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Near Field Blast Effects from BLEVE

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There is a need to have a better understanding of the near field blast and impulse from boiling liquid expanding vapour explosions. Emergency responders and response planners need to know the ground loading on a bridge if there is a tank truck BLEVE, or the loading on a building if a tank truck suffers a BLEVE near a high rise building.

When a tank suffers a BLEVE the vessel opens fully to release the contained energy. The release is strongly directional since the tank wall does not move away instantaneously. The piston effect of the expanding vapour generates a shock at some distance away from the tank. This shock then propagates into the surroundings. Behind this shock is an additional blast wind caused by liquid flashing. This may also produce a shock. When the tank opens fully and is flattened on the ground this produces a large impulse load. Long range projectiles are also possible.

Experiments have been conducted using 50 mm diameter tubes filled with water or propane. These tubes have been heated until failure to produce a BLEVE release. The tube failure mode and kinematics was representative of pressure vessel failures. The tube supports contained load cells to measure the ground force. Pencil blast gages were located close to tube to measure overpressures. High speed shadowgraph imaging was used to capture the formation and movement of the shocks.

The results include detailed data on near field blast and ground loading effects from a boiling liquid expanding vapour explosion.

1. Introduction

A BLEVE takes place when a pressure vessel holding a pressure liquefied gas fails catastrophically. This occurs mostly when an external fire impacts the tank (Heymes et al., 2013). When the vessel opens fully the contained vapour and liquid are released very rapidly and the high velocity piston effect of this release causes the formation of shocks in the surrounding air. These shocks are then followed by a blast wind that can cause significant drag loading on near field objects. The BLEVE also generates a large load on the ground where the vessel was supported.

Emergency responders and planners have been asking questions about BLEVE blast such as – what is the load if a tank truck BLEVEs on a bridge? Or what is the loading on buildings if a tank truck suffers a BLEVE near a high rise building?

There is little or no data on the near field blast effect from a BLEVE. This work presents some preliminary results from an experimental study of near field blast effects from a BLEVE.

2. Previous work

Very little detailed information is available on near field blast effects from a BLEVE. Near field blasts effects may cause harmful effects in transportation or may cause domino effects in petrochemical facilities (Heymes et al., 2014). Near field modelling has been done by van den Berg et al. (2008). Most of the available data applies for distances greater than ten or twenty tank diameters (see for example Planas-Cuchi et al., 2004, Birk et al., 2007). There have also been recent experiments using shock tubes (Skacel et al., 2013). It is

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questionable if these one-dimensional tests really are applicable to the true three – dimension BLEVEs of pressure vessels.

Recent work by Laboureur et al. (2015) obtained high speed shadowgraph images of shocks forming around a small cylinder filled with a supercritical fluid. Although this is not strictly a BLEVE it is an interesting 2-phase release with similarities to a BLEVE.

3. Apparatus

A small scale apparatus has been constructed as shown in Figure 1, to study the near field blast effects from a boiling liquid expanding vapour explosion (BLEVE). The small scale apparatus consists of a 51 mm diameter by 305 mm long aluminium tube. The tube ends were closed using Swagelok fittings. These ends were modified as follows:

i) at one end there is a 38 mm diameter quartz window for optical access
ii) at the other end there are penetrations for two 1.5 mm thermocouples, two 3 mm tube fittings for fill and vent lines and attachment of pressure transducers, and finally a penetration for a high speed transient pressure transducer

The tube was supported above a blast plate on top of load cells so that the ground force and impulse could be measured. A cooling system was designed to prevent the load cells from heating due to the fire impacting the tube.

