Critical Conditions for Explosion Transmission between Two Chambers

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1 Experimental Setup

A number of previous studies have indicated that the quenching of flames, as they propagate in a combustible gas mixture from one chamber to another through an orifice, depends not only on orifice diameter but also on flow velocity [1-2]. The problem may be divided into three regimes with increasing flow velocity at the orifice: 1) a "thermal diffusion" quenching regime associated with laminar burning velocity and loss of heat and free radicals to the orifice wall, 2) a "turbulent mixing" regime where the rate of turbulence entrainment of cold unburned mixtures into burned mixtures dominates the overall quenching and 3) a "sonic choking" regime where a temperature decrease in an underexpanded jet structure downstream of the orifice contributes to the flame quenching. Motivated by the importance of quenching or transmission of the explosion from a condensed explosive in chambers, the present paper investigates critical conditions for explosion transmission from a donor chamber (where detonation of an explosive charge occurs) to a receptor chamber (initially filled with air only).

Figure 1. Two chambers with orifice plates

The experimental facility consisted of two steel chambers connected with an orifice plate between them (Fig. 1). The donor chamber, 26 m^3 in volume and 3 m in diameter, was designed to sustain a 1500 psi hydrostatic pressure and can be vacuum-sealed using a blind flange, while the receptor chamber was 23 m^3 in volume and has the same internal diameter. The venting orifice plate was interchangeable for various hole diameters up to 1.22 m corresponding to a venting area of 1.169 m^2. The donor chamber was equipped with 12 gauge holes 33 cm in interval along the two sides and the front end, and 7 circular windows 10 cm in diameter, three pairs on the two sides facing each other and one on the front end. The receptor chamber was equipped with 25 gauge mounts, three 45 cm x 15 cm windows on the side and a window 15 cm in diameter looking through the end wall downstream and opposite the orifice. The diagnostics included pressure transducers, a pyrometer and high-speed digital video cameras. The experiments were conducted using IPN/Mg and IPN/RDX/Al heterogeneous mixtures and baseline C-4 charges in three masses: 1.1 kg, 4 kg and 7.7 kg. The mixtures were contained in a thin-walled polyethylene cylindrical casing whose length/diameter ratio has been maintained at $L/D \approx 1$. The charge was suspended and detonated in the center of the donor chamber.

2 Explosion in a closed chamber

A number of experimental studies of explosion in a closed chamber can be found in the literature [3-7]. In order to obtain a closed volume explosion reference, experiments were first conducted in the donor chamber alone (closed by a blind flange). Figure 2 displays a typical explosion process for a 1.1 kg IPN/RDX/Al mixture in the early time recorded from the front end window. The instabilities of the combustion products interface are influenced by the expanding particle cloud that crosses the interface in the form of reacting particle jets

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surrounded with an added mass of gases. Interaction of particle wakes with the products interface further generates micro-scale turbulent mixing regions for the combustion products and air. At a critical mass, the combustion rate of the expanding frontal particles cannot compete with the cooling rate due to the heat transfer to the air and turbulent mixing of burned mixture with fresh air. Hence, the flame intensity is then reduced and inhibited. After the blast reflects on the wall and implodes, the after-burning is again enhanced. Figure 3 provides over-pressure histories for the 1.1 kg IPN/Mg and IPN/RDX/Al heterogeneous mixtures as well as for the reference C-4 explosive. A dynamic loading time, t_B, is defined to be completed once the pressure reaches 97% of the final quasi-static pressure (QSP) observed on the scale of the recording. The fact that geometry effects are dominant within this dynamic regime is substantiated by the significant variation of the pressures with different transducer locations. The QSP after t_B, however, appears independent of transducer location and remains unchanged up to 90 ms when the recording ends. The constant QSP during this time results in an impulse which varies less than 3% with gauge location, thereby indicating the donor chamber meets both adiabatic and closed system conditions. For a 1.1 kg charge mass, t_B is about 12 ms for C-4, 24 ms for IPN/RDX/Al and 40 ms for IPN/Mg. Thus, the dynamic loading time strongly depends on the afterburning rate of the mixture of metal particles, detonation products and air contained in the chamber. Figure 4 summarizes the average experimental QSP in absolute pressure and the theoretical equilibrium explosion pressure using Cheetah 2.0 with the BKWS equation of state for detonation products. Considering that the equilibrium value provides a limit for a reactive system perfectly mixed at the molecular level, the deficit in the experimental value with respect to the equilibrium calculation is due to the non-uniform mixing and afterburning of the detonation products with the air enclosed in the chamber under conditions of unsteady flow during the explosion. For the heterogeneous mixtures, the non-uniform mixing and afterburning also include the heterogeneous nature introduced by the finite-sized particles. The higher QSP values for the heterogeneous mixtures are due to the energy content of the metal particles and the higher oxygen deficiency of the mixtures compared to C-4. These results indicate a basic feature of the heterogeneous explosion performance, that is, the dependence of blast enhancement on both the stoichiometric degree of the system consisting of the mixture and the air in the confinement, and on the mixing and reaction under unsteady conditions.

