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| cetlogo ***CHEMICAL ENGINEERING TRANSACTIONS***  ***VOL. xxx, 2025*** | A publication of  aidiclogo_grande |
| The Italian Association  of Chemical Engineering  Online at www.cetjournal.it |
| Guest Editors: Bruno Fabiano, Valerio Cozzani  Copyright © 2025, AIDIC Servizi S.r.l. **ISBN** 979-12-81206-xx-y; **ISSN** 2283-9216 | |

Experimental Investigation of the Influence of Opening Dynamics on the Blast Overpressure Anisotropy in BLEVEs

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The Boiling Liquid Expanding Vapor Explosion (BLEVE) is one of the most dangerous industrial accidents, occurring when a pressure vessel containing a pressure liquefied gas like LPG or heated water suffers a catastrophic structural failure. Once the vessel opens, the vapor phase leaves the vessel pushing the surrounding atmosphere out of the way, leading to compression waves that then pile up to form a shock overpressure. The vessel progressively opens causing a rapid depressurization and violent boiling. A BLEVE results in many other hazards including projectiles, flammable or toxic release and ground loading. To date, many experiments have been carried out to predict the BLEVE hazards. Most of these studies have been performed with limited data on far-field overpressure and mainly focusing on the blast data measured on perpendicular horizontal directions. These studies showed that the blast shape is contingent upon vessel’s geometry; in cylindrical vessels the blast is not directionally uniform. This is also true for spherical vessels. Given that most industrial pressure vessels are cylindrical, this paper investigates blast overpressure resulting from top-initiated failures in cylindrical vessels, utilizing small-scale BLEVE experiments. The results indicated that the Top blast gauges recorded the highest overpressure, followed by the 45-degree angle and end gauges.

* 1. Introduction

A sudden failure of a pressure vessel containing pressurized liquid can lead to a Boiling Liquid Expanding Vapor Explosion (BLEVE), often resulting in human casualties, material loss, property damage, and social disruption. These explosions, well-known within the loss prevention community, occur during transportation, storage, or handling of pressurized vessels in industries like refineries, hospitals, and small businesses. For instance, in December 2022 a truck carrying PLG did burst near a hospital in Johannesburg, South Africa resulting in the death of eleven healthcare workers and thirty-seven other suffering serious burns.

The severity of a BLEVE depends on factors such as vessel size, liquid fill level, substance types, and vessel material, all of which affect the intensity of hazards. Blast overpressure remains the most studied hazard, often quantified through energy models, with Planas-Cuchi et al. (2004) assuming an adiabatic and irreversible expansion process, and Casal and Salla (2006) focusing on the liquid’s flash fraction.

More recent models, focusing on the blast effect above the vessel, such as Birk et al. (2018) using the tube spherical shock approach and Laamarti et al. (2024, a) with correlations, have successfully predicted the vertical near-field overpressure in small-scale BLEVE experiments. Maximum overpressure was found to occur at three to four times the vessel diameter vertically. These studies assume ideal hemispherical propagation of peak overpressure, but do not account for the real anisotropic pressure fields in actual BLEVEs. They simplified the vapor phase as an ideal gas, ignore fragment mass, and overlook the complexities of vessel opening dynamics, which are influenced by crack location (middle or side) and vessel wall material properties.

The shape of a vessel, whether spherical or cylindrical, significantly influences the blast pattern. Spherical vessels may produce more uniform blasts, while cylindrical vessels, especially those with a high length to diameter ratio, generate stronger directional overpressure, particularly at the top, sides and ends. Since cylindrical vessels are the most common in industry due to ease of handling and transportation, addressing this anisotropy is crucial for risk assessment and emergency response. Understanding the directional blast effects helps determine safety distances for people and infrastructure, including vertical impacts, as seen in the 2022 Johannesburg incident, where a BLEVE from a tank truck lodged under a bridge caused its partial collapse. This consideration is essential in global safety considerations (Heymes et al. (2014)).

Few studies have been focusing on the directional overpressure effects of the BLEVE, among them Baker et al. (1985) that proposed approximate adjustments factors to account for the cylindrical vessel shape and ground effect relative to the scaled distance. Experimentally, Birk et al. (2007) and Johnson et al. (1991) investigated the directional effect across different compounds, vessel volumes and operating conditions. Geng et al. (2011) and Hanssen et al. (2016) carried out CFD modelling to calculate the blast effects for a cylindrical burst in axial and radial directions showing that the blast effects are not symmetric. Most of the studies done on blast overpressure have primarily focused on far-field measurements and on overpressure in the horizontal direction. Few researchers have investigated the vertical direction, among them, Laboureur et al. (2015) that recommend measuring the blast from the top, side and end of the reservoir. However, no experimental studies to date have specifically examined near-field overpressure at different orientations of a BLEVE involving a realistic rupture of the vessel but heavier end caps.

