Vapour cloud explosions in steel clad structures

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Process areas are commonly enclosed with lightweight steel sheeting to provide weather protection for plant and to improve working conditions. It is common practice to assume that the greatest effect that cladding may have is to cause the pressure to increase to the point where the sheet is pushed over the fixing. It should be noted however that cladding may increase the probability of explosion in the event of loss of containment since dispersal of flammables is reduced.

This experimental study has considered the effect of cladding on the consequences of explosions; in particular the intensification of the external explosion that consumes unburned gas which is driven out of the enclosure in the early stages of flame spread.

Results from a programme of tests in an uncongested 50 m^3 vessel are reported. Explosions were monitored with fast response pressure transducers and high speed video cameras. The following parameters were varied to investigate the effect of cladding on the overpressure and impulse of the external explosion:

i. Use of steel profiled cladding (with comparison to plastic membrane with low burst pressure)

ii. Mixture equivalence ratio

iii. Substance reactivity – propane and methane were tested

iv. Configuration and strength of cladding fixings

The results showed that the cladding increased the maximum overpressure generated by several times that of a plastic membrane. The pressure wave at distance was dominated by the burning of gas outside the enclosure. Explosion strength was significantly increased by cladding the enclosure with steel sheets and increasing the fuel to air ratio.

The most severe external explosions occurred not for the strongest fixings but when cladding sheets failed in a way that allowed vented streams of unburned gas to overlap whilst minimising dilution.

Informed approaches for the assessment of external explosion strength are considered, and potential approaches to mitigation of risk from overpressure and missile damage are discussed.

Keywords: VCE (vapour cloud explosions), gas explosions, process safety, explosion relief venting, explosion severity, overpressure, venting explosion, external explosion, risk assessment.

Introduction

Process areas are commonly enclosed in buildings constructed of lightweight steel sheet cladding panels, to provide weather protection for plant and to improve working conditions. It is generally recognised that enclosing process areas may increase the probability of explosion in the event of loss of containment since dispersal of flammables is reduced. However, the effects on explosion are less well understood and it is often assumed that the only effect of cladding is to raise the minimum overpressure to roughly the level at which the cladding is displaced or sheet fixings fail.

Cladding systems generally comprise horizontal Z-shaped purlins that are fixed to vertical structural steels. The cladding sheets are then usually fixed to the purlins with self-drilling screws. Cladding systems are typically designed to withstand pressure and suction pressures of around 10 mbar (1 mbar = 100 Pa) corresponding to wind forces in extreme but foreseeable weather conditions. The drive to ease installation and minimise material costs means that all elements of cladding system e.g. sheet thickness and screw diameter tend to be specified to meet design loads without large safety factors. Cladding failure modes have been described by Chen (2014); the fixing screw may be pulled out of the purlin or the cladding may be pushed over the fixing or torn out if the fixing is near the edge of the sheet.

Because the failure pressure of cladding is relatively low, some assessments of explosion severity in very lightly congested spaces have concluded that the maximum explosion pressure is a few tens of millibars, corresponding to Explosion Level 1 to 3 in the TNO Multi-energy Method for explosion analysis (TNO Yellow Book, 1997). Such low overpressures would not normally have significant effects on other buildings or process equipment nearby.

The flaw in this approach is that it ignores the potential for a more severe external explosion beyond a clad enclosure. If gas initially fills a high proportion of a building, only a small fraction (<25%, depending on ignition location) will burn inside the building; the bulk of the unburned gas will be driven out of the building before it is overtaken by the flame front. In an unclad structure, this gas expands freely ahead of the flame and does not normally sustain rapid burning and high overpressures. In a clad structure, the gas is forced out through the cladding panels as they become detached from the purlins. There is potential for the panels to form an array of obstacles capable of efficiently inducing turbulence in the unburned gas that is driven past them; this will lead to higher flame speeds and overpressures well in excess of the failure pressure of the cladding sheets. The main purpose of the work described in this paper is to investigate the significance of this effect through analysis of the effects of explosions in lightly congested clad enclosures.

Development of external explosions

The development of an internal explosion in an enclosure with weak surface elements has been described by Fakandu et al. (2015) and Tomlin et al. (2015). The initial stages of the explosion cause a pressure rise to the point that there is a failure in the enclosure and a vent or vents are created; at this point the rate of pressure rise drops or stabilises as the explosion continues and the unburnt gas is pushed through the vent(s) to the exterior. The flame front then exits the enclosure and ignites the gas that has previously been vented, causing an external explosion. The pressure pulse from the external explosion affects targets outside the enclosure and is also propagated back into the enclosure. This may interfere coherently with other pressure pulses caused by the explosion, leading to a higher overpressure being seen within. Ferrara et al. (2008) described how the severity of the external explosion can be linked to the mechanisms operating in the internal explosion. Bauwens et al. (2010), Chan et al. (1983), Hall et al. (2009) Na'inna et al. (2013), Park et al. (2008), Phylaktou and Andrews (1994), Tomlin et al. (2015) and van Wingerden and Zeeuwen (1983) have all investigated how the severity of the internal explosion and therefore the external explosion, can be increased by internal obstacles which induce turbulence and consequently increase the flame speed.

