Effect of Vent Deployment Pressure and Panel Inertia on Vented Gaseous Explosions

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1. Introduction

Explosion venting is a commonly used method to minimize or prevent damage to an enclosure caused by an accidental explosion. By opening part of the surface area of the enclosure, venting relieves the pressure generated by the explosion with the goal of maintaining a pressure below the design strength of the structure. The size, type and release pressure of the vent, however, can play a strong role on how pressure inside the enclosure develops.

Engineering guidelines and standards such as NFPA 68 [1] have correlations for vent sizing based on the size of the enclosure, its design strength and the mixture present; however, these guidelines are based on a limited set of experimental data and, in certain situations, they can be off by more than an order of magnitude. In particular, while studies have been performed examining the role of inertial vent panels on vented explosions, many of which have been summarized in [2], there is a lack of data for panel weights and deployment pressures relevant for room-sized enclosures.

Because of the limited reliability of the current methods for prediction of pressure increase during vented explosions, a research project was initiated with the goal of generating a set of experimental data examining how different parameters affect the enclosure pressure during vented explosions. The set of data will be used to develop new models and engineering tools. In a previous study, the effect of mixture composition, ignition location, vent size and obstacles [3] was examined. In this study, it was found that the overall peak pressure reached during a vented explosion was dominated by one of a number of specific pressure transients, corresponding to different phenomena such as the external explosion and the development of structure-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 correlations for each individual pressure peak. However, these studies were all performed without a vent panel in place, and it was unknown what effect the opening of the vent would have on subsequent peaks.

For the current study, the effect of panel release pressure and panel density is examined for the range of values typically used for room-sized enclosures and industrial occupancies. In addition to the experimental results, a simple model for the prediction of the pressure transient associated with the opening of the vent is developed.

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2. Experimental Setup

The experiments were performed in the 64-m^3 chamber that was used in the previous study with an open vent [3]. The test chamber had overall dimensions of 4.6 x 4.6 x 3.0 m with a 5.4 m^2 vent on one of the chamber's vertical walls. Four chamber pressure transducers were mounted to the enclosure and a high-speed camera was used to observe the tests, directed either into the chamber to observe the effect of the vent deployment on the flame surface or outside to observe the opening of the vent and the external explosion. Ignition was supplied using a carbon rod igniter at one of three locations in the chamber, either at the center of the chamber (center ignition), 0.25 m from the center of the wall opposite the vent (back ignition), or 0.25 m from the center of the vent (front ignition).

Stoichiometric propane-air mixtures were used for all tests. The initial mixture was supplied by injecting pure propane from the ceiling of the chamber while mixing fans within the chamber were used to create a uniform mixture. The concentration of the mixture was sampled using a Cirrus mass spectrometer and a final gas concentration of 4.0 ± 0.2% was used for all tests. 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 bidirectional velocity probe.

A single 5.4-m^2 vent was used for all tests and tests were performed both with and without a vent panel. When a vent panel was used, it was hinged along the bottom of the vent and explosion vent fasteners, designed to deploy at a specific force, were used to hold the vent closed and control the pressure at which the vent opened. Two panel densities, 8.3 kg/m^2 and 32.4 kg/m^2, and four vent deployment pressures, 0.01, 0.03, 0.06 and 0.08 bar, were used in this study. In the tests without a vent panel, a plastic sheet was used to contain the unburned mixture which was then cut at the time of ignition.

3. Experimental Results

The experiments performed in this study, and the peak pressures achieved associated with different pressure transients are summarized below in Table 1.

In the previous study, it was found that, without obstacles, two main pressure peaks would be possible throughout the tests. The first pressure transient occurred when previously vented unburned gas is consumed outside the chamber. This peak was called the external explosion peak, later referred to as P_{ext}. The second pressure transient occurs later, when most of the fuel inside the chamber is already consumed and the flame approaches the walls of the chamber. As the flame approaches the walls, acoustic interactions with the flame surface cause it to vibrate and increase the wrinkling of the flame surface. At this stage, the remaining unburned fuel in the chamber is rapidly consumed, resulting in the second pressure transient, P_{vib}. In the tests performed with the hinged vent panel, a new pressure peak was observed. This pressure value, P_{vent}, occurs before the external explosion and the magnitude of the peak varied with panel density and release pressure.

