Understanding How Mixture Composition Affects Flame-Acoustic Interactions in Large-Scale Vented Explosions

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1 Introduction

Accidental explosions present a major hazard to industrial safety and significant effort is made to effectively control or mitigate their consequences. For gas explosions in confined areas, the most common method to reduce the severity of an explosion is venting, where a section of the enclosure is designed to fail in order to relieve the pressure generated by combustion. To adequately protect an enclosure through venting, however, it is necessary to size the vent appropriately. Significant effort has been performed in the past to quantify the pressures that develop and the vent sizes needed [1, 2, 3]. These studies have found that the complex interaction between the flame and the venting process generates multiple pressure peaks.

In virtually all large-scale experimental studies, the development of strong flame-acoustic interactions have been observed, except when the enclosure is lined with acoustic dampening wall materials. While some studies have suggested that this phenomenon may not be significant in real-world applications [4, 5, 6], their pervasiveness suggests that, unless an active effort is made to disrupt these flame-acoustic interactions, it is difficult to eliminate the possibility that they develop. As such, it is important to understand the mechanisms that control the growth of flame-acoustics instabilities during vented explosions, to properly ensure that they do not develop in practice.

While previous work examined the factors that affect the magnitude of the overpressures generated [6], this study examines the nature of the acoustics, specifically the frequencies that develop and how mixture composition affects them, and their potential implications on peak overpressure. To do this, previously obtained experimental data studying spherical-flame acceleration, [7, 8, 9], will be used to examine the effect of mixture composition on the acoustics that develop during vented explosions. In addition, recent experimental work performed in an 8 m^3 vessel, [10], will be used to examine this behavior under both confined and vented conditions. This analysis will include frequency analysis of pressure data obtained from multiple measurement locations within the enclosures, to gain a better understanding of how the acoustics develop and how they vary with equivalence ratio for propane-air, methane-air and hydrogen-air fuels.

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2 Experiments

Experimental data from two test setups are examined in this study. First, experiments that were performed studying spherical-flame acceleration in a 64 m^3 chamber, with a 5.4 m^2 vent, for propane-air [7], methane-air [8], and hydrogen-air [9] mixtures were used. While those studies were performed to evaluate spherical-flame acceleration using optical flame tracking, pressure was also measured at four locations within the chamber, using Kistler 4260A piezoresistive pressure transducers, as shown in Fig. 1, left panel. From those studies, experiments performed under quiescent initial conditions were used, including: 54 propane-air experiments, with equivalence ratios, ϕ = 0.9 – 1.5; 19 methane-air experiments, with ϕ = 0.9 – 1.15; and 25 hydrogen-air experiments, with ϕ = 0.3 – 0.6. In addition to the 64 m^3 test data, experiments were recently performed in an 8 m^3 vessel with propane-air mixtures, Fig. 1, right panel, to examine the effect of venting on the development of flame-acoustic instability [10]. From that study, 23 unvented tests and 17 tests with a 0.4 m diameter circular vent were examined, with ϕ = 0.8 – 1.5.

