure 8.4.2 Typical height of the neutral plane in different opening heights, (a) 1/3 opening height; (b) 2/3 opening height

Combining the equations and the height of the neutral plane, an estimation of the incoming air can be obtained. **Figure 8.4.3** shows the relationship between the ratio of the incoming air / the volume of the compartment with the reciprocal delay time of backdraught.

Figure 8.4.3 Ratio of inflow to compartment volume vs reciprocal delay time of backdraught. (w/o spark, 1/3 height in triangles, 2/3 height in squares)

In those experiments with 1/3 opening height (not including the red squares), it can be seen that when the ratio of the inflow to the total volume ($\dot{m}_{air}/V_c$) below about 0.016, backdraught or reignition is not possible as the boundary layer (i.e. discharge coefficients) probably considerably decrease the time-average velocities, this should be an explanation for the apparent straight line on the graph is valid only when the ratio is above 0.016. The R-square fit is 0.9408.

From the information in **Figure 8.4.1** and **Figure 8.4.3**, this type of backdraught, non-piloted, requires a well-mixing to achieve a condition for backdraught to occur, a continuing incoming air that occupied a specific ratio of the compartment is required. This can be used to estimate the time of the backdraught after the door opening.

For experiments with 2/3 opening height, most of the experiments fit (four of six) the linear relationship in **Figure 8.4.3**, however, when the value is above about 0.12, the linear relationship appears to break down. In **Figure 8.3.1** (red squares), it can be seen that the delay times for the 2/3 opening were quicker than for the 1/3 opening height when the A_o/V_c was similar. Two separate trend lines seem to divide the data into two parts, $A_o/V_c > 0.08$, or $A_o/V_c < 0.08$; correlations between these two ranges of opening size to compartment volume to the delay time of backdraught are evident, even though only 6 experiments were conducted in this experimental series. When A_o/V_c is about 0.08 to 0.1, a turning point appears, and the trend line cannot predict the delay time when the opening is too small compared to the compartment.

In **Figure 8.3.1**, it shows backdraught at a different opening size at double height of the opening. Traced back to earlier part in this section, a similar result can be seen. The difference is that the opening height was only 1/3 of the height of the fire compartment. When the ratio A_o/V_c was below 0.08, the delay time was much longer, if the value dropped to 0.05 or less, backdraught was impossible to occur. This suggests that 0.08 is a critical value to determine the mixing process of hot and cold gases and implies the discharge coefficient of the opening may affect the mixing efficiency.

Figure 8.4.4 Development of backdraught, with different areas. $A=0.053\text{m}^2$, $B=0.027\text{m}^2$, $C=0.003\text{m}^2$ (Each image is one video frame after the preceding image, 29 fps.)

But it should be noted that even with an incredibly tiny (2/3 height) opening of 1 cm (see **Figure 8.2.3**) backdraught always resulted. A possible reason for this may be that when the opening height is larger, the mixing of the cold and hot gases is more effective. This is because the hot smoke tends to accumulate below the ceiling of the fire compartment owing to buoyancy. When there is an opening at 2/3 of the total height, a quicker gas mixing process will occur, compared to the opening installed 1/3 of the height of the compartment, which is the same as the results (the gravity wave (current) accelerated) given by the previous research [19].

It should be noted that the 2/3 opening height experiment, the same fire development was set, all conditions were kept the same before the door closing procedure. The fire allows to develop to flashover with 1/3 opening, then follow a quick opening change (removing the mid baffles and closing the door) before the door closing, which enables to control the width of the opening at the time of opening the door. At the time, some hot smoke may leak as a sudden change of the size of the opening even if had tried to cover the opening immediately. Although the time gap had been controlled to be only less than 0.5 second, leading to some uncertainties which may influence the delay time of backdraught.

In general, the quantity of air flow required for backdraught to occur is constant for the same material. But the air flow rate may change as the density difference varies with the mixing time, which means that the temperature is cooled down with longer times of ventilation. Also, the energy keeps releasing from the walls, ceiling, and floor of the fire compartment. Although the material of the boards is thermally insulating, it is still unable to stop the energy transfer process. All these possibilities led to the experimental results with some uncertainties.

It is commonly found that some features of fully developed compartment fire dynamics vary with the 'ventilation factor ($AH^{1/2}$)', so it might be expected to find a relationship between backdraught delay time and the ventilation factor. Here, before the door opening, the compartment has experienced the same conditions as a fully developed fire although the fire will diminish and probably extinguish during the period of the door closure (the fire compartment was nearly well-sealed). If the same rules apply as to fully developed compartment fires, the rate of inflow of air ($\dot{m}_{air}$) in equation (5) may be approximately expressed by [16],

$$\dot{m}_{air} \approx 0.52A_oH_z^{\frac{1}{2}} \quad (8)$$

In **Figure 8.4.5**, a linear relationship is observed when the height of the opening was kept 1/3 of the total height of the full opening. However, if using this correlation to predict the delay time with double height, the delay time would be underestimated. It would seem, from these data, that there is no single relationship with ventilation factor uniting tests with 1/3 and 2/3 height openings, suggesting that other factors, perhaps the aspect ratio of the opening, are controlling the process. This will need to be uncovered through future research.

Figure 8.4.5 Ventilation factor to compartment volume vs reciprocal delay time of backdraught. (w/o spark, 1/3 height in triangles, 2/3 height in squares)

Although a generic single correlation was unable to be discovered to predict the relationship with the ventilation factor regarding the delay time of backdraught, the data still show a clear linear correlation, which indicates the backdraught requires a specific ratio between the quantity of incoming air and the volume of the fire compartment. Both approaches shown in this section are valid to justify that a well-mixing is required for non-piloted backdraught events.

8.4.2 Testing with pilot spark

15 experiments were conducted to observe if there is different behaviour with a spark as the ignition source, see **Figure 8.4.6** (parts of **Figure 8.3.1**). Two of them with a smaller opening size than 0.08 (Ao/Vc), and these showed a longer delay time, marked in white, the same observation (a turning point) that is similar

to the experimental result without the extra ignition. The rest followed approximately linear trends but with different slopes. In addition, in every compartment size, results show a very similar delay time of backdraught with the full width opening; approximately 2 seconds.