Figures 1-3 show comparisons of 80 Hz low-pass filtered pressure-time histories of the tests for each of the three ignition locations with different release pressures. These figures are used to illustrate the effect of the hinged vent panel on the subsequent pressures that developed during the vented explosions. The pressure transient associated with the deployment of the vent occurs at approximately 0.2 s across the tests performed, regardless of ignition location. With the exception of some low amplitude Helmholtz oscillations for front ignition cases, it is clearly seen that following P_{vent}, the subsequent pressure trace and peaks, P_{ext} and P_{vib} are not strongly affected by the opening of the vent. While there is some variability in the magnitude of P_{vib}, the previous study [3] also observed this variability which is consistent with the repeatability of the tests.

It important to note, however, that the observation that P_{vent} did not impact the subsequent pressure peaks may only be valid close to the range of panel masses and deployment pressures used in this study. Panels with significantly higher density (>100 kg/m^2) and/or higher deployment pressures may not open sufficiently by the time of the external explosion, thereby possibly affecting P_{ext}. Also, other studies [2] have observed that panels with very low mass or that open suddenly, such as bursting membranes or rupture diaphragms, may influence the subsequent pressure-time history through the generation of turbulence and or flame instabilities. In this study, however, this was not observed, even for the lighter 8.3-kg/m^2 panel.

Table 1: Summary of peak pressure results from propane tests.

Test #	Ignition Location	Panel Density (kg/m^2)	Release Pressure (bar)	P_{vent} (bar)	P_{ext} (bar)	P_{vib} (bar)
1	Back	8.3	0.01	0.018	0.035	-
2	Back	8.3	0.01	0.023	0.038	-
3	Center	8.3	0.01	0.026	-	0.052
4	Center	8.3	0.01	0.025	-	0.036
5	Center	8.3	0.01	0.022	-	0.036
6	Front	8.3	0.01	0.019	-	-
7	Front	8.3	0.01	0.020	-	-
8	Front	8.3	0.01	0.018	-	-
9	Back	8.3	0.03	0.030	0.043	-
10	Back	8.3	0.03	0.033	0.044	-
11	Center	8.3	0.03	0.037	-	0.061
12	Center	8.3	0.03	0.029	-	0.016
13	Front	8.3	0.03	0.022	-	-
14	Front	8.3	0.03	0.025	-	0.029
15	Back	32.4	0.01	0.034	0.026	-
16	Center	32.4	0.01	0.042	-	0.019
17	Center	32.4	0.01	0.040	0	0.063
18	Front	32.4	0.01	0.033	-	-
19	Back	32.4	0.03	0.040	0.031	-
20	Center	32.4	0.03	0.051	-	0.031
21	Center	32.4	0.03	0.054	-	0.063
22	Front	32.4	0.03	0.042	-	-
23	Center	32.4	0.06	0.080	-	0.024
24	Center	32.4	0.06	0.076	-	0.085
25	Center	32.4	0.08	0.101	-	0.042

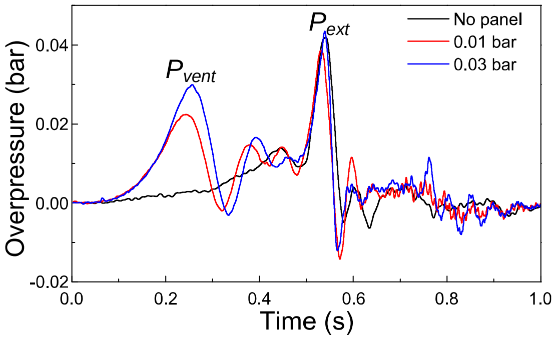

Figure 1. Pressure-time histories inside the enclosure for back ignition cases with the 8.3 kg/m^2 vent.

It is also interesting to note that, in the case of the back ignition tests, the peak associated with the external explosion had a consistent magnitude and duration with and without the vent panel, despite observations from the high-speed camera that the shape of the cloud of unburned gas outside of the chamber was significantly altered by the presence of the vent panel.

