Effect of Instabilities and Acoustics on Pressure Generated in Vented Propane-Air Explosions

C. Regis Bauwens, Jeff Chaffee, Sergey Dorofeev,

FM Global, Research Division, Norwood, USA

A deflagration contained within a closed volume filled with a flammable fuel-air mixture can produce maximum internal pressures up to 6 to 10 times that of its initial pressure. Most structures however, will fail at a far lower pressure, in the range of tenths of bars. Often, venting is used as a means to prevent or minimize damage to an enclosure by relieving the pressure developed within the volume during an explosion. Experimentally, the subject of vented explosions has been studied extensively with research performed over a wide range of scales, including laboratory scale tests [1] and large scale tests [2, 3, 4]. Factors, contributing to the pressure build-up in vented explosions, have been found to include Helmholtz oscillations [1, 4], the external explosion [1, 5], flame instabilities [1, 3], flame-acoustic interactions [1, 2, 3], and turbulence generation [3, 4, 6].

A series of parametric vented explosion experiments have been performed for stoichiometric propane mixtures with air in FM Global's 64 m^3 explosion test chamber. The chamber had overall dimensions of 4.6 x 4.6 x 3.0 m with a single vent opening on one side. Pressure data, as function of time, and flame time-of-arrival data were obtained both inside and outside the chamber.

The objective of the present work is to analyze the data and to further investigate the effect of flame instabilities and acoustics on pressure generation in vented explosions. This is accomplished by frequency analysis of the pressure data, comparison of the pressure data with higher speed videos, and by numerical simulation of various aspects of the explosion process and flame structure interactions.

The physical phenomena observed in a typical vented explosion can be seen below in Fig. 1 showing the filtered and unfiltered pressure time history of a stoichiometric propane-air test. This test can be used to describe the main physical effects responsible for the development of pressure build-up for the range of initial conditions used in the current series of tests. The general shape of the pressure time history and the phenomena observed are similar to those seen in natural gas deflagrations in a smaller 2.5 m^3 chamber [1].

The pressure time-history shown in Fig. 1 is broken up into four distinct regions where the combustion process and pressure generation is dominated by a single major flame instability. The first phase of the combustion process occurs between $t \approx 0$ - 0.3 s where the flame is ignited and the hydrodynamic flame instability forms cellular structures on the flame surface, as seen in figure 2a.

This is followed by a second region dominated by 30 Hz oscillations occurring between $t \approx 0.3$ - 0.6 s. The 30 Hz oscillations are in fact Helmholtz, or organ pipe, oscillations caused by the inertia of the gas being vented. As the burned gas exits the chamber through the vent the volumetric flow rate of gas increases due to the lower density of the burned gas compared to the previously vented unburned gas. This sudden change in flow rate through the vent causes the chamber to over-vent, outpacing the volume expansion due to combustion and decreases the pressure within the chamber below ambient. Eventually this pressure difference is large enough to create a flow reversal and gas flows into the chamber through the vent. Due to the inertia of the gas the pressure in the chamber increases and the chamber enters an under-vented state. The internal pressure of the chamber then oscillates between the over and under-vented states until the oscillation eventually decays due to friction and drag losses.

