Parameters Affecting Flame-Acoustic Flame Instabilities in Vented Explosions

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1 Introduction

In buildings and enclosures where accidental explosions may occur, explosion venting is a commonly used method to minimize or prevent damage to the structure. While existing engineering guidelines and standards, such as NFPA 68 [1], have correlations for vent sizing, these guidelines are based on a limited set of experimental data and, in certain situations, have been found to be off by more than an order of magnitude. The difficulty in predicting the pressures that develops in a vented explosion is due to the complex nature of the combustion process and the multiple pressure peaks that develop.

In a previous studies [2,3], it was found that the overall maximum pressure achieved during a vented explosion was dominated by one of a number of specific pressure transients. These transients correspond to different physical phenomena such as vent deployment, external explosions, increases in flame surface area due to obstacles, and the development of flame-acoustic oscillations. It was also found that these pressure transients were typically separated by a sufficient time such that they could each be considered individually and effectively independent of one another. This allowed for the development of separate correlations for each pressure peak [3,4].

Of the multiple pressure peaks, the peak associated with flame-acoustic oscillations, P_{vib}, was found to have the greatest experimental variability [3,4] both for repeated experiments and when compared between different experimental apparatus. In addition, studies have suggested that this peak is highly sensitive to various parameters, such as acoustic dampening wall materials [5,6], which can completely eliminate this peak.

For the current work, a detailed experimental study on various parameters that influence the development of flame-acoustic oscillations was performed. The objective of the study is to identify which parameters control the development of the flame-acoustic peak and also identify the scenarios where consideration of this peak can be safely neglected. The effects of four parameters on the flame-acoustic peak were examined in this study. These parameters were: mixture concentration, presence of obstacles, non-symmetric ignition location, and acoustic dampening wall materials.

2 Experimental Setup

The experiments were performed in the 64 m^3 chamber that was used in prior studies [3,4]. The test chamber had overall dimensions of 4.6 m x 4.6 m x 3.0 m with a 5.4 m^2 vent on one of the chamber's

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vertical walls. Prior to ignition, a thin plastic sheet was used to contain the unburned mixture and was perforated after mounting to deploy evenly on three sides and produce a minimal (less than 0.5 kPa) deployment pressure. Four chamber pressure transducers were mounted to the enclosure and a high speed camera was used to measure the initial propagation velocity of the flame.

Propane-air mixtures were used for all tests in this series. The mixture was sampled using a Cirrus mass spectrometer which allowed the initial mixture concentration to be controlled to within an estimated accuracy of ± 0.15% vol. The initial mixture was supplied by injecting instrument grade propane from the ceiling of the chamber while mixing fans were used to create a uniform mixture. The time between when the mixing fans were stopped and ignition was controlled to ensure a consistent initial turbulent intensity ($u' \approx 0.1$ m/s), which was determined in a series of tests using a sonic anemometer. Ignition was supplied using a carbon rod igniter at a height midway between the chamber floor and ceiling. For most of the tests in this study, one of two ignition locations in the chamber was used, either at the center of the chamber (center ignition), or 0.25 m from the center of the wall opposite the vent (back ignition).

3 Effect of Mixture Concentration

Existing data [2] from a smaller scale (1 m^3) geometry suggested the flame-acoustic peak had a strong dependence on the mixture composition in propane-air mixtures. This effect is likely tied to flame instabilities associated with thermal diffusion that make some mixtures, such as rich propane or lean hydrogen more cellular and unstable. To study this effect, vented explosion experiments were performed with propane-air concentrations varying from 3.7 to 6.2% vol.

The results of these tests are show in Figs. 1 and 2. Figure 1 shows the 80 Hz low-pass filtered pressure-time histories over a range of concentrations while Fig. 2 shows a summary of the test results across the full range of experimental data including both the maximum flame-acoustic pressure peak, P_{vib}, achieved during the experiment as well as the time after ignition that the pressure peak develops. This time delay was found to correlate with the initial flame speed observed during the tests using the high speed camera where the mixtures that produced faster flames yielded shorter time delays.

