Experimental Investigation of Potential Confined Ignition Sources for Vapour Cloud Explosions

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Electrical control boxes are prolific on high vapour cloud hazard sites, and in the case of the Buncefield explosion the ignition source was inside such a box that was sited in an emergency pump house building. There has, however, been relatively little previous research into this type of ignition mechanism and its effect on the explosion severity. Commercially available electrical control boxes measuring 600 mm high, 400 mm wide and 250 mm deep were used to explore the pressure development, venting processes and flame characteristics of stoichiometric propane/air explosions using aluminium foil and the supplied doors as vent coverings. In this work, the boxes were empty of their usual contents in order to establish a baseline for the effect of the internal congestion of the boxes. It was found that, in these empty-box tests, the door produced a flat petal shaped flame, which differed drastically from the mushroom flame shape, associated rolling vortex bubble venting traditionally observed with large orifice vented explosions.

Keywords: VCE, Vapour cloud explosion, vented explosion, bang-box ignition, Buncefield. process safety, explosion relief venting, explosion severity, overpressure, venting explosion, external explosion, risk assessment.

Introduction

The most recent severe Vapour Cloud Explosion (VCE) in the United Kingdom was the Buncefield incident in 2005 (Major Incident Investigation Board, 2007). The vapour cloud was a large unconfined, gravity driven pancake cloud and the resultant explosion was severe. A recent review (Atkinson et al., 2017b) into VCE events at large fuel storage sites has shown that nearly all of these events have occurred at times when weather conditions allow the formation and persistence of a pancake type cloud. The idea of very large homogenous cloud development (Atkinson and Coldrick, 2012, Atkinson et al., 2015, Atkinson et al., 2017a, Coldrick et al., 2011) is relatively new and not widely understood.

The potential ignition source for the Buncefield explosion was within an electrical control box situated inside an emergency pump house (Atkinson, 2006), and it can be expected that in the event of a large persistent homogenous cloud on a site with controlled ignition sources that an eventual ignition source would be confined. There is a lot of discussion regarding the mechanisms that contributed to the severity of the explosion, but there is a potential that this multi-compartment confined ignition source, in essence a 'nested bang-box', may have been a contributing factor (Gill et al., 2019). There has, however, been little in the way of research into the effects of such bang-box ignition sources on the severity of VCEs, despite the need for such work being identified some years ago (Bradley et al., 2012).

Recent research into the propagation of a confined explosion to an external cloud by Daubech et al. (2017) concluded that there was little interaction between the venting flame and external volume when the vent was large enough that the discharging gases assumed the shape of a rolling vortex bubble. Conversely, when the vent area was reduced to the point that the flame venting from the confined space formed a jet, the severity of the explosion in the external cloud was increased. This research, however, did not take into account the hinged-door confinement of typical equipment cabinets and the effect this has on venting and flame propagation.

This paper describes experimental results comparing the effect on flame shape from a hinged door with that from a bursting membrane vent cover, often used in vented explosion experiments. This work forms the initial stages of a larger programme of work, which will investigate the propagation of a congested and confined explosion from a hinged door electrical control box into an external flammable volume.

Methodology

Commercially available electrical control boxes 600 mm high, 400 mm wide and 250 mm deep, volume 0.06 m^3, with a 3 point locking mechanism were fitted to the back wall of a 8 m^3 frame rig as shown in figures 1 and 2. The left side wall of each box was cut away and replaced with 5 mm polycarbonate for viewing purposes. For two of the tests the door was removed using the hinge pins and the opening was covered with an aluminium foil membrane: this foil produces comparable bursting pressures to the door (Gill et al., 2019).

Tests were conducted using stoichiometric propane/air mixtures ignited by a Talon^{TM} tungsten hot wire firework central ignitor on the back wall of the box. The gas concentration was controlled with mass flow controllers. The box was filled by purging the box with pre-mixed gas at the desired concentration and monitoring the exhaust with a gas analyser to ensure purging was complete. Overpressure measurements were made using fast response pressure transducers, which were located internally and externally to the box, as shown in figure 3. The tests were filmed at 240 frames per second.

