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An experimental study on backdraught: the dependence on temperature

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ABSTRACT

This paper presents the results of a series of reduced scale experiments to investigate the temperature conditions leading to backdraught in a fire compartment (0.8m x 0.4m x 0.4m), 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 auto-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.

KEYWORDS: backdraught, temperature, auto-ignition, piloted ignition

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, Fleishmann *et al.* [2][3][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][6][7], using an apparatus half the size of Fleishmann'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][3][4][8][9][10][11][12][13][14][15][16][17][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.

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 Fig. 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.

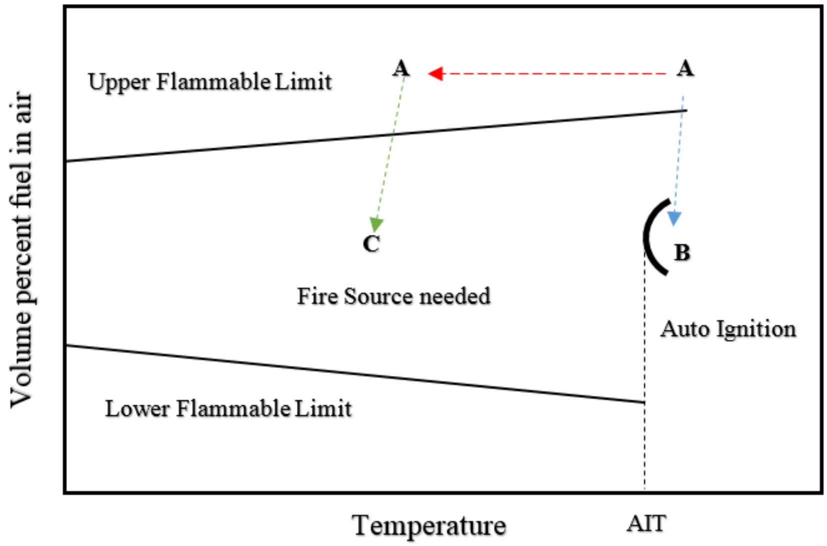

Fig 1. Flammability limits change with temperature.
(Adapted from Zabetakis [20])

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.

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].

In the present study, a small scale fire compartment (0.8m × 0.4m × 0.4m) was designed and built for backdraught research, see Fig. 2 and 3. It is instrumented with 7 thermocouple trees (24 type K thermocouples in total). TC trees 3 and 6 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. Trees 2 and 4 are positioned on either side of tree 3, halfway between the centreline of the compartment and the wall. Similarly, trees 5 and 7 are positioned on either side of tree 6. Trees 2, 4, 5 & 7 have TCs at 0.1, 0.2 and 0.3 m below the ceiling. Tree 1 is positioned in line with trees 2 and 5, 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 0.2m × 0.2m × 0.05 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 °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.

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 × 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.

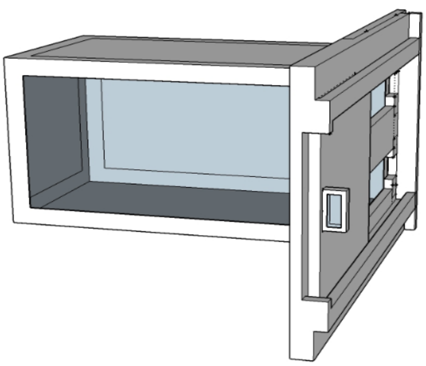

Fig 2. Test compartment

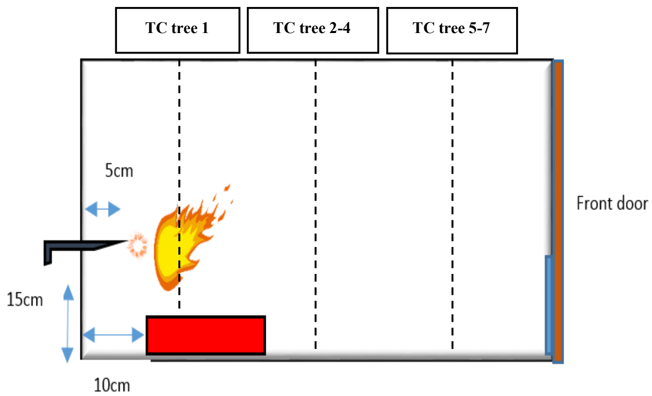

Fig 3. Spark apparatus (side view)

Design fire

In order to simulate a realistic backdraught phenomenon, a solid fuel was used as a fire source. 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.