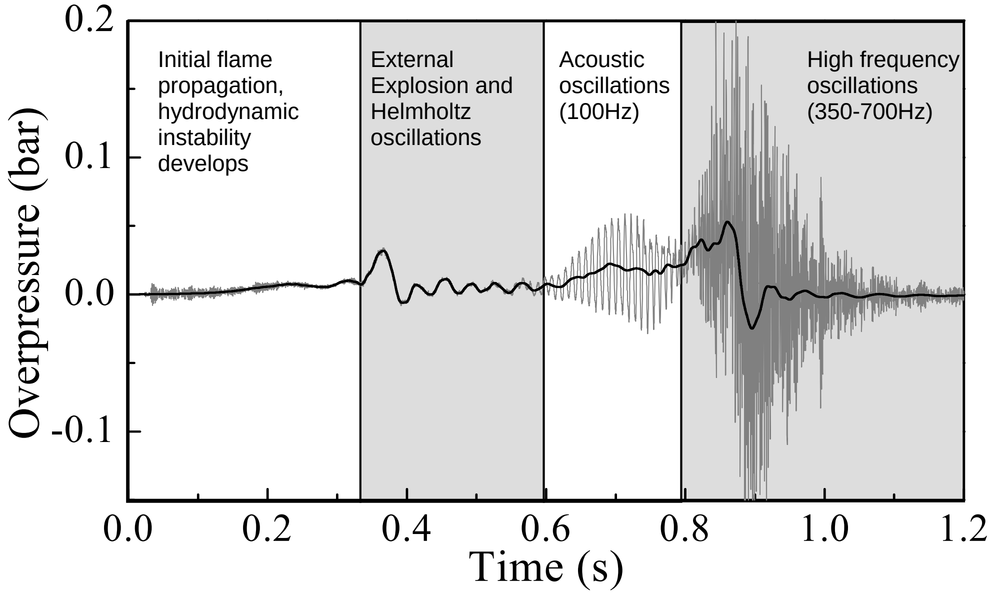

Figure 1. Filtered and unfiltered pressure time history of a stoichiometric propane-air mixture used to illustrate major phenomena observed during a typical vent explosion test.

There are two phenomena that occur during this time which greatly amplify the observed Helmholtz oscillations. The first is the Taylor instability that is introduced when a less dense burned gas is accelerated into the denser unburned mixture. In this case it occurs when the flame front, a density interface, is accelerated toward the unburned mixture. When the front is accelerated in the Taylor unstable direction the Taylor instability creates a large increase in flame surface area. When the front is accelerated in the opposite direction the flame surface is seen to smooth out. This can be seen in the high speed photographs shown in Fig. 2. Figure 2b shows the flame surface as the front is accelerated out of the chamber during the initial venting of burned gas. When the flame front is accelerated in this direction, the Taylor effect stabilizes the flame surface reducing the surface area of the front and decreasing the rate of volume generation within the chamber, causing a drop in the rate of pressure generation. When the flow reverses the front is accelerated in the opposite direction causing the front to become Taylor unstable, increasing the flame surface area as seen in Fig. 2c and increasing the rate of pressure generation in the chamber. Thus it can be seen that the Taylor instability acts in phase with the Helmholtz oscillation, and can greatly increase its amplitude.

The other significant effect that occurs as the Helmholtz oscillation is initiated is the external explosion, which occurs when the previously vented unburned gas is consumed outside of the chamber by the flame after it exits the chamber. The external explosion increases the pressure immediately outside of the chamber, reducing the pressure difference across the vent, effectively reducing or completely stopping the venting process. By slowing the vented gas, the external explosion also accelerates the flame front within the chamber toward the unburned gas in the Taylor unstable direction causing an increase in internal pressure due to both the reduction of venting and an increased rate of gas generation.

The third region shown in Fig. 1 is where acoustics oscillations develop, with a frequency of approximately 100 Hz. This frequency matches the first fundamental mode of a wave propagating parallel to the vent within the chamber, assuming the chamber is largely filled with burned gas. These acoustic waves interact with the flame surface creating the fine small scale structures seen in Fig. 2d.

The final region shown in Fig. 1 occurs when $t \approx 0.8$. At this time the flame approaches the chamber walls and the 100 Hz oscillations are almost completely attenuated. At this time higher frequency acoustics, in the range of 700 Hz are excited. This frequency was found to correspond with the natural frequency of major structural components of the chamber. The coupling between the combustion processes, acoustics and the structural response of chamber leads to the increase in filtered over-pressure seen at $t \approx 0.85$ s.