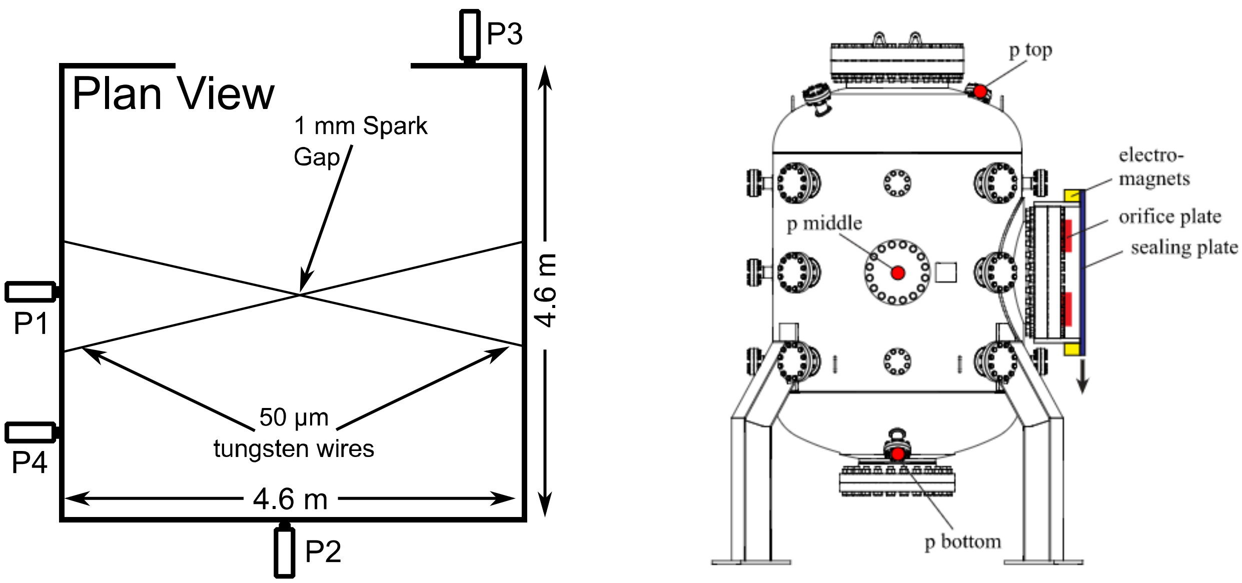

Figure 1. Diagrams of the 64 m^3 chamber [7, 8, 9] (left) and the 8 m^3 vessel [10] (right)

3 Results/Discussion

For both of these experimental setups, pressure was measured at multiple locations. It is important to note, that while mean filtered pressures were uniform throughout, the local pressure fluctuations were found to vary significantly with measurement location and between repeated tests. As these pressure fluctuations can be highly complex, due to frequency shifts during flame propagation and the abundance of acoustic modes in the enclosures, isolating and tracking the development of individual frequencies was found to be impractical. Instead, selected frequency ranges were extracted using a third-order bandpass filter and a Hilbert transformation to isolate the average contribution of the pressure fluctuations within a range of frequencies. This result was further processed using a 20 Hz low pass filter to produce a pressure envelope that can be compared between different frequency ranges. Using this method, the individual contributions of the different frequency ranges are isolated temporally from one another, as illustrated in Fig. 2, where the acoustic fluctuations at location P1 in the 64 m^3 chamber are shown for a ϕ = 0.9 methane-air mixture.

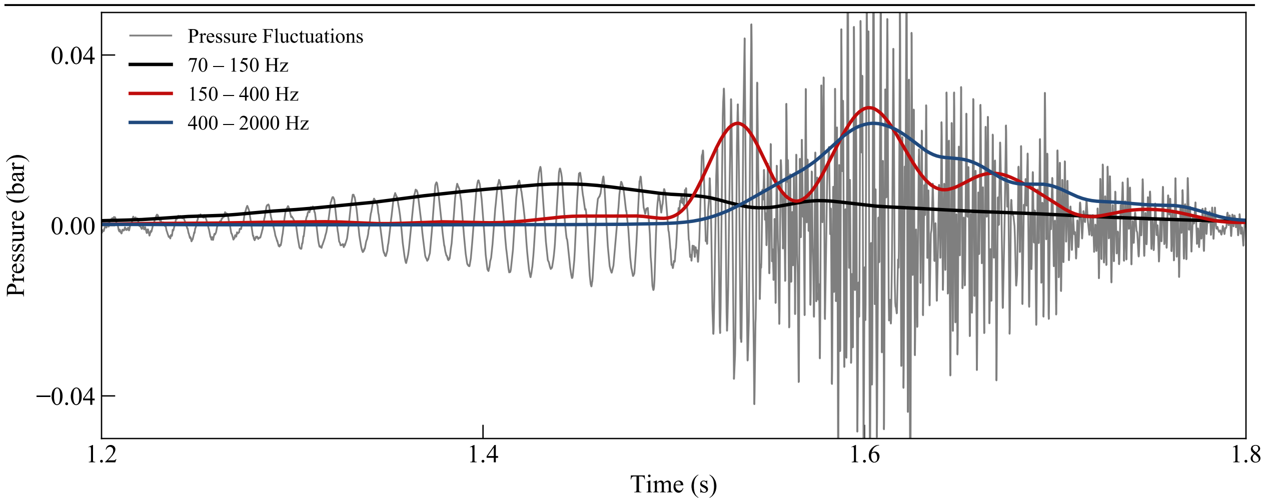

Figure 2. Illustration of how the Hilbert transform isolates the contribution of different frequency ranges.