Fig 4. 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.

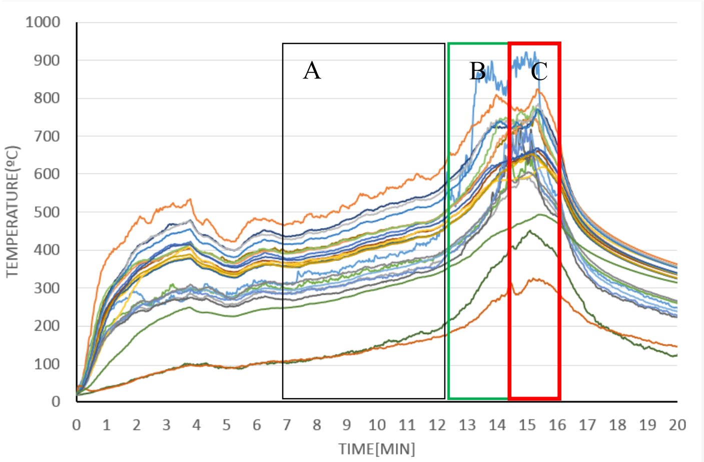

Fig 4. Free burn of the design fire

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 Fig. 5. 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.

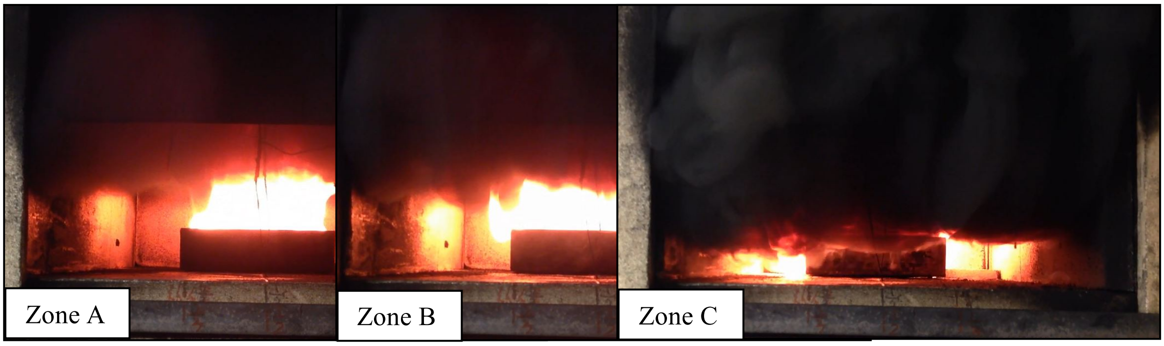

Fig 5. Development of the design fire

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 Fig. 6.

In each of these three fire scenarios, we observed a consistent and repeatable temperature decline 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.

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, we can identify trends in the temperature dependence of backdraught, independent of questions of gas concentration / composition.

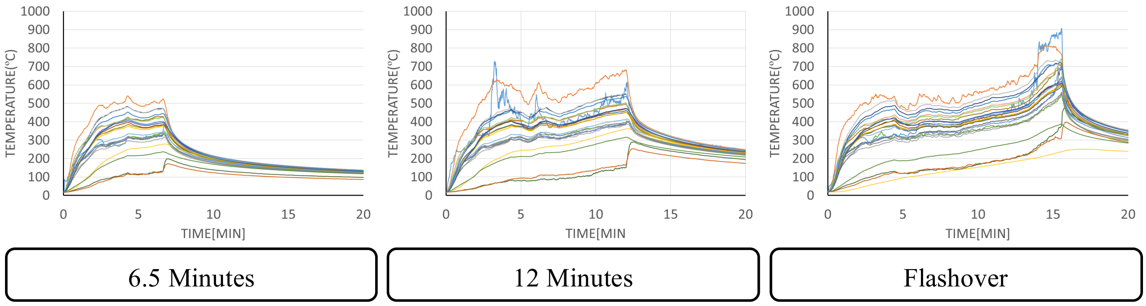

Fig 6. Temperature histories (close the door at 6.5min, 12min, and after flashover)

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.

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. Fig. 7 presents a typical temperature plot for a test that did exhibit backdraught.