This study enhances the understanding of overpressure directionality and anisotropy in BLEVEs through controlled small-scale experiments (Laamarti et al. (2024, b)) on cylindrical vessels filled with pure propane under various failure conditions (failure pressure, liquid fill level, weakened length). The aluminum vessels produced different types of openings across 80 experiments. Thirteen blast gauges, positioned at various angles and elevations, recorded near-field overpressure from eighteen sensors. Data from these gauges were used to reconstruct the aerial overpressure shape at various orientations. High-speed cameras captured vessel opening dynamics, synchronized with overpressure data for thorough analysis.

* 1. Experimental apparatus

The small-scale BLEVE experiments represent a cost-effective alternative to large scale experiments. They afford greater flexibility in adjusting operating parameters to explore diverse facets of the BLEVE. In the case of a BLEVE, conducting experiments offer a controlled environment to replicate real-world scenarios without the potential for catastrophic damage, while still providing valuable insights into failure modes and explosion dynamics. These experiments were conducted indoors on cylindrical horizontal aluminum tubes measuring 305 ± 5 mm long, 50.8 ± 0.8 mm in diameter and 1.65 ± 0.05 mm in thickness. The tubes are made of aluminum 6061 T6 and were annealed to T0 temper to reduce the material yield strength. They were then machined and filed on the top along a defined weakened length so they can burst at the desired burst pressures. The tubes were supported by cradles with a blast plate and mounted on four high-speed load cells with all siting on 1 meter bloc of concrete. To heat the tube bottom and correspondingly the propane liquid, an electric heater was placed below. The instrumentation introduced to measure the data including high/low speed measurements are:

* Five high-speed cameras strategically positioned and going up to 88,000 fps.
* Thirteen pencil blast gages with a total of eighteen sensors across different locations to measure the overpressure. Four vertical blast sensors above the tube are PCB137B28 [1 µs response time / 0.2 % uncertainty] Other gages around the tube are PCB 137A23 [ 4 µs response time / 0.2 % uncertainty].
  + Thermocouples type K, static pressure transducer TC-direct 716-072, High-speed transducer PCB M101A02, four piezoelectric load cells PCB M202B, Electric valves, Swagelok end fittings with Dk-Lok ferrules, an infrared camera FLIR GF320 GASFIND to detect leaks.

More details of the apparatus can be found in Laamarti et al. (2024, b).

Figure 1 illustrates the positioning of the gauges relative to the tube. Each sensor was named according to space rules: HOR means horizontal; FT means front; BK means back; RGT means right; 45 means tilted on an axis at 45° from vertical axis; TOP means top position.

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*Figure 1: Top and side view of the pressure vessel from 2022/2024 BLEVE apparatus*

* 1. Blast overpressure from the BLEVE

Upon rupture, the stored pressurized vapor inside the container is released, rapidly expanding into the surrounding environment. This sudden expansion generates a high-pressure shockwave or blast wave, which is characterized by three key parameters: magnitude, duration and impulse. The intensity of these parameters depends heavily on the opening dynamics and the operating conditions of the container, such as its internal pressure, temperature and the nature of the stored substance.

The understanding of this blast directionality and anisotropic behavior of the blast has been made possible through 80 small-scale propane BLEVE experiments, conducted in March 2022 and April 2024. Various blast gauges positioned around the tube recorded the overpressure signals at different locations, as shown in Figures 2,3 and 4 for experiment 31 from the 2022 BLEVE campaign. While some noise in the data was noted, possibly due to obstacles or sensor interference, the overall trends remained clear. Experimental results for these vessel top failures showed that the highest overpressure was recorded in the vertical direction at the TOP1 gauge, located 15 cm above the tube upper surface, measuring 382 mbar in experiment 31. Across all experiments, the maximum peak overpressure consistently occurred between 15 cm and 20 cm (TOP2 gauge). When comparing overpressure at the same distance (40 cm) across orientations, the vertical gauges recorded the highest overpressure at 153 mbar (TOP4). The 45-degree tilt gauges, as shown in Figure 3, recorded a lower peak overpressure of 146 mbar (45FT2), while the horizontal gauges measured the lowest overpressure at 129 mbar (HORFT1), in the front direction. Overpressures at the back and front sides of the vessel were nearly identical across orientations, likely due to the vessel’s symmetrical opening. However, in some experiments where only one side of the vessel opened fully, the resulting overpressure was non-symmetrical, leading to uneven blast effects between the back and the front sides. The cause of this asymmetrical rupture, where the vessel opened on a preferred side, is likely due to variations in the weakened length’s thickness that is not uniform along the tube. Thus, the tube opens first from the side of least resistance, where the thickness is the least. Finally, comparing the overpressure at back/front sides with those at the tube ends in the horizontal direction at the same distance reveals a significant discrepancy, with values of 129 mbar and 66 mbar (HORRGT1) respectively. The tube end fittings were not typical of cylindrical pressure vessel ends. The ends were closed with heavy Swagelok caps. The impact of the end fitting on the end overpressure is not yet known.