As the result shows a distribution, a higher ratio of A_o/V_c results in a shorter time delay, the size of the compartment may affect the difference of the delay time

Figure 8.4.6 Testing result at different compartment geometries (with spark)

Figure 8.4.7 Opening size to compartment volume vs the delay time of backdraught

When enlarging the part of the values which are in colour (i.e. neglecting the reignition cases), three groups of experimental results are shown, grey markers represent original compartment size (0.8m×0.4m×0.4m); red markers represent the medium size (0.8m×0.4m×0.35m); and black markers represent the smallest testing compartment (0.8m×0.4m×0.256m), see **Figure 8.4.7**.

It is observed that there are linear trend lines for each group, i.e. for the different compartment spaces. The values of the R square are nearly 1, which means the increase of the delay time can be estimated with confidence if the sizes of the opening and the volume of the compartment are known. The minimum 2 seconds delay time is about the time for the gravity current travelling time to arrive at the ignition source (on the back wall of the compartment). Therefore, any size of compartment (only change the width, the rest of the variables kept the same) should have an equal delay time of backdraught if the depth of the compartment is the same and there is a pilot spark. The delay time is the time of gas mixing (driven by gravity current) to the rear wall of the compartment (the location where the spark is). When decreasing the opening size, the incoming air will be reduced with the change of the boundary layer, which will lead to the air inflow not being able to arrive at the spark (on the rear wall) efficiently. As the $A_o/V_c < 0.08$, the efficiency of the air mixing dramatically decreases, it is unable to predict the delay time based on this correlation.

8.5 Conclusion and future work

In this research, from the experimental results, it can be seen that the delay time is directly related to the type of ignition source. Also, the size of the door opening directly influences the delay time of backdraught. Both non-piloted and pilot ignition can lead to backdraught when the experimental fire had reached flashover before door closure, but with a significant difference in the delay times because of different mechanisms.

In terms of non-piloted backdraught events, it has been found that $\dot{m}_{air}/V_c = \text{const.}$, from the experimental result in this research, indicating that the ratio of incoming air to the compartment volume is almost a constant. This result implies that the incoming air should at least occupy a specific portion of the fire

compartment, which means that the type of non-piloted backdraught requires a 'well-mixed' condition to initiate the beginning of backdraught where at least a local hot spot is above the critical temperature.

When an ignition source is present, the mechanism of backdraught ignition changes. A well-mixed condition is not essential, the delay time of backdraught is dependent on the time when the gravity current arrives at the ignition source (pilot spark), in the configuration tested, this type of backdraught relies on a distance relationship rather than a volumetric correlation. For experiments with fully open doors, no matter what the width of the compartments were (with the same distance from the rear wall to the opening), the delay time of backdraught was almost constant, about 2 seconds. When the opening was partly closed, the waiting time increased. To anticipate the possible delay time of backdraught is possible by investigating the flow travelling time arriving at the spark. If the opening is extremely small, the delay time of backdraught is more extended. The value is determined by the opening size/ compartment volume ratio, where the critical value is 0.08. Flow modelling in future work may help to validate the result in the research.

The severe scenario of backdraught events was obtained in this research, when the fire has experienced flashover, and a long-time door closing led to the stable period (stage II, see Chapter 7). The smaller the opening was, the longer the delay time of backdraught was. The opening size is a critical factor for both non-piloted and piloted ignition backdraught; a double height of the opening accelerates the time to backdraught.

It should be noted that conclusions of this research were based on PP fuel only, in fact, a fire scene/ scenario that can trigger possible backdraught may contain any fuels, PP can be a potential fuel, but it is unable to predict all backdraught events by the investigation results here. Hence, further research needs to compare different solid fuels (and combinations) to map out the possibility regime of backdraught, also to investigate further the delay time of backdraught after implementing the door opening procedure.

8.6 References

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Chapter 9. Conclusions and future work

9.1 Summary of research outcomes

In this thesis, a novel way of investigating the backdraught phenomenon is described, by using a realistic fuel to develop fires to all stages of a typical fire, which includes incipient, growth, fully-developed, and decay stage. This design allows us to compare with real fire conditions by simulating possible fire conditions. It is true that the experimental fire is unlike a real compartment fire as there are always a plenty of flammable materials, and sophisticated layout and compartmentation in a fire scene. But the results still provide some useful qualitative and quantitative information that have never been demonstrated or discovered in previous related research.

The first stage of this thesis (**Chapter 4**) was to understand:

- a) Whether temperature affects the occurrence of backdraught?***
- b) What is the baseline requirement for a backdraught to be triggered?***
- c) Will the presence of an ignition source change the behaviour of backdraught?***

From these experiments, it was shown that a flashover condition is not essential to permit backdraught in the experiments, in fact, a backdraught can be triggered at the middle of the steady-state burning stage of the experimental fire. Also, a temperature (maximum observed) of 350 °C is a minimum condition for backdraught occurring during the testing when there is no extra heat source apart from the hot smoke inside the compartment, i.e. in non-piloted conditions.

When it comes to the ignition source, a pilot spark was used to ignite/ trigger backdraught at temperatures lower than 350 °C. It was found that an ignition source can lower the temperature required for a backdraught by about 50 °C, compared to that needed for the non-piloted backdraught event. Ignition sources also play a role to change the behaviour of backdraught, if a spark is present, this will result in a quicker occurrence of backdraught.

In fact, either backdraught or fire re-ignition can always be triggered when there is a spark as the ignition source. Compared to a typical backdraught phenomenon, in those experiments defined as 'fire re-ignition' this remains that the result of the piloted ignition leads to no explosive external fireball. Even with a longer time of door closing (more than 27 minutes), a fire re-ignition can still happen if the pilot was present. The average temperature was only 205 °C inside the fire

compartment, which means it only requires a hot spot to provide energy to ignite all flammable unburned gases, see **Figure 9.1.1**.