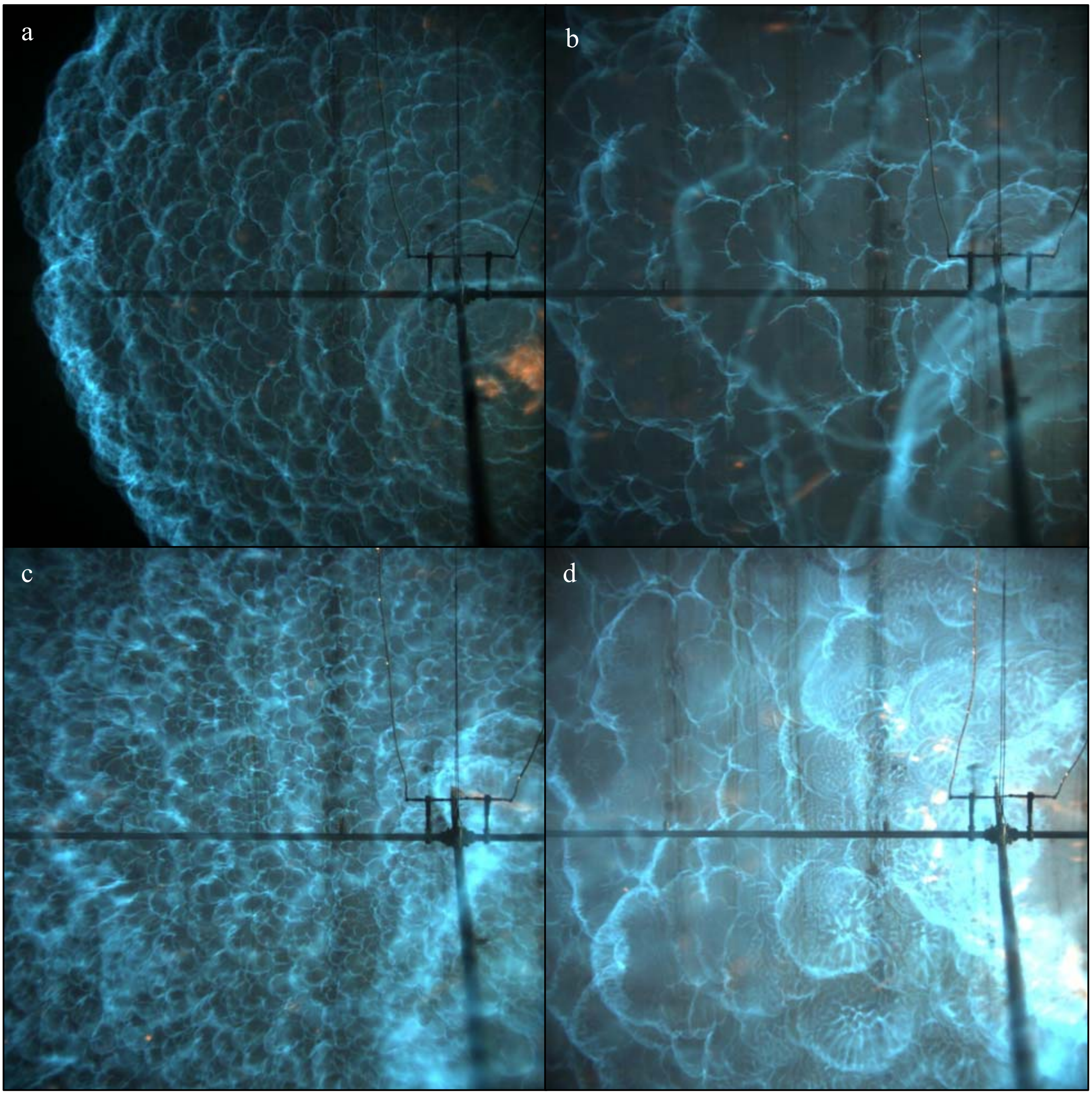

Figure 2. Images obtained using a high speed camera at t = 0.244, 0.374, 0.396, and 0.662 s for the case shown in Fig. 1.