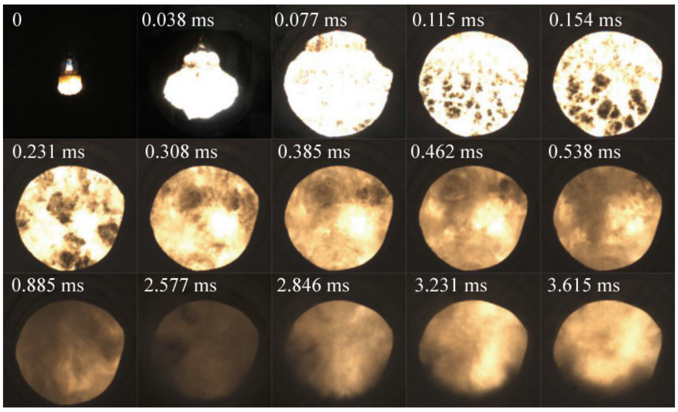


Figure 2. Explosion process of 1.1 kg IPN/RDX/Al in the closed 26 m^3 chamber (U05-164A).

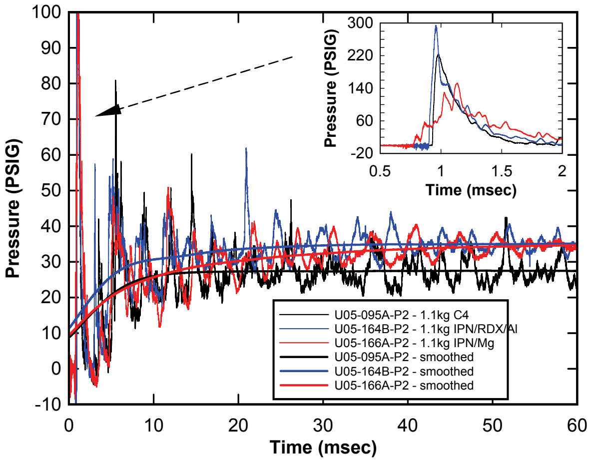


Figure 3. Overpressure histories from 1.1 kg C-4 and heterogeneous charge explosions in the closed 26 m^3 chamber.

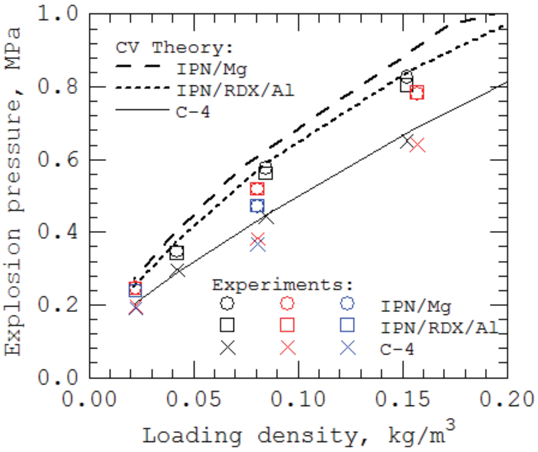


Figure 4. Equilibrium calculations and experimental QSP (black symbols: closed 26 m^3 chamber; red: two chambers with 0.305 m ID orifice; blue: 1.22 m ID orifice).

3 Critical transmission regimes

Figure 5 shows a turbulent mixing quenching process of flames from a 1.1 kg C-4 explosion as they propagate from the donor chamber into the receptor chamber through a 1.22 m diameter orifice. Flame quenching starts at the lateral interfaces separating the fireball and air where the turbulent entrainment occurs. A temperature decrease due to the expansion of the flow downstream of the orifice also contributes to the overall quenching. When C-4 is replaced with heterogeneous mixtures of IPN/Mg or IPN/RDX/Al, flames are transmitted successfully through the same orifice and further propagate in the receptor chamber.