Figure 9.1.1 Reignition process (interval every 4 frames, with spark; frame rate=29 fps)

In **Figure 9.1.1**, it can be seen that the development of the fire propagation (re-ignition without an explosive fireball) behaves in quite a different way. Flame propagates to ignite to all the combustible gases (accumulated smoke) rather than releasing pressure. It took more than 2 seconds to the extent the fire spread to most of the fire compartment. If observing from the side of the compartment, there was no visible flaming coming out from the front door. The fire remained inside.

Given that the temperature is one of the critical factors relating to the onset of backdraught, it is needed to investigate if the rest of the TCs provide useful results /information, as Chapter 4 only used the highest temperature as the indicator. Therefore, **Chapter 5** provides a more extensive discussion on temperature data, the aim here was to discover:

- a) Does the compartment temperature affect the occurrence of backdraught?**
- b) The influence of compartment temperature on the delay time of a backdraught.**

It was found that the temperature distributions were not correlated well with the backdraught occurrence, but the highest temperature does appear to determine

whether a backdraught is going to happen or not. Therefore, a considerably high temperature environment is not imperative for initiating backdraught, but a localised temperature of above 350 °C is required.

In addition, the delay time of backdraught was not a specific /fixed value when non-piloted ignition backdraughts were triggered. On the contrary, it varied between 3 and 12 seconds, with hotter temperatures leading to faster backdraughts, which implies there are other factors to assist or hinder the existence of backdraught

Given that there is a critical temperature for backdraught when using PP as the fuel, it is essential to investigate if the value can be universally applied or is only a characteristic of the material. Also, as backdraught is a combustion process, some chemical aspects may provide information to get a better understanding of backdraught, even though the process of the formation of backdraught is complicated. Hence, in **Chapter 6**, some new findings are:

a) Critical temperatures in fuels.

b) Gas components corresponding to the onset of backdraught, based on different fuels and ignition sources.

It was found that the critical temperatures are different between PP and HDPE, which means that the critical temperature for backdraught is material-dependent. This relies on the pyrolysis process during the time of the door closure and the accumulation of unburned flammable gases, etc.

Also, the CO/CO₂ ratio was found to be able to define boundaries of whether a backdraught may occur. Also, this ratio also varies with temperature values. Backdraught can happen at early stage of the fire if CO/CO₂ >0.08. When an electric spark is used as the ignition source, the value required is increased to 0.4 as the mechanism of backdraught is different as ignition sources behave differently.

The observed CO concentration shows a similar trend, with higher values of CO, the required temperature decreases. But the required temperature did not decrease endlessly, only to a value above the critical temperature. This suggests that the critical temperature is at some point fixed, even if there is an accumulation of unburned flammable smoke in the fire compartment.

The delay time of backdraught is the most relevant issue to the safety of firefighters. If a backdraught is going to occur, then how long will the delay be after

opening the doors /windows? From previous chapters, there is a clear understanding that the delay time is not a constant value. Also, it cannot make sure that the opening is always equal size as uncertainties still exist when conducting firefighting. **Chapter 7** was designed to understand:

a) The relationship between the time of the door closure and backdraught delay time.

b) The relationship between temperature and the backdraught delay time.

It was found that longer times of door closure lead to a longer time delays, also, the observed temperature and the reciprocal of the delay time appears to have a linear relationship for non-piloted backdraught events. But still, there exists a correlation to types of burning material, i.e. for different materials, the slopes of the linear correlations are different.

When the spark apparatus was on during tests, the results showed that the delay time of backdraught / re-ignition was almost constant, and about equal to the time when the gravity current arrives at the far wall opposite to the opening.

This all suggests that the delay time of backdraught should be predictable.

If a fire has experienced flashover condition before the door is closed, it is found to have the longest delay time before backdraught occurs. Therefore, this should be deemed as the worst scenario that firefighters may encounter in fire scenes. As compartment spaces are not the same, it is crucial to investigate the delay time of backdraught in different sized compartments, and with different opening sizes. **chapter 8** was designed to:

a) Investigate the relationship between the delay time with the opening and compartment sizes.

b) Investigate the delay time of backdraught with different ignition sources.

For non-piloted ignition backdraught, it was found that the delay time is only related to the opening size and compartment size, which means that a specific gas mixing condition between hot smoke and cold air is required.

The height of the opening plays a critical role to control the mixing of the gravity current, even when the areas of the opening were kept the same, an opening with double height tends to generate a quicker backdraught event, because it is easier

for the incoming fresh to have more mixing with the accumulated unburned smoke close to the ceiling of the compartment. All the observations support that this type of backdraught requires a 'suitable mixing condition'.

When the ignition source was provided by the spark apparatus, no matter what the sizes of the compartments were, the delay time of backdraught was about 2 seconds for a full width door. If the opening and compartment size is known, the prediction of the delay time is reliable for the experimental compartment as it was found that there is a clear linear correlation between the delay time and the opening and compartment sizes.

9.2 Novel understanding of backdraught

This thesis uses a different approach from the previous backdraught research, starting from establishing a fire with typical development stages, to discover at which stage backdraught can occur. Also, the fuels adopted were solids (PP and HDPE) to satisfy the needs of society as no residential houses, hospitals, or hotels are full of methane when a fire is occurring.

This design of the fire may be more useful as methane backdraughts are unlikely to occur in residential areas. At the same time, in a real fire scene, too many uncertainties exist. Any heat sources can provide energy to initiate a possible backdraught event. Only relying on an electrical spark, can only represent a single type of backdraught. From this point of view, this research focuses on a comparison of ignition sources to get a better understanding of a range of possible backdraught results, trying to investigate and discover how the mechanism of backdraught varies under different ignition scenarios.

9.2.1 Definition of backdraught on ignition sources

From the experimental results, the following conclusions and definitions for backdraught phenomena using different mechanisms in the reduced-scale fire, using PP as the fuel, can be made.

Non-piloted ignition backdraught.

'After a well-developed fire experiences a time of door closure, when the door is suddenly opened, any local temperature above the critical temperature (350°C) and accumulation of CO/CO₂ above 0.4 (or CO>2.8%), with a suitable mixture of cold air entrainment and hot smoke, result in a fast expanding fire spread and leads to an external explosive fireball.'

Piloted-ignition backdraught.

