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Observations on the delay time of backdraught in the absence of a pilot source

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ABSTRACT

Most backdraught studies to date have used gaseous fuels and piloted ignition scenarios. In such circumstances the delay between the opening of the compartment door and the onset of backdraught is entirely dependent on the time taken for the gravity current to extend from the open doorway to the location of the ignition source, typically on the opposite wall in experimental studies. Few studies have investigated backdraught in the absence of a pilot source. A series of reduced scale backdraught tests have been carried out using solid polypropylene and polyethylene fuel sources, without a pilot source being present. The observed backdraught delay times are considerably longer than the times suggested in the literature, based on the velocity of the gravity current. The delay times are shorter at higher temperatures, but vary with the chemistry of the fuel as well as the temperature and geometry of the compartment. A simple theory of auto-ignition chemistry is presented to explain the observations.

KEYWORDS: compartment fires, backdraught, underventilated fires, ignition.

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 unresolved issues in the field of fire science. Research has so far explained the mechanisms involved in backdraught, as will be discussed, but rigorous definitions of instances where backdraught can occur, and detailed definitions of backdraught dynamics remain 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. 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 sometimes due to the intervention of fire-fighters, a backdraught may occur. 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. [1,2,3] 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 primary mechanisms of the phenomenon, and identified experimentally what fire-fighters had previously observed anecdotally, that there is always a delay between the time the compartment door is opened and the onset of backdraught. To explain this delay time, Fleischmann et al. observed, studied and quantified the "gravity current" phenomenon using compartment fire experiments [1] and salt water modelling techniques [4]. Subsequently, a number of studies investigating the gravity current have been carried out, using full scale fire experiments [5], reduced scale apparatuses [6], salt water modelling [7] and computational fluid dynamics models [8]. The consensus among this literature is that the delay time of backdraught is dependent on the velocity of the gravity current, which itself is dependent on the density difference between the hot compartment gases and the cooler inflowing air.

In general, the velocity of the gravity current is:

$$v_{GC} = v^* \sqrt{\frac{\Delta\rho}{\rho} gH} \quad (1)$$

where H is the height of the compartment, g is the acceleration due to gravity, ρ is the density of the gases in the compartment, $\Delta\rho$ is the density difference between the compartment gases and the inflowing air, and v^* is the non-dimensional velocity; this varies with compartment opening geometry and was quantified by Fleischmann et al. [4] as 0.44 for a full side opening, 0.35 for a door, 0.32 for a slot opening and 0.22 for a window.

Most studies assume, and some have shown, that the delay time of backdraught is the time taken for the gravity current to travel from the compartment opening to the rear wall of the compartment. This has generally been observed because most backdraught studies have had a pilot source in the compartment, positioned on the rear wall of the compartment, directly opposite the opening.

However, it has also been shown that backdraught does not require the presence of a pilot spark [9]. The present study was carried out to experimentally measure the delay time of backdraught in a compartment when no pilot source is present. This scenario may be more representative of real backdraught conditions than situations with a pilot spark present.

EXPERIMENTAL

A small scale fire compartment (0.8m × 0.4m × 0.4m) was designed and built for backdraught research, see Figs. 1 and 2. It was instrumented with 24 K type thermocouples distributed across 7 thermocouple trees. The configuration of these is detailed in [9] and need not be repeated here. The fuel was contained in a steel tray, which is 0.2m × 0.2m × 0.05 m, and was positioned 100 mm 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.

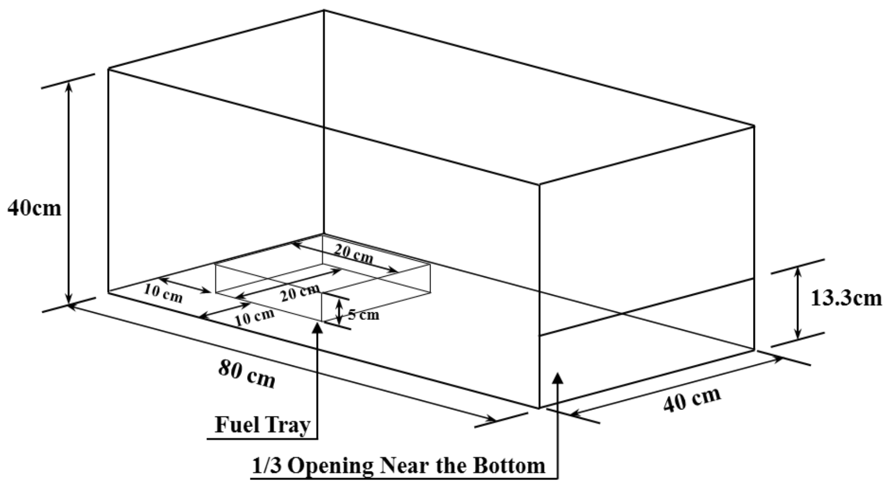

Fig. 1. Schematic of the test compartment

Fig. 2. Photographs of the test compartment

There were three removable baffles which could 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. Experiments where the opening size was varied have been published elsewhere [10]. 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.

