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Fully-involved fire dynamics in ceiling-vented Compartments

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ABSTRACT

Side-vented compartment fires are well described in the literature. Compartment fires with only a ceiling-vent are poorly understood in comparison. A series of 29 experiments in a reduced-scale, ceiling-vented compartment have been carried out to observe and characterise the four expected modes of burning. Ghosting flames and pool fire behaviour are both observed when the compartment temperatures are above 500°C, the former occurring at lower fuel loadings, the latter at higher fuel loadings. Pulsing behaviour is less common and exists at lower temperatures as a transition between other modes of burning. Asymmetric flow patterns can also occur with asymmetric arrangements of fuel or with very large ceiling vents.

KEYWORDS: compartment fires, post-flashover, underventilated fires, ceiling vents.

INTRODUCTION

Fire conditions in compartments with vertical side openings have been extensively researched, with significant theoretical analysis and multiple experimental studies. The fire behaviour is relatively well understood and flow through the opening has two distinct regions consisting of hot gases being exhausted from the upper segment, and cold air being entrained below. Various correlations and relationships have been derived based on this flow exchange and currently form the foundation of compartment design for fire safety [1,2].

The same cannot be said with regard to fire behaviour in compartments with only a horizontal opening in the roof. This is a more complex situation that has not been adequately explored in previous research. Due to the location of the vent, the flow exchange is complicated by buoyancy effects and the inflowing and outflowing gases compete for all parts of the vent.

Although this is a relatively immature area of research, ceiling vented compartments represent a number of real scenarios including basements and fires in the holds of ships. Subsequently, there is a need for research into fire behaviour under such conditions, to ultimately offer advice to Fire Safety Engineers for design, and to offer practical guidance to fire brigades in approaching and fighting such fires.

LITERATURE REVIEW

The SFPE Handbook has a chapter on "Vent Flows" (authored by Emmons in the 1st to 4th editions of the book, and expanded by Tanaka for the 5th edition) [3,4] which briefly addresses the question of flow through horizontal vents. This treats the issue of vent flows from a purely fluid dynamics perspective, and questions of fire dynamics are not addressed.

The earliest work systematically investigating flow through horizontal openings was carried out by Epstein [5] using the salt-water modelling technique. In these experiments there was a density difference across the opening, but no pressure or temperature differences. Epstein identified four regimes of flow which varied with the dimensions of the opening (and hence with the Froude number); these were: (i) oscillatory exchange flow, (ii) Bernoulli flow, (iii) turbulent diffusion with Bernoulli flow, and (iv) turbulent diffusion flow. Epstein & Kenton [6] advanced the study with the addition of pressure as well as buoyancy effects, they defined the conditions under which pressure overcomes the density effects to give a unidirectional flow.

In parallel to these experimental studies, Emmons [3] derived a theoretical 'standard vent model' from first principles. This was critiqued and refined by Cooper [7,8], resulting in the VENTCF2 algorithm which was incorporated into fire 'zone' models in the 1990s.

Jaluria and Tan [9] also used salt-water experiments to study flow under combined pressure and buoyancy effects, and concluded that the impact on flow velocity resulting from a unidirectional pressure-driven flow is much greater than the effect of a bi-directional, buoyancy-governed regime. They defined the buoyancy parameter, B, as a means of distinguishing between unidirectional flow and bidirectional flows. This parameter essentially represents the ratio of density difference to pressure difference, and continues to be used in more recent research, including the work of Chow and Gao [10].

Satoh *et al.* [11] conducted early research into airflow oscillation across a horizontal vent by using a thermal heat source in a top (and bottom) vented compartment. In observing temperature oscillation representative of vent flow behaviour, a relationship between the frequency of oscillation and thermal power was empirically derived. Kerrison *et al.* [12] later conducted a two-dimensional numerical analysis of the same concept and derived an expression that showed a good agreement with that identified by Satoh.

Building on this previous research, Chow and Gao [10] presented a more comprehensive theoretical analysis of the oscillation of airflow across a ceiling vent. They identified the transient flow oscillation to consist of three distinct phases: (i) linear growth, (ii) non-linear growth and (iii) stable. Whilst the equations derived appear to show some level of correlation to previous experiments using a thermal power source, it is important to note that there is still insufficient data to confirm their accuracy or even applicability when applied to vent flows for a real fire.