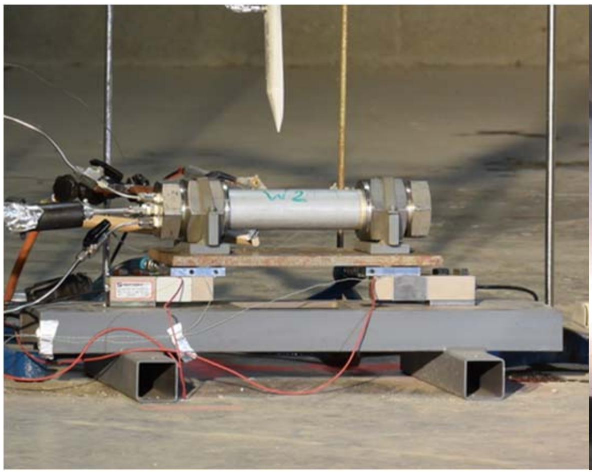

Figure 1: Small Scale BLEVE Apparatus

Figure 2: detailed view of the machined slot

The tubes were machined along the top with a slot (50 – 200 mm in length) to achieve a specific weakened length and failure pressure (between 14 – 30 Barg) (Figure 2). The tube material properties, wall thickness, weakened length and the failure pressure determine if the tube will fail catastrophically or as a finite failure. Catastrophic failure is needed to produce a BLEVE. For example, for our tests with 6061 T6 aluminum, 1.6 mm wall thickness, for failure pressure around 30 Barg, the weakened length Lw had to be greater than around 50 mm (Lw = 1D) for catastrophic failure.

The test tube was surrounded by pencil type blast gages (nominal 3.5 Barg range) at various positions and distances to measure static overpressure. The closest probes were located about four tube diameters away from the tube surface. There were also two high speed transient pressure transducers facing the tube to measure stagnation pressure.

High speed video cameras were used to capture the explosion and also to obtain shadowgraph (PILS – pure in-line shadowgraphy) video images to observe the shocks. A high speed video camera was also used to capture the end-on view of the tube failure and liquid flashing through the quartz window. These cameras were operating at approximately 20,000 frames per second with exposure of approximately 40 microseconds.

4. Testing

For a test, the tube was filled to the desired fill level with the test fluid (water, LPG, propane, light crude oil, etc). The tube was then purged of air using some suitable procedure. The tube was then heated from below using a small propane flame to achieve the failure pressure. At the instant of failure the following were measured:

i) lading temperature, pressure
ii) high speed transient pressure at tube end
iii) high speed ground loading (using load cells)
iv) high speed static and stagnation pressure around cylinder
v) high speed video images
vi) regular video

So far about thirty five tests have been conducted with water and propane mixtures. Tube failure pressures have varied between 8 and 37 Barg. Weakened lengths varied from 50 – 200 mm.

5. Results

5.1 General

There are two basic outcomes from the tests conducted. They were:

i) catastrophic failure and BLEVE (for weakened length Lw > 50 mm)
ii) finite failure with no BLEVE

All failures started with a finite failure that grew axially along the machined slot towards the ends of the weakened length. At the end of the machined slot, the failure turned and split and went circumferentially. This usually resulted in the separation of the ends. In one test where the failure pressure was low (8 Barg) the ends stayed attached to the flattened cylinder.

For the BLEVE cases the failure resulted in the full opening of the cylinder and usually the opened cylinder was flattened on the blast plate. In most cases the ends separated from the cylinder.

Figure 3 shows the early frames of the failure (at 4,000 fps). In the first frame we see the bulge on the tube surface. This is the instant of failure and before any material is released. The first material released is the vapour and it condenses to form the white cloud (2nd frame). The lead shock has already formed in the second frame but is not visible in this ordinary image.