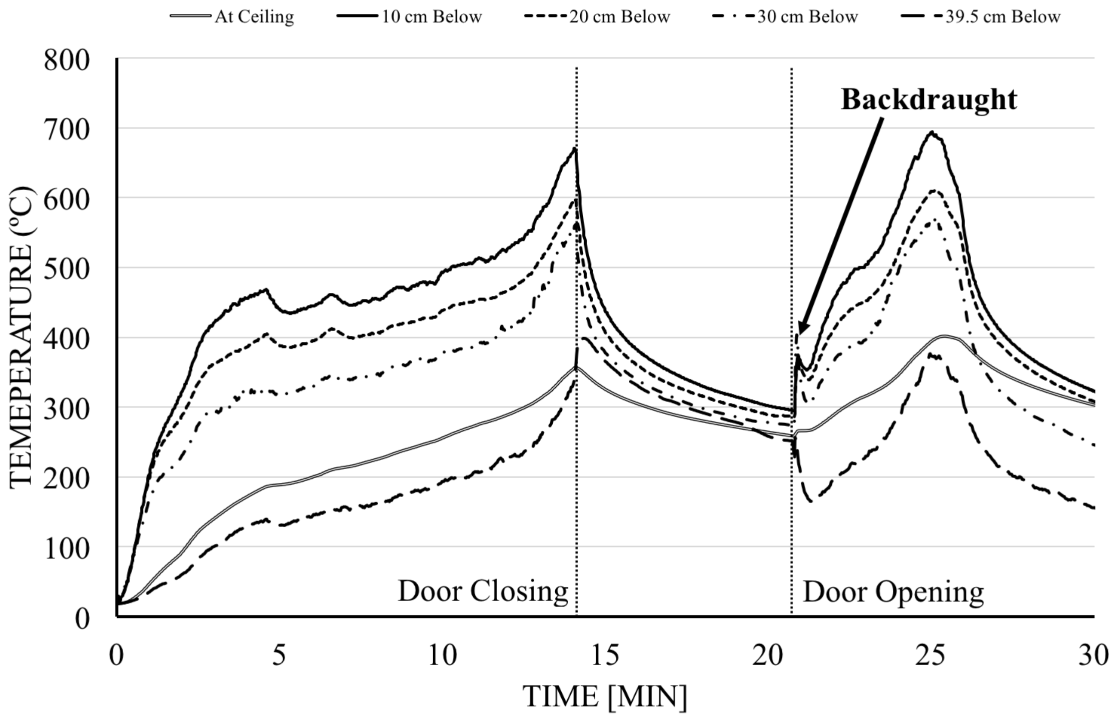

Fig 7. Typical temperature variations with time

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 we quote 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 Fig 8. 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 Fig. 8 represent experiments where backdraught occurred, and the unfilled triangles indicate no backdraught occurring.

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 TC1003 was over 350°C. From the free burn tests we know 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.

