Blast from pressurized CO_2 released into a vented chamber

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1 Introduction

Accidental release of carbon dioxide (CO_2) from a high-pressure reservoir (a tank, or pipeline) into an atmospheric, vented room (laboratory, factory hall etc.) range from small releases (erroneous opening of a valve) to big, abrupt releases (complete tank rupture and BLEVE). Hazards associated with the larger CO_2 releases are related to both the harmful properties of the fluid (asphyxiation and frost injuries) and the energy release (phase transition rate, blast wave, accelerated fragments, dynamic loads on structures). The pressure buildup and impulse will be a function of the initial state of the fluid, the degree of superheat, the amount of mass released, the vent opening area and the volume ratio between the high-pressure reservoir and vented room / chamber. Zhang et al. [1] have discussed previous accidents involving CO_2 tank explosions.

This paper presents results from small-scale experiments on the release of saturated pressurized CO_2 from a high-pressure reservoir at ambient temperature (19 °C) into a vented, atmospheric chamber. The main goal was to investigate the effect of vent opening and initial liquid content on the measured pressure and calculated impulse response in the atmospheric chamber. In addition, an objective was to study if the volume increase resulting from the rapid boiling would contribute to shock strength in the current test geometry. The contribution includes experimental results from two different vent-opening areas (100 and 10 cm^2) and two different liquid portions (vapor only and a liquid/vapor mixture). Experimental results showing the release of CO_2 from a high pressure reservoir has been previously described by others [2,3,4,5,6], but not with a test rig geometry similar to the one presented here.

2 Materials and methods

Figure. 1 shows a schematic diagram of the experimental setup (a), and a photograph of the test rig (b). The test setup consisted of following main parts (1-5): (1) a high pressure reservoir with borosilicate windows at the front and back, sensor side ports and flanges at the main outlet; (2) an atmospheric chamber with an adjustable vent opening; (3) a pneumatic plunger actuator with a cross shaped knife; (4) a multi-layer aluminum foil diaphragm; and (5) a CO_2 supply system with two 40-liter industry grade cylinders. One cylinder supplied liquid phase feed while the other cylinder delivered vapor phase only. Pressure sensors and temperature sensors were installed at various positions on the test rig. Before each test run, the high-

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pressure chamber was flushed 3 times with vapor phase CO_2 at 10 bar to remove air initially present in the reservoir. The high-pressure reservoir was a custom-designed level gauge with a square channel rated at 100 barg. The maximum liquid fill volume was 0.13 dm^3 and the total volume was 0.19 dm^3. Sensors (temperature T1-T6 and pressure P1-P6) were mounted on the two sidewalls.