Takeda [13] and Tu [14] conducted some of the earliest experimental research into compartments with horizontal vent openings and real fires. In both cases, the horizontal opening and the fuel load were positioned symmetrically in the middle of the compartment.

In a series of compartment fire experiments using polymethylmethacrylate (PMMA) slabs as fuel, Takeda [13] observed two significant effects arising from the presence of a top opening. Given the position of the vent, a hot upper layer was not able to form as generally observed in a side-vented compartment, this significantly reduced the fire growth rate. Furthermore, results indicated the inflow of air was reduced to around 30-50% of the value expected for a similarly sized, side-vented compartment fire. This reduced airflow led to a reduced mass-burning rate. In those experiments where an approximately steady-state mass loss rate was achieved, a transformation in the burning mode became apparent, with evidence of a pale blue flame that detached from the fuel surface and appeared to "float" within the compartment. This burning behaviour is similar to the "ghost" flame observed by Sugawa *et al.* [15] in a side-vented compartment with restricted ventilation.

Tu [14] used a replenishing ethanol fuel system as a fire source. By varying the vent opening, three different burning scenarios were identified: (i) choked and then extinguished, (ii) erratic pulsating pool fire, and (iii) strong steady-state pool fire. Increasing vent size led to a greater mass loss rate, which tended towards a constant value for each opening size. That is, the steady burning rate is generally limited by the ventilation flow, not by the fuel properties.

Quintiere [2] comments on the inefficiency of horizontal vents at supplying air for a fire to consume, he notes that the flow through a horizontal vent modelled using Epstein's [5] empirical relationship is approximately $1/10^{th}$ that of a vertical opening of the same size. This inefficiency suggests that top-vented compartment fires may be broadly analogous to aspects of underventilated compartment fires, such as those studied by Sugawa *et al.* [15] and Utiskul *et al.* [16].

The influence of vent opening size on temperature rise was recently studied by Li et al. [17] using a heptane fuel source in a full size compartment (3m × 3m × 1.95m) with an asymmetrically located ceiling opening. In agreement with the findings of Takeda [13], this research indicated that the temperature variation in the compartment increased gradually over its height, with no clear thermal stratification layers, indicating that the gases within the compartment were relatively well mixed. This profile is notably different to the pre-flashover, side-vented compartment fire, which generally exhibits well defined hot upper and cool lower layers.

Li et al. observed that when the fire is growing, it is the fire size and not the opening size which is the most significant factor governing the maximum gas temperature in the compartment and rate of temperature rise. It is acknowledged that this study focused on a pre-flashover fire, in the early stages of fire growth, and the behaviour is thus still controlled by the fuel characteristics, and largely independent of the ventilation. The influence of varying the vent size on a fully developed regime with established compartment temperatures might be expected to yield different results, but this remains to be investigated.

Chen *et al.* [18], using the same apparatus as Li *et al.* [17], investigated the relationship between the rate of gas temperature rise in the compartment and the mass loss rate of the fuel. The study demonstrated a strong correlation between the two variables and a resulting relationship was derived between the average rate of non-dimensional temperature rise and the mass loss rate. This study, therefore, provides a valuable method of estimating the mass loss rate of a fuel based on the transient temperature profile. This is one of the first relationships that may have a practical application in predicting the fire dynamics in a top vented compartment.

Zhang et al. [19] also investigated the relationship between the rate of gas temperature rise and the heat release rate. Their theoretical analysis derived a correlation using Epstein's vent flow equation [5] considering the energy balance within the compartment. A series of experimental tests were then conducted and the results used to provide constants for the theoretical equation. They concluded that the average gas temperature rise in a ceiling vented compartment was proportional to the heat release rate to the power ⅔.

During the research conducted by Zhang *et al.* [19] and Chen *et al.* [18] experimental results have generally evidenced a uniform temperature across any horizontal plane throughout the compartment. This agrees with previous research conducted by Chen [20] and indicates that hot gases are well mixed within the compartment.