Figure 5. Quenching of flames from 1.1 kg C-4 explosion through a 1.22 m ID orifice (U06-296A)

When decreasing the orifice diameter to 0.305 m, a sonic choking quenching process takes place for all 1.1 kg charges including C-4 and the heterogeneous mixtures, as displayed in Fig. 6. Since the pressure ratio across the orifice is larger than a critical value (approximately 1.8 for ideal gas with $\gamma = 1.4$), an underexpanded jet structure is formed downstream of the orifice and flames are completely quenched as they propagate through the orifice due to expansion cooling. Figure 7 shows that increasing charge mass to 4 kg results in a re-initiation of flames downstream of the same orifice. An increase in charge mass increases upstream explosion pressures and therefore pressure ratios across the orifice (see Fig. 8 for over-pressure histories in the donor and receptor chamber). For sufficiently high pressure ratios, the underexpanded jet flow downstream of the orifice consists of an expansion immediately followed by a recompression in the form of a normal shock or Mach disc. With increasing upstream pressures, the strength and diameter of the Mach disc become sufficiently large to significantly enhance the lateral

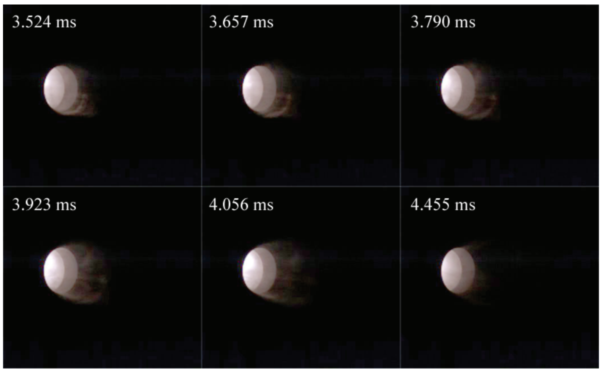
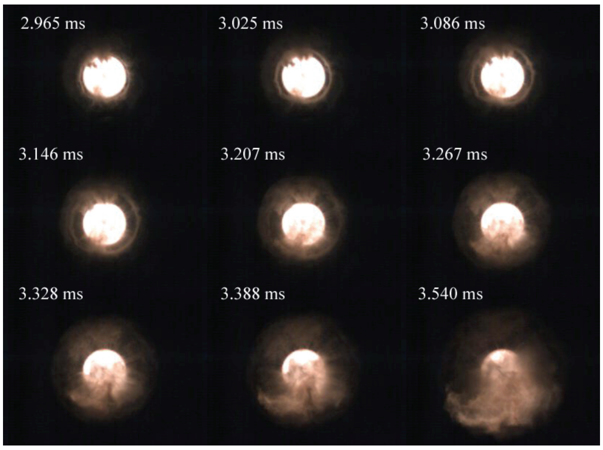


Figure 6. Flame quenching from 1.1 kg IPN/RDX/Al explosion through a 0.305 m orifice (U06-326B)



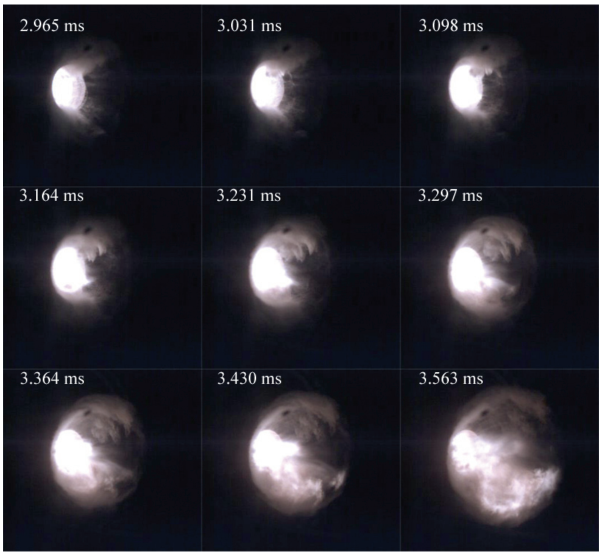


Figure 7. Re-initiation of flames from 4 kg IPN/RDX/Al explosion through a 0.305 m orifice. Left: end wall view; right: side wall view (U06-327B).

barrel shock and turbulent mixing at the jet boundary between the reacting products and air, thus resulting in an increase in reaction rate and re-initiation near the jet boundary behind the Mach disc. Due to the competitive effect of expansion cooling and Mach disc recompression and mixing, there exists a critical charge mass for quenching of flames for a given orifice diameter. Beyond this critical charge mass, the transmission and propagation of the explosion in the receptor chamber takes place.