Samaraweera et al (2015) demonstrated through modelling that the severity of a venting explosion can be increased if the vent consists of more than one opening and the openings are close enough together to allow the venting streams to interact allowing the development of turbulence without excessive dilution with air. The case of an explosion in a clad structure with uncontrolled failure of cladding sheets is very likely to progress in a way that allows adjacent venting streams to interact in this way. Modelling of such an explosion is not currently practical because of the complexity of the failure mechanism and the fact that the panels undergo high amplitude flexural oscillations during venting. The aim of this study was to investigate experimentally whether cladding failure can have an escalating effect on the overall severity of an explosion in a steel clad structure.

Experimental setup

The test programme was a series of large-scale test in a vessel to investigate if the failure mechanism of steel cladding sheets affects the severity of the external explosion. Tests 2 to 7 were carried out with polythene membrane providing a seal on the open end of the vessel, these acted as controls giving baseline explosion data and investigating the effects of changes in conditions such as polythene sheet thickness, fan operation and mixture equivalence ratio. The results provided an upper bound on the pressures to be expected in an unconfined cloud.

Test 1 and 8 to 14 were carried out with steel cladding sheets, these investigate the effects of the cladding failure method, as well as assessing the effects of fixture strength, fan operation, fuel type and the reproducibility of cladding failure.

Experimental rig

The experimental rig is a steel vessel (Figure 1) measuring 7.5 m x 2.5 m x 2.5 m with an open end and a flange 0.25 m wide. The effects to be studied largely depend on the velocities induced in unburned gas as it vents. At first the flame spreads in a hemispherical shape away from the ignition point on the back wall of the rig. At this stage, the velocities induced at the exit of the chamber are significantly higher than they would be in a larger structure with potential for venting over the whole external surface (because in the test rig all of the venting has to go in one direction). However when the flame fills the cross section of the rig and adopts a reasonably planar shape, the ratio of induced velocity at the exit to the fundamental burning velocity will be reasonably close to that expected if the flame were propagating spherically in a large building.

Figure 1: Test vessel

The vessel has an internal fan in the centre of a side wall to provide internal mixing of the gas mixture. Timber was attached to the flange of the steel vessel to create a recess for the cladding panels to fit into and to provide a method of fitting a polythene membrane.

Three fast response pressure transducers, logged at 100 kHz were used: two inside the wall of the vessel and one outside (Figure 2). The gas concentration was measured using ADC 3000 series multi-gas analysers with an intrinsic accuracy of 1% of the reading. The gas mixture was ignited with a 1 J electronic match head at the back wall of the vessel to optimise the conditions for the venting of the unburnt gas out of the vessel opening.

For the polythene membrane tests, two sheet thicknesses were used: heavy duty (120 microns thick) and medium duty (60 microns thick).

For steel cladding tests, industry standard, reversible 3 m x 1 m galvanized steel sheets were used. The sheet thickness was 0.5 gauge and box profile depth was 32mm. The sheets were fitted to 140 mm Z purlins using industry standard 25 mm long, self-drilling screws with 19 mm washers. The manufacturer’s advice is to fix the sheets in every valley, but depending on which profile is outward facing, it is common on many buildings to see the panels fixed in every other valley.

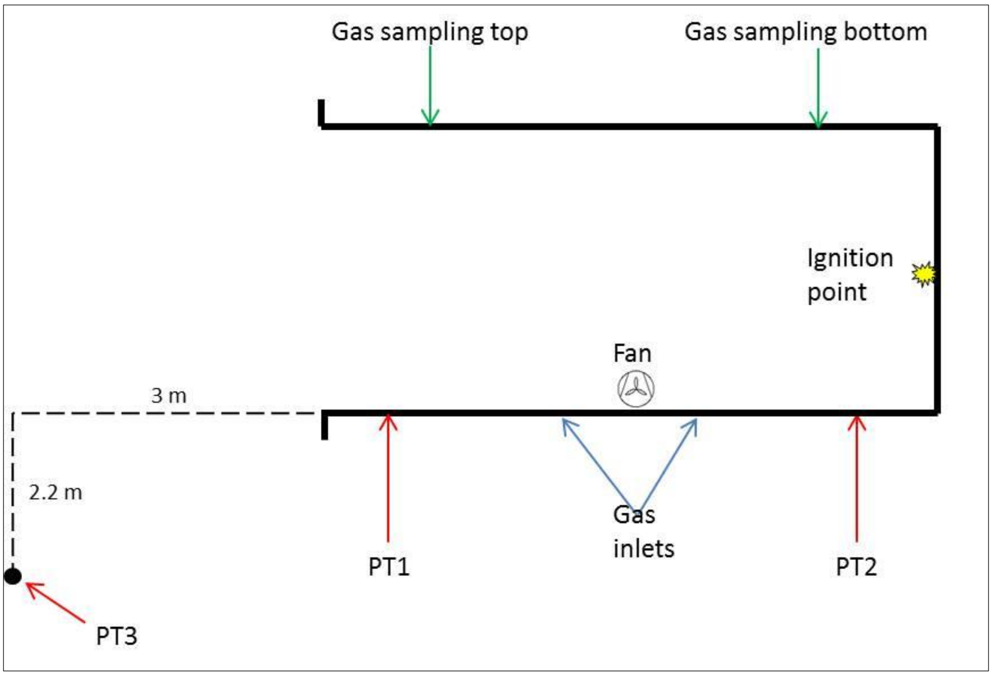


Figure 2: Plan view of the vessel configuration

Experimental conditions

Table 1 gives a summary of the test conditions. A fan provided a means of increasing the homogeneity of the gas mixture during filling. In a small number of tests the fan was left running up to the point of ignition to provide a reproducible means of adding turbulence to the gas mixture as turbulence is known to increase the severity of an explosion in a vessel (EN14994).