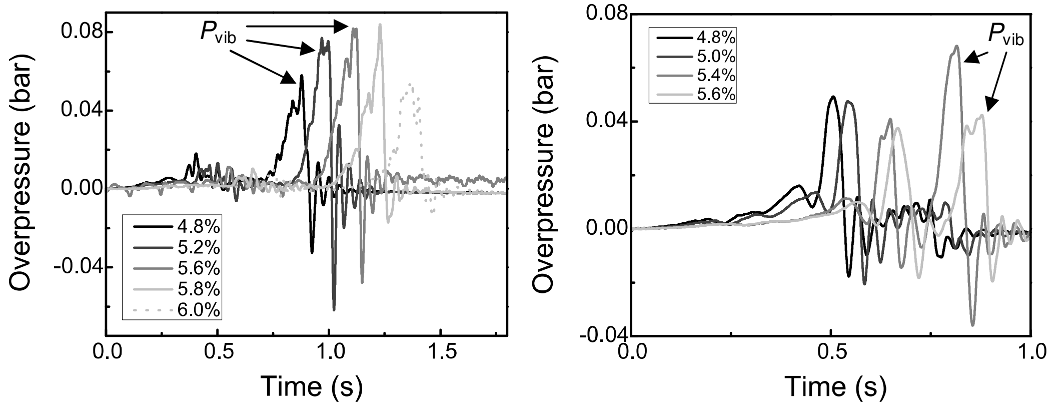

Figure 1. 80 Hz low-pass filtered pressure time-histories of center (left) and back (right) ignition vented explosion experiments for a range of propane-air concentrations

Figure 2 shows that a wide range of concentrations produce significant flame-acoustic pressures peaks and pressure increases with concentration up to 5.8% propane-air mixtures in center ignition cases. This result is interesting as the maximum flame speeds for the propane-air mixtures were observed to occur at concentrations in the region of 4.4 - 4.8%. This suggests that the increase in burning rate due to chamber acoustics is significantly enhanced for richer propane-air mixtures and that this increase exceeds the drop in burning velocity seen in the richer mixtures.

It should also be noted that back ignition experiments performed with concentrations higher than 5.0% also produced flame-acoustic peaks. This is an unexpected result as none of the previous studies using stoichiometric mixtures had observed any flame-acoustic peaks in back ignition experiments. This phenomenon may explain unusual results observed in some lean hydrogen-air experiments performed with back ignition [7] where reducing hydrogen concentration from 10% vol. to 9% vol. resulted in a significant increase of overall maximum pressure.

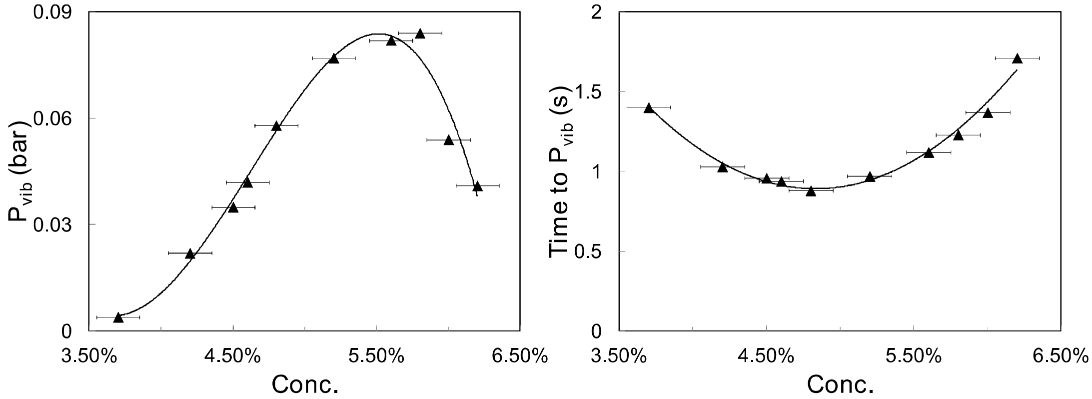

Figure 2. Summary of flame-acoustic peak data for center ignition experiments showing the maximum filtered peak pressure (left) and time after ignition to maximum filtered pressure (right).

4 Effect of Obstacles

Previously performed experiments [3] showed a significant effect of obstacles on the amplitude of the flame-acoustic peak. It is likely that obstacles reduce the amplitude of this peak by disrupting acoustic waves in the chamber through the generation of multiple reflections and prevent acoustic coupling of the pressure waves to the flame surface.

To examine the effect of obstacles, additional experimental data from a previously performed test series was used [3] and the results of tests with and without obstacles were directly compared. In these tests, the obstacles configuration consisted of eight 40 x 40 cm^2 square cross-sectioned obstacles spanning the full height of the chamber. The obstacles were uniformly distributed in two rows of four, oriented parallel to the chamber vent, with 75 cm of spacing between obstacles. For these comparisons, tests performed using a 4.0% propane-air mixture were used.

