Effect of Venting on Flame-Acoustic Instability in Large-Scale Propane-Air Explosions

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1 Introduction

Explosion venting is a passive method to protect an enclosure by reducing the overpressure related to confined accidental explosions. Vented gas explosions can exhibit multiple pressure peaks, each of which depends on several factors, such as the enclosure geometry, obstructions, reactive mixture, and characteristics of the vent itself, such as vent size, geometry, and deployment dynamics. Predicting the magnitudes of these peaks is critical for the determination of the required vent size. In addition to the pressure peaks related to vent deployment, external explosion, and maximum flame surface area, it has been shown that also flame-acoustic instability can generate a pressure peak which typically appears near burn-out [1,2,3].

Tamanini and Chaffee [2] showed that flame-acoustic instabilities manifest themselves through exponentially growing pressure oscillations, enhanced combustion rates, and increased peak explosion pressure for propane-air mixtures in a vented 1.35-m^3 vessel. The onset of instability was related to vent deployment. Frequencies corresponding to the fundamental acoustic mode of the vessel occurred at early times, and transitioned to higher frequencies close to burn-out. When acoustically absorbing material was introduced at the vessel walls, acoustics were suppressed and the peak pressure was reduced. Al-Shahrany et al. [4] studied iso-octane and hydrogen-air mixtures in a closed, 30-L spherical bomb, and observed flame-acoustic instability for mixtures with negative Markstein numbers. Similar phenomenology occurs during flame propagation in pipes. Searby et al. [5] experimentally characterized primary and secondary acoustic instabilities of a flame propagating from the open end of a pipe toward a closed end. The primary instability was studied more specifically by Clanet et al. [6]; Searby and Rochwerger [7] presented analyses on the secondary, parametric instability.

The present experimental study contributes to the understanding of flame-acoustic instabilities in large-scale explosions. Experiments were performed in an 8-m^3 vessel with propane-air mixtures, both for closed-vessel and vented configurations. The effects of venting and mixture composition on the development of flame-acoustic instability and mean explosion parameters are characterized, and the mechanisms that trigger the onset of instability are identified.

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2 Experimental setup

Confined and vented tests were performed with initially quiescent propane-air mixtures in an 8-m^3 vessel with a nominal aspect ratio of 1.4, shown in Fig. 1. For the vented tests, the vessel was equipped with an adapter flange and an orifice plate with an internal diameter of 400 mm.

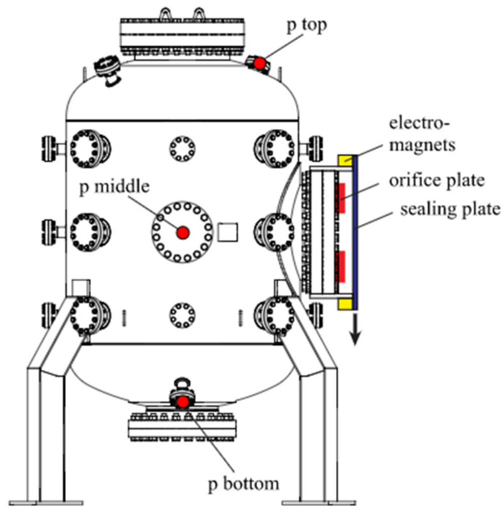

Figure 1. 8-m^3 explosion vessel, orifice plate used for vented tests, sealing plate with electro-magnetic release mechanism, and pressure transducer locations (red circles).

A sealing plate, held in place by electromagnets, was used to close the vent during mixture preparation and was released 1 s prior to ignition. Using this method, the vent was fully open at the time of ignition, representing an ideal vent deployment, in contrast to other procedures using a plastic film or vent panels. The mixture was prepared by flushing the vessel with fresh air, adding propane to achieve the target concentration, using a recirculation pump to generate a uniform mixture, and measuring the propane concentration using both infrared absorption and speed of sound analysis. The mixtures were ignited by a weak electric spark (miniature spark plug with a 2-mm spark gap) at the center of the vessel. Pressure in the vessel was measured using three piezoresistive Kistler 4260A 0-10 bara transducers with a 2-kHz maximum frequency response, at locations as indicated in Fig. 1. The noise level for pressure measurements was $\leq \pm$ 0.01 bar for all reported experiments. A Phantom Flex color camera was used to determine the time of flame-exit from the vent, operating at a framing rate of 1000 fps.