The majority of existing experimental studies focus on consistent test parameters, with little variation in the physical conditions. However, the influence of vent position has been investigated by Zhang *et al.* [21] by comparing the results obtained from an opening in the corner of the ceiling with results for the centrally positioned opening. Using a fire source of 100 kW it was evident that whilst gas temperatures for the corner opening were greater, the pressure difference and mass loss rate across the centrally positioned opening were more significant. On the basis of the observed conditions, conclusions were reached that a 'more dangerous' fire was apparent for the central opening position due to the increased pressure difference and the ejection of flames from the compartment observed.

Rodriguez [22] has identified correlations between the mass loss rate and the experimental configuration, as part of an unpublished Masters' thesis at the University of Edinburgh. Unlike other studies, Rodriguez focused on fully developed fire behaviour using wooden cribs in addition to polypropylene pellets. A correlation between the mass loss rate and the opening size was identified for both fuel types with an increase in the ventilation area proportional to an increase in the mass loss rate. The influence of varying the experimental conditions was also studied and analysis indicated that a centrally positioned fire provided a higher mass loss rate than a fire positioned in a corner or beside a wall. The limitations of this study were part of the motivation for the present study.

Finally, Chitty and Fraser-Mitchell [23] carried out three full-scale ceiling-vented compartment fire tests in 2015. The compartment was 3.6 × 3.6 × 2.4 m high, constructed of concrete blocks, and insulated with ceramic blankets. The three tests had the same fuel loading of wooden cribs, but varied in the size of the ceiling vent. There was a sealed door on one compartment wall, but results suggest it was not airtight through the experimental test campaign. The ceiling-vents were nominally 1 × 2 m, 1 × 1.5 m, and 1 × 1 m, but due to the construction of the compartment, there was a beam (wrapped in ceramic insulation) bisecting the opening in the longer dimension, which slightly reduced the opening area, splitting it into two rectangles. Temperature data and gas concentrations (O_2, CO, CO_2) were recorded, and some limited visual observations were made. In the two tests with the larger openings, the fires grew from ignition to fully involved fires, with external flaming through the ceiling vents after 23 minutes and 30 minutes, respectively. The test with the 1 m^2 opening did not exhibit external flaming. Temperatures reached a steady-state 'plateau' up to about 1000°C in the first test, about 700°C in the second test and about 600°C in the last. However, the temperature data show considerable temperature gradients between the 'front' of the compartment and the 'rear' suggesting that the 'front' door leakage played a role in the fire dynamics. The lack of visual observations of the mode(s) of burning in these tests was the other motivation for the present study

OBJECTIVES AND METHODOLOGY

Based on the literature review, above, it is apparent that different modes of burning may occur in a fully established ceiling vented compartment fire, depending on the thermal conditions in the compartment, the nature and location of the fuel, and the size and location of the opening. The aim of the experiments described here was to observe the various modes of burning and quantify the conditions under which they occur.

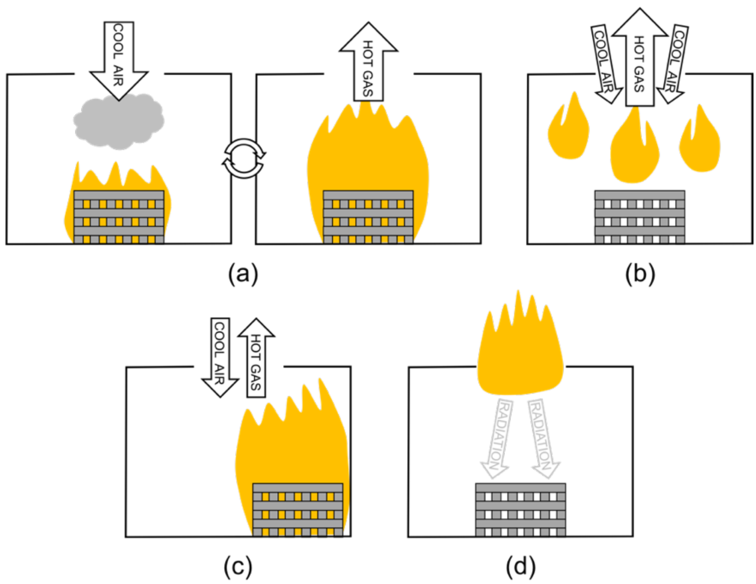

Fig. 1. Burning modes: (a) pulsating flame, (b) detached ghost flame, (c) asymmetric burning, and (d) pool fire.