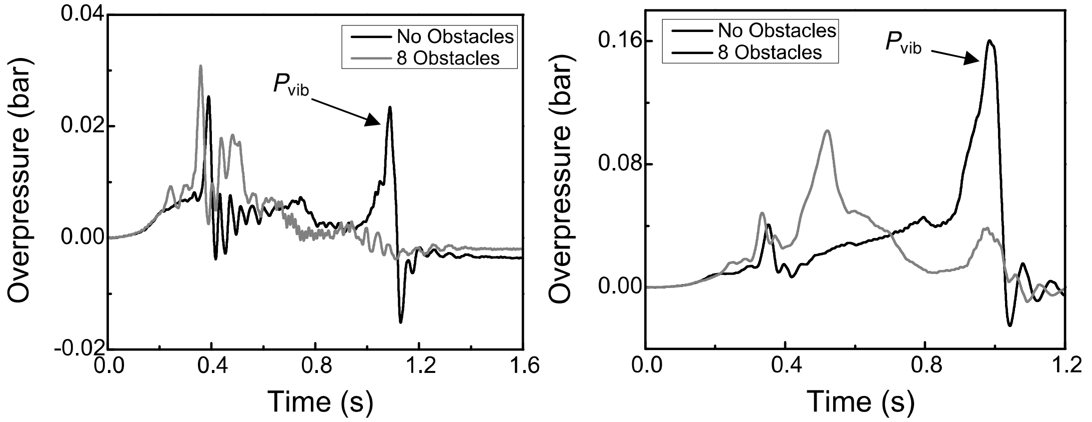

Figure 3. 80 Hz low-pass filtered pressure time-histories of center ignition vented explosion experiments with and without obstacles for a 5.4 m^2 vent (left) and a 2.7 m^2 vent (right).

Figure 3 shows the 80 Hz low-pass filtered pressure time-histories of center ignition vented explosion experiments with and without obstacles. From these plots, it is clear that a small number of relatively large obstacles completely eliminate the flame-acoustic peak. This is a significant effect to consider as typically rooms with an exposure to an explosion hazard would contain equipment or obstacles of some type.

5 Effect of Non-Symmetric Ignition

In the past, vented explosion experiments have almost exclusively been performed with symmetric ignition locations (ignition at a point along the centerline of the enclosure). Symmetric ignition likely provides a worst case ignition location for the development of the flame-acoustic peak as it maximizes flame surface area at the time of the peak. Symmetric ignition also has the potential to amplify the development of chamber acoustics as the initial pressure disturbance is produced at one of the primary acoustic nodes of the chamber.

To test non-symmetric ignition, two new ignition locations were used. The first new ignition location was shifted both 1.2 m off the centerline of the chamber and 0.5 m in the direction of the vent (X-Y offset). The second new ignition location was performed at the same X-Y location with the ignition point moved 0.5 m higher in the chamber (X-Y-Z offset). To ensure the potential for the development of flame-acoustic peaks, a 4.8% propane-air mixture concentration was used in all offset ignition tests.

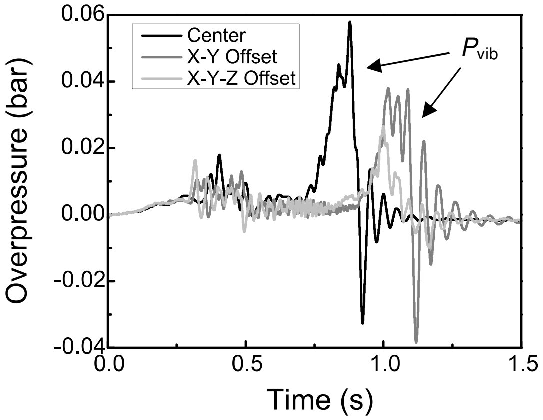

Figure 4. 80 Hz low-pass filtered pressure time-histories of vented propane-air explosion experiments with different ignition locations.

Figure 4 shows the 80 Hz low-pass filtered pressure time-histories of vented propane-air explosion experiments with different ignition locations. Several observations can be made from these experiments. First, the offset ignition location delayed the development of the flame-acoustic pressure peak due to the increased distance the flame had to propagate to two of the chamber walls. This offset also resulted in a slight decrease in peak pressure as the flame comes into full contact with one of the chamber walls prior to the development of the flame-acoustic peak. When the ignition location is offset in all three dimensions, the peak is further reduced. Neither of these ignition locations, however, completely eliminates the flame-acoustic peak.