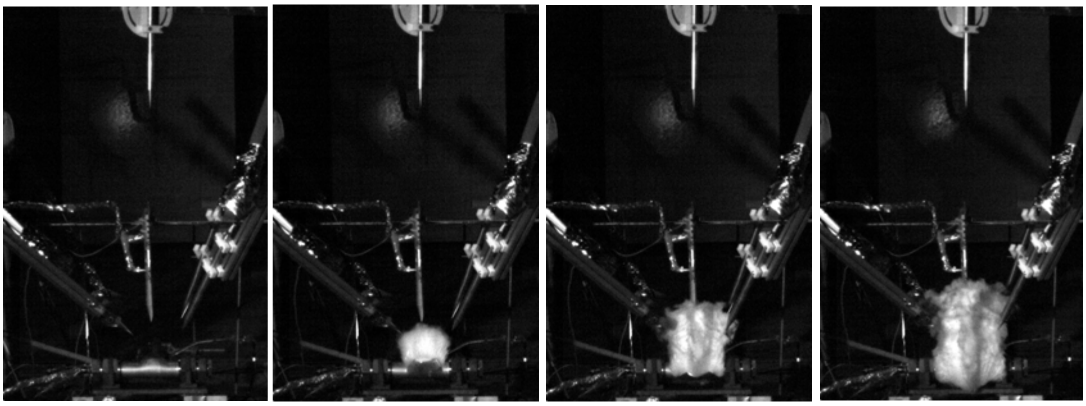

Figure 3: Early frames of BLEVE failure of 51 mm diameter tube

Figure 4 shows the window end view of the failure. Here we see the flashing process inside the vessel. The failure process starts as a minor fissure at the weakened part of the wall (top of tube). This fissure grows axially and the edges of the failure are pushed open by the internal pressure to produce a fish mouth opening. This grows to catastrophic failure. The initial vapour flow leaving the cylinder expands to supersonic velocity and the shock patterns (Mach diamonds) are visible for this over expanded flow (due to condensation). We can see how the liquid at the end of the tube (window) reacts to the failure of the vessel. Initially the liquid at the tube end does not react, but in later frames we see flashing at the liquid surface and then a flashing wave that travels down through the liquid. This of course happens earlier at the tube middle where the failure starts. Eventually the tube fills with the 2-phase mixture. This takes several frames.

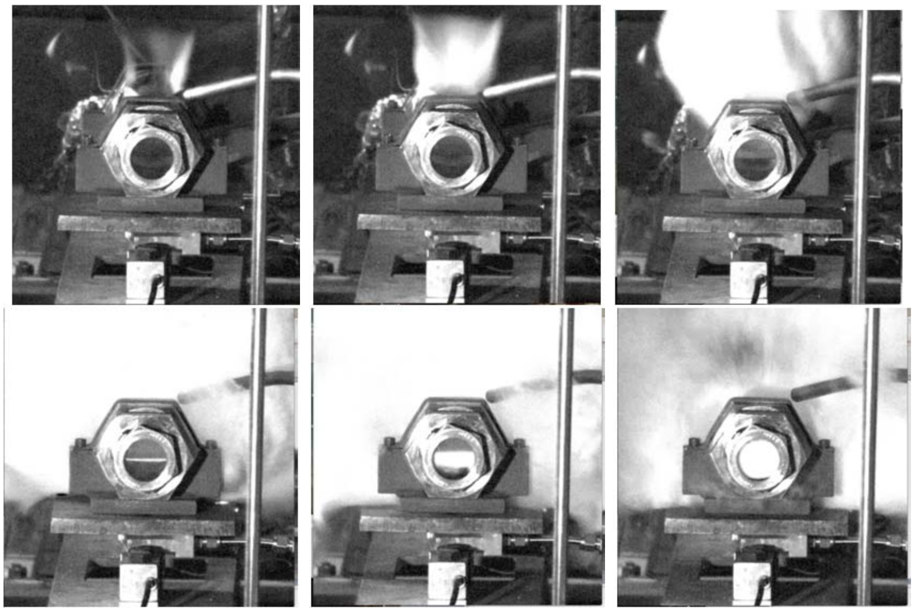

Figure 4: View of end window during early stage of BLEVE (frames 4;5;10;22;28;50 at 25,000 fps)

5.2 Blast over pressure

Figures 5 and 6 show the measured static and stagnation pressure near the tube surface. The static pressure above the cylinder is shown in Figure 5. We see the initial overpressure followed by an underpressure, then a second overpressure and underpressure and finally a slower overpressure that recovers to ambient pressure. This is a typical pressure plot from a BLEVE. The first two peaks are normally seen with compressed gas explosions. It is believed the third longer duration peak is the flashing liquid.

Figure 6 shows the stagnation pressure measured from the upper back side of the cylinder at a slighter larger range. Here we see a lower initial peak followed by a large second peak that seems to correlate with the second static pressure peak that was measured at the tube top. We would expect the pressure at the side to be affected by the way the vessels opened (i.e. the flaps of the opening cylinder would shield the pressure measurement. What is very clear is that the stagnation probe indicates a very high overpressure of around 3 Barg. It is not clear what caused this but this reading is theoretically possible. It is possible that this high reading was caused by some kind of impact with the stagnation probe. Further testing is needed to see if this result is repeatable.