Figure 1- Test rig with electrical control box in place

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Figure 2- Three point locking mechanism of the control box doors

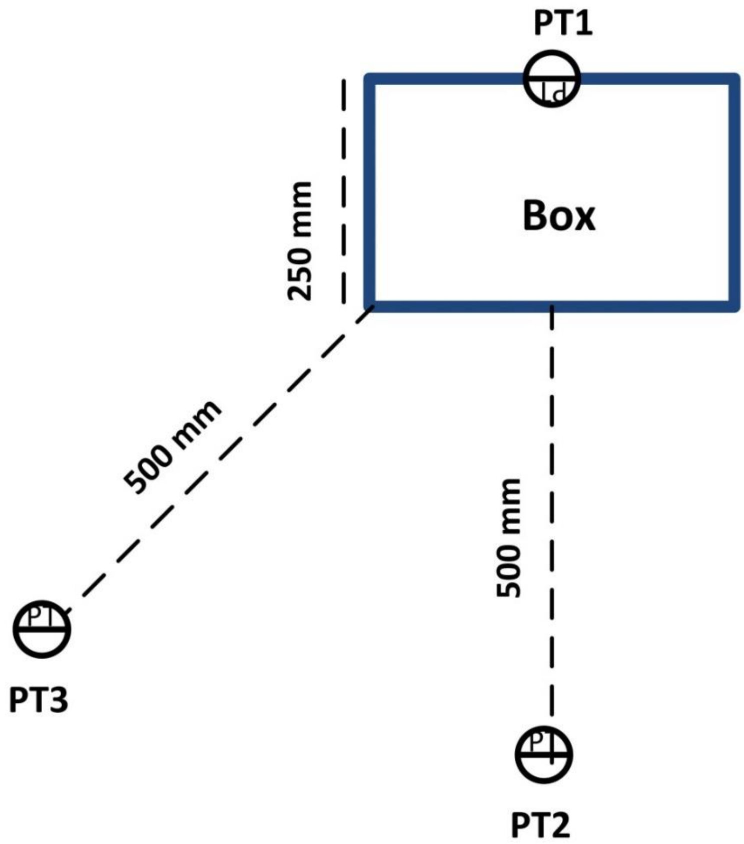

Figure 3 - Plan view of location of pressure transducers (PT)

Results

Five tests were conducted, three with a door and two with foil covering the opening. The overpressures and flame characteristics were recorded. Note that PT 2 and 3 were not active for test 3.

Overpressures

The overpressures recorded (Table 1) in the tests showed similarities in the maximum pressures between the foil and door vent coverings. The bursting pressure was dominant in all tests and any external explosion was inconsequential. It is, however, evident from the pressure traces (figures 4 and 5) that the tests performed using the door (tests 3-5) encountered a momentary pause in pressure rise due to the effect of venting. This is due to the pressure rise causing deflection in the door, which breeches the gas tight seal made by the door; the foil remains gas tight until it bursts or tears.

Table 1 – Results of overpressure measurements for tests 1-5

Test	Vent covering	PT1 (mbar)	PT2 (mbar)	PT3 (mbar)
1	foil	97	5	5
2	foil	72	3	3
3	door	75	-	-
4	door	90	4	7
5	door	78	2	4