The four expected modes of burning are shown schematically in Fig. 1. These are:

a) The *pulsing mode* or *pulsing diffusion flame*. This describes a burning behaviour with an oscillation between a reduced fire with an entrainment of air inward, and a period of large flames with an outward flow of hot gases.

b) The *ghost flame* or *ghosting mode*. This was expected to occur under restricted ventilation, which results in a detached flame circulating around the compartment.

c) The *asymmetric burning mode*. This was anticipated to occur under larger openings where, contrary to the other modes, there is a clear segregation between the hot outflow gases and cooler air inflow.

d) The *'pool fire' mode*. This was expected to occur at high temperatures, with high fuel loads. Under these conditions, the flames detach from the fuel and move to the opening, where there is a plentiful supply of oxygen, but radiate down to the fuel in the compartment at a sufficient intensity to maintain a supply of pyrolysis gases.

To observe and characterize these modes of burning, a test compartment was constructed with inner dimensions of 600 mm × 600 mm × 400 mm high. (This is essentially a 1/6th scale replica of the compartment used by Chitty & Fraser-Mitchell [23].) The housing was constructed from 25 mm thick ceramic fibreboard, with all joints sealed using fire cement and taped externally to minimise air leakage. The compartment also contained a 180 mm × 275 mm glass viewing panel to allow for observation during testing.

The compartment was fitted with an adjustable vertical opening on one sidewall to permit conventional side-vented flashover conditions to be achieved within the enclosure, as will be discussed below. The roof consisted of a six-hatch-system that enabled the horizontal opening area and position to be varied. Each hatch measured 200 mm × 100 mm allowing the area to be varied from 0.02 m^2 to 0.12 m^2. The apparatus is shown in Fig. 2.

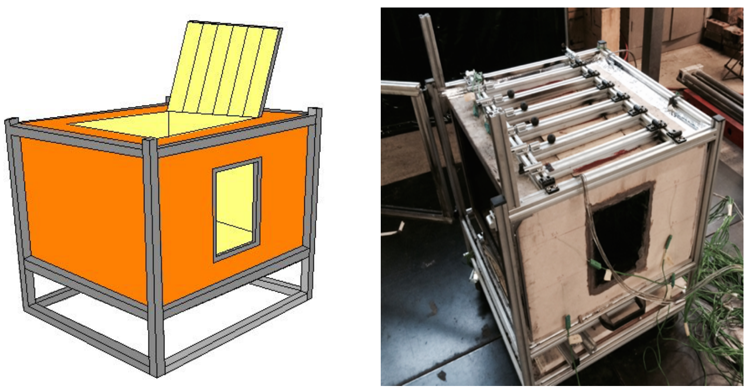

Fig. 2. Schematic and photograph of the test apparatus.

A wooden crib of Scandinavian Spruce was used in all experiments. For most experiments, the crib was constructed of 8 layers, each consisting of 4 sticks measuring 225 mm × 32 mm × 16 mm. To ensure repeatability of the tests, the wood was oven dried at 103°C for a period of 24 hours before being used. In each test small quantities of heptane soaked into rolls of tissue paper were used to ignite the cribs.

Temperatures were recorded in the compartment using four thermocouple trees each with eight semi-rigid K type thermocouples spaced equally over the height of the compartment. The trees were placed towards the corners of the compartment at positions approximately 100 mm from the adjacent walls, as shown in Fig. 3. In some tests bi-directional probes were positioned across the opening to quantify the flow, and various thin-skin calorimeters were positioned on the walls of the compartment to quantify heat flux. Results from these will not be discussed in this paper.

As the aim of this study was to observe and quantify fully-involved, post flashover fire dynamics, and does not concern the mechanism or likelihood of a ceiling vented compartment actually attaining such conditions, the fire was generally allowed to grow to 'conventional' (i.e. side-vented) flashover conditions by igniting the crib with all the ceiling vents closed, and one side of the compartment was raised to give a rectangular opening of 600 mm × 150 mm high. After about 4 minutes of burning, the compartment reached flashover conditions (that is, external flaming was established), after this, the ceiling vents were opened in the desired configuration and the side wall lowered into place.