'After a well-developed fire experiences a time of door closure, when the door is suddenly opened, accumulation of CO/CO₂ is above 0.35 (or CO>2.8%), when the interface of the cold air entrainment and hot smoke reaches a pilot spark, fast flame spreads along the interface and leads to an external explosive fireball.' In some of the events, fire re-ignition occurs without external fireball.

It should be noted that the statements are based on observation of the experiments only, the values may change when using a different combination of fuels or in other fire compartments.

9.2.2 Delay time of backdraught

9.2.2.1 Temperature and delay time-same fire compartment

So far, before this research, there was a lack of research on backdraught using solid fuels to discuss the critical factors that may hinder or assist backdraught in occurring. Most of the previous research focuses on the "gravity current" and to mimic a possible backdraught scenario based entirely on the gas mixing process, assuming this is to be the driving force of backdraught. In this thesis, this is defined as the '**induction time**' of backdraught. It is true that without a door opening, there is no possibility for backdraught to occur, keeping the door closed is one way to prevent backdraught from occurring. However, this is almost impossible for firefighters not to break the integrity of the fire compartment when firefighting is carrying on.

Hence, the thesis discovers that the delay time of backdraught is temperature related, which means that when the temperature is higher than its critical temperature, a faster backdraught will occur because of the instability of the gas mixture. On the other hand, a pilot spark will reduce the delay time of backdraught,

even at different stages of the fire or with different temperature variations. The approximate time to reignite the unburned smoke was about 2 seconds, even if some experiments resulted in only fire re-ignition.

Therefore, this suggests that most real fires with backdraught occurrence were non-piloted backdraught events as the delay time was far beyond the observed results, even taking the scale into consideration (see **Figure 7.7.2**).

9.2.2.2 Delay time with sizes of fire compartment and opening

It is almost impossible to use the size of a compartment to establish a holistic approach to understand the behaviour of backdraught. In the final part of the thesis, the observations focus on the changes of the opening sizes and the size of the fire compartment. This allows us to observe how the delay time of backdraught will change according to the given boundary conditions (opening sizes, compartment sizes and ignition sources).

The initial fire condition was kept the same in all experiments, closing the door at the time when the fire achieved flashover and using the maximum temperature as an indicator to conduct the opening procedure at near the critical temperature. As shown in the previous chapters, the delay time should be constant.

In the experiments without an extra ignition source, it was found that ratio of the quantity of the air inflow to the size of the compartment is almost constant before the time to be able to trigger backdraught, this is the '**suitable well-mixture**' condition. The condition is related to these factors (opening sizes, compartment sizes), which means that if the size of the compartment and door opening are known, then the induction time mentioned above can be predicted.

For piloted ignition, the delay time is only correlated with the time at which the gravity current reaches the location of the electric spark. In tests with the full width opening (1/3 height of the front area), for all widths of compartment, the delay time was constant, 2 seconds; the same as the previous finding. The delay time only changes with the size of the opening, by way of linear relationships, and the linear relationships are found to be parallel for different compartment widths.

9.3 Limitations

In the research, only PP and HDPE fuels were used to investigate the backdraught phenomenon. It has been shown that a critical temperature exists for the onset of backdraught, however, the two materials demonstrated two different temperature values. This suggests that it is impossible to use the temperatures observed in these experiments to allow firefighters to develop a robust firefighting tactic to avoid a possible backdraught event.

In some tests, gas data was obtained from a specific location in the fire compartment. As the fire and smoke are dynamic, different places in the compartment may show different information. Given that the possible starting point of backdraught was found to be somewhere above the fuel tray, the location of the gas analyser was installed in adjacent to the possibility of the ignition of backdraught, however, uncertainties may still exist.

All the research in the thesis used a small-scale fire compartment to investigate backdraught phenomenon and the related delay time. Results show that whether a backdraught will occur or not is independent of the compartment size. Therefore, the design of this research should be reliable to study the mechanism of backdraught. But the delay time of backdraught may not be scalable to predict in a real size fire compartment. Several additional large (or medium) scale experiments will help to validate the findings of this thesis.

Also, the fuel tray was installed a fixed location near the rear end wall of the fire compartment, resulting in the hottest temperature in the compartment always being located nearby this. A real fire is complex, it is impossible to represent every possible situation using only one fuel supply in a specific area.

9.4 Suggestion and future work

In the thesis, the mechanism of backdraught was investigated using solid fuels, but limited to only two materials, PP and HDPE. It is needed to use different common materials to map out the possible backdraught hot zone for combinations of fuel components. In that way, a generic approach may be established to use to predict a backdraught even if the fuel component is unknown.

Simulation on backdraught phenomenon should be experimentally based, the reason is that the mechanism of backdraught is not yet fully understood, therefore, a simulation on this phenomenon may mislead other researchers or firefighters or provide an unfaithful presentation. Future work should simulate the experimental results in this research as the database, based on the given boundary conditions (a specific time of backdraught occurring, CO/CO₂ ratio etc.) to simulate this phenomenon to investigate if numerical results are acceptable. Therefore, it should be able to provide a more realistic backdraught phenomenon using CFD to not only qualitative backdraught observation but also quantitatively.

Also, detailed research projects on chemical reactions are essential to understand factors for backdraught involving under-ventilated combustion, low oxygen oxidation, and thermal pyrolysis. Therefore, it may be useful to define the boundary conditions of flammable components on backdraught of either non-piloted or piloted ignition.

9.5 Concluding remarks

Backdraught has been regarded as one of the difficulties in fire science for a long-time. In this thesis, a systematic approach has been adopted, starting from the very first question about when it may be triggered in fire development process. Without an ignition source, apart from the heat from the hot room temperature, there is not any clue showing at which the fire stage is required for backdraught to happen. This trouble got this research project into “hot water” at the first stage, as to ignite /trigger a backdraught seemed to be pure luck, let alone to conduct data induction and analysis for it.

It takes time to solve a problem by a ‘bracketing’ approach to determine a suitable condition, therefore, this may be the reason that this sort of research in fire science is still lacking.