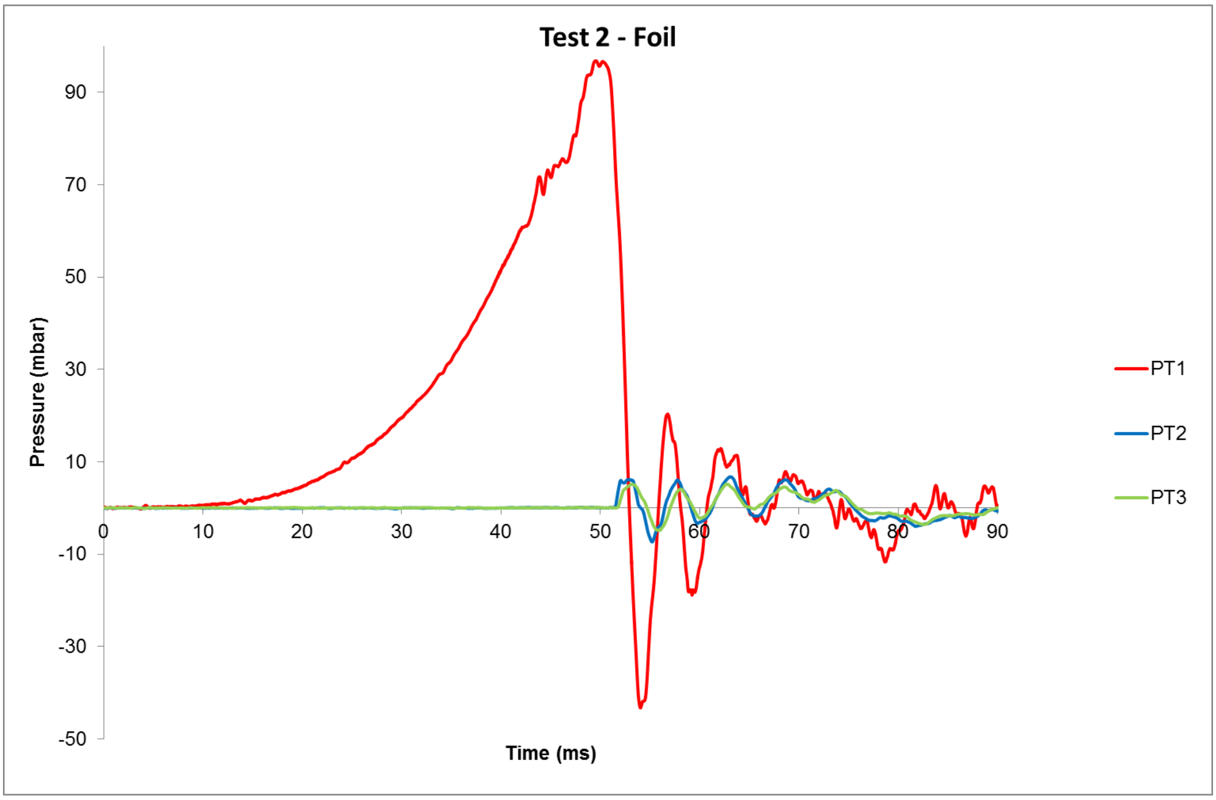

Figure 4 - Pressure trace for test 2

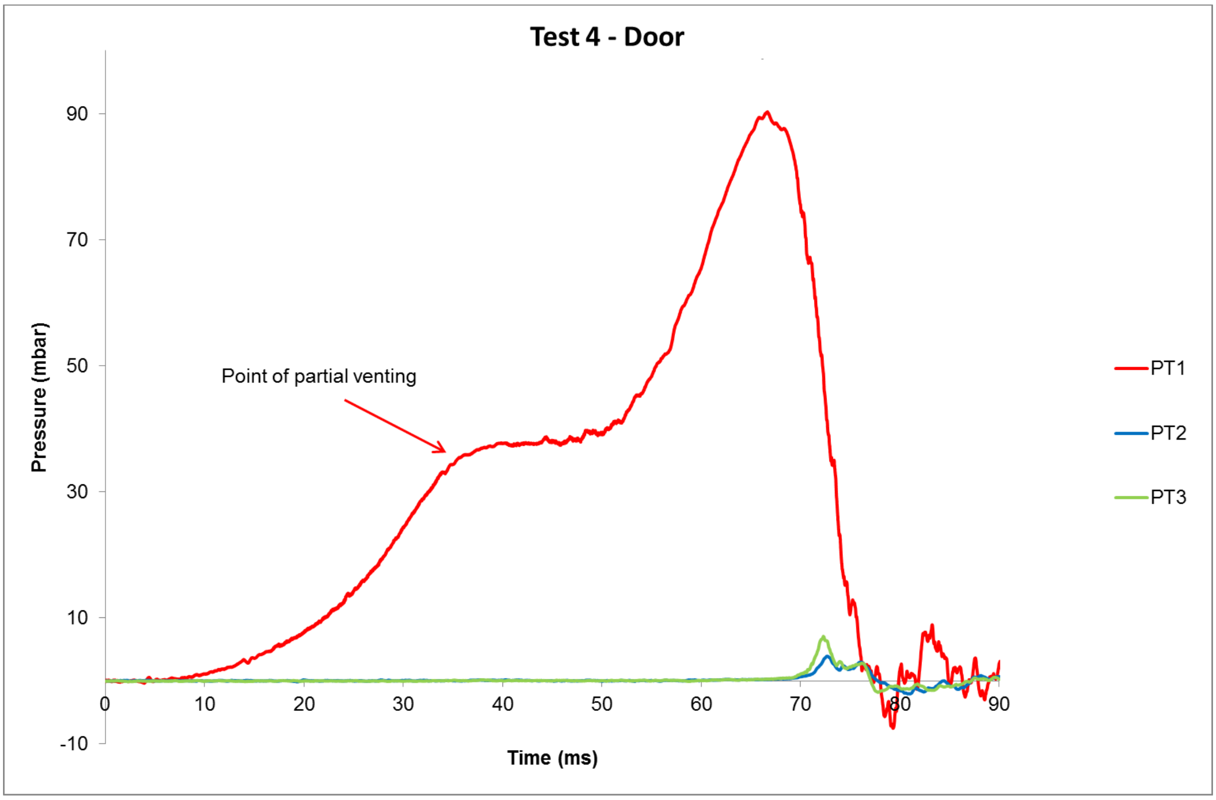

Figure 5 - Pressure trace for test 4

Flame Characteristics

In the foil test, the flame develops near spherically towards the front of the box from the initial kernel, with some distortion and elongation caused by the back wall of the box. The foil is pushed forward and taut before tearing vertically, and as the flame exits it establishes a typical mushroom shape (Figures 6 and 7). This shape is characteristic of the vented gases forming a rolling vortex bubble described by Maxworthy (1972) and witnessed by Daubech et al. (2017). As the flame extends, it forms a second mushroom shape, which reinforces the theory that the rolling vortex bubble method of venting applies in this case (Figure 8). The flame extends to near the edge of the 2 m long rig.

In the door tests, the flame develops in a similar manner described previously; however, the door starts to deflect before the flame has reached a diameter of 200 mm, due to yielding of the locking bar mechanism (Figure 9). As the pressure builds, either one or both of the locking bars fail, which facilitates door opening. The door is open by no more than 30 mm when the flame begins to exit, and combustion is complete before the door is completely open. The flame does not develop into a mushroom shape, but is initially a flat petal shape which expands sideward and in the direction of the door for approximately 1 metre (Figure 10).