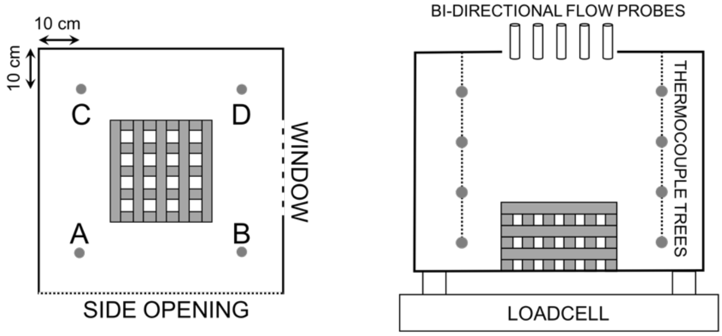

Fig. 3. Plan and side view of the compartment showing the location of the thermocouple trees

RESULTS

A total of 29 experiments were carried out as summarised in Table 1. It is not necessary to present all the data here. Fuel load, fuel position, and the number and arrangement of open ceiling vents were varied between tests. All four modes of burning were observed in the test series, some tests exhibited transitions between modes of burning as the temperatures in the compartment changed and/or the fuel began to deplete. All tests were allowed to burn to extinction, but the quantity of wood/char remaining at the end of a test varied considerably between tests. In some tests the fire self-extinguished then violently reignited after a period of 10s of seconds or sometimes minutes, these instances are denoted ‘reignition’ in Table 1.

Temperature and heat release rate (HRR) data from Test 17, a reasonably typical test, are shown in Fig. 4 (note: The temperature data come from Tree A, with TC1A being the thermocouple closest the ceiling and TC8A being the thermocouple closest to the floor). In this test, flashover occurred at about 240 s, after which the central two ceiling vents were opened, creating a 100 × 100 mm centrally located opening, and the side vent was closed.

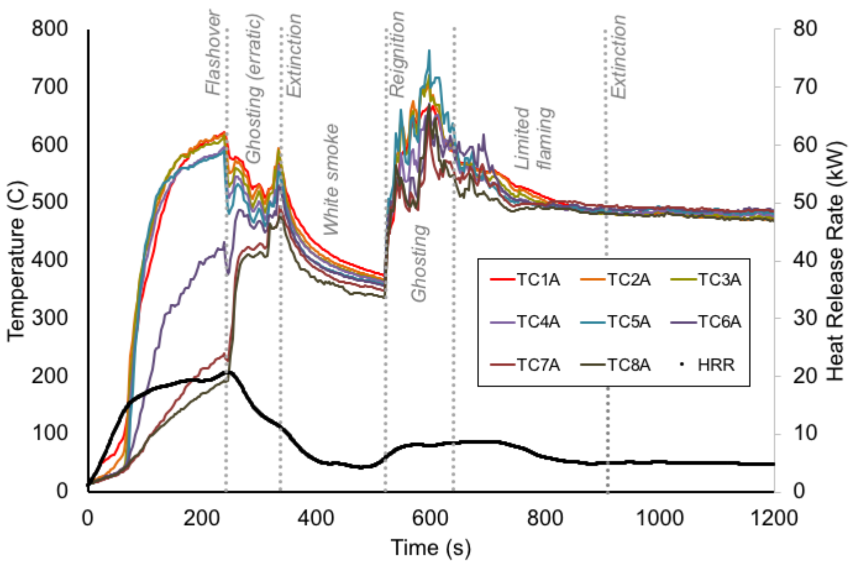

Fig. 4. Temperature and HRR data from Test 17 (double opening), with some observations.

Table 1. Summary of experiments

Test Number†	Number of vent openings‡	Number of sticks in crib#	Pulsing	Ghosting	Asymmetric	Pool	Other observations
9	2	64	X	X		X	
10	2	32		X			Reignition
11	2	32		X			
12	2	32 (side)			X		
13	2 (side)	32 (side)		X			Erratic
14	2	32 (corner)		X			
15	2	32		X			
16	2	32					No flashover
17	2	32		X			Reignition
18	2	32 (side)		X			
19	4	32			X		
20	3 (offset)	32		X			
21	1 (offset)	32	X				Reignition
22	3 (offset)	32 (side)			X		
23	2	32 (bigger sticks)		X		X	
24	2	32	X	X			
25	Varied 2 to 4	32		X	X		Reignition
26	Varied 2 to 4	32 (side)		X	X		
27	Varied 4 to 2	32		X	X		Erratic
28	Varied 3 to 4	32		X	X		
29	Varied 3 to 1	32		X			Erratic

† Tests 1 to 8 were exploratory in nature, varying number of openings and fuel configurations during tests; detailed records and observations were not kept, so these tests are not included here.
‡ Openings positioned symmetrically on the compartment, except where noted.
# Fire positioned centrally in the compartment, except where noted.