From data analysis and experimental observations, it has been proved that the flashover condition is not an essential factor for the occurrence of backdraught. On the other hand, specific temperatures and burning conditions are required. Using realistic fuels in backdraught research is needed, it means the experimental results are not only on the scientific side, but useful for public aspects (firefighters).

When high-tech seems to be able to solve almost everything in this technology widespread society, firefighters are still not exempt from the risk of backdraught, which means the understanding this phenomenon is not in step with the trend of world progress. That is, continuing research on this phenomenon is imperative as no tolerance to afford any more loss of firefighters in this high-tech world.

Appendix A. Supplementary experimental description

A.1 Summary

In this research, unlike most of fire research projects, the design of the backdraught testing did not follow a typical experimental design, we did not use every equipment to detect or observe at once, on the contrary, we kept it simple (as backdraught is very sensitive) at every stage of the experimental design as it was unknown which factors (or combination of factors) may affect the result of backdraught occurring. Therefore, the procedure of the experimental design for this thesis can be seen in **Figure A.1.1**.

Figure A.1.1 Flow of experimental stages

Initially, to understand where backdraught is usually triggered, we placed a camera in front of the fire compartment, then added TC trees to conduct temperature observation, finally adding the gas analysis part.

In the previous chapters, temperature, gas, and delay time of backdraught were discussed separately. To provide information on how the data was analysed, an experiment is used to demonstrate the way we obtained useful data.

A.2 Experimental data and information selection

To demonstrate the way to obtain useful/related data in this thesis, a test with a pre-burn time 14 minutes (date: 1st June 2017) is presented here.

A -Video/image observation

Two cameras were used to capture the development of backdraught and the external fireball (one is in front of the compartment; the other is at the side of the chamber), as backdraught does not occur instantly, still pictures may not be a reliable method to judge when backdraught is triggered. Therefore, video observation was used to observe all changes during experiments. The relative positions can be seen in **Figure A.2.1**.

Figure A.2.1 Positions of cameras

To visualise the development of backdraught, video recordings are essential. But it should be noted that the time of the door opening should follow the same procedure. It is judged, frame by frame, from the sliding door to the intersection of the side wall (or to the testing size), to reduce uncertainties among tests.

If using one camera only, the consequence is sometimes difficult to understand as some experiments only resulted in fire re-ignition. The side view, tells nothing about the time when the re-ignition starts.

It is not required and hard to sync the time of the start of the experiment and two cameras during the test as the camera on the side only provides little information before door opening, and it is used for observing the shape and the distance of the external fireball only, which are not the main focus of the research.

B-Temperature data selection

24 TCs were used to measure the temperature histories during the test. Before experimenting, it is essential to make sure the temperatures are equal to the room temperature and make sure the locations did not change from the previous experiment.

In the test, TC-1003 was used to control the time of the door opening, as it was observed that the starting point of backdraught was always somewhere near this TC in the blank test (pre-test). Also, in chapter 5, it was demonstrated that this TC, compared to the other TCs, is more representative for backdraught predicting. As the compartment has experienced a long time of door closing, the temperature decrease was only the heat loss through the compartment to the ambient and stratification became more stable with time. Therefore, temperature should not change dramatically during the closure time.

With regard to the time of the door opening, this is a tricky issue to cope with as backdraught does not happen immediately at the moment of door opening, it always followed with several seconds time delay.

Based on this, a way to judge the time of the door opening from the data is to check temperature histories to find out when the temperature decreases faster than the previous seconds.

In **Figure A.2.2**, it can be seen that TC-1031 should be the thermocouple experiences the quickest cooling down after door opening as it is the closest TC to the opening.

Figure A.2.2 Side view of compartment

By checking the temperature data (**Figure A.2.3**), it can be seen that the opening was about 18 minutes. Therefore, the information helps to locate the opening time.

Figure A.2.3 Temperature history during experiment

By checking the raw data, normally it requires 3 second to decrease 1 °C before the door opening, however, at 17 minutes 59 seconds, it is found that the temperature dropped about 10 °C compared to previous second (from 290.3 °C to 280.8°C), also, the value of TC-1003 is 350.8, was the same as the target testing value of this experiment. Hence, the way to locate the door opening time here is defined as the time of the door opening for the whole experiments in the thesis.

C-Gas data acquisition

As to gas data part, detecting the whole gas variation history during the entire testing is not required or desirable. One reason is that the onset of backdraught is only dependent on the total accumulated gas concentration before the door is opened. The other is that the fire compartment is relatively small compared to a full-scale room. If the gas was sampled through the whole testing, this would have changed the flow conditions and changed the mixing process during the time of the door closure.

Also, the testing space is a closed environment before door opening, too much smoke been sucking out have led to the compartment becoming negatively

pressurised, which would have affected the behaviour of the delay time of backdraught.

Before each test, we turned on the gas analyser about for 4 minutes to make sure the observed O_2 at ambient was about 20.9 % for calibration according to the product manual.

The gas sampling tube does not directly connect to the PC because it requires a cooling process before passing through the gas analyser. Therefore, the first few seconds of gas sampling does not represent the gas concentrations, see **Table A.2.1**.

It can be seen that the data is unstable in the first few seconds. But about 5 seconds later, a constant value was obtained. Averaged data from these three values was regarded as the gas concentration used in all the experimental investigation of this research.

A period of time (6 to 8 seconds) before opening the door was used to extract gases with a flow rate of 1 litre/min for every experiment. The gas concentration after the door was opened is not of interest of this research.