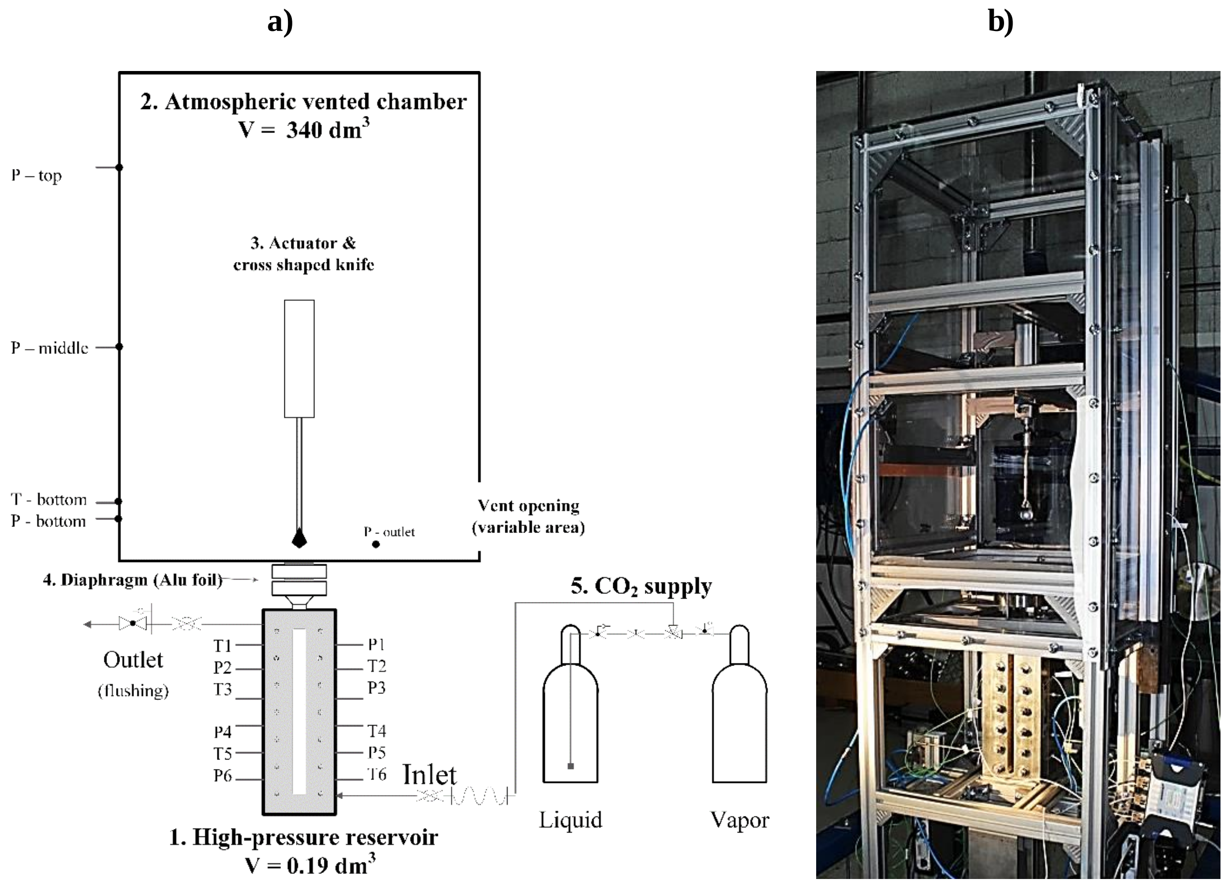

Figure 1. Left: a schematic diagram of the test setup; right a photograph showing the experimental test rig

The atmospheric vented chamber was equipped with transparent polycarbonate sidewalls enabling visual observation of CO_2 release. The chamber dimensions (width, depth and height) were 0.59 x 0.59 x 0.98 meter. The volume was 340 dm^3, after subtracting the volume of the actuator and aluminums profiles.

Four pressure sensors were installed inside the atmospheric vented chamber. Three sensors were mounted on a vertical U-channel steel beam at the rear sidewall while the last sensor was mounted on the sidewall close to the vent opening. A Kulite-XTM-190-100G piezoresistive transducer with a measuring range of 0-100 psig was installed in the steel beam bottom position. The remaining sensors were Kistler 7001 piezoelectric transducers with a measuring range of 0-250 barg.

A temperature sensor was installed close to the bottom pressure sensor on the steel beam. The temperature sensors were type –K thermocouples with a measurement error limit of ± 1.5°C.

A Photron Fastcam SA-1 high-speed camera operating at 5000 fps was used to record the release from the high-pressure reservoir into the vented chamber. High-speed movies with sensor data included were prepared in MATLAB. The matching of the image observations with the sensor measurements provided a basis for interpretation of the experimental results. The measurements shown in Fig. 2 include temperature T_1 and pressure P_1, located in the high-pressure reservoir (0.13m below the outlet), pressure $P_{LP\ Chamber}$, located in the atmospheric vented chamber (0.18 m above the bottom), and calculated impulse of $P_{LP\ chamber}$ (time integrated pressure measurement). The rapid CO_2 expansion and phase transition processes in the high-pressure reservoir could be similar to the results published by Tosse et al. [2] and Hansen et al. [3]. These observations included well-known phenomena such as the rarefaction fan, a condensation wave, a contact surface and an evaporation wave.

3 Results and discussion

Table 1 shows test parameters and experimental results from the four presented test runs (TR1-TR4). The vent opening area and the liquid content in the high-pressure reservoir were the main varied parameters. Initial conditions were saturated CO_2 at ambient temperature (19°C).

Table 1: Test parameters and experimental results from the four presented test runs.