Prior to testing little was known about the likely trajectory of the cladding sheets; Test 1 was therefore designed to investigate how the cladding would behave when fixed in the strongest possible configuration on the vessel. The fan was left running during the explosion and the test provided a worst case scenario for positioning cameras, confirming exclusion zones, assessing sound levels etc.

Tests 2 to 7 were the polythene membrane tests; Tests 2 and 5 were carried out in similar conditions but using the two different gauges of polythene film to seal the end of the rig. In Tests 3 and 4 the reproducibility of the explosion was assessed, the data providing a baseline for comparison with the results of the other tests. Test 5 assessed the effect of fan induced turbulence by comparison with Tests 3 and 4, when the fan was not deployed. Tests 6 and 7 investigated the effects of rich mixtures on the explosion.

The steel panels in Tests 8 to 14 were fitted with fewer fixings on at least some of the sheets, to ensure that individual panels were lost rather than all the purlins and cladding sheets coming off as a block. Tests 8 and 9 assessed the reproducibility of the steel clad tests. Test 10 used the fan to add turbulence. Test 11 assessed the effect of introducing a deliberate weakness to the cladding system as mitigation for the external explosion.

Tests 1 to 11 used propane (LPG) as a fuel: the purpose of Tests 12 to 14 was to repeat the conditions of the steel cladding tests but using methane as a fuel.

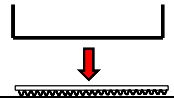
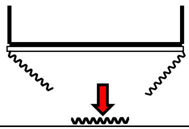
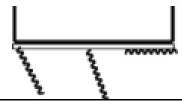
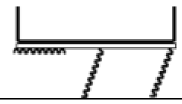
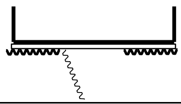
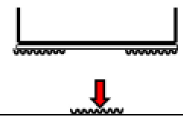
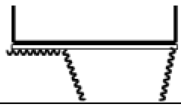
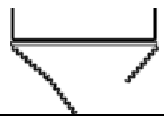
Table 1: Summary of test conditions

Test Number	**Gas**	**Top of vessel concentration (%)**	**Bottom of vessel concentration (%)**	**Fan**	**Covering of the end of the vessel**
Test 1	C_3H_8	4.2	4.2	On	Full strength steel system
Test 2	C_3H_8	4.4	4.4	On	120 micron polythene
Test 3	C_3H_8	4.2	4.2	Off	60 micron polythene
Test 4	C_3H_8	4.3	4.2	Off	60 micron polythene
Test 5	C_3H_8	4.2	4.2	On	60 micron polythene
Test 6	C_3H_8	5.7	5.6	Off	60 micron polythene
Test 7	C_3H_8	5.7	5.7	Off	60 micron polythene
Test 8	C_3H_8	Not measured	4.2	Off	Weak steel system
Test 9	C_3H_8	4.2	4.2	Off	Weak steel system
Test 10	C_3H_8	4.2	4.2	On	Weak steel system
Test 11	C_3H_8	4.2	4.2	Off	Strong steel system with weak centre panel
Test 12	CH_4	9.4	Not measured	Off	Strong steel system with weak centre panel
Test 13	CH_4	9.4	Not measured	Off	Weak steel system
Test 14	CH_4	9.6	Not measured	Off	Weak steel system with extra fittings

Results and Discussion

Table 2 gives a summary of the peak pressures recorded and the failure configuration of the cladding panels during the venting stage of the explosion.

Table 2: Summary of test results

Test	**Vessel opening event peak overpressure at PT 2 (mbar)**	**External explosion event peak overpressure at PT3 (mbar)**	**External explosion event peak overpressure at PT2 (mbar)**	**External explosion event peak overpressure at PT1 (mbar)**	**Pattern of cladding sheet initial failure**
Test 1	133	38	55	35	
Test 2	23	38	110	74	
Test 3	11	20	33	24	
Test 4	12	23	47	34	
Test 5	20	22	80	50	
Test 6	8	22	45	37	
Test 7	9	45	146	98	
Test 8	36	38	70	62	
Test 9	26	71	156	131	
Test 10	42	103	170	153	
Test 11	41	46	70.1	64	
Test 12	50	21 and 23	57	46	
Test 13	22	50	107	81	
Test 14	42	23	42	33	

Test 1: Strongly fixed cladding

The central purlin detached from the vessel with all three cladding panels still attached. The complete assembly was propelled upwards and landed 27 m away from the rig. Single cladding sheets that detached in subsequent tests did not travel so far. Out of the 30 screws used to fix the panels to the top and bottom purlins, 17 were pulled out of the purlins and 13 of the screws were left in the purlins with the washers and heads pulled through the panels. This mixture of failure modes reflects the fact that screws, washers and sheets were selected to resist similar loads. In this test, the high number of cladding fixings meant that the cladding system was stronger than the fixings of the central purlin to the vessel flanges. In buildings this is not always the case, especially if the purlins span several columns. Since the aim of the experiment was measure the effect of panel failure on the external explosions, further tests were conducted using fewer fixing screws.

The pressure measurements (see **Figure 3**) show that the explosion was multi-staged and the internal explosion overpressure required to remove the cladding was higher than the overpressure caused by the explosion of the unburnt gas vented from the vessel.