To understand the development of acoustics during a vented explosion, it is important to distinguish the formation of global acoustic waves, which traverse the entire enclosure, and localized flame-acoustic interactions that develop in spaces between the flame and the structure. Throughout the experiments, it was found that low-frequency acoustics were, in general, the first to develop, manifesting as standing waves that clearly involve the entire enclosure. Figure 3 illustrates how this behavior was observed in both test enclosures, where regular oscillations are seen on multiple transducers and the measurements on opposite sides of the enclosures are 180 degrees out of phase. Transducers in the midpoint of the standing wave, P2 and P middle, correspond to pressure nodes and show minimal oscillation. These standing waves generate acoustics that globally excite the flame, where large portions of the flame surface experience the effect simultaneously.

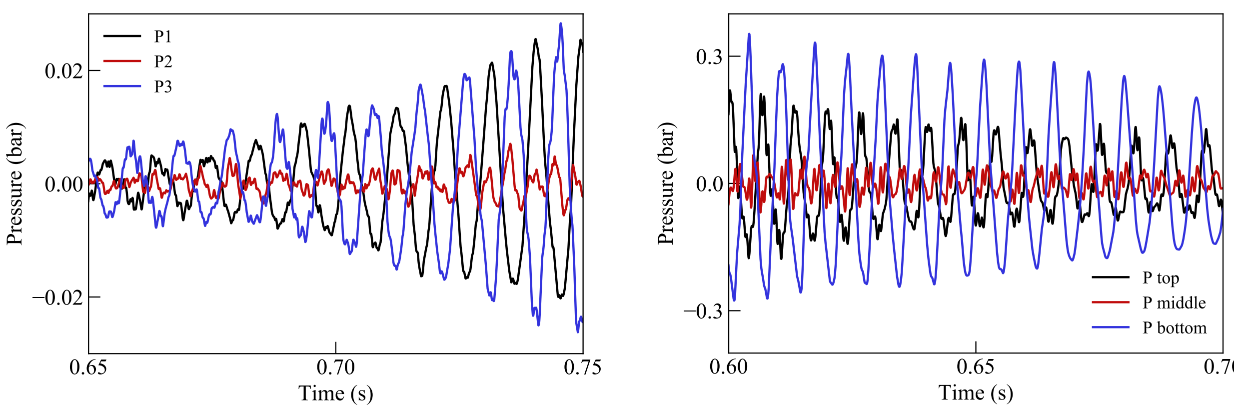

Figure 3. Example plots showing the presence of a 100 Hz standing wave in 64 m^3 chamber and a 150 Hz standing wave in the 8 m^3 vessel.

For the higher-frequency acoustic oscillations that were observed, it was found that these oscillations present very local effects and vary significantly with measurement location [10]. This suggests a coupling between the local flame structure and either the gap between the flame and the enclosure wall, or a coupling with the structural response of the enclosure itself. As these oscillations do not traverse the enclosure, they have been seen to exhibit significant variation, both temporally and spatially, and these variations are likely responsible for the strong variability in peak acoustic pressure that has been seen in experiments [1, 6].

Pressure development in the 64 m^3 chamber

When the peak mean pressure, obtained using a 75 Hz low-pass filter of the raw pressure trace, is examined, the pressure peak associated with the development of acoustics can be identified. The peak mean pressure for experiments performed in the 64 m^3 chamber is summarized in Fig 4a, as a function of equivalence ratio. It should be noted that, even though initial flame propagation was highly repeatable in these studies, significant variability and scatter is seen in the peak pressures that develop. This variability is likely due to the local flame-acoustic interaction and the tests where the highest mean overpressures develop may be the cases where acoustics independently develop simultaneously over a large flame area, maximizing the overall flame surface area and global fuel consumption rate. Despite this variability, a clear trend is observed that the peak pressure increases with equivalence ratio for all three mixtures.