6 Effect of Acoustic Dampening Wall Materials

Previous studies [5, 6] have found that covering all of the internal walls of the enclosure with acoustic dampening material can completely eliminate the flame-acoustic peak. In this test series, a single wall and a partial wall of the chamber were covered to determine the effect of partial coverage. In these tests, four inch thick sections of ROCKWOOL® insulation were used to dampen the chamber acoustics. A 4.8% propane-air mixture was used for all tests performed with acoustic dampening wall materials.

Three test configurations were studied. In one configuration, the insulation was installed covering the floor of the chamber (≈ 20% of the entire chamber internal surface area). In the second configuration, the insulation was installed on one of the side walls of the chamber, covering approximately 30% of the sidewall area (≈ 5% of the entire chamber internal surface area). In addition, tests where a single ceramic wall covering (with dimensions of 0.6 m x 1.2 m, ≈ 1% of the chamber internal surface area) were also performed.

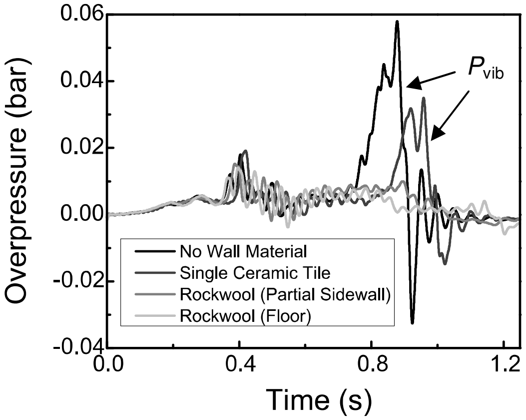

Figure 5. 80 Hz low-pass filtered pressure time-histories of center ignition vented explosion experiments with different chamber wall materials.

Figure 5 shows the 80 Hz low-pass filtered pressure time-histories of center ignition vented explosion experiments with different chamber wall materials. These results show that even a small area of insulation covering less than 5% of the total internal surface area of the enclosure is sufficient to completely eliminate the flame-acoustic peak. It was also found that a small ceramic ceiling tile measurably reduced peak pressure.

These results, where a small area of acoustic dampening material can prevent the development of the flame-acoustic peak, and the results where obstacles are present in the chamber indicates that the development of the flame-acoustic peak requires the contribution of acoustic waves that traverse the entire chamber and that acoustic interactions that occur in the space between the flame and chamber walls alone are not sufficient to generate the peak.

7 Discussion

From the results of this study, it is clearly seen that several parameters have a significant effect on the development of flame-acoustic peaks in vented explosions and these parameters may explain certain behavior observed in previous experiments. The test variability of the magnitude of the flame-acoustic peak seen in previous studies can easily be explained by experimental variations in the initial mixture composition. Also, the variation in results from different sources, or the difficulty correlating results for the flame-acoustic peak from different experimental setups, can at least be partially attributed to differences in construction of the test apparatus and wall materials used. These variations and the sensitivity of the flame-acoustic peak to the different parameters make proper handling of the peak challenging when developing vent sizing correlations.

For propane-air mixtures, rich concentrations significantly enhance the flame-acoustic peak and a produces a wide range of dangerous mixtures. Many previous experiments were performed for stoichiometric mixtures or mixtures producing the maximum laminar burning velocity which were assumed to be the worst case. The results from this study show that mixtures with laminar burning velocity well below the maximum can result in higher overpressures in certain situations. This wider range of dangerous concentrations also suggests that it is more likely that a real world release can generate pressures close to the worst case scenario compared to the assumption that the generation of high overpressures is limited to a narrow range of concentrations close that which produces the highest laminar burning velocity.

The test results also show that the worst case chamber configurations for the flame-acoustic peak are empty chambers with reflective wall materials and symmetric ignition. This is the configuration used in most experiments which may overstate the actual development of flame-acoustic peaks in real world scenarios. Using the results of this study, it may be possible to discount this peak when considering chambers with obstacles or to install acoustic dampening wall material in enclosures where the flame-acoustic peak are predicted to produce the strongest peaks.

8 Conclusions

Vented explosion experiments were performed in a 64 m^3 chamber studying parameters that affect the development of flame-acoustic interactions in vented explosions. It was found that mixture concentration had a strong effect on the development of this peak, with rich mixtures producing significantly higher overpressure over a wide range of concentrations. The study also found that the use of acoustically dampening wall material, covering only a fraction of the internal surface area of the enclosure, or the presence of obstacles is sufficient to completely eliminate the flame acoustic peak.

These results can be used in future studies to give guidance on when to consider the flame-acoustic peak in vented explosions and identify scenarios where the flame-acoustic peak may be significant and further mitigation may be necessary. The results will also be used to in future work to improve vent sizing correlations.

References

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