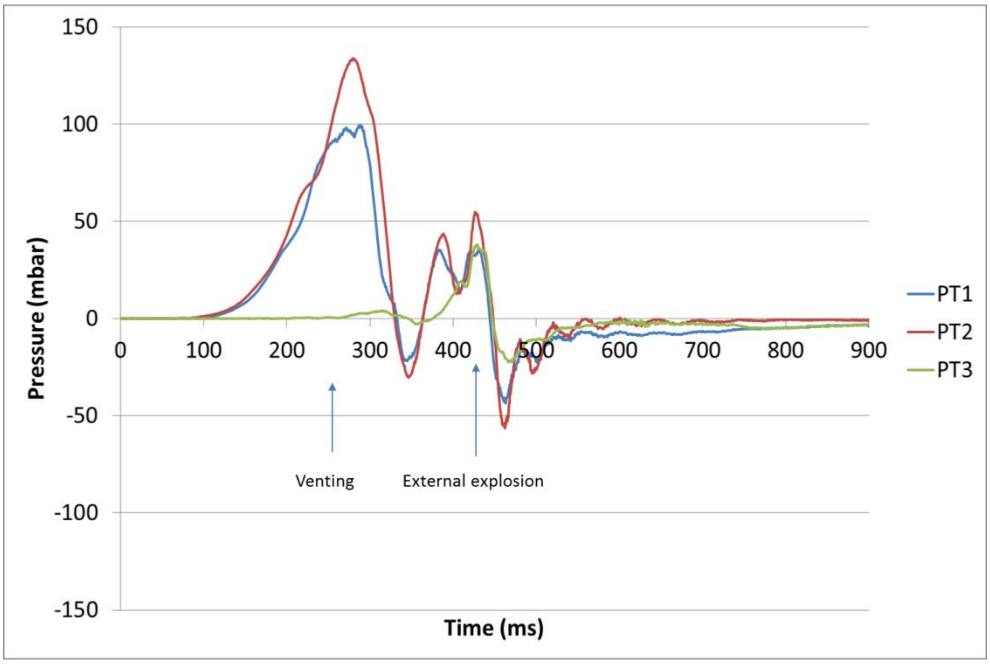


Figure 3: Pressure traces for Test 1

Tests 2-7: Polythene Membrane

The purpose of the polythene membrane tests was to limit the severity of the explosion that could have been expected if the gas cloud was not enclosed. The tests were also used to explore the repeatability of the results and examine the effects of equivalence ratio and internal turbulence intensity. During the explosion in these tests, there were at least three peaks in pressure corresponding to: opening of the vessel (venting), flame front exiting the vessel and explosion of the unburnt gas outside of the vessel. A comparison of Tests 3 and 4, which are duplicate tests on non-turbulent stoichiometric propane, shows that there was good reproducibility in timings and in the pressure recorded by the external pressure transducer (Figure 4. The average flame speed between the ignition point and the end of the rig was around 20 m/s which, allowing for expansion, corresponds to a burning velocity of about 20/6 = 3.5 m/s. This is reasonably representative of turbulent burning velocities in very lightly congested areas.

The maximum pressure reading at an internal pressure transducer during the external explosion is the sum of the pressure wave from the external explosion, the reflected pulse and residual pressure oscillations set up within the enclosure by the internal explosion. If the timing of the external explosion gives particularly complete coherence, then higher peak pressures are recorded at devices within the enclosure. There was no pattern in the coherence in these tests, which means that pressure maxima inside the enclosure were less reproducible than those outside.

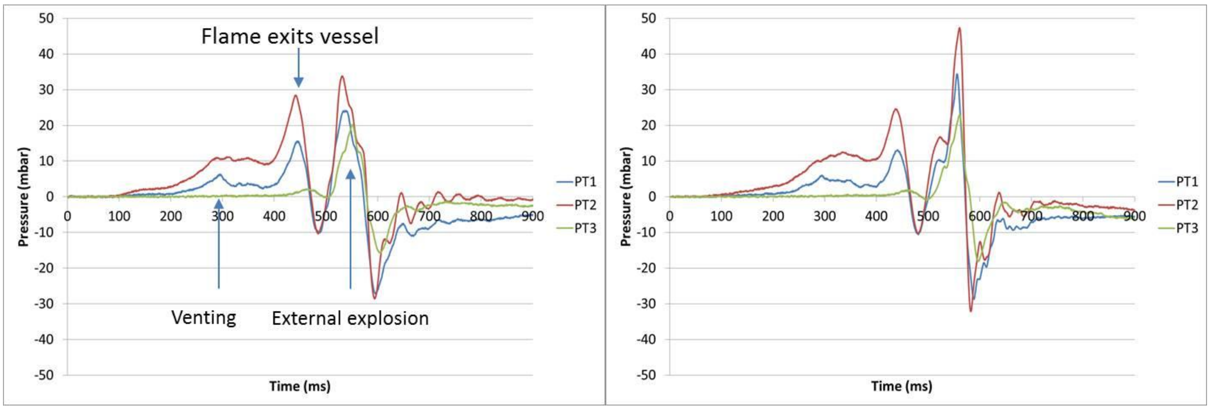


Figure 4: Pressure traces of Test 3 (left) and Test 4 (right)

Test 5 showed the effect of igniting a turbulent mixture, i.e. with the fan turned on. By comparing Test 5 to Test 4 (Figure 5) it is clear that igniting the gas when it is turbulent affected the speed of development of the event. Turbulence in the unburned gas increases flame speed; time to venting, flame exit and external explosion are all reduced by about 25%. Pressures recorded were significantly higher in the higher turbulence case.