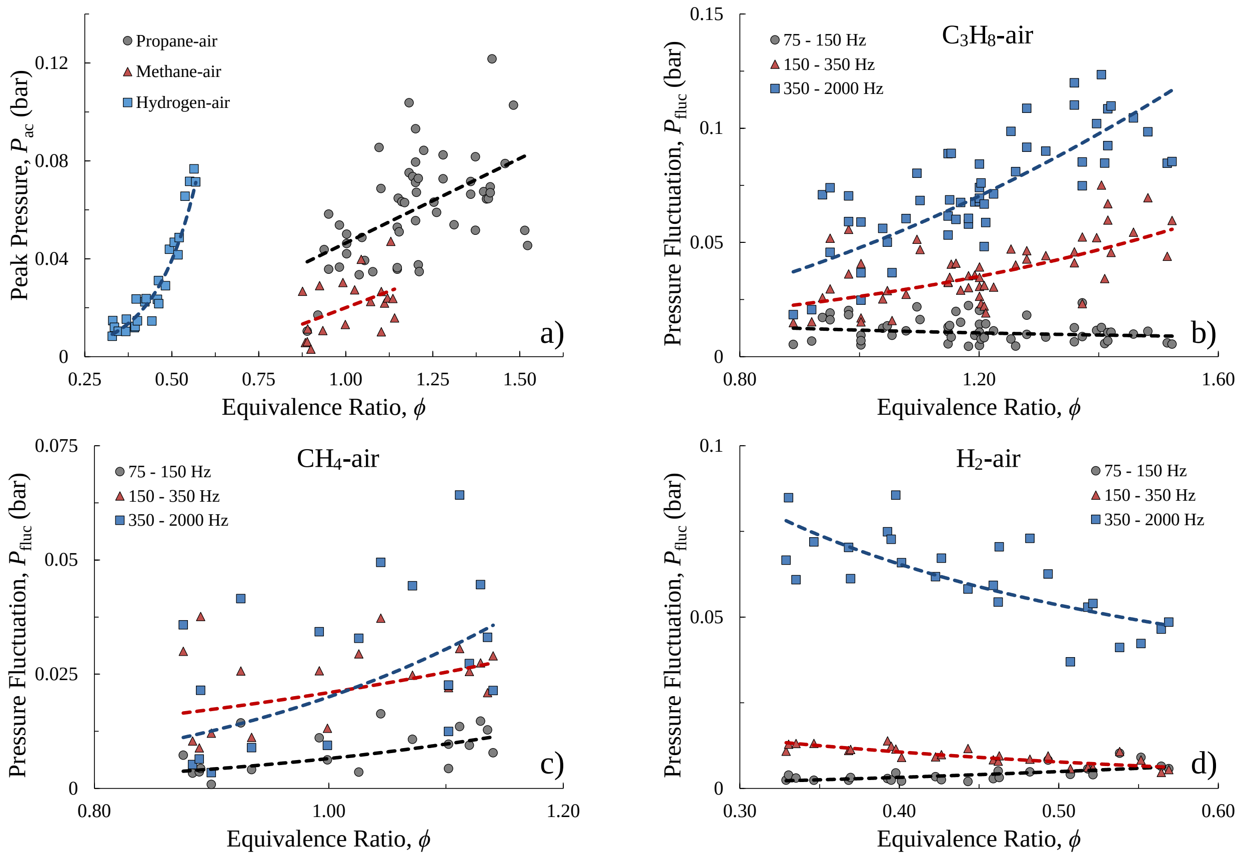

Figure 4. Plots showing a) the peak mean pressure associated with flame-acoustic instabilities in the 64 m^3 chamber, and the peak pressure fluctuations, for three pressure ranges, in b) propane, c) methane, and d) hydrogen mixtures.