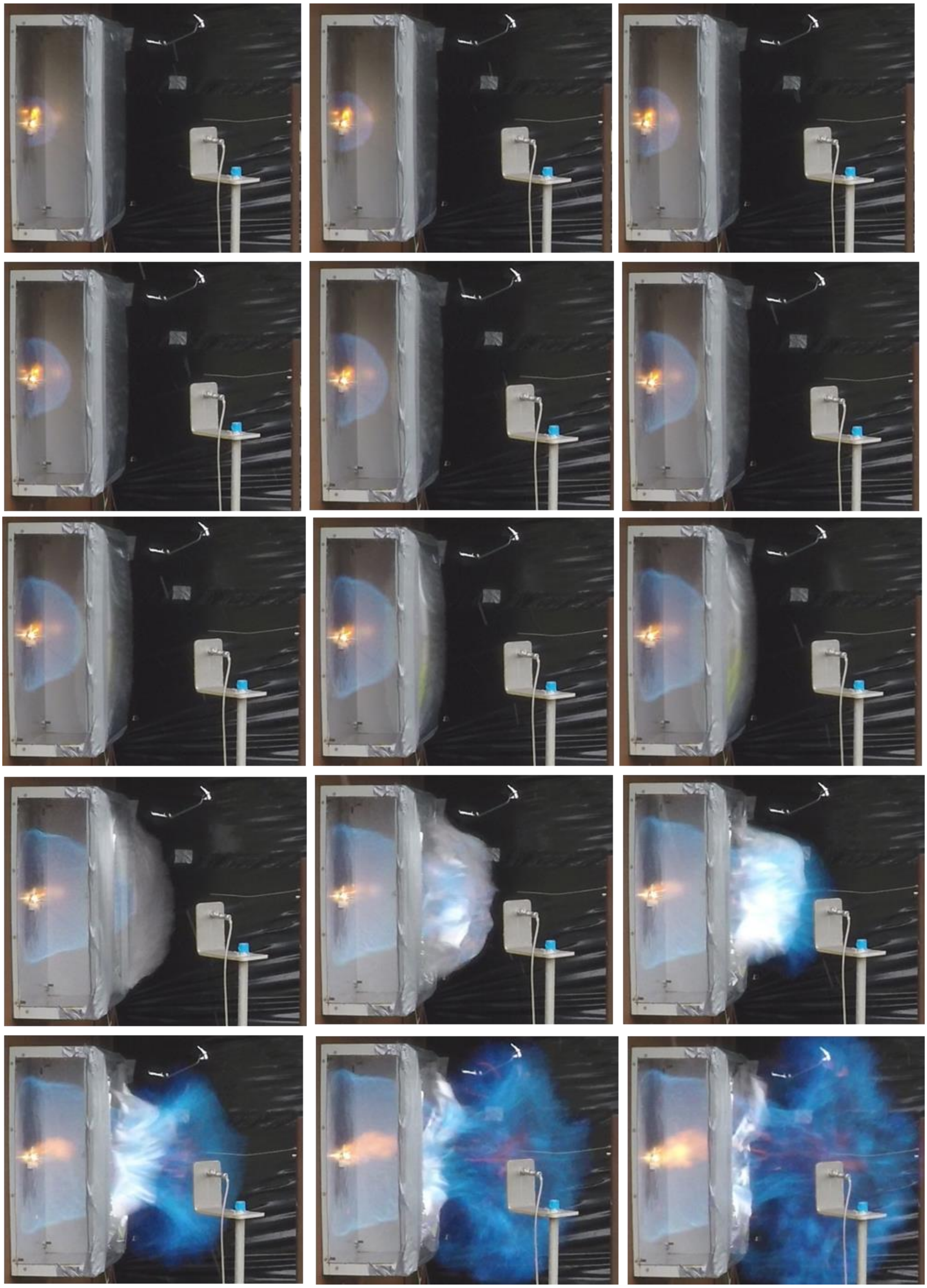

Figure 6 - flame development in test 1; frame intervals 4.17 ms

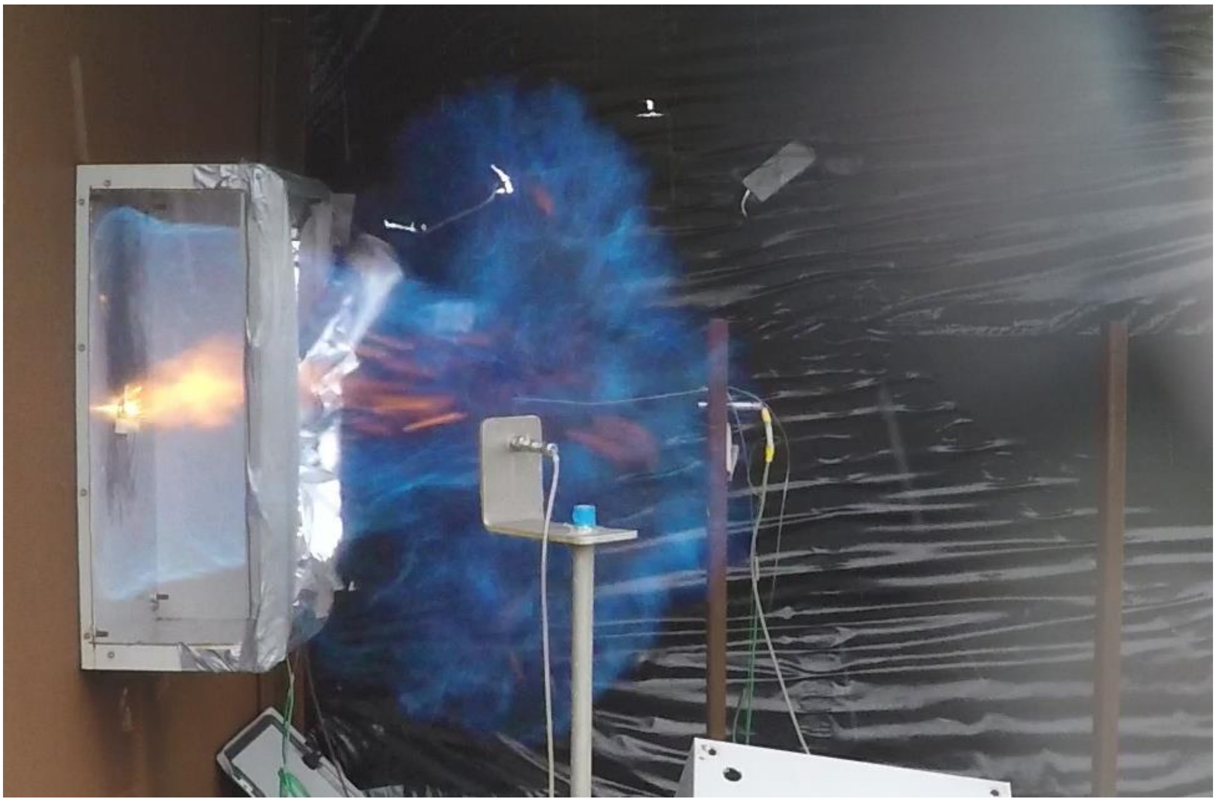

Figure 7 - Test 1 – initial mushroom flame, typical of rolling vortex bubble venting

Figure 8 - Test 1 - secondary mushroom flame, typical of rolling vortex bubble venting