It is difficult to say if there was an increase in the severity of the external explosion because of the additional turbulence; the peak pressures recorded at PT3 were almost identical in the two tests. There was, however, a strong wind blowing across the mouth of the vessel in Test 5 this may have reduced the severity of the external explosion, presumably by slightly increasing the dilution of the vented unburned gas as it exited the vessel.

More significant increases in internal and external explosion severity would be associated with obstacles within the enclosure that would allow flame acceleration by the Shelkin Mechanism (Shelkin 1940 as described by Valiev et al. 2010).

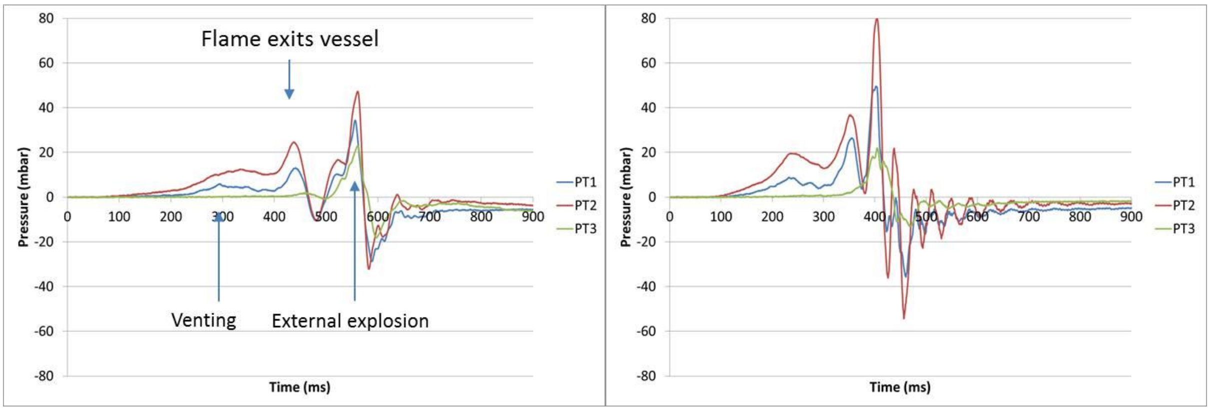


Figure 5: Pressure traces of Test 4 – low turbulence (left) and Test 5 - fan left on (right)

A comparison between results from Test 5 and Test 2 shows the effect of the gauge of polythene used to close the end of the rig (Figure 6. The results show that the thicker polythene is associated with higher venting pressures as expected. The severity of the external explosion was also significantly increased. This is probably because the edges of the tears in the thicker polythene are better able to induce shear in the venting gas, which in turn leads to higher turbulence levels and flame speeds.

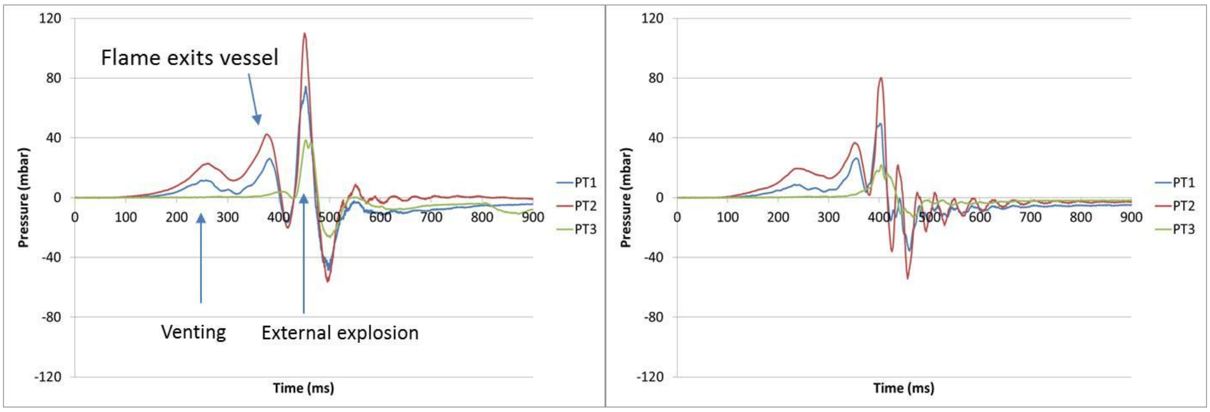


Figure 6: Pressure traces of Test 2 – 120 micron polythene (left) and Test 5 – 60 micron polythene (right)

Tests 6 and 7 investigated the effect of rich mixtures on the explosion (Figure 7). In both tests the over-rich mixture led to a reduction in flame speed and an increase in the time taken for the flame to exit. The two test were carried out on the same day but there was a change in wind direction and strength between the tests. In Test 6 the wind was strong and travelling across the vessel aperture. The resultant vibration induced in the polythene sheet may have affected the progress of the internal explosion which showed a series of peaks and troughs in pressure. The external explosion was very weak and it is likely that the strong external wind displaced and dispersed much of the additional fuel before it could be overtaken by the flame. It is widely assumed that explosive venting events are too fast to be affected by external weather conditions, but these results suggest that this may not always be the case.

In Test 7 the wind had subsided and was travelling coaxially to the rig. In this case the external explosion was noticeably stronger than in the base case tests (Tests 3 and 4) with near stoichiometric mixtures (Figure 4. The overpressure (at PT3) associated with the external explosion in a rich mixture (Test 7) was twice that in Test 4. Although a rich mixture reduces the power of the internal explosion it does mean that more fuel is available for the external explosion. At the edge of the jet of vented gas, turbulence levels will be high but mixing with air rapidly reduces the concentration and potential for explosion. If the gas mixture is initially rich, then a greater proportion of this shear layer can support an explosion.