3 Experimental results

Results from stoichiometric propane-air mixtures are shown first to describe the general observations made throughout this experimental series for closed-vessel and vented cases. Then, the discussion is extended to rich and lean mixtures to determine the effect of mixture composition.

3.1 Closed-vessel and vented explosions with stoichiometric propane-air mixture

Figure 2 presents pressure traces and (mean) rate of pressure rise histories of closed-vessel (left) and vented (right) experiments with stoichiometric (4.0±0.1%) propane-air mixture. The rate of pressure rise histories were computed from the unfiltered pressure traces by applying a phase-neutral 75-Hz low-pass filter, which generates the filtered (mean) pressure histories, and taking the temporal derivative. The filter cut-off frequency of 75 Hz lies below the lowest experimentally observed acoustic mode of the vessel corresponding to a frequency of about 150 Hz, and therefore provides a threshold that differentiates between acoustics and mean pressure transients.

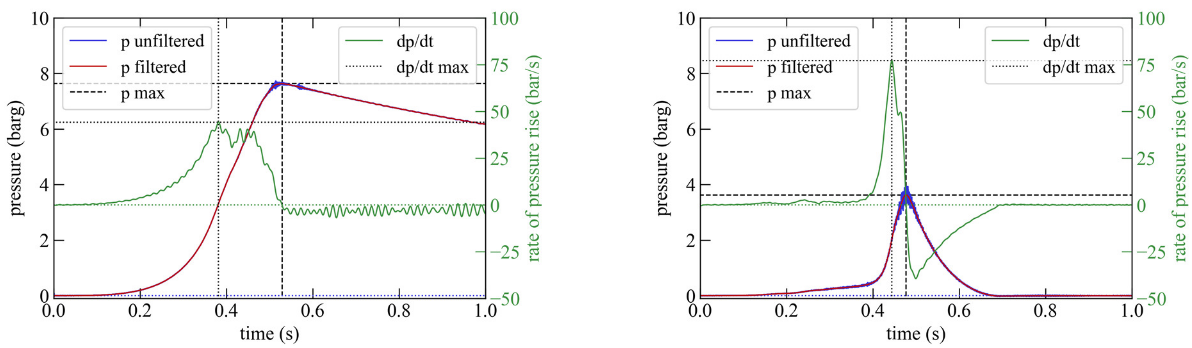

Figure 2. Pressure traces and rate of pressure rise of closed-vessel (left) and vented (right) explosions in stoichiometric propane-air. Unfiltered pressure traces (blue), low-pass filtered pressure traces (red) and rate of pressure rise histories (green).

The closed-vessel case, Fig. 2, left panel, shows a steady increase in pressure after ignition (t = 0 s), reaching a peak pressure of 7.6 barg at t = 0.53 s as determined from the filtered (mean) pressure history. The rate of pressure rise increases up to a peak value of 44 bar/s at t = 0.38 s, subsequently plateaus due to the competition of heat release, heat loss and flame extinction at the vessel walls as the expanding flame interacts with the vessel side-walls, and finally decreases before the time of peak pressure, which coincides closely with burn-out. The vented case, Fig. 2, right panel, shows a slow initial increase in pressure, before a secondary steep increase in pressure occurs at t ≈ 0.38 s, which leads to a peak pressure of 3.6 barg at t = 0.48 s. The rate of pressure rise is lower than 5 bar/s for t < 0.38 s, and increases sharply between 0.38 s and 0.44 s, to a peak value of 77 bar/s, which exceeds the value in the closed vessel. Around the time of peak pressure, oscillations appear in the unfiltered pressure trace (blue line), indicative of flame-acoustic instability.

3.2 Closed-vessel and vented explosions with varying propane concentration

To explore the effect of mixture composition on the development of flame-acoustic instability in closed and vented vessels, a comparison was made between lean (3.7±0.1%) and rich (5.1±0.1%) propane-air mixtures. These two mixtures were chosen because they burn at a very similar rate, prior to the development of flame-acoustic instability, but have been shown to exhibit significantly different acoustic sensitivity [3]. This allows for the effect of flame-acoustic instabilities to be isolated.