Table A.2.1 Gas data at time of door opening
(In this experiment, the door was opened at 9 seconds)

Time (s)	CO ₂ %	CO %	O ₂ %
1	0.97	0.113	20.68
2	1.33	0.325	20.44
3	5.41	2.781	19.22
4	7.34	3.576	14.48
5	7.88	3.745	4.74
6	8.01	3.812	1.94
7	8.08	3.752	1.51
8	8.07	3.747	1.48
9	5.58	2.477	1.48
10	3.81	1.809	3.51
11	1.92	0.787	8.29
12	1	0.443	12.49
13	0.73	0.295	16.22
14	0.25	0.09	18.39
15	0.15	0.056	19.45

Appendix B. Experiment results used for different chapters

B.1. Experimental result used in Chapter 4 & 5**Table B.1.1 Backdraught experiments at different burning time (with pilot spark)**

Ignition type (Non-piloted (N)/ piloted(P))	Case no. (PP)	Burning time (min)	Time of closure (s)	TC- 1003(°C)	Backdraught(B), reignition(R), or extinguishment(E)
N	1	6.5	30	398.17	E
N	2	6.5	60	310.6	E
N	3	8	60	312.32	E
N	4	8	30	367.3	E
N	5	8.75	33	331.89	E
N	6	9	30	363.22	E
N	7	9.25	35	371	E
N	8	9.5	30	387.16	B
N	9	9.5	60	335.81	E
N	10	9.75	60	354.12	B
N	11	9.75	88	326.87	E
N	12	9.75	57	337.94	E
N	13	9.75	60	337.38	E
N	14	9.75	55	346.64	B
N	15	9.75	32	382.65	B
N	16	10	30	387.43	B
N	17	10	60	351.89	B
N	18	10	59	385.93	B
N	19	10	91	352.52	B
N	20	10	120	345.71	E
N	21	10	109	341.32	E
N	22	10	52	342.28	B
N	23	11	97	343.2	E
N	24	11	101	344.05	E
N	25	11	113	346.82	B
N	26	12	60	435.97	B
N	27	12	90	379.04	B
N	28	12	120	362.49	B
N	29	12	135	349.97	E
N	30	12	150	356.67	E
N	31	12	150	356.18	E
N	32	12	164	340.8	E
N	33	12	175	343.53	B
N	34	12	86	348.15	B
N	35	13	152	347.16	B

N	36	14	247	347.42	B
N	37	After F.O.	154	404.64	B
N	38	After F.O.	303	341	B
N	39	After F.O.	260	349.95	B
N	40	After F.O.	244	365.12	B
N	41	After F.O.	32	536.38	B
N	42	After F.O.	120	437.82	B
N	43	After F.O.	180	387.11	B
N	44	After F.O.	60	484.57	B
N	45	After F.O.	333	336.52	B
N	46	After F.O.	414	347.87	E
N	47	After F.O.	86	451.37	B
N	48	After F.O.	116	432.27	B
N	49	After F.O.	376	338.29	E
N	50	After F.O.	374	335.23	E
N	51	After F.O.	368	349.59	E
N	52	After F.O.	120	408.82	B
N	53	After F.O.	328	331.89	E
N	54	After F.O.	374	336.21	E
N	55	After F.O.	360	336.8	E
N	56	After F.O.	321	336.2	E
N	57	After F.O.	279	337.85	B
N	58	After F.O.	293	340.58	B
N	59	After F.O.	318	343.58	E
N	60	After F.O.	328	348	B
N	61	After F.O.	217	378.45	B
N	62	After F.O.	367	356.15	B
N	63	After F.O.	391	339.73	E
N ⁸	64	After F.O.	365.12	332.2	B

⁸ This additional experiment used in Chapter 5

Table B.1.2 Backdraught experiments at different burning time (with pilot spark)

Ignition type (Non-piloted (N)/ piloted(P))	Case no. (PP)	Burning time (min)	Time of closure (s)	TC- 1003(°C)	Backdraught(B), reignition(R), or extinguishment(E)
P	65	10	170	300.63	R
P	66	10	156	312.29	R
P	67	10	78	330.12	R
P	68	11	184	301.18	R
P	69	11	164	314	R
P	70	11	132	330.34	R
P	71	12	240	301.59	R
P	72	12	198	314.5	R
P	73	12	207	303.79	R
P	74	12	155	331.81	B
P	75	12	167	330.26	R
P	76	13	327	301.43	R
P	77	13	285	329.4	B
P	78	13	314	315.79	R
P	79	14	393	300.41	B
P	80	14	458	295.37	B
P	81	After F.O.	1247	241.29	R
P	82	After F.O.	1649	212.83	R
P	83	After F.O.	638	297.05	B
P	84	After F.O.	814	270.98	R
P	85	After F.O.	113	421.37	B
P	86	After F.O.	665	294.16	B
P	87	After F.O.	271	369.13	B
P	88	After F.O.	350	330.49	B
P	89	After F.O.	509	315.72	B
P	90	After F.O.	701	285.18	R
P	91	After F.O.	723	291.33	R

B.2. Experimental result used in Chapter 6**Table B.2.1 Experiments for investigating the correlation between gas concentrations to the occurrence of backdraught**

Case no. (PP)	Ignition type (N/P)	Burning time (min)	Opening width	Time of closure (s)	TC-1003 (°C)	CO (%)	CO ₂ (%)	CO/CO ₂ ratio	Result (B,R or E)
1	N	8	0.4	26	385.57	0.58	7.64	0.076	E
2		8.5	0.4	30	384.67	0.59	7.16	0.082	B
3		9	0.4	37	360.48	0.52	4.08	0.127	E
4		9	0.4	32	378.74	0.57	7.34	0.078	B
5		10	0.4	71	368.73	0.97	5.44	0.178	B
6		10	0.4	112	349.71	1.76	7.25	0.243	E
7		11	0.4	67	381.43	1.21	7.05	0.172	B
8		11	0.4	82	366.47	1.28	6.75	0.190	B
9		11	0.4	113	356.17	1.93	7.06	0.273	B
10		11	0.4	116	348.27	1.85	6.87	0.269	E
11		12	0.4	132	360.33	1.24	5.53	0.224	E
12		12	0.4	94	380.01	2.26	7.69	0.294	B
13		12	0.4	127	358.81	1.56	5.59	0.279	B
14		13	0.4	149	359.79	2.23	7.46	0.299	B
15		13	0.4	152	369.85	3.03	6.42	0.472	B
16		14	0.4	238	350.81	3.77	8.05	0.468	B
17		14	0.4	277	340.29	3.38	7.58	0.446	E
18		After F.O.	0.4	273	359.57	3.56	7.56	0.471	B
19		After F.O.	0.4	298	356.42	2.42	6.55	0.369	B
20		After F.O.	0.4	334	340.21	2.57	5.44	0.472	E
21		After F.O.	0.4	298	349.75	2.77	6.84	0.405	B
22		After F.O.	0.4	188	370.04	3.20	6.11	0.524	B
23		After F.O.	0.4	378	345.24	5.22	6.56	0.796	E
24		After F.O.	0.4	368	334.77	3.53	7.18	0.492	E
25		After F.O.	0.4	275	360.98	3.47	7.91	0.439	B
26	P	9	0.4	52	367.95	0.80	6.40	0.125	R
27		11	0.4	124	337.54	1.79	6.92	0.259	R
28		12	0.4	95	365.87	1.86	6.81	0.273	R
29		12	0.4	148	338.79	2.57	7.41	0.347	R
30		12	0.4	78	383.91	0.57	2.19	0.260	R
31		13	0.4	234	341.11	3.34	8.13	0.411	B
32		After F.O.	0.4	382	329.63	3.16	6.94	0.455	B
33		After F.O.	0.4	474	316.67	2.72	7.60	0.358	B