In order to generate realistic backdraught phenomena, solid fuels were used as the fire source. For most of the experiments described here, this was Polypropylene (PP) in the form of pellets (approx. 3 mm diameter). A short series of tests using High Density Polyethylene (HDPE) in the form of thin strips (20 mm × 100 mm × 2 mm) is also presented. To aid ignition and repeatability, a small quantity of n-Heptane (C_7H_{16}) was used as accelerant to start and establish the burning process. Initial tests were carried out to identify the optimum fuel load for these experiments. It was determined that 300 g of PP with 150 mL of n-Heptane was sufficient to achieve flashover conditions in the compartment, and that most of the liquid accelerant was consumed in the first 5 minutes of burning. 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. The fire transitioned to flashover after about 13 minutes. With 300 g of HDPE fuel the fire growth was slightly slower, with the steady growth phase lasting from 13 to 18 minutes after ignition, and reaching flashover after about 20 minutes. The primary focus of this research concerns what happens when the door is closed during the steady growth or post-flashover time frames, is kept closed for a variable period of time, and is then opened again.

It has previously been shown that backdraught behaviour correlates better using the maximum recorded temperature in the compartment at the time of door closure or opening, rather than the average temperature [9]. The highest temperature in the compartment was consistently observed directly above the fuel tray, and it is this temperature value which will be used as the characteristic compartment temperature in the discussion that follows.

RESULTS

Results show that when the door is closed, the fire self-extinguishes within seconds, and the overall temperature in the compartment begins to diminish (although the temperature at low level increases in the first few seconds). Due to the insulating nature of the compartment construction, the temperatures take hundreds of seconds to diminish to ambient. Fig. 3. Shows the temperature variation in the compartment after the door was closed at 12 minutes after ignition of a PP fire, and the door was kept closed. In Fig. 3 the red line represents the maximum temperature in the compartment, near the ceiling at the rear, and the grey line represents a thermocouple near the floor and near the door.

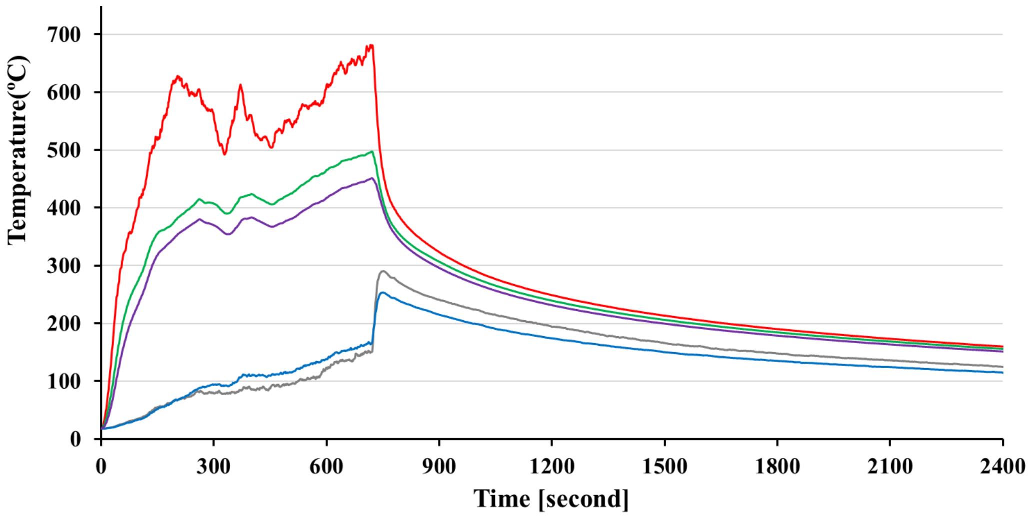

Fig. 3. Selected temperatures in the compartment when the door is kept closed.

When the temperatures in the compartment are high, the fuel will continue to pyrolyse, but the evolved gases cannot burn as there is insufficient oxygen present. If/when the temperature drops below the pyrolysis temperature, no further gaseous fuel will be produced and the compartment will enter a phase entirely dominated by cooling. The compartment is reasonably well sealed when closed, so when the door is closed the proportion of fuel in the gas phase will not diminish significantly unless condensation occurs.