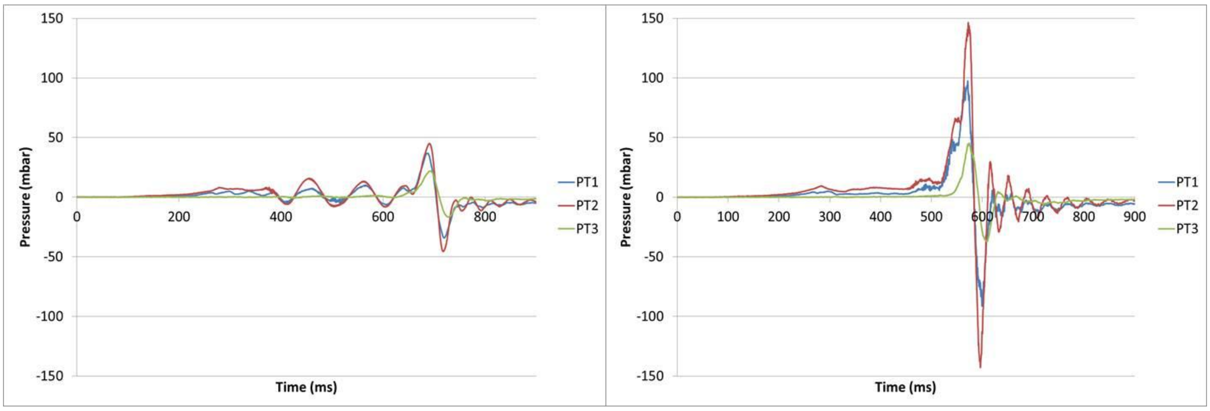


Figure 7: Pressure traces in tests on rich mixtures - Test 6 – strong cross-wind (left) and Test 7 – (right)

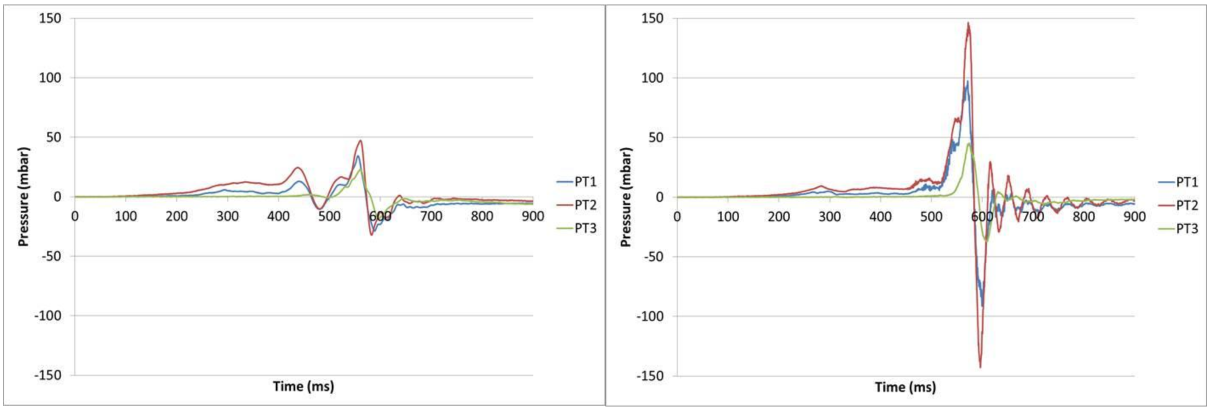


Figure 8: Pressure traces of Test 4 (left) and Test 7 (right)

Tests 8 – 14: Steel Cladding System

In the main series of tests with steel cladding – Tests 8 -14 - the cladding sheets were fixed at the edges of each panel or through both panels where they overlapped. This allowed individual panels to be projected whilst leaving the purlins in place.

The set up condition of Tests 8 and 9 was the same, but the sequence of panel failure in the two tests was significantly different in the early stages of the event when the unburned gas was vented but before the flame front exited the vessel. In Test 8 the central panel was completely removed and the end panels hinged open leaving a single large vent area (Figure 9 and Table 2). In Test 9 one end panel remained in place and two of the panels hinged open (this also occurred in Test 10; see Figure 10) leading to two vent areas immediately next to each other, separated by a partially detached sheet. This geometry would allow the development of shear layers in the wake of the central sheet without the dilution with air that is associated with shear layers at the edges of the jet.

Figure 9: Video stills of the venting event showing panel failure in Test 8

Figure 10: Video stills of the venting event showing panel failure in Test 10

The peak pressure measured by PT3 in Test 8 was nearly double that in Test 9 (Figure 11). The explosion impulse in Test 9 (but not Test 8) was detected by the occupants of buildings at a distance of >500m. The only difference in the two test conditions was the way the panels failed.