After this, as can be seen in Fig. 4, the heat release rate and temperature in the compartment both began to diminish, with ghosting flames being observed in the compartment over a period of about 90 s. These are designated ‘erratic’ ghost flames as there was some rapid but not periodic fluctuation between reduced flaming and intensified flaming, but with the flames clearly detached from the wooden crib, so this was not the pulsing behaviour expected from the literature review. While the overall temperature of the compartment diminished in this period, it should be noted that the temperature at low levels in the compartment increased until there was less than a 100°C temperature gradient across the compartment height.

Following this period of ghosting, there was a brief surge in flaming followed by flame extinction, and a column of white smoke emerged from the opening, with no obvious inflow of air into the compartment. This lasted for about 3 minutes. Without warning, this was followed by a backdraught-like smoke explosion, a rapid increase of temperature inside the compartment and a return to the ghosting flame behaviour (less erratic) over a period of about two minutes. After this, the fuel was much depleted and the flames localised around the base of the crib until final extinction.

Tests 10, 11 and 15 were carried out with the same test parameters as Test 17, resulting in similar observations, with the ghosting flame behaviour being observed within the same temperature range.

Test 24 was slightly different from Test 17, in that the ceiling vents were opened, and the side vent closed, at an earlier stage in fire development, before the compartment had attained flashover. The data from Test 24 are shown in Fig. 5.

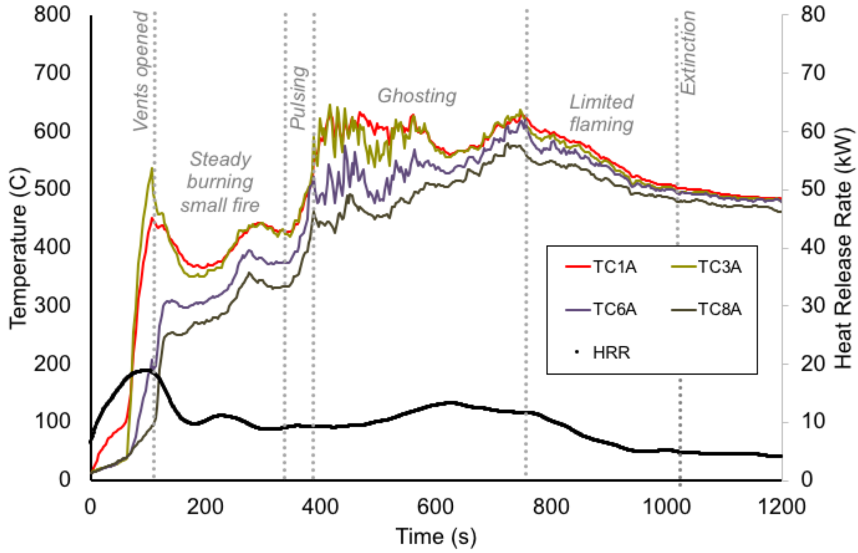

Fig. 5. Temperature and HRR data from Test 24 (double opening), with some observations.