To isolate the contribution of the different frequencies that develop, three spectral ranges were examined. The 75 – 150 Hz range corresponds to the maximum frequency of the first harmonic of a standing wave that can develop in the chamber. The higher 150 – 350 Hz and 350 – 2000 Hz ranges corresponds to two distinct bands of frequencies that were observed to develop when the full range of mixtures and equivalence ratios were examined. For propane-air mixtures, it was found that the development of higher-frequency oscillations increased with equivalence ratio, as shown in Fig. 4b. The lower frequency standing waves, however, did not exhibit the same response, slightly increasing in strength for leaner mixtures. When the same analysis is performed for methane-air mixtures, Fig. 4c, it was found that the response of all three frequency ranges was relatively flat across the concentration range, with only a slight increase in the magnitude of the pressure fluctuations with higher equivalence ratio. In addition, it was seen that the 350 – 2000 Hz range did not show a significantly higher response than the 150 – 350 Hz band. The hydrogen-air mixtures, on the other hand, developed strong high-frequency oscillations, which increased as equivalence ratio decreased, and a minimal response to the lower frequencies, as shown in Fig. 4d. It is also interesting to note that in the hydrogen-air mixtures, the strong oscillations did not translate into higher peak mean pressures, Fig. 4a, likely due to the large change in burning velocity over this concentration range.

The different flame responses observed between these mixtures are likely due to a combination of factors including: the cellular structure of the flame surface, the Markstein length, the laminar burning velocity, and the expansion ratio of the various mixtures. The strong response of lean hydrogen-air and rich propane-air mixtures to high-frequency acoustics are consistent with the small hydrodynamic cell sizes of these mixtures [7, 9], allowing the flame to respond to shorter duration pressure pulses. It is interesting to note, however, that methane-air mixtures produce higher flame-acoustic fluctuations on the rich side of stoichiometry, a behavior also observed in previous experimental studies [1], while the cell size decreases on the lean side of stoichiometry. This difference may be the result of the weaker relationship between cell size and equivalence ratio for methane-air mixtures in this concentration range, as all of the mixtures have positive Markstein length. Instead, it is possible that the increase of expansion ratio with equivalence ratio over this range is responsible for the increased sensitivity. For hydrogen-air mixtures, the peak mean acoustic pressure increases with equivalence ratio, despite a decrease in acoustic fluctuation, which is likely the result of an increase in laminar burning velocity and expansion ratio.

Effect of venting on the frequencies generated in confined explosions

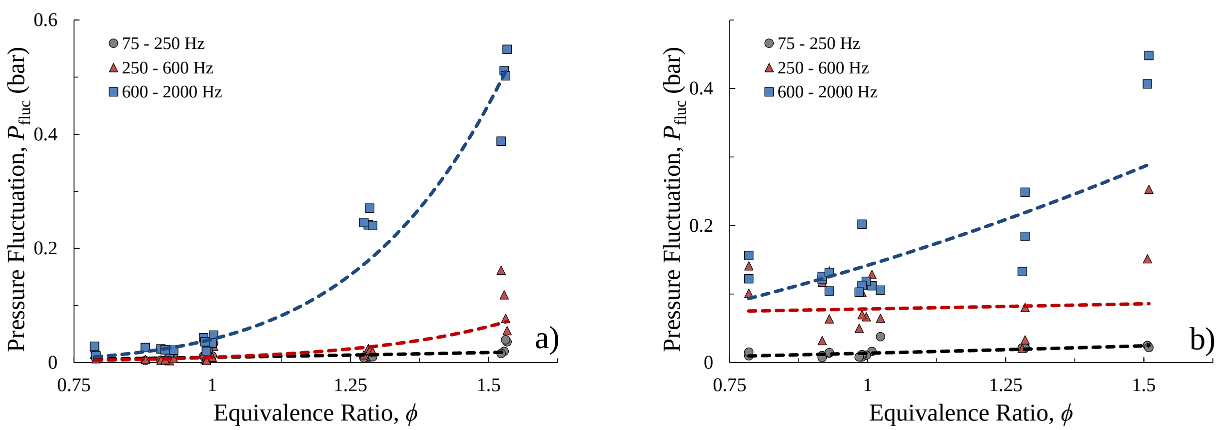

Figure 5. Peak pressure fluctuations, for propane-air mixtures, in an a) confined and b) vented, 8 m^3 vessel.