Parameter \ Test run	TR1	TR2	TR3	TR4
Vent opening – atmospheric chamber (cm^2)	100	10	100	10
Liquid volume – high-pressure reservoir (dm^3)	0	0	0.13	0.13
Vapor volume – high-pressure reservoir (dm^3)	0.19	0.19	0.06	0.06
Mass of CO_2, estimated (g)	35	35	110	110
Pressure, initial (barg)	53	52	55	55
Temperature, initial (°C)	19	19	19	19
Pressure, peak – vented chamber bottom (barg)	0.15	0.17	0.20	0.15
Impulse, calculated at 100 ms (kPa·ms)	55	149	346	426

Figure 2 shows three high-speed images from two different test runs (TR1 and TR3), captured at 20 ms and 100 ms after initiation. Initial time t_0 = 0 ms was defined as the time of diaphragm rupture. First, a jet of partially condensed vapor / dry ice was observed, moving out of the high-pressure reservoir and into the atmospheric vented chamber. The initial blast wave could not be observed with the current camera arrangement. The peak pressure from the initial blast wave ranged from 0.15 to 0.20 barg.

In the test runs containing a liquid / vapor mixture (T3 and T4), an increase in the jet intensity / mass flow rate was observed, about 3 ms after the diaphragm rupture. This was most probably the contact surface between liquid and liquid/vapor. The boiling liquid / expanding vapor then increased the intensity of the multi-phase jet flow, which completely filled the vented chamber with white mist.

The high-speed movies showed periodic wall oscillations due to pressure reflections inside the vented chamber. The Kulite sensor (bottom position) seemed to provide more reliable results than the Kistler sensors (top, middle and outlet) in the present experimental study. It seemed less sensitive to vibrations and could provide pressure measurements for a longer period due to the piezoresistive operation. Consequently, the presented pressure measurements from the vented chamber originate from the Kulite bottom sensor only.

Figure 3 shows an impulse plot and two pressure plots from the first 20-millisecond period. The pressure measurements suggested that the rapid phase transition (boiling) was too slow in the current test geometry to contribute to the initial shock strength. No additional peak or pressure increase could be related to the boiling liquid released from the high-pressure reservoir during this period (0-20 ms).

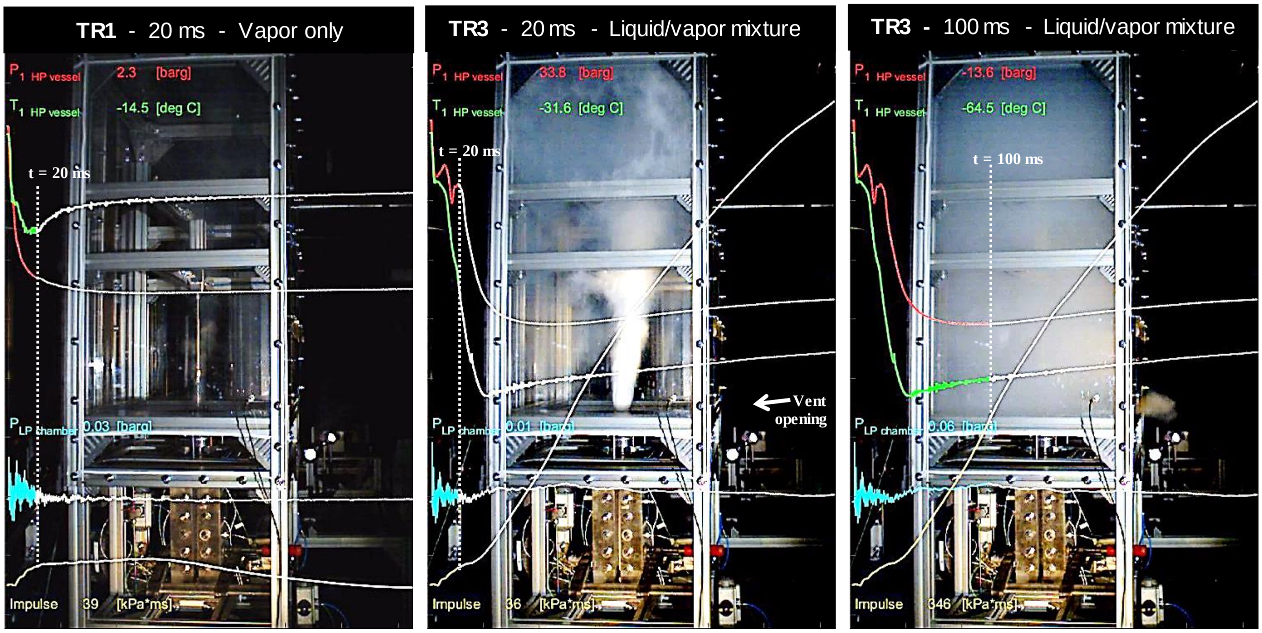

Figure 2. High-speed images and sensor data showing the release of CO_2 from the high-pressure reservoir into the atmospheric chamber with a 100 cm^2 vent opening. Left: After 20 ms, vapor only; Middle: After 20 ms, (liquid/vapor mixture); Right: After 100 ms, 100% (liquid/vapor mixture).