Attempts were made to quantify the rate of production of the pyrolysis gases and the duration of the pyrolysis phase, using mass-loss measurements; placing the fuel tray on a platform on a spindle which passed through the floor of the compartment, and which was attached to a loadcell below. Unfortunately, the small variations in mass following the closure of the door were almost completely masked by errors and noise in the data due to the experimental configuration. So far, it has not been possible to quantify the duration of the pyrolysis phase or distinguish it from the cooling phase. The most reliable data obtained so far, for door closures made at around flashover for both fuels, 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.

In this test series two parameters were varied to affect the compartment conditions at the time of door opening: the pre-burn duration and the duration of door closure. Varying the pre-burn time controls the temperature in the compartment at the start of the pyrolysis phase (and hence the length of the pyrolysis phase), and varying the door closure time controls the temperature of the compartment at the time of door opening.

Results from a series of 21 tests using PP fuel and 6 tests using HDPE fuel are presented in Fig. 4. Tests using PP are indicated using triangles, tests with HDPE are indicated using circles. The trendlines have been added to the data for clarity. The data are plotted as maximum temperature in the compartment at the time of door opening, versus the observed backdraught delay time.

It is clear from the data that there are reasonably well defined trends in behaviour; at higher temperatures the delay times are short, but at lower temperatures the delays can be much longer. Previous research has shown that backdraught will not occur for PP in the absence of a pilot flame at temperatures below about 340°C and below about 320°C for HDPE [11,12].

It is also clear from the data that there are two distinct trends for the different fuels, so the delay time is seen to be clearly dependent on the chemistry of the fuel, not merely the temperature of the compartment.

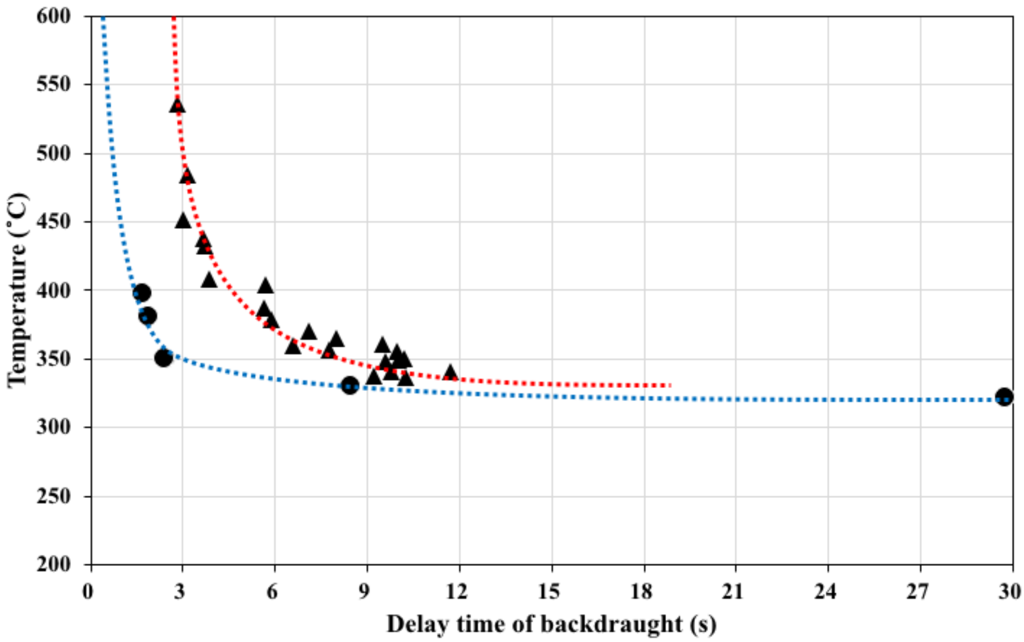

Fig. 4. Backdraught delay time vs. maximum temperature in the compartment at the time of door opening. (Note there are two HDPE data points at 350°C which are almost exactly the same.)