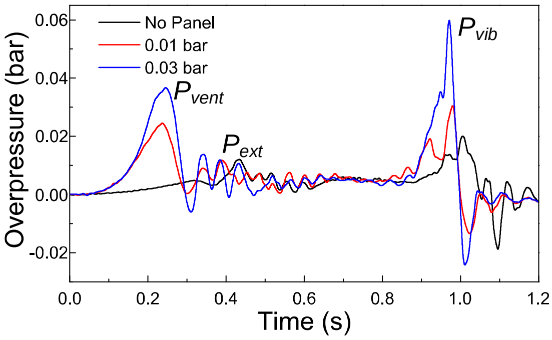

Figure 2. Pressure-time histories inside the enclosure for center ignition cases with the 8.3 kg/m^2 vent.

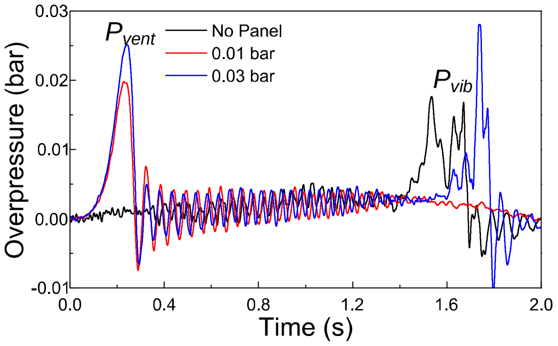

Figure 3. Pressure-time histories inside the enclosure for front ignition cases with the 8.3 kg/m^2 vent.

There were also some inconsistent experimental results, for front ignition cases where P_{vent} was lower than the design deployment pressure. However, the cause of the premature fastener deployment could not be determined.

4. Model

As the presence of the vent panel did not significantly change the pressure-time history after P_{vent}, it is only necessary to account for the effect of the vent panel on determining P_{vent}. This allows for the use of a correlation based on each individual peak, as described in [3].

To illustrate how P_{vent} can be correlated individually, a simple model accounting for the physics of how a hinged vent panel opens is described below. This approach is similar to those adopted in other studies [4, 5].

First, a description is needed for how volume is generated inside the chamber as the flame propagates and consumes the unburned fuel. For this, a simple assumption that the flame propagates at a speed of $\sigma\Xi S_L$ is used, where σ is the expansion ratio of the mixture, S_L is the burning velocity and Ξ is a fitted wrinkling factor accounting for the increase in flame surface area due to flame instabilities, such as the Landau instability, and turbulence. Next it is assumed that the flame propagates spherically, such that its surface area as a function of time can be described as: $A_{flame} = 4\pi(\sigma\Xi S_L t)^2$, where t is the time after ignition. This yields the following equation for the rate of volume generation in the chamber:

$$\frac{dV_{flame}}{dt} = A_{flame}\left[(\sigma - 1)\Xi S_L\right]$$

The unknown factor Ξ is fitted to match the initial pressure rise seen in tests during the portion of the pressure-time history when the vent panel is closed. A factor of Ξ = 1.25 was found to closely match the initial pressure rise throughout the tests. Next, a description for the rate at which volume is vented from the chamber is needed. For this a simple volumetric flow rate relation [6] is used:

$$\frac{dV_{vented}}{dt} = a_{cd} A_v \sqrt{\frac{p - p_e}{p_{cr} - p_e}},$$

where A_v is the vent area, p is the internal pressure of the enclosure, p_e is the external pressure, p_{cr} is the critical pressure for choked flowed through the vent, and a_{cd} is a velocity scale constant defined by:

$$a_{cd} = c_d \sqrt{\gamma \frac{\gamma + 1}{2} \frac{RT_0}{\mu}},$$

where, c_d is the discharge coefficient (taken to be 0.61), γ is the ratio of specific heats of the vented gas, R is the gas constant, T_0 is the initial temperature, and μ is the molecular weight of the vented gas.