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Description générée automatiquementFigure 2: Vertical overpressure Experiment 31 Figure 3: 45-degree overpressure Experiment 31

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*Figure 4: Horizontal overpressure Experiment 31 [Failure pressure: 29.4 Barg ; Fill level: 90% ; Weakened length : 75 mm ; Full opening of the vessel]*

The overpressure anisotropy between the gauges at different orientations (vertical, 45-degree tilt, horizontal) in the same direction, for instance the front side is explained by the opening dynamics of the vessel. The maximum overpressure is obtained in the vertical direction (TOP) because the vessel opens first at the top and then the free edges of cylinder flaps open. But what can explain the lower overpressure from the horizontal gauges?

Different approaches can be suggested to explain this discrepancy:

* + Using an energy conservation approach, in the vertical direction most of the released energy contributes to overpressure. In contrast, in the horizontal direction a portion of the energy is used to push the vessel walls outward, resulting in a lower peak overpressure.
  + Since most of the energy escaped vertically to generate overpressure, less energy remains to exert force on the vessel walls and build horizontal overpressure.

What can explain the lower overpressure from the ends compared to the sides?

The ends of the cylinder are structurally stronger and act as shielding barriers; thus, the overpressure will follow the path of least resistance along the sides of the cylinder. Due to the vessel’s geometry and the unequal stress distribution between the cylindrical wall and the end caps, the overpressure will have a directional and more forceful release at the top. Because there is a greater surface area over which internal pressure has been acting, then most of the energy acts on the side walls of the cylinder.

Two experiments under similar conditions and final vessel geometry (Laamarti et al. (2024, c)) were compared:

Table 1: Experiment 1 and Experiment 7 from the 2024 BLEVE campaign

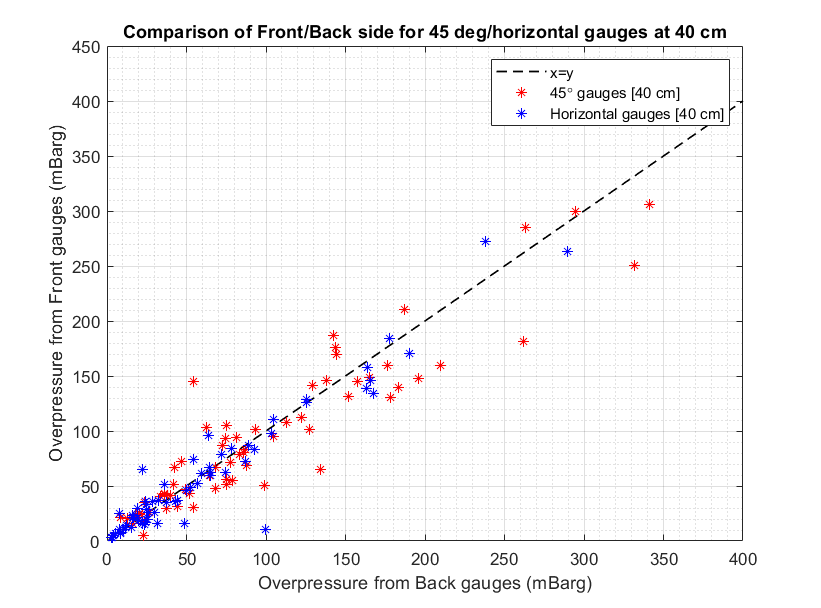
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| # | Failure pressure (Barg) | Liquid fill level (%) | Weakened length (mm) | Type of opening | TOP 1 (mbar) | TOP 4 (mbar) | HORFT1 (mbar) | Crack speed (m/s) |
| 1 | 12.4 ± 0.1 | 57 ± 3 | 150 ± 2 | Partial Symmetrical | 272 | 104 | 12 | 223± 3 |
| 7 | 12.4 ± 0.1 | 51 ± 3 | 150 ± 2 | Partial Symmetrical | 494 | 166 | 21 | 196± 3 |

These results show that the same opening of the vessel produces a stronger blast overpressure TOP1 for experiment 7 because of the faster crack that allows for the rapid expansion of the contents, while both cases have similar impulse. Moreover, the stronger blast overpressure from experiment 7 decays faster with distance compared to experiment 1 because stronger shock has more friction and heat transfer with surrounding environment. Comparing the overpressure from TOP4 with HORFT1 shows that 12 % and 13 % respectively, of the vertical values correspond to the horizontal overpressure.