75-Hz low-pass filtered pressure traces from closed-vessel experiments are shown in Fig. 3 (a), including signals from all three pressure transducers. Deviations between the transducer signals are negligible, indicating that the mean pressure is spatially uniform within the vessel. Experimental pressures are compared to predictions from an adiabatic spherical-flame model [8], which computes pressure transients, including the effects of pressure and temperature on the laminar burning velocity, as well as thermal-diffusive flame instabilities. At early times, t < 0.4 s, the experimental curves for lean and rich mixtures coincide, indicating very similar burning rates, and agree well with the adiabatic model predictions. At t > 0.4 s, the experimental traces gradually depart from the model predictions. This departure is related to the interaction of the expanding flame with the vessel side-walls in the experiments, which is not considered in the model, leading to flame extinction, heat loss, and a decrease in burning rate in the experiments. Traces for rich and lean mixtures deviate from each other at t ≈ 0.45 s. The rich mixture develops higher peak mean pressure and earlier burn-out, which is caused by flame-acoustic instability. Figure 3 (b) presents normalized acoustic pressure, obtained by subtracting the filtered (mean) pressure traces from the unfiltered pressure traces, and dividing by the instantaneous absolute mean pressure. For the rich mixture, acoustic pressure begins to increase at about t ≈ 0.4 s, and peak acoustic pressure is reached when the mean pressure peaks, which coincides closely with burn-out.