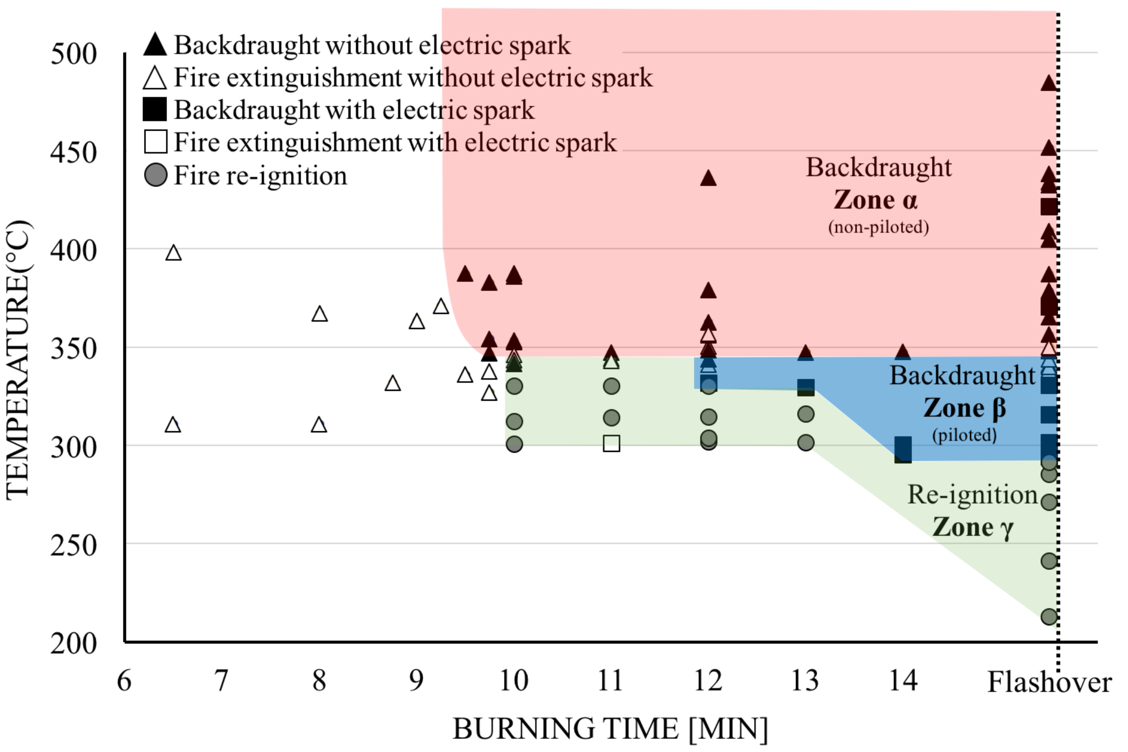

Fig 8. Results of backdraught testing

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 Fig. 8 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 Fig. 8.

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 Fig. 9. 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.

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 Fig. 8) 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.

Fig 9. Testing leaked gases

Fig 10. The electric spark ignites the unburned gases

Characteristics of backdraught- with and without electric spark

Having identified that TC1003 being 350°C is critical for backdraught, we compared the development of backdraught in three difference cases, 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 Fig. 11, 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.