B.3. Experimental result used in Chapter 7

Table B.3.1 Experiments for investigating the correlation between temperatures to the delay time of backdraught/ fire reignition (PP, without pilot spark)

Case no. (PP)	Ignition type (N/P)	Burning time (min)	Opening width	Time of closure (s)	TC-1003 (°C)	Delay time of BD/Reignition (s)
N-P-1	N	9.5	0.4	30	387.16	3.90
N-P-2		9.75	0.4	60	354.12	5.17
N-P-3		9.75	0.4	55	346.64	5.52
N-P-4		9.75	0.4	32	382.65	3.93
N-P-5		10	0.4	30	387.43	3.93
N-P-6		10	0.4	60	351.89	4.69
N-P-7		10	0.4	59	385.93	4.76
N-P-8		10	0.4	91	352.52	5.07
N-P-9		10	0.4	52	342.28	5.48
N-P-10		10	0.4	56	358.76	4.83
N-P-11		10	0.4	71	368.73	4.21
N-P-12		11	0.4	113	346.82	6.28
N-P-13		11	0.4	67	381.43	4.31
N-P-14		11	0.4	82	366.47	4.83
N-P-15		11	0.4	113	356.17	6.52
N-P-16		12	0.4	60	435.97	3.10
N-P-17		12	0.4	90	379.04	3.10
N-P-18		12	0.4	120	362.49	4.86
N-P-19		12	0.4	175	343.53	7.34
N-P-20		12	0.4	86	348.15	5.79
N-P-21		12	0.4	94	380.01	5.00
N-P-22		12	0.4	127	358.81	8.52
N-P-23		13	0.4	152	347.16	6.52
N-P-24		13	0.4	149	359.79	6.00
N-P-25		13	0.4	152	369.85	5.31
N-P-26		14	0.4	247	347.42	8.90
N-P-27		14	0.4	238	350.81	10.14
N-P-28		After F.O.	0.4	303	341	11.69
N-P-29		After F.O.	0.4	260	349.95	10.21
N-P-30		After F.O.	0.4	244	365.12	7.97

N-P-31	After F.O.	0.4	333	336.52	10.24
N-P-32	After F.O.	0.4	279	337.85	9.21
N-P-33	After F.O.	0.4	293	340.58	9.76
N-P-34	After F.O.	0.4	328	348	9.59
N-P-35	After F.O.	0.4	367	356.15	9.97
N-P-36	After F.O.	0.4	273	359.57	6.59
N-P-37	After F.O.	0.4	298	356.42	7.76
N-P-38	After F.O.	0.4	298	349.75	10.00
N-P-39	After F.O.	0.4	188	370.04	7.10
N-P-40	After F.O.	0.4	275	360.98	9.48
N-P-41	After F.O.	0.4	154	404.64	5.69
N-P-42	After F.O.	0.4	32	536.38	2.79
N-P-43	After F.O.	0.4	120	437.82	3.66
N-P-44	After F.O.	0.4	60	484.57	3.14
N-P-45	After F.O.	0.4	86	451.37	3.00
N-P-46	After F.O.	0.4	116	432.27	3.72
N-P-47	After F.O.	0.4	120	408.82	3.86
N-P-48	After F.O.	0.4	180	387.11	5.66
N-P-49	After F.O.	0.4	217	378.45	5.86

Table B.3.2 Experiments for investigating the correlation between temperatures to the delay time of backdraught/ fire reignition (PP, with pilot spark)

Case no. (PP)	Ignition type (N/P)	Burning time (min)	Opening width	Time of closure (s)	TC-1003 (°C)	Delay time of BD/Reignition (s)
P-P-1	P	10	0.4	170	300.63	2.72
P-P-2		10	0.4	156	312.29	1.03
P-P-3		10	0.4	78	330.12	1.79
P-P-4		11	0.4	164	314	1.79
P-P-5		11	0.4	132	330.34	1.66
P-P-6		12	0.4	240	301.59	1.59
P-P-7		12	0.4	198	314.5	1.66
P-P-8		12	0.4	207	303.79	1.48
P-P-9		12	0.4	155	331.81	1.72
P-P-10		12	0.4	167	330.26	1.76
P-P-11		12	0.4	52	367.95	1.38
P-P-12		12	0.4	124	337.54	1.34

P-P-13		12	0.4	95	365.87	1.45
P-P-14		12	0.4	148	338.79	1.34
P-P-15		12	0.4	78	383.91	2.14
P-P-16		13	0.4	327	301.43	1.38
P-P-17		13	0.4	285	329.4	2.55
P-P-18		14	0.4	314	315.79	1.48
P-P-19		14	0.4	393	300.41	2.17
P-P-20		14	0.4	458	295.37	2.31
P-P-21		14	0.4	234	341.11	1.76
P-P-22		After F.O.	0.4	1247	241.29	1.59
P-P-23		After F.O.	0.4	1649	212.83	1.93
P-P-24		After F.O.	0.4	638	297.05	1.72
P-P-25		After F.O.	0.4	814	270.98	2.00
P-P-26		After F.O.	0.4	665	294.16	1.55
P-P-27		After F.O.	0.4	271	369.13	2.86
P-P-28		After F.O.	0.4	350	330.49	1.62
P-P-29		After F.O.	0.4	509	315.72	1.59
P-P-30		After F.O.	0.4	701	285.18	1.72
P-P-31		After F.O.	0.4	723	291.33	2.07
P-P-32		After F.O.	0.4	382	329.63	2.69
P-P-33		After F.O.	0.4	474	316.67	1.90