As the panel opens over time, the vent area is not constant. The effective vent area for a square hinged panel, of height H_v, opened an angle θ can be given by:

$$A_v = H_v^2 \left[\sin(\theta) \left(1 + \frac{1}{\cos(\theta/2)} \right) \right].$$

The motion of the panel, assuming that the pressure acting on the panel is uniform across the panel and equal to the internal pressure of the chamber, can then be described as:

$$\frac{d^2\theta}{dt^2} = \frac{pH_v^3}{2I_v},$$

where I_v is the moment of inertia of the panel.

Assuming adiabatic expansion of the gas inside the chamber, these equations result in the following expression for the pressure inside the chamber, which can be solved numerically to form a pressure-time history:

$$\frac{dp}{dt} = \frac{p_0 \gamma}{V} \left(\frac{dV_{flame}}{dt} - \frac{dV_{venting}}{dt} \right).$$

5. Model Results

The results of the model are summarized below in Fig. 4. It can be seen that, despite the simplicity of the model, there is good agreement for higher deployment pressures, reproducing both the peak pressure and duration of the pressure transient. For lower deployment pressures, however, the model under predicts the peak pressure in many cases, particularly for center ignition. This difference may be caused by the model assumption that the pressure on the vent panel is uniform across the panel and equal to the pressure inside the chamber. In reality, the moment the panel opens, the pressure across the vent surface drops, particularly near the vent, reducing the force on the panel. Also, in the tests with lower deployment pressures, it is possible that the fasteners had difficulty deploying at their design pressure due to leakage around the vent panel and the slow rate of pressure rise. From the modeled vs. measured P_{vent} plot it is also seen that center ignition cases were typically under predicted more than back and front ignition tests. This is may be due to the model assumption that the flame propagates spherically. While initially the flame propagates spherically for front and back ignition, the presence of the wall near these ignition locations causes the flame to propagate slower in the direction of the wall altering the shape of the flame ball.

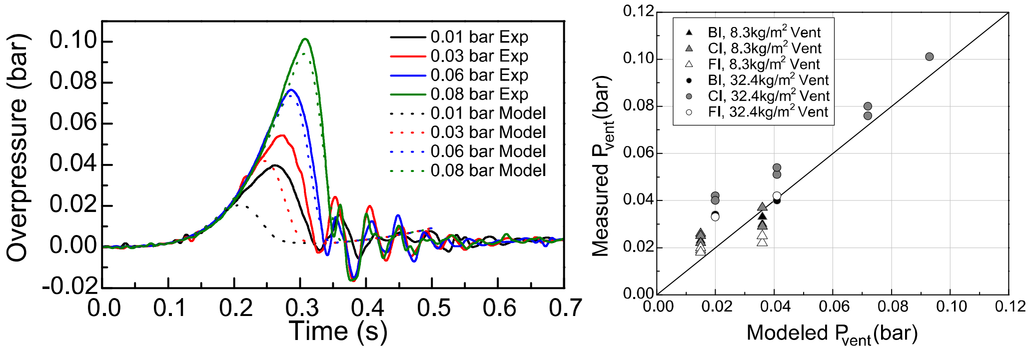

Figure 4. Summary of model results. Left: Comparison of experimental and model pressure-time histories for center ignition tests with the 32.4 kg/m^2 vent. Right: Overall model performance across all tests.

6. Conclusion

For the range of deployment pressures and panel densities used in this study, it was found that the vent deployment pressure transient depended on both the release pressure and on the panel density, increasing with both parameters. It was also found that the pressure transient associated with the opening of the vent had little or no impact on the subsequent external explosion and structure-acoustic pressure peaks. Thus, for panel densities and release pressures typical for room-sized or larger enclosures, it was found that the pressure transient caused by the deployment of the panel can be treated independently from the rest of the process. This allows for each pressure transient to be correlated individually and for the use of the peak with maximum overpressure to size the vent panel. To illustrate a correlation for P_{vent}, a simple model to describe the opening of the vent and its associated pressure transient was developed. The model performed well, particularly for higher vent deployment pressures, providing reasonable estimates for the external explosion pressure transients.

References

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