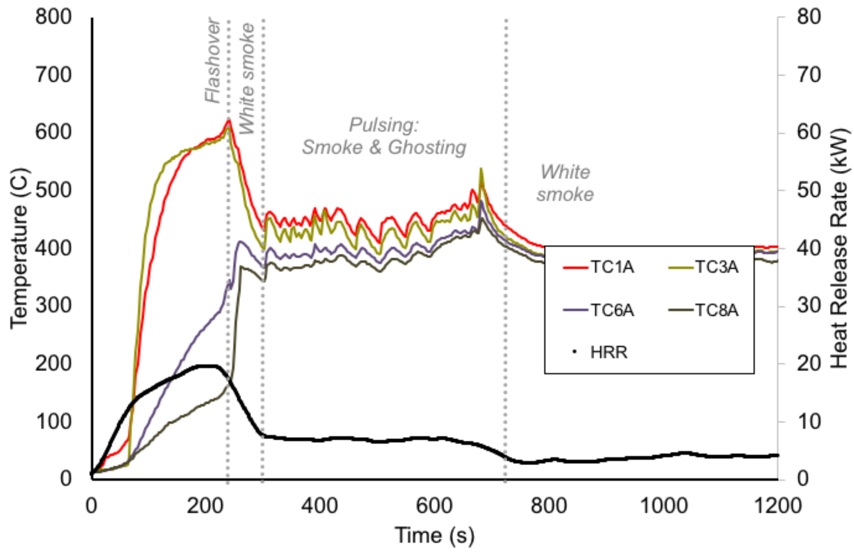

Fig. 6. Temperature and HRR data from Test 21 (single opening), with some observations.

This was one of the three tests where the pulsing regime was clearly evident. However, the pulsing period only lasted for about 30 seconds, transitioning to the ghosting regime once the compartment temperatures were in the 500 to 600°C range. The pulsing mode served to rapidly elevate the temperatures in the compartment much faster than the localised burning did. It would appear that the pulsing mode exists as a transitional mode in between localised burning and generalised burning in the form of ghosting; in some ways it may be analogous to flashover in side-vented compartments.

When smaller ventilation openings were used (i.e. when only one ceiling vent was open as in Tests 21 and 29), the pulsing mode was observed again, but in these instances the pulsing varied (somewhat erratically) between a brief outflow of white smoke with no flaming evident, and short periods of reignition followed by ghosting. In Test 21, data for which can be seen in Fig. 6, this pulsing behaviour was observed over an extended period of over 6 minutes. Consistent with the observations from Test 24, above, the temperatures in the compartment were in the 400 to 500°C range during the pulsing regime. In this instance it seems that the small ventilation opening prevented the temperature rise necessary to sustain 'steady' ghosting behaviour.

The 'pool fire' regime was only observed in the two tests with a very high fuel load, Tests 9 and 23. Data for Test 23 are presented in Fig.7. Here, there was a brief period of pulsing after the ceiling vents had been opened and the side vent closed. Once the temperatures in the compartment had stabilised, the flames moved to the opening and persisted there for over 5 minutes, with flames emerging from the opening, and no apparent inflow of air into the compartment. During this time the temperature inside the compartment increased steadily, while there was a slight diminishing of the heat release rate.

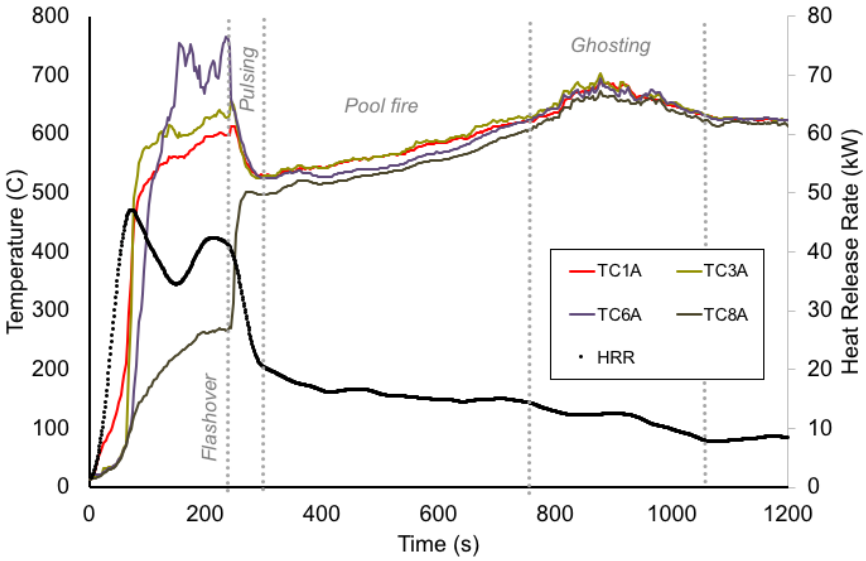

Fig. 7. Temperature and HRR data from Test 23 (double opening, larger fuel source), with some observations

At about 750 s after ignition, the rate of production of pyrolysis gases must have dropped below the critical level to sustain the pool fire mode, and the compartment transitioned to the ghosting mode until the fuel became depleted.