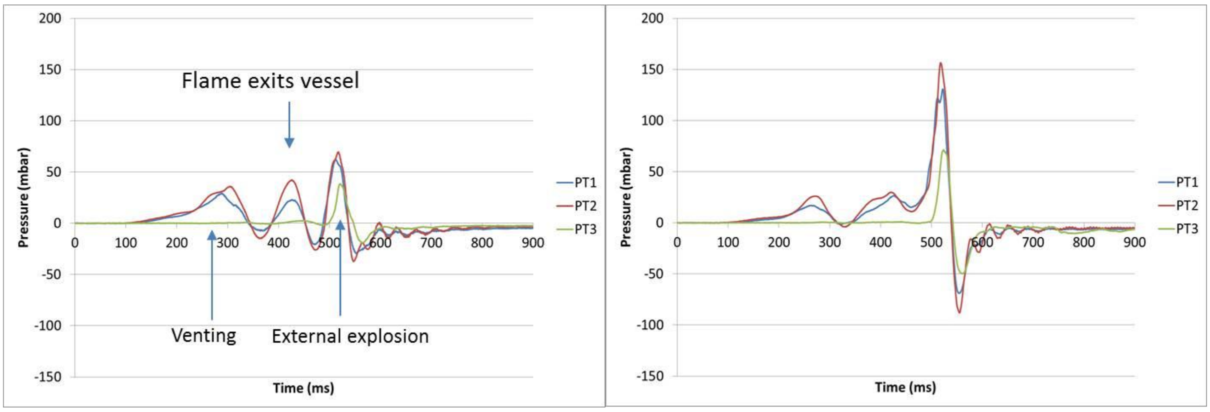


Figure 11: Pressure traces of Test 8 – single vent (left) and Test 9- two adjacent vents (right)

In Test 10 the panels failed in a similar way to Test 9; the only major change in conditions was the addition of the ignition of a turbulent mixture. The pressure traces were similar (see Figure 12), although there was an increase in the speed of the event and an increase in opening pressure, as noted in the polythene tests, Tests 2 and 5, conducted with the fan on. The peak pressure of the external explosion event recorded by PT3 was greater in Test 10 than in Test 9.

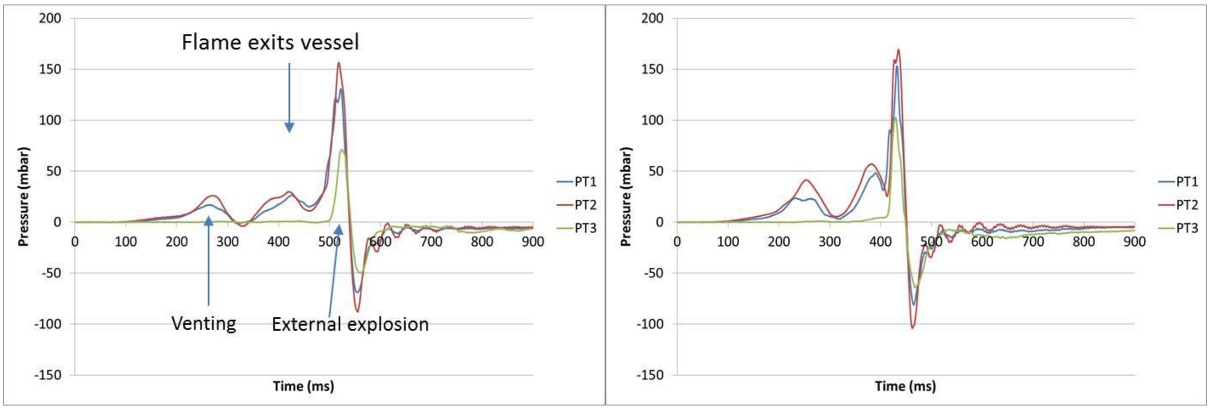


Figure 12: Pressure traces of Test 9 – still (left) and Test 10 – fan on (right)

The purpose of Test 11 was to explore whether the severity of the external explosion events could be reduced by deliberately fixing some panels less strongly than others in order to control the venting of the structure and reduce the potential for the development of the kind of jet interaction seen in Tests 9 and 10. The two end panels were fixed using a screw fastener in every valley as per the manufacturer's instructions, but the central panel was fixed only at the edges. The central panel could therefore 'hinge' open during the explosion creating a vent area of approximately a third of the overall opening of the unclad vessel. The peak pressure recorded by PT3 was slightly higher than in Test 8 (where the panels failed to give a much wider single opening) but very much lower than that seen in Test 9. These preliminary results suggest that the power of the external explosion is not greatly affected by the overall vented area, but is very sensitive to any closely spaced vents created. The effects of engineering a proportion of somewhat weaker panels that would maximise dilution of vented gas would be worth exploring further.

Methane tests

The purpose of Tests 12, 13 and 14 was to try to replicate the conditions of Tests 9 and 11 but using methane as a fuel. Test 12 (methane) replicated the results of Test 11 (propane) reasonably closely but the central panel was completely removed in the early stages of the explosion. The maximum pressures in the early stages of the explosion were similar for the equivalent propane and methane tests (Figure 13), but the external explosion event with methane progressed in two phases leading to two peak pressure readings by PT3.