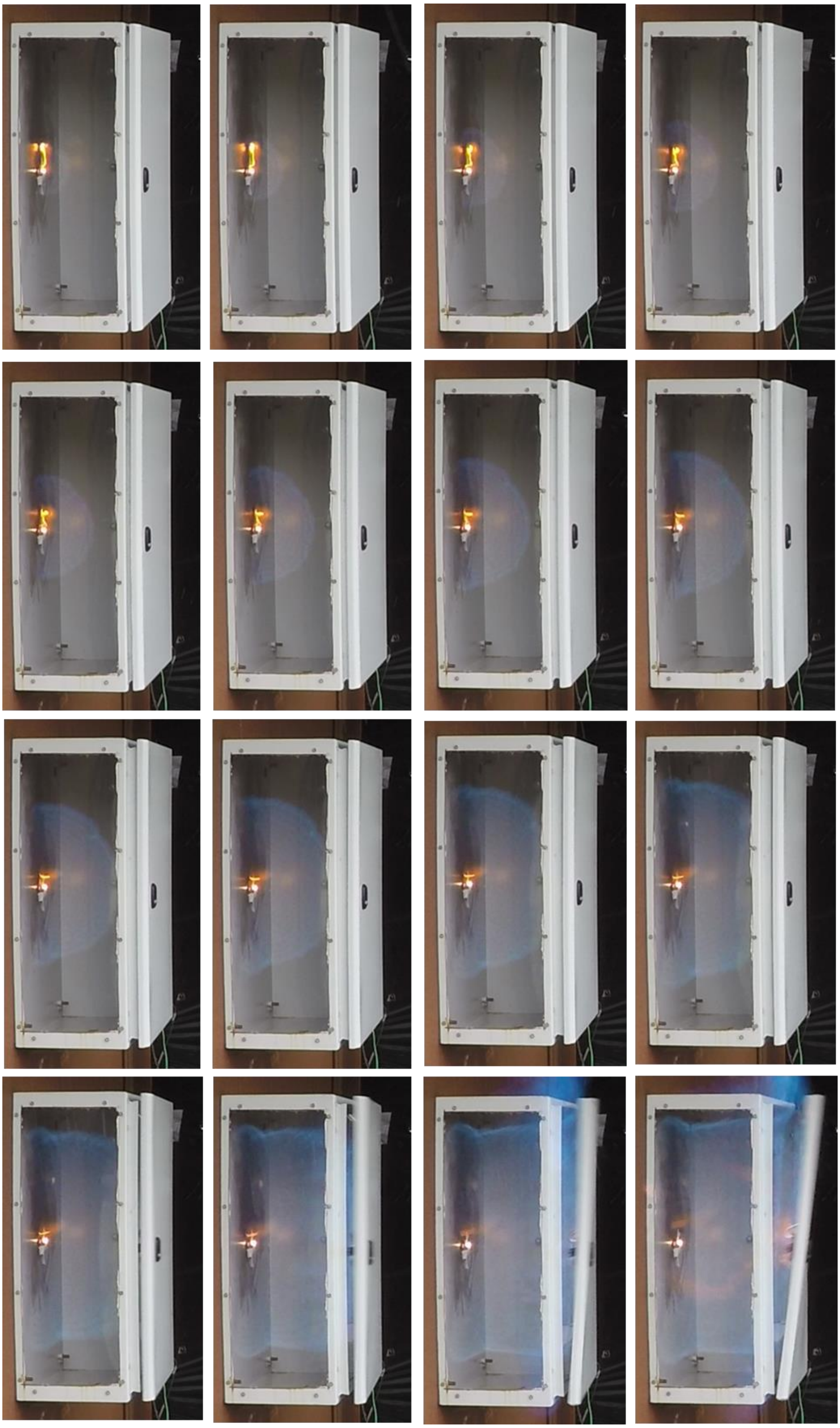

Figure 9 - Flame development in test 4; frame intervals 4.17 ms

Figure 10 - front view of venting flame shape in test 3; frame interval 20 ms

Discussion

Overpressures and venting

Given the large size of the vent relative to the volume of the box, it would typically be expected that if the vent closure was fairly weak then the peak pressure would be dominated by the external part of explosion (Proust and Leprette, 2010). In this case, however, the burst pressure is dominant, an effect also observed by Fakandu et al. (2015).

In the case of the foil, the burst pressure is relatively high, but once a crack is initiated it propagates rapidly and a large area vent is available within a few milliseconds. Internal overpressure and outflow velocities decline immediately, and there is no extended period of high speed jetting through a small opening. The resulting outflow of gas has a broad central core in which the flow is irrotational and not affected by the vorticity in the shear layers at the edge. As these layers roll up, the potential core of the resulting vortex is eroded slowly by relatively low levels of shear, resulting in slow combustion and low external overpressures.

In the door tests, venting commenced at lower pressures (40 mbar) as the door begins to deflect, and this venting initially offsets the rate of pressure rise. There is an extended period (~20 ms) in which gas is forced out of the resulting crack at a speed of around 80 m/s. Eventually, increasing levels of volume production associated with the developing flame cannot be offset by venting through the crack associated with flexure of the door and the pressure begins to rise again. The internal pressure and outflow velocity increase to 90 mbar and 120 m/s respectively. The final pressure at which the catch fails is comparable with the foil, but even when the catch has failed the inertia of the door restricts the rate of opening. The rate of depressurisation is, therefore, relatively less, and there is a significant period (of order 10 ms) in which the jet outflow continues.

The ejected gas in the door tests formed a narrow high-speed jet. Only a very small proportion of the gas remains in the irrotational potential core of the jet and most of the ejected gas is immediately entrained into the turbulent shear layer where high flame speeds could develop. In these initial experiments, the box is surrounded by air, so entrainment also leads to rapid dilution of the pre-mixed gas below the initial (stoichiometric) concentration; this limits the rate of burning and overpressure when the flame arrives. This would not be the case if the atmosphere outside the box was also flammable. Future tests with external flammable atmospheres are expected to show much more severe external explosions in door tests as a result of the sustained high speed jetting.