To examine the effect of confinement and venting on the acoustic frequencies that develop, experimental data from the study performed in the 8 m^3 vessel is used. In the unvented configuration, strong high-frequency oscillations arose for rich mixtures, as shown in Fig. 5a. These high-frequency oscillations increased rapidly with equivalence ratio, while in lean mixtures, very weak, or minimal, flame-acoustic instabilities were observed. It can be seen that the lower-frequency oscillations, corresponding to the fundamental modes of the vessel, and the intermediate range of frequencies, also increased with equivalence ratio, but to a much lesser extent. When the 0.4 m diameter circular vent was introduced, a much wider range of frequencies developed across the full range of propane equivalence ratios. This suggests that the vent itself is generating acoustic energy across a wide spectral range that can interact with the flame, as these lower-frequency contributions were not present in the confined cases.

4 Conclusions

In this study, previously obtained experimental pressure data was analyzed to determine the frequencies that develop during vented explosions over a range of fuels and equivalence ratios for two test geometries. Two primary classes of acoustics were observed: lower frequency standing waves that traverse the entire enclosure, and high-frequency acoustics created by local interactions between the enclosure and the flame.

Universally, it was found that rich propane-air explosions generated strong high-frequency acoustics that increased with equivalence ratio. A similar trend was observed for methane-air mixtures; the resulting acoustics, however, were much weaker for all frequencies, and only increased slightly with concentration. For hydrogen-air mixtures, the acoustics generated were strongly biased toward higher frequencies, and minimal low-frequency response was observed. The high-frequency flame-acoustic interactions significantly increased in intensity as hydrogen concentration decreased; however, this did not result in an increase in peak explosion overpressure, due to a decrease in laminar burning velocity.

In a closed vessel, rich propane-air mixtures were found to generate strong high-frequency oscillations, while venting introduced a wide range of lower-frequency acoustics. These lower-frequency oscillations were likely responsible for the higher flame-acoustic peak mean pressures seen in lean propane experiments.

These results demonstrate how different mixtures can present significantly different trends for the variation of frequency response with equivalence ratio for the same enclosure and can be used in future studies to gain insight into when flame-acoustic interactions must be considered in real-world scenarios.

References

[1] Cooper MG, Fairweather M, Tite JP. (1986). On the mechanisms of pressure generation in vented explosions. Combust. Flame. 65(1): 1.

[2] Bradley D, Mitcheson A. (1978). The venting of gaseous explosions in spherical vessels. II – Theory and experiment. Combust. Flame, 32: 237.

[3] McCann DPJ, Thomas GO, Edwards DH. (1985). Gasdynamics of vented explosions. Part I: Experimental studies. Combust. Flame, 59(3): 233.

[4] Zalosh RG. (1979). Gas explosion tests in room-size vented enclosures, Proceedings of the 13th Loss Prevention Symposium, Houston, USA.

[5] van Wingerden CJM. (1989). On the venting of large-scale methane-air explosions, 6th Int. Symp. Loss Prevention and Safety Promotion in the Process Indust., Oslo, Norway.

[6] Bauwens CR, Dorofeev SB. (2013). Parameters affecting flame-acoustic flame instabilities in vented explosions. 24th ICDERS, Taipei, Taiwan.

[7] Bauwens CR, Bergthorson JM, Dorofeev SB. (2015). Experimental study of spherical-flame acceleration mechanisms in large-scale propane–air flames. Proc. Combust. Inst. 35(2): 2059.

[8] Bauwens CR, Bergthorson JM, Dorofeev SB. (2017). On the interaction of the Darrieus–Landau instability with weak initial turbulence. Proc. Combust. Inst. 36(2): 2815.

[9] Bauwens CRL, Bergthorson JM, Dorofeev SB. (2017). Experimental investigation of spherical-flame acceleration in lean hydrogen-air mixtures. Int. J. Hyd. Energy. 42(11): 7691.

[10] Boeck LR, Bauwens CR, Dorofeev SB. (2019). Effect of venting on flame-acoustic instability in large-scale propane-air explosions. Submitted to the 27th ICDERS, Beijing, China.