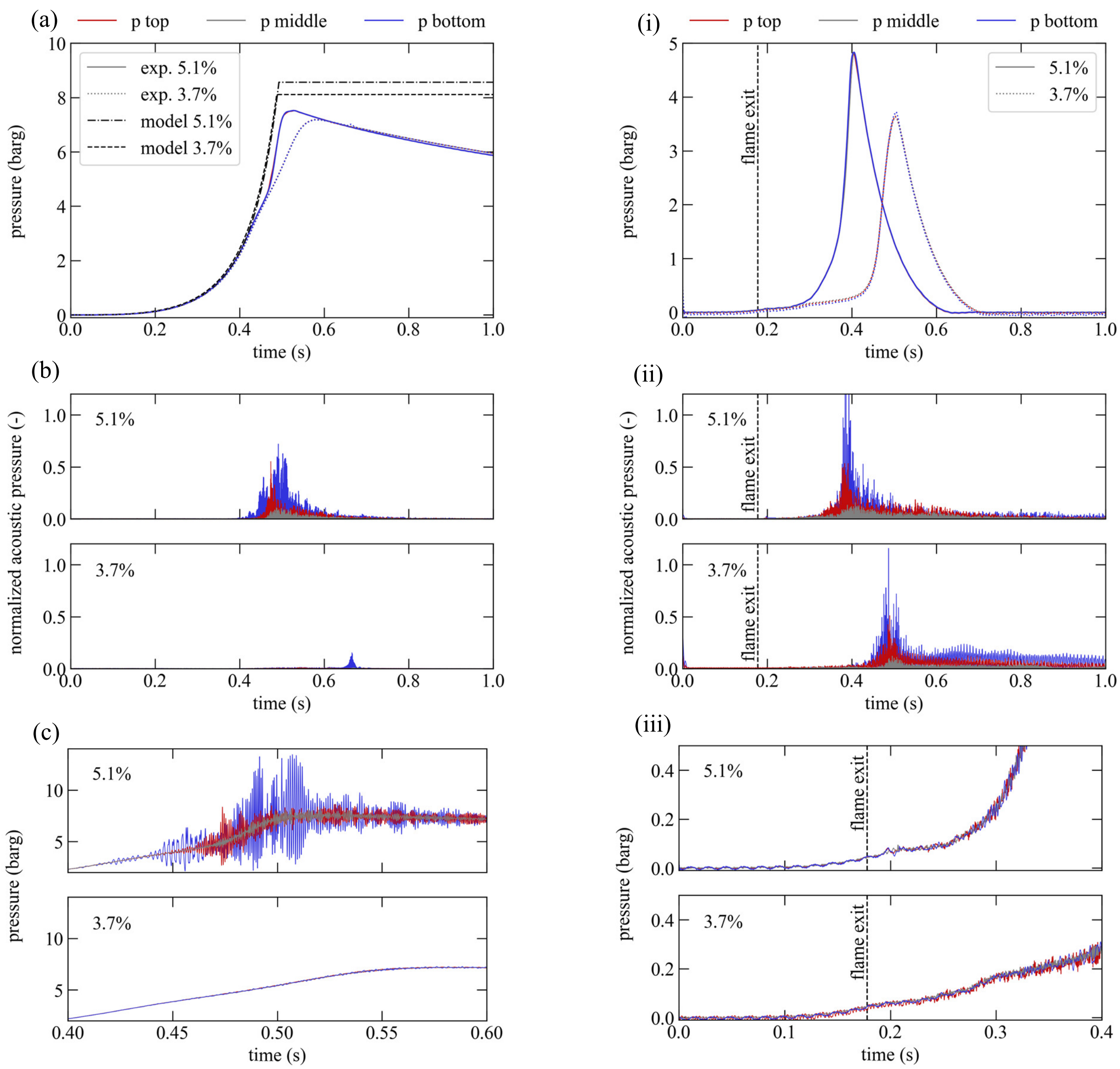

Figure 3. Pressure traces (top: low-pass filtered; bottom: unfiltered, details) and acoustic pressure (middle) for rich (5.1%) and lean (3.7%) propane-air mixtures. Closed vessel (left) and vented vessel (right).

The lean mixture, by contrast, shows negligible acoustic pressure, with a short-lived burst after reaching peak mean pressure, which may be related to late burn-out of pockets of mixture in flange cavities. Flame-acoustic instability observed in the rich mixture results in an accelerated increase of mean pressure, see

Fig. 3 (a), t > 0.45 s. The differences in acoustic pressure between the three transducers indicate that acoustic pressure varies spatially within the vessel, in contrast to mean pressure. Figure 3 (c) shows a detailed view of unfiltered pressure traces around the time of peak mean pressure. A clear departure between the traces for lean and rich mixtures is observed at t ≈ 0.45 s, with strong pressure oscillations, faster burn-out, higher peak rate of pressure rise, and higher peak mean pressure for the rich mixture, compared to negligible oscillations in the lean mixture. The onset of instability in the rich mixture is closely related to the time of flame-wall interaction inferred from the comparison between experimental traces and model predictions.

Filtered pressure traces from the vented vessel, Fig. 3 (i), show very similar initial development for rich and lean mixtures for t < 0.2 s, and subsequently a clearly faster process in the rich mixture, with higher peak mean pressure and higher peak rate of pressure rise. Figure 3 (ii) displays acoustic pressure from the vented tests and demonstrates that significant oscillations occur for both rich and lean mixtures, in contrast to the closed-vessel experiments, where only the rich mixture shows strong oscillations. Figure 3 (iii) focuses on the early process, including the period between ignition (t = 0 s) and flame-exit from the vent (t = 0.178 s, equal for both mixtures, as determined from high-speed video; dashed line), where the pressure traces coincide for rich and lean mixtures. Shortly after flame-exit, the rich mixture shows significantly faster pressure rise compared to the lean mixture, as well as the onset of pressure oscillations, indicating that flame-exit triggers flame-acoustic instability. Flame-exit results in a sudden change in venting rate due to the change in vented gas density, in addition to the pressure pulse from the external explosion, which occurs when the flame consumes the cloud of previously vented unburned mixture outside the vent; either mechanism may trigger flame-acoustic instability. The deployment of a vent panel is not a requirement for triggering flame-acoustic instability; flame-exit and external explosion are sufficiently strong triggers.