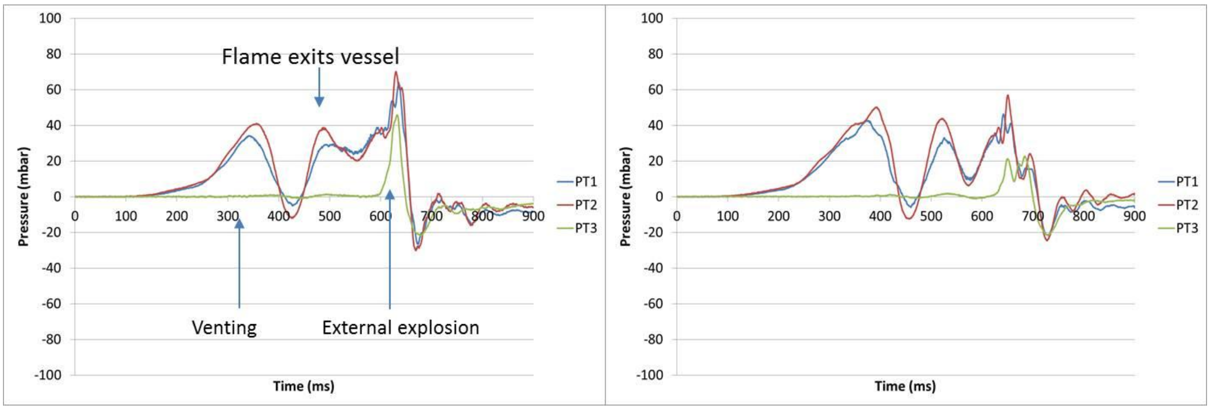


Figure 13: Pressure traces of Test 11 – propane (left) and Test 12 - methane (right)

The conditions for Test 13 were the same as Tests 9 and 10 but the panels failed differently (Table 2) and in a way that did not involve closely spaced jets with a central obstruction. Internal and external pressures were higher than in many of the propane tests but less than in Tests 9 or 10. The sequence of sheet failure appears more important in influencing the severity of the external explosion than a change from propane to methane.

In Test 14 extra fixing screws were used to try to force failure in the sequence shown in Test 9; one panel was fixed with screws in every other valley and extra screws at the edges of the other panel to try to encourage 'hinging' rather than complete detachment. However the panels failed in a different way, more closely resembling the results of Test 8. The peak pressure recorded by PT3 was quite low but during the test the wind was increasing and at ignition the wind was strong and blowing across the mouth of the vessel, which may have accounted for the differences.

Conclusions

The aim of the tests was to investigate if a building clad with lightweight steel sheets will have an escalating effect on the severity of a vapour cloud explosion beyond the effect of raising the minimum overpressure to roughly the level at which the cladding is displaced or sheet fixings fail. This was done by investigating the characteristics of explosions under different conditions in the vessel with the opening covered with a polythene membrane and comparing the results to tests conducted with the opening covered with industry standard steel cladding, attached to purlins.

The results show that the peak pressure of the external explosion event at a distance from the enclosure can be substantially affected by the failure mechanisms/sequence of detachment of the enclosure cladding. In Tests 9 and 10 the panels failed in a manner that generated two closely spaced streams of venting gas either side of a central obstruction. This allowed increases in turbulence intensity with limited entrainment of excess air, greatly increasing the severity of the external explosion. In a large building it would be possible for a much larger proportion of the total outflow of gas to be affected by these non-diluting shear layers. Considerably higher flame speeds and overpressures could be expected. Given that pressures of up to 170 mbar were observed in these tests, it would be reasonable to assume a minimum source pressure of 200 mbar for uncongested spaces clad with steel panels: this corresponds to an explosion intensity of 5 in the TNO Multi-energy Method. Larger scale experiments on fully clad structures would be needed to validate this assumption.

The tests also show that the gas concentration can affect the severity of the external explosion. As the gas vents from the enclosure, it mixes with the air at the edges of the jets, which induces turbulence but also takes the affected gas further from the stoichiometric ratio. Significant amounts of gas are diluted below the flammable limit and never burn. If the mixture in the vessel is rich, there is greater potential for mixing before the venting gas becomes over-diluted by air. The fuel-rich tests in this study were well below the upper explosive limit (UEL); it is possible that higher concentrations of fuel in the enclosure could lead to more severe external explosions. This study has not included cases where there is both unfavourable failure of cladding panels and a rich mixture, but the results indicate that such events could be much more violent.

Inducing additional internal turbulence (using the fan) can raise the opening pressure and the severity of the external explosion. The effect is relatively small compared to the large increases in explosion severity caused by obstacles that can drive internal flame acceleration by the Shelkin Mechanism (Tomlin et al. 2015). Further experimental work would be required to determine whether the significant enhancement of external explosions by cladding also occurs for more congested enclosures.

The assumption that weather will not affect a venting explosion appears to be incorrect for relatively uncongested explosions. A strong cross-wind can dilute the venting gas and reduce the intensity of what would otherwise be a significant external explosion. Therefore the assumption that the weather has no effect is generally a reasonable, conservative assumption, corresponding to a worst case scenario. It is also likely that the effect of reduction in explosion intensity by cross-winds would be less noticeable in larger buildings.

The results of this study show that when assessing the risks presented by loss of containment in a process area, attention should be paid not only to the internal congestion, but also to the construction of the building's skin. The effect of the walls is two-fold; firstly the widely known effect that confinement can allow the build-up of a flammable mixture, and secondly as shown here, that for some cladding systems as the sheets fail they can act as congesting elements, increasing the severity of the external explosion.

The ideal case has been described by Kletz (2001), i.e. 'the best buildings have no walls'. Where this is not possible, buildings with substantial permanent openings will at least reduce the risk of cladding failure and enhancement of an external explosion. If full enclosure of the space is required, cladding with a proportion of relatively weak (lightweight) panels would normally be preferable – these should be spaced so that the venting gas is diluted with air before interacting with neighbouring vents, and be situated in a location that allows the gas to be vented into a safe place. Further work on larger fully clad structures would be useful to develop design guidelines.

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