In these tests the boxes were largely empty. In real world applications there is an economic driver to use the fewest, smallest boxes. This means that control boxes gravitate towards having more equipment and cabling inside, which introduces congestion. Congestion will likely increase the speed of the explosion, but by how much in such a shallow vessel is unknown. In the door tests, an increase in flame speed would potentially lead to higher internal pressures and outflow speeds as the inertia of the door becomes increasingly important, but the duration of the outflow and possibly the total volume of jetted fluid are likely to decline. Again, the effect of congestion on the characteristics of the external explosion is not known.

Flame Characteristics

The foil tests produced mushroom flame shapes, typical of a rolling vortex bubble venting of the unburnt gases from the box. Work by Daubech et al. (2017) has shown that the venting gas mechanisms indicated by this shape interact little with any external volume it is vented into, and the explosion of this vented gas is almost separate to the explosion of the flammable gas already present in the external volume.

In the door tests, venting of unburnt gas began when the door deflected due to the initial pressure, which consequently broke the gas seal. The door only opens about 20 mm before the flame emerges into the jetted fluid. A high proportion of the unburned gas is therefore ejected as a flat jet - maximising the potential to accelerate external flames. Accelerated burning in the jet (and probably dilution of some gas below the LFL) is indicated by the reduced flame length and burn time in the door tests compared to the foil tests. If venting was into a flammable external volume, the turbulence generation that can occur without dilution would allow rapid and complete combustion of ejected gas, which would inject additional turbulence into a relatively large volume of entrained gas from outside the box. This is similar to the process observed by Daubech et al. (2017) when the vent area was restricted to the point that the vortex bubble was disrupted to form a jet.