DISCUSSION

At first glance, the data for these non-piloted experiments appears to be consistent with the theory of backdraught delay time established in the literature using piloted experiments. Superficially, the trends are the same, with shorter delays at high temperatures and longer delays at lower temperatures. However, the delays shown in Fig. 4 do not correspond to the gravity current travel time. Using Equn. (1) it can be shown that for the small compartment used here, at temperatures around 350°C, the gravity current will reach the rear wall of the compartment in less than two seconds. Even when it is acknowledged that, due to thermal stratification, the temperatures near the floor of the compartment may be up to 100°C lower than the characteristic maximum temperature plotted here, the corresponding slower gravity current time is still less than 2.2 s. This is notably shorter than the observed delay times for HDPE fuel, and considerably shorter than the delay time for PP fuel. It is clear that something other than the transit of the gravity current to the back of the compartment determines the backdraught delay.

Results for piloted backdraught experiments, carried out in the same apparatus, have been published previously [9,10,11,12]. The observed backdraught delay in these experiments is broadly consistent with the theory of backdraught delay due to gravity current transit. Something else is determining the backdraught delay time when no pilot source is provided.

Analysis of the pyrolysis products from PP and HDPE samples in low oxygen conditions have shown that the dominant pyrolysis species for PP are from the pentane family, while PE pyrolyses to members of the hexane family (identified by FTIR spectrometry) [11,12]. Auto ignition of pentane requires generally higher temperatures than those for hexane.

For mixtures above the auto-ignition temperature for both fuels, for any given initial temperature, more mixing with the inflowing air is required for pentane to auto-ignite than for hexane. This is perhaps best explained using a flammability diagram, see Fig. 5. Suppose the initial fuel mixture in the closed compartment, which is above the upper flammability limit (UFL), is 300°C. In order to reach a flammable mixture which is above the auto-ignition limit, a pentane mixture requires more air, and more mixing time with the air, to form an auto-ignitable flammable mixture than a hexane mixture. This is best visualised by following the arrow on Fig. 5, the conditions for auto-ignition of a hexane mixture would clearly be reached before those for a pentane mixture. Of course, the pyrolysis products present here are not pure pentane or hexane, the mixtures are far more complex than that, but the general trends will be the same.

This explains the two clearly distinct trends in the data. All other factors being equal, the pyrolysis products from PP fuel need more mixing time, and to reach a mixture closer to stoichiometric than with the products from PE pyrolysis. If a pilot source is present, the different auto-ignition properties of the fuels make no difference, as the zone for piloted ignition is considerably larger, as shown. In such instances the chemistry of the fuel has less of an influence on the backdraught delay.

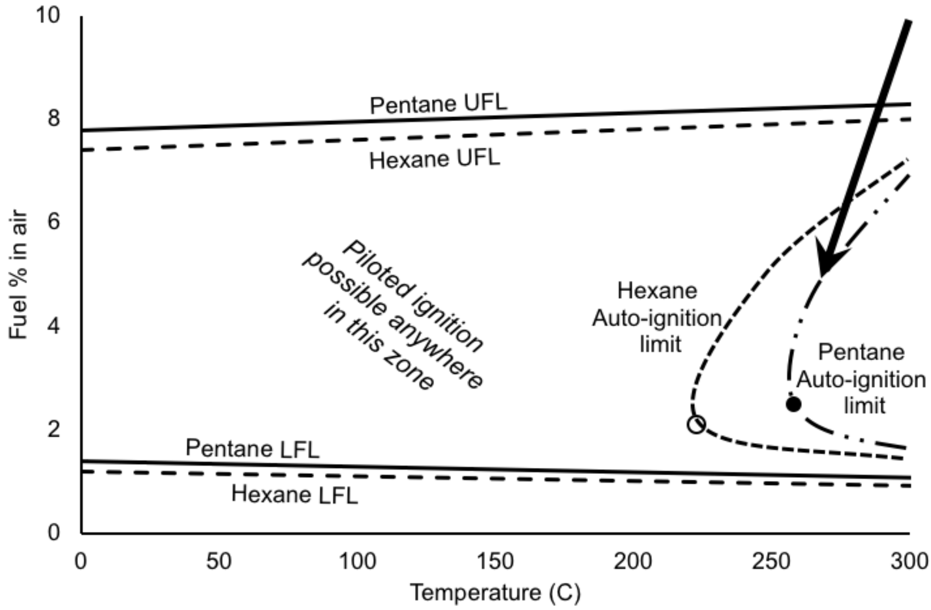

Fig. 5. Approximate representation of flammability limits and auto-ignition limits for Pentane and Hexane fuels in air. Based on data from Zabetakis [13].

CONCLUSIONS

Backdraught experiments, using polypropylene and polyethylene solid fuels, in a reduced scale apparatus, with no pilot source present, have clearly shown that the backdraught delay time is not directly related to the gravity current velocity, as in piloted ignition scenarios, but varies with the chemistry of the pyrolysis products, and gas mixing.

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