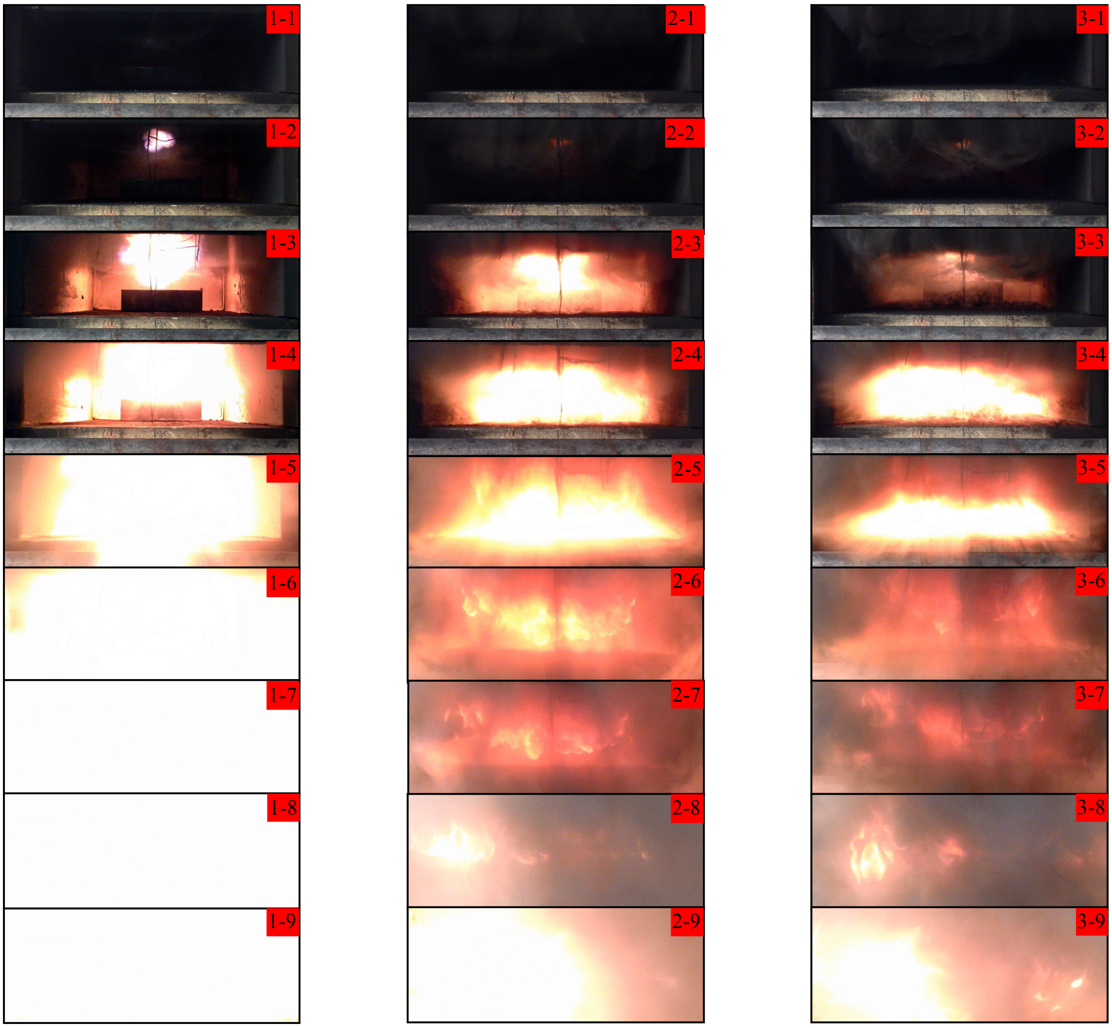

Fig 11. Development of backdraught (front view)

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.)

Auto-ignition point & fire point

From the experimental results, we can conclude 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 auto-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.

The relationship of backdraught delay time and gravity current

So far we have considered the occurrence (or not) of backdraught, but have not discussed 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 Fig. 4) was only 1 second. As conditions tended towards flashover (i.e. zone B in Fig. 4) the average delay was 2.7s, while for experiments where the door was closed after flashover (i.e. zone C in Fig. 4) the average delay was 3.2s. The corresponding average delay times for the auto-ignition tests were 5.1, 7.5 and 7.2, respectively.

According to Fleishmann 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 0.7s and 1.0s. 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 lengthscale, 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 we only use the time of gravity current, we may underpredict the occurrence time of backdraught. 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.

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 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 Fig. 12. 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. 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.

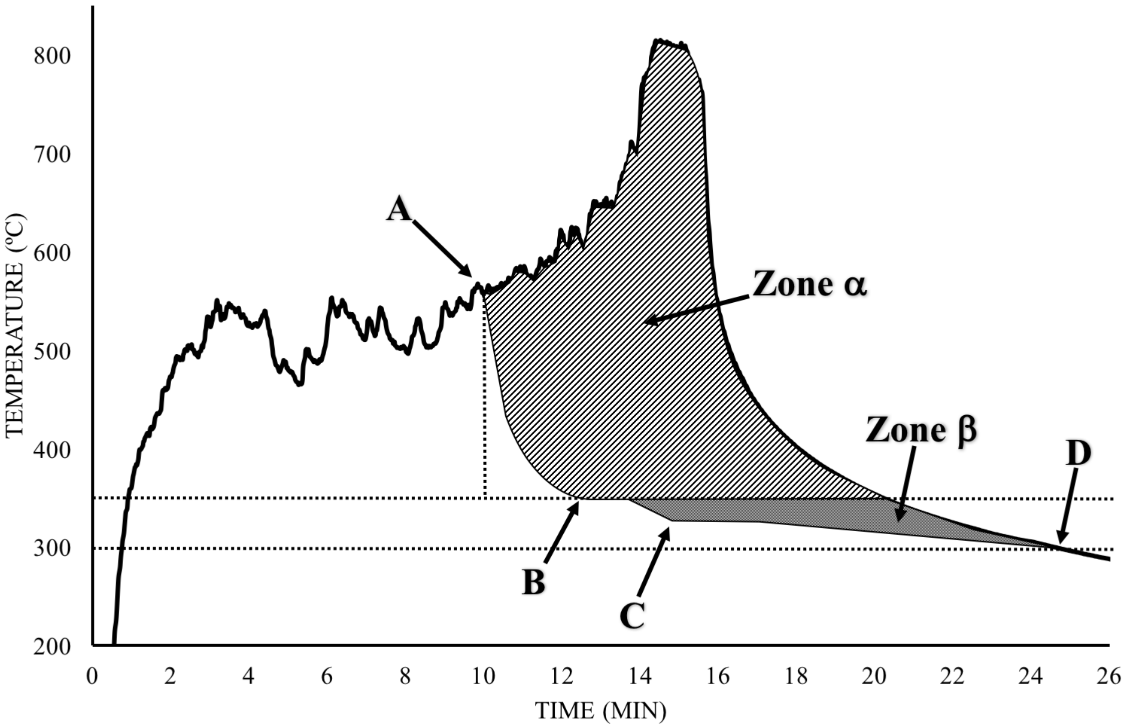

Fig 12. Temperature hot zones for backdraught. Temperature data from TC1003.

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 an auto-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.

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. 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 we can 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 Fig 12 connecting points A, B, C and D.

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