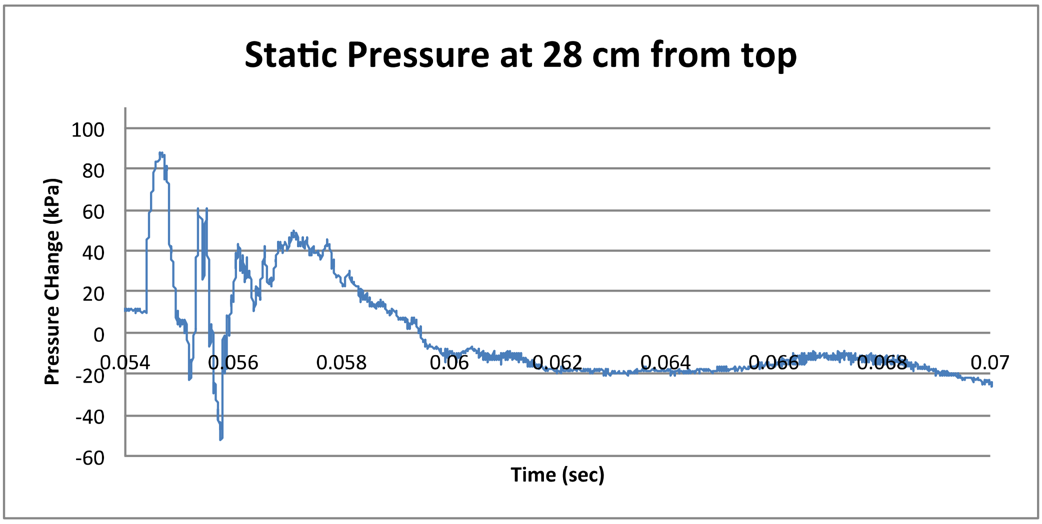

Figure 5: Static overpressure above vessel (50% fill, propane-butane mix failure at 31 Barg)

Figure 7 shows some samples of failed tubes. The BLEVE failures are shown with the centre section of the tube ejected as a single flattened piece of aluminium. The width of this sheet correlates almost exactly with the machined slot in the tube (weakened length). The failure starts in the weakened length and grows axially and then it turns circumferential when the crack meets the stronger thicker wall. The other view shows a tube where the tube did not full open. In this case the release was a transient jet which resulted in a slower blowdown of the vessel pressure.
It is expected that the BLEVE overpressure for the same burst energy will be higher for longer weakened length and faster and fuller opening of the vessel. Further testing is necessary to confirm this hypothesis.

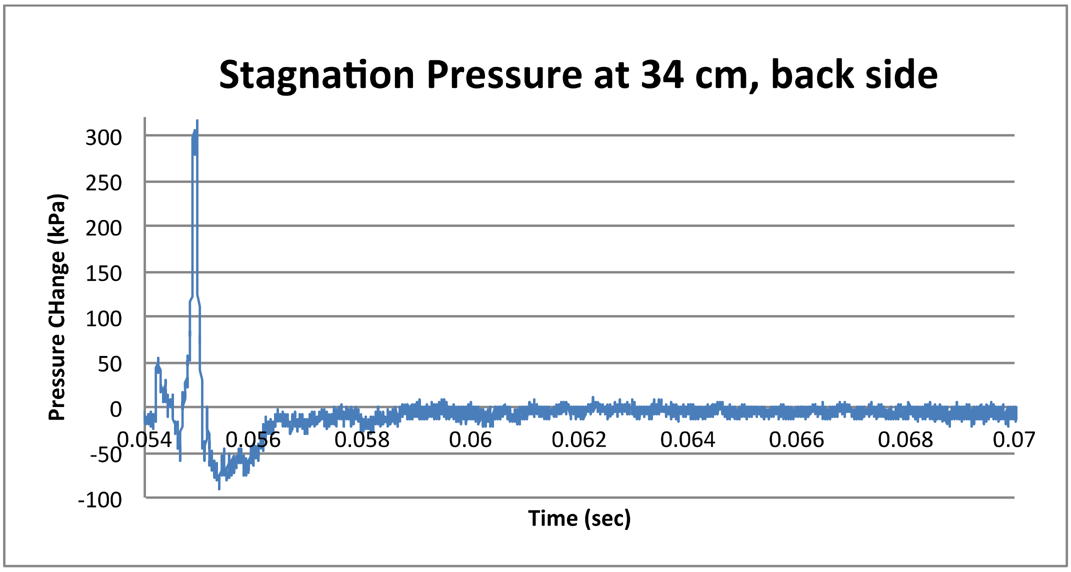

Figure 6: Stagnation pressure at upper side of vessel (50% fill, propane-Butane mix failure at 31 Barg)

Figure 7: Sample views of failed vessel (BLEVE and non-BLEVE failures)

6. Conclusions

A small scale apparatus has been constructed to study the close in blast effects of a BLEVE. The apparatus results in realistic failure models of pressure vessels. Limited testing has been done with water or LPG. Initial results have sown the directional nature of the blast and the delayed flashing of the liquid in the vessel. Further experiments are necessary to obtain consistent and repeatable data for this interesting phenomenon.

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