Table B.3.3 Experiments for investigating the correlation between temperatures to the delay time of backdraught/ fire reignition (HDPE, without pilot spark)

Case no. (HDPE)	Ignition type (N/P)	Burning time (min)	Opening width	Time of closure (s)	TC-1003 (°C)	Delay time of BD/Reignition (s)
N-HDPE-1	N	After F.O.	0.4	209	397.75	1.69
N-HDPE-2		After F.O.	0.4	256	380.3	1.90
N-HDPE-3		After F.O.	0.4	328	349.93	2.48
N-HDPE-4		After F.O.	0.4	281	349.94	2.41
N-HDPE-5		After F.O.	0.4	373	330.28	8.48
N-HDPE-6		After F.O.	0.4	446	321.48	29.76

B.4. Experimental result used in Chapter 8

Table B.4.1 Experiments for investigating the correlation between opening sizes and the delay time of backdraught/ fire reignition (PP, without pilot spark)

Case no. (PP)	Ignition type (N/P)	Original width	Opening width(m)	Opening area (m ²)	Height (m)	Delay time of BD/Reignition (s)
N-PP-0.4-1	N	0.4	0.13	0.053	0.133	15.79
N-PP-0.4-2	N	0.4	0.2	0.080	0.133	13.66
N-PP-0.4-3	N	0.4	0.1	0.040	0.133	21.24
N-PP-0.4-4	N	0.4	0.08	0.032	0.133	22.59
N-PP-0.4-5	N	0.4	0.07	0.028	0.133	39.48
N-PP-0.4-6	N	0.4	0.05	0.020	0.133	45.69
N-PP-0.4-7	N	0.4	0.266	0.106	0.133	9.97
N-PP-0.4-8	N	0.4	0.4	0.160	0.133	7.10
N-PP-0.4-9	N	0.4	0.04	0.0053	0.133	n/a
N-PP-0.4-10	N	0.4	0.04	0.0053	0.133	n/a
N-PP-0.4-11	N	0.4	0.04	0.0053	0.133	n/a
N-PP-0.35-1	N	0.35	0.350	0.123	0.133	8.17
N-PP-0.35-2	N	0.35	0.175	0.061	0.133	12.69
N-PP-0.35-3	N	0.35	0.117	0.041	0.133	21.34
N-PP-0.35-4	N	0.35	0.030	0.011	0.133	n/a
N-PP-0.35-5	N	0.35	0.030	0.011	0.133	n/a
N-PP-0.35-6	N	0.35	0.030	0.011	0.133	n/a
N-PP-0.35-7	N	0.35	0.030	0.011	0.133	n/a
N-PP-0.256-1	N	0.256	0.256	0.066	0.133	7.38
N-PP-0.256-2	N	0.256	0.128	0.033	0.133	13.76
N-PP-0.256-3	N	0.256	0.064	0.016	0.133	23.00
N-PP-0.256-4	N	0.256	0.096	0.025	0.133	15.28
N-PP-0.256-5	N	0.256	0.044	0.011	0.133	65.00
N-PP-0.256-6	N	0.256	0.188	0.048	0.133	11.90
N-PP-0.256-7	N	0.256	0.03	0.004	0.133	60.00
N-PP-0.256-8	N	0.256	0.028	0.0037	0.133	n/a
N-PP-0.256-9	N	0.256	0.025	0.0033	0.133	n/a
N-PP-0.256-10	N	0.256	0.025	0.0033	0.133	n/a

Table B.4.2 Experiments for investigating the correlation between opening sizes and the delay time of backdraught/ fire reignition (PP, with pilot spark)

Case no. (PP)	Ignition type (N/P)	Original width	Opening width	Opening area (m ²)	Height (m)	Delay time of BD/Reignition (s)
P-PP-0.4-1	P	0.4	0.4	0.160	0.133	1.94
P-PP-0.4-2	P	0.4	0.27	0.107	0.133	9.14
P-PP-0.4-3	P	0.4	0.13	0.053	0.133	15.48
P-PP-0.4-4	P	0.4	0.09	0.036	0.133	18.00
P-PP-0.4-5	P	0.4	0.05	0.020	0.133	54.00
P-PP-0.4-6	P	0.4	0.07	0.028	0.133	27.62
P-PP-0.35-1	P	0.35	0.350	0.123	0.133	2.34
P-PP-0.35-2	P	0.35	0.175	0.061	0.133	10.52
P-PP-0.35-3	P	0.35	0.100	0.035	0.133	14.00
P-PP-0.35-4	P	0.35	0.070	0.025	0.133	16.52
P-PP-0.256-1	P	0.256	0.256	0.066	0.133	1.59
P-PP-0.256-2	P	0.256	0.192	0.049	0.133	4.14
P-PP-0.256-3	P	0.256	0.128	0.033	0.133	6.24
P-PP-0.256-4	P	0.256	0.220	0.056	0.133	3.38
P-PP-0.256-5	P	0.256	0.060	0.015	0.133	11.17

Table B.4.3 Experiments for investigating the correlation between opening sizes and the delay time of backdraught/ fire reignition (PP, double the height of the opening)

Case no. (PP)	Ignition type (N/P)	Original width	Opening width	height (m)	Opening area (m ²)	Delay time of BD/Reignition (s)
N-PP-D-0.4-1	N	0.4	0.200	0.266	0.0532	7.00
N-PP-D-0.4-2	N	0.4	0.1	0.266	0.0266	8.31
N-PP-D-0.4-3	N	0.4	0.05	0.266	0.0133	9.14
N-PP-D-0.4-4	N	0.4	0.04	0.266	0.01064	11.38
N-PP-D-0.4-5	N	0.4	0.020	0.266	0.00532	18.31
N-PP-D-0.4-6	N	0.4	0.010	0.266	0.00266	21.55