* 1. Anisotropy of the blast overpressure

This section aims to examine how overpressure varies with direction and orientation across all experiments. Initially, the front side (Y axis) and the back side (X axis) lead peak overpressures from the 45-degree angles and horizontal gauges at 40 cm were compared in Figure 5. Results reveal that overpressure from both sides is nearly identical, clustering around the line (x=y). Additionally, the lead peak overpressures recorded by the 45-degree angle gauges (red) are generally higher than those from the horizontal gauges (blue). This remains true for symmetrical breaches. However, several experiments exhibited partial failures with asymmetrical partial openings, where only one side of the vessel ruptured. For these cases the blast wave is directed more forcefully toward the opening side, leading to anisotropic behavior in the overpressure distribution. Figure 6 shows that asymmetric openings result in stronger overpressure in the preferential direction. Those scenarios happened when the vessel was liquid-full before rupture, had reduced weakened length or failed at low pressures.

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*Figure 5: Front/Back overpressure at 40 cm Figure 6: Front back overpressure from asymmetrical openings*

Symmetrical openings have similar overpressure at the front and back sides. Thus, in Figure 7, the back side and the right end, both positioned 40 cm from the vessel, are compared for the 45-degree angle and horizontal orientations across both experimental campaigns. All points fall mostly below the line (x=y), where back gauges record higher overpressure than the right end. Furthermore, the horizontal end gauge consistently produces lower peak overpressure compared to the 45-degree angle end gauge. The maximum side/end ratio overpressure from horizontal gauges was found to be 2.2, with a minimum value of 0.7.

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Figure 7: Front/Right-end overpressure at 40 cm Figure 8: Overpressure ratios w.r.t Failure pressure

A comparison of dimensionless overpressures, normalized by the maximum overpressure observed at TOP4, is shown in Figure 8 relative to the failure pressure. The graph illustrates how lead peak overpressure is significantly influenced by the failure pressure, as well as by orientation and direction. As the burst pressure increases, the overpressure becomes more isotropic in the side/end directions with the ratio approaching 1.

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Figure 9: A-A view of the overpressure distribution at 40 cm from the tube across all experiments

The graph reaffirms that the vertical gauges consistently record the highest lead peak overpressures, with the magnitude decreasing as orientation changes. At high overpressure levels, and respectively high burst pressures, the overpressure tends to become isotropic due to faster and more complete opening of the vessel.

* 1. Conclusion

This paper explores the directional behavior of blast overpressure based on experimental data from two small scale BLEVE campaigns involving cylindrical pressure vessels. Using thirteen blast gauges, overpressure was tracked at various locations, orientations and distances. Results showed that the lead peak overpressure was the highest for the vertical gauges, followed by 45-degree gauges, and lowest for the horizontal gauges at the same distance. The intensity of the overpressure is contingent about how fast the vessel opens allowing for the rapid expansion of the contents. Thus, the complete opening of the vessel will produce the strongest overpressure. Moreover, the magnitude of the overpressure reduces with distance because of conservation of energy and losses – friction etc... and with orientation as one portion of the energy is lost in opening the vessel walls. Symmetrical vessel openings led to consistent overpressure between the front and the back side gauges, while asymmetrical openings (where only one side of the vessel fully opened) caused a twofold reduction of the blast strength in the closed direction. Additionally, as expected for cylindrical vessels, the overpressure is highly directional, depending on whether the measurement is taken at the tube end or side. This behavior is explained by the shielding effect from the tube’s end fitting (Swagelok) as the vessel opens. The end-to-side ratio was found to range from 0.7 to 2.2 for L/D = 6, and is expected to increase with higher L/D. At higher failure pressures, overpressure distribution became more isotropic due to faster and more full opening of the vessel. Other ratios with respect to the orientation were presented in the following paper. This helps, if validated at larger scale, predict the impact of explosions on surrounding structures/people allowing for more accurate safety measures.

Acknowledgments

The authors are grateful to Natural Sciences and Engineering Research Council Canada (NSERC) for supporting this research work.

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