As expected, in fire tests where the fuel or openings were positioned asymmetrically, the asymmetrical burning mode was observed. It is of interest to note that in Test 13, where the fire was positioned under the opening, but at the side (not centrally in the compartment), asymmetric burning was not observed, and the test observations were largely similar to Test 17.

Asymmetric burning was also observed in tests with very large ceiling vents (i.e. 4 vents open), even when the fuel was positioned centrally under the opening. In these instances, the opening was considerably larger than the area (in plan) of the wood crib, so it is easy to visualise the configuration permitting inflow at the ends of the large opening and outflow at the centre of the vent. The rectangular form of the opening (as opposed to square) may promote this, but this cannot be confirmed without further testing.

DISCUSSION

A common rule of thumb for the onset of flashover in a conventional, side-vented compartment fire is when the temperature at the ceiling reaches about 600°C [1]. This temperature would seem to be critical in ceiling vented compartment fire scenarios as well. When the temperatures (at all heights) in the compartment were about 500 to 600°C, the compartment could sustain 'fully involved' ghosting fire behaviour for periods of several minutes. This scenario appears to be analogous to post-flashover conditions in conventional compartments, where temperatures are high and the rate of burning is dependent on the inflow of air through the vent. However, unlike side-vented compartments, this mode of burning is not characterised by a rapid increase in heat release rate or the onset of external flaming, rather this mode of burning is characterised by a largely steady HRR, in some instances even a slight reduction in HRR.

When more fuel is present, the temperatures are about 500 to 600°C (and possibly higher), and the pyrolysis rate/HRR is slightly larger, the fully involved fire can exhibit a 'pool fire' behaviour, where external flames are formed at the opening, and are sustained by the mass flow of pyrolysis gases from the fuel and the plentiful supply of air outside the compartment. The observations in these tests are consistent with the results of the first two tests by Chitty and Fraser-Mitchell [23].

It is clear across all tests that 'fully involved' fire behaviour in a ceiling-vented compartment only occurs when the temperatures in the compartment exceed 500°C. Below this limit the fire may simply self-extinguish, or may exhibit pulsing behaviour. Self-extinction may occur while there is a significant concentration of pyrolysis products in the gas phase, this will also be followed by an increase in airflow into the compartment as it cools, which may result in a flammable mixture being formed in the compartment some seconds or minutes after the extinction event. If this occurs while the compartment remains hot enough [24] or if there is a pilot source or residual smouldering present, a smoke explosion could occur. Fire-fighters, in particular, need to be aware of this possibility.

At the outset of this study, it was expected that the pulsing fire behaviour would be observed regularly. However, this is not the case, with the pulsing behaviour only being observed occasionally, for brief moments, and as a transition between other modes of burning. The pulsing mode appears to function as a mechanism for rapidly raising the temperature of the compartment fire, and it may be an indicator of a flashover-like transition from localised burning to the generalised burning behaviours of ghosting and the pool fire mode.

These experiments were carried out at reduced scale. At this scale, the ghosting mode was evident while the HRR was about 10 kW, and the pool fire mode was evident while the HRR was about 15 kW. Assuming these phenomena scale according to conservation of the Froude number [2], the HRR will vary with the compartment scale to the power $^5/_2$. While HRR data were not recorded for the full scale tests of Chitty & Fraser-Mitchell [23], this would suggest that the HRR in those cases was about $6^{5/2} = 88$ times larger than here, so perhaps above 1.3 MW in the cases where external burning was observed, and perhaps below about 880 kW in the third instance, where external burning was not observed. Further testing needs to be carried out to confirm the scalability of these observations.

CONCLUSIONS

Fully-involved, ceiling-vented compartment fire behaviour has been studied in a reduced scale laboratory compartment. When temperatures are above 500°C, such compartments may exhibit sustained periods of either ghosting flames, when pyrolysis rates are lower, or pool fire behaviour when pyrolysis rates are higher. At temperatures below this a pulsing mode may also exist, but only as a short transient period between other burning modes. An asymmetric burning pattern is only observed with very large ceiling vents or when there is asymmetry between the fuel and the vent.

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