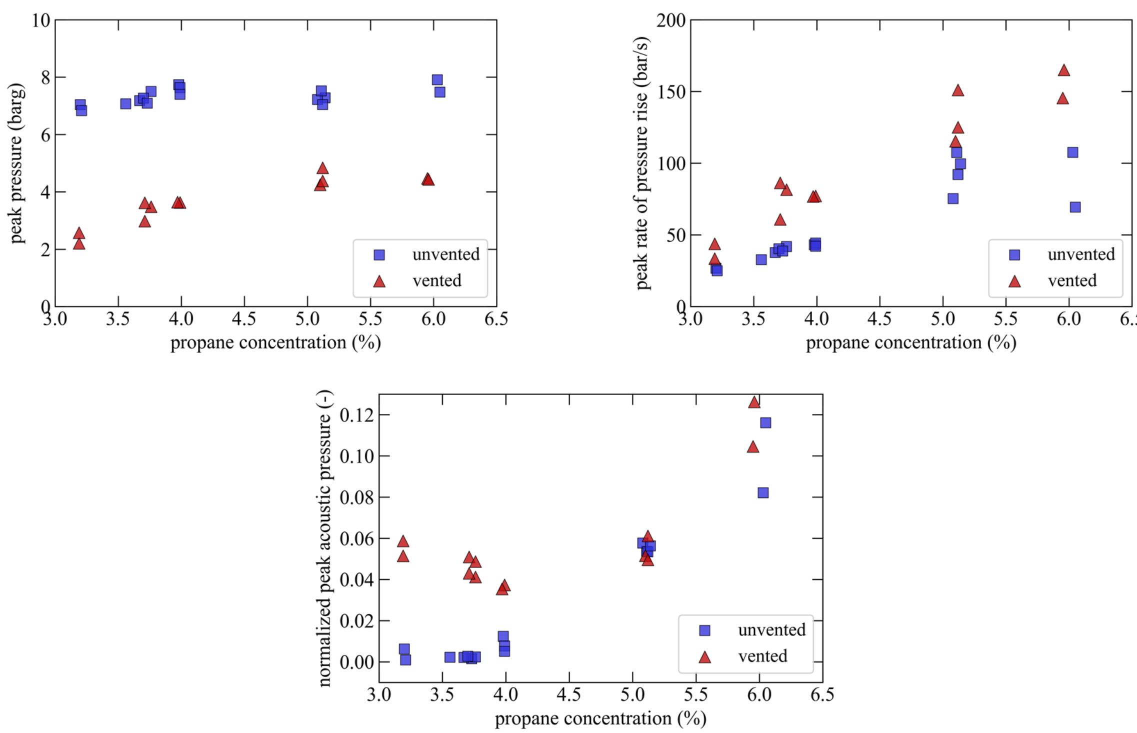

Figure 4. Peak mean pressure (top left), peak mean rate of pressure rise (top right) and peak acoustic pressure (bottom) as a function of propane concentration, measured at the middle pressure transducer.

Further experiments were performed with propane concentrations between 3.2 and 6%. Figure 4 summarizes peak mean pressure (top left), peak rate of pressure rise (top right), and normalized peak acoustic pressure (bottom, inferred from normalized acoustic pressure traces using a Hilbert transform and a 20-Hz low-pass filter; the filtered Hilbert transform creates an envelope to the pressure fluctuations, which removes single pressure peaks from the analysis). Results are shown for the middle pressure transducer which minimizes local effects of the specific vessel geometry which are most significant at the top and bottom transducers. The quantitative values of peak acoustic pressure should be interpreted with care, since the measurement location drastically affects the results, see Fig. 3.

As expected, vented peak mean pressures are consistently lower than closed-vessel peak pressures. The peak rates of pressure rise are consistently higher in vented tests and increase with increasing propane concentration. Significant variations between repeat tests are seen in rich mixtures, indicating high sensitivity of flame-acoustic instability to the experimental conditions. In the closed vessel, peak acoustic pressures are negligible for lean mixtures and increase toward rich mixtures, whereas venting leads to significant acoustic pressure both in lean and rich mixtures.

4. Conclusions

The present experiments on flame-acoustic instability in closed and vented vessels with propane-air mixtures provided the following insights:

- In a closed vessel, flame-acoustic instability only occurred for rich propane-air mixtures. With venting, however, lean mixtures also exhibited instability. Peak rates of pressure rise were consistently higher in vented explosions, compared to closed-vessel explosions, and venting led to earlier burn-out.
- When flame-acoustic instability was present, accelerated global combustion rates were observed, leading to higher peak mean pressures and higher rates of pressure rise.
- In the closed vessel, flame-wall interactions triggered instability, whereas onset of instability in vented explosions without vent panels was related to flame-exit from the vent and external explosion.
- The magnitude of acoustic pressure was strongly dependent on the measurement location in the vessel. Further studies will explore the correlation between different measurement locations and provide a frequency analysis of the pressure signals.

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