Numerical simulations suggest that the pressure transient which occurs as the flame approaches the chamber walls require that the chamber walls oscillate. In numerical simulations performed where the chamber walls were vibrated at the frequency and amplitude seen in experiments good agreement with experimental results can be found. Simulations without vibrating chamber walls show that no higher frequency acoustics develop, and the second peak does not develop (see Fig. 3 below). It should be noted that the importance of the two-way coupling between the structure and the combustion process on pressure generation in vented explosions described above has not been reported previously.

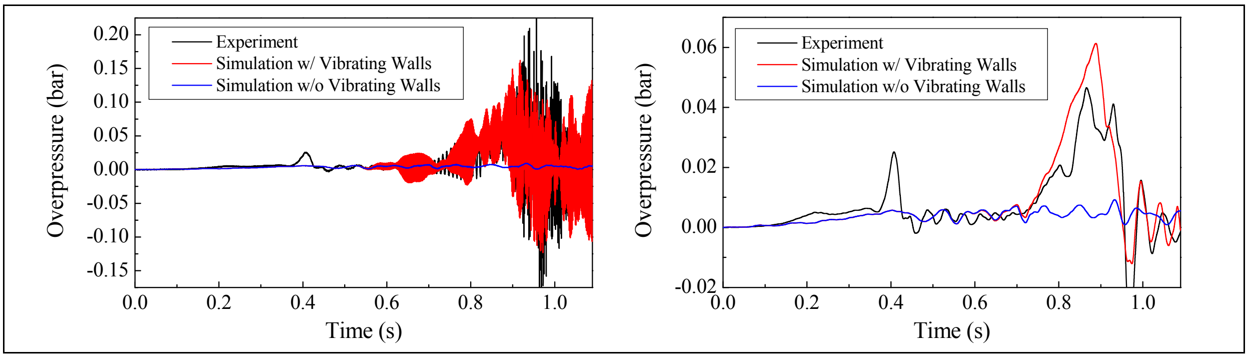

Figure 3. Comparison between experiments and simulations of a vented explosion, with unfiltered results on the left, and filtered by an 80 Hz low pass filter on the right.

The hydrodynamic, Taylor and flame acoustic instabilities described above were found to be of key importance in modeling vented explosions and computational models neglecting these phenomena fail to capture the correct pressure time history profiles. Results of several attempts to model the flame instabilities are presented and the strengths and limitations of these models are discussed.

References

[1] Cooper MG, Fairweather M, Tite JP. (1986). On the Mechanisms of Pressure Generation in Vented Explosions, Combustion and Flame, 65: 1-14.

[2] Zalosh RG. (1979). Gas Explosion Tests in Room-Size Vented Enclosures, Proceedings of the 13th Loss Prevention Symposium, Houston, pp. 98-108.

[3] van Wingerden CJM. (1989). On the Venting of Large-Scale Methane-Air Explosions, 6th International Symposium of Loss Prevention and Safety Promotion in the Process Industries, Oslo, 19-22, June 1989.

[4] Bimson SJ, Bull DC, Cresswell TM, Marks PR, Masters AP, Prothero A, Puttock JS, Rowson JJ, Samuels B. (1993) An Experimental Study of the Physics of Gaseous Deflagration in a Very Large Enclosure, Fourteenth International Colloquium on the Dynamics of Explosions and Reactive Systems, Coimbra, Portugal, August 1st – 6th.

[5] Harrison AJ, Eyre JA. (1987). External Explosions as a Result of Explosion Venting, Combust. Sci. and Tech. 52: pp 91-106.

[6] Tamanini F , Chaffee JL. (1992). Combined Turbulence and Flame Instability Effects in Vented Explosions, Seventh International Symposium on Loss Prevention and Safety Promotion in the Process Industries, 1992, pp. 38-11/38-19, 1992.