The calculated impulses from all four test runs were almost identical up to about 7.5 ms. Then, for a few milliseconds, the impulse in the vapor only test runs (TR1 and TR2) increased faster than in the liquid/vapor mixture test runs (TR3 and TR4). In the vapor only test runs (TR1 and TR2), the jet from the high-pressure reservoir decayed rapidly and was no longer visible after about 20 ms, as is shown in Fig.2 - left image. The middle image in Fig. 2 shows that an increased initial liquid content resulted in an increased duration of the CO_2 jet. The jet release then lasted about 40 milliseconds.

Figure 4 shows an impulse plot and pressure plot from the 0-500 millisecond period. The right plot shows a connection between the pressure response in the vented chamber with the liquid content in the high-pressure reservoir (vapor only or a liquid/vapor mixture). For the liquid / vapor mixture test runs (TR3 and TR4), a rise from zero to 0.05 – 0.07 barg in the vented chamber bottom pressure was observed, starting at about 30 ms. A high liquid content resulted in a longer period at an elevated pressure. Consequently, the calculated impulse was significantly larger when the high-pressure reservoir contained a liquid / gas mixture, as compared to vapor phase only. The duration of the liquid / vapor mixture test runs was longer than 100 ms, due to the time needed to push the cloudy mist of CO_2 in the vented chamber out through the vent opening.

An unexpected crossover in impulse history between TR3 and TR4 (both liquid / vapor mixture) was observed in Fig. 4 after about 150 milliseconds. One would expect that the smallest vent opening area (10 cm^2) should result in a higher calculated impulse than the 100 cm^2 opening due to a larger pressure buildup. A possible reason why this was not observed here could be an effect of the temperature dependency on the pressure measurements. As a conservative estimation, the impulse for the liquid/vapor mixture (TR3 and TR4) stated in table 1 was calculated at 100 ms. This is because a permanent offset originating from a thermal zero shift would result in a significant error contribution in the impulse calculations. The temperature decreased significantly both inside the high-pressure reservoir and inside the vented chamber, due to the rapid boiling and expansion.

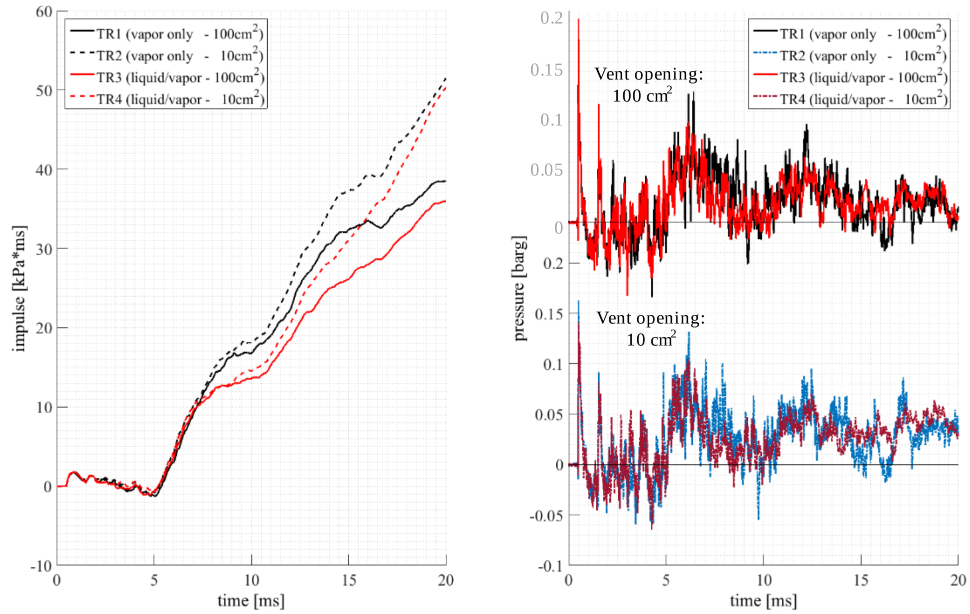

Figure 3. Impulse calculations (left) and pressure measurements (right) from the vented chamber bottom sensor showing the first 20 milliseconds after diaphragm rupture. There are four test runs (TR1-TR4) with two vent-opening areas (100 and 10 cm^2) and two different liquid/vapor proportions (vapor only and a liquid/vapor mixture).