Conclusions

The use of a film or foil membrane over a large vent is not appropriate when evaluating the escalating effects of an explosion propagating from an electrical control box, as the dynamics of the door opening has a significant effect on venting and flame exit. Modelling of the initial venting caused by door deflection and the dynamics of door opening would improve understand of how explosions respond to changes in box design. It is evident that sustained high-velocity venting of gas during this process will have the effect of inducing turbulence in the external volume. Movement of the door as it swings open (and especially if it detaches) are also likely to cause significant turbulence in unburned gas, aside to any venting process.

In the second stage of the Buncefield pump house explosion, all the steel cladding panels were simultaneously driven at high speed into the surrounding gas cloud. Previous work (Gill et al., 2016) has shown that panel detachment can also have an escalating effect on the severity of a venting explosion.

The boxes used in these tests were uncongested and therefore unrealistic; boxes will have contents that act as congestion on high hazard sites. Further work will be undertaken to understand the effects of congestion on the rate of door opening and venting. Further work will also be undertaken to understand the effect of venting and flame propagation from these small enclosures with doors into an external flammable volume.

Disclaimer

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References

Atkinson, G. (2006) Buncefield Investigation: Forensic examination of an emergency pumphouse. *HSL Report FS/06/11.*

Atkinson, G. & Coldrick, S. (2012) Vapour cloud formation experiments and modelling. *HSE Research Report RR908*.

Atkinson, G., Coldrick, S., Gant, S. & Cusco, L. (2015) Flammable vapor cloud generation from overfilling tanks: Learning the lessons from Buncefield. *Journal of Loss Prevention in the Process Industries* **35**:329-338.

Atkinson, G., Cowpe, E., Halliday, J. & Painter, D. (2017a) A review of very large vapour cloud explosions: Cloud formation and explosion severity. *Journal of Loss Prevention in the Process Industries* **48**:367-375.

Atkinson, G., Hall, J. & McGillivray, A. (2017b) Review of Vapor Cloud Explosion Incidents. *HSE Research Report RR1113* **2016 (01/09/2016)**.

Bradley, D., Chamberlain, G. A. & Drysdale, D. D. (2012) Large vapour cloud explosions, with particular reference to that at Buncefield. *Philosophical Transactions of the Royal Society a-Mathematical Physical and Engineering Sciences* **370 (1960)**:544-566.

Coldrick, S., Gant, S. E., Atkinson, G. T. & Dakin, R. (2011) Factors affecting vapour production in large scale evaporating liquid cascades. *Process Safety and Environmental Protection* **89(6)**:371-381.

Daubech, J., Proust, C. & Lecocq, G. (2017) Propagation of a confined explosion to an external cloud. *Journal of Loss Prevention in the Process Industries* **49**:805-813.

Fakandu, B. M., Andrews, G. E. & Phylaktou, H. N. (2015) Vent burst pressure effects on vented gas explosion reduced pressure. *Journal of Loss Prevention in the Process Industries* **36**:429-438.

Gill, J., Atkinson, G., Cowpe, E. & Painter, D. (2016) Vapour cloud explosions in steel clad structures. *Symposium Series No 161, HAZARDS 26 Conference*.

Gill, J., Atkinson, G., Phylaktou, H., Andrews, G. E. & Cowpe, E. (2019) Explosions in Electrical Control Boxes as a Potential "Nested Bang-Box" Mechanism for Severe Vapour Cloud Explosions In *Proceedings of Ninth International Seminar on Fire and Explosion Hazards* (accepted paper)

Major Incident Investigation Board. (2007) The Buncefield Incident – 11th December 2005 – The Final Report of the Major Incident Investigation Board, Vol 1.

Maxworthy, T. (1972) The structure and stability of vortex rings. *Journal of Fluid Mechanics* **51(1)**:15-32.

Proust, C. & Leprette, E. (2010) The Dynamics of Vented Gas Explosions. *Process Safety Progress* **29(3)**:231-235.