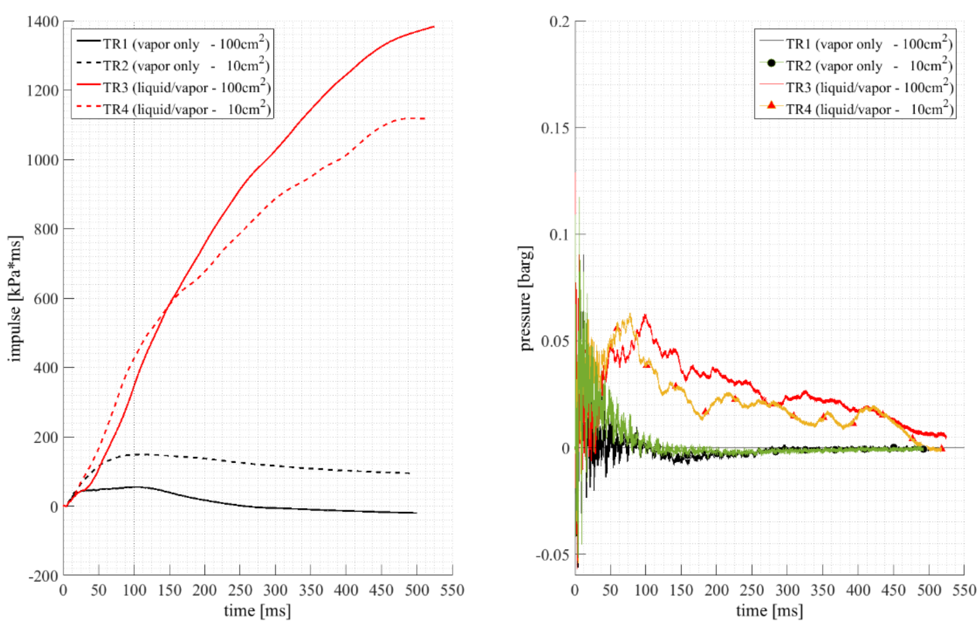

Figure 4. Impulse calculations (left) and pressure measurements (right) from the vented chamber bottom sensor showing the first 500 milliseconds after diaphragm rupture. There are four test runs (TR1-TR4) with two vent-opening areas (100 and 10 cm^2) and two different liquid/vapor proportions (vapor only and a liquid/vapor mixture).

The jet that formed at the exit of the diaphragm was under-expanded. The main part of the expansion occurred downstream of the diaphragm. The outlet section could probably influence the experimental results to some extent. With sonic conditions at the throat and by replacing the original straight slip-on flange to a divergent outlet section, the flow could be accelerated and then influence the outlet pressure and velocity. However, the mass flow rate was still believed to be unchanged for a period of time due to choking conditions at the throat upstream if the diaphragm. It would be desirable to achieve an instantaneous release of liquid CO_2 into the vented chamber, similar to the work by van der Voort et al. [6]. That would provide a better opportunity to investigate the effect of the rapid phase transition on blast wave pressure and calculated impulse.

Further investigations should include test runs with a reduced vapor headspace in the high-pressure reservoir, giving a liquid content closer to 100%. In addition, the volume of the vented chamber could be reduced, to study the response of venting opening area on the measured peak pressure inside the chamber.

4 Conclusions

This paper presents results from small-scale experiments on the blast effect of pressurized liquefied CO_2 released from a high-pressure reservoir into a vented atmospheric chamber. Some main findings are summarized below. The rapid phase transition (boiling) did not contribute to the initial shock strength in the current test geometry. The boiling process seemed too slow or the release rate from the high-pressure reservoir was too low to contribute to the measured peak pressure, which was in the range 0.15-0.20 barg. The test runs with a liquid/vapor mixture in the high-pressure reservoir, showed a significantly higher impulse (time integrated pressure response) compared to test runs with vapor phase only. Reducing the vent opening from 100cm^2 to 10cm^2 resulted in a slight increase in impulse calculated at 100 milliseconds. The effect of vent opening on the impulse was evident in the test runs with vapor only, but not so clear in the test runs with the liquid/vapor mixture.

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