Figure 9 provides an example to compare the pressure histories for various venting orifice diameters. The QSP values in the two chambers for various charge masses and venting orifice diameters are summarized in Fig. 4 for C-4 and two heterogeneous mixtures. As shown in these figures, a decrease in orifice diameter results in a slight decrease in QSP, partially due to an increase in non-uniform mixing but also due to the heat loss to the wall from longer equilibrium time in the two chambers required for the smaller orifice. Due to the fuel lean condition in the donor chamber, the QSP for 1.1 kg charges undergoes very little reduction when comparing the flame quenching cases with the flame transmitted cases. Thus, caution must be taken for the pressure loading even when flames are quenched.

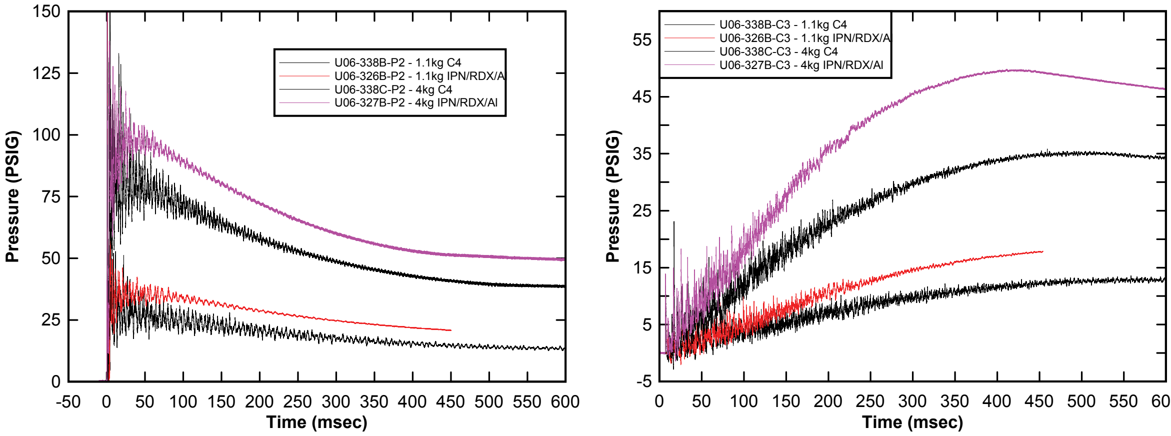


Figure 8. Overpressure histories in the donor (left) and receptor (right) chamber with a 0.305 m ID orifice from 1.1 kg and 4 kg C-4 and IPN/RDX/Al explosions.

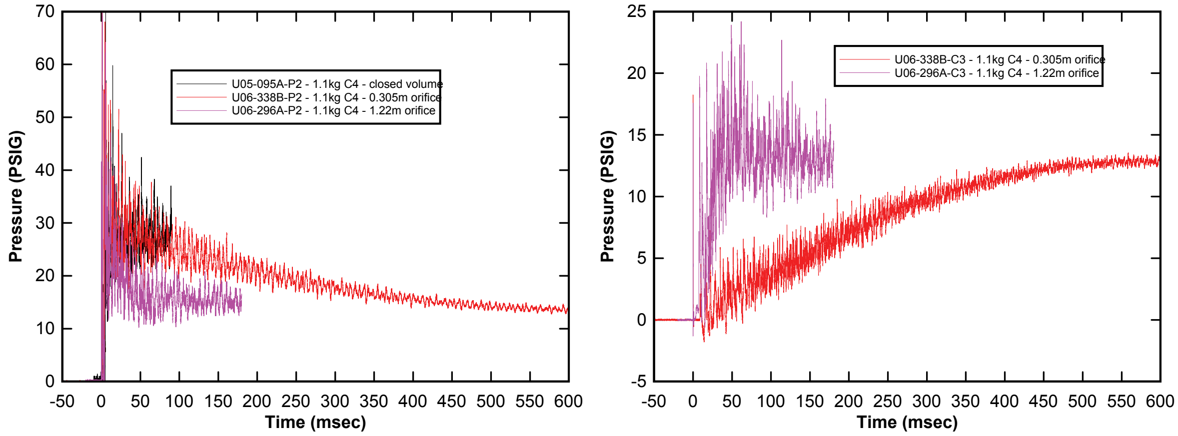


Figure 9. Overpressure histories in the donor (left) and receptor (right) chamber from 1.1 kg C-4 explosions (black line: closed; red: 0.305 m ID orifice; pink: 1.22 m ID orifice).

4 Conclusion

Critical conditions for explosion quenching or transmission from a 26 m^3 donor chamber (where detonation of an explosive charge occurs) to a 23 m^3 receptor chamber (initially filled with air only) through an orifice have been investigated experimentally for both C-4 explosives and metallized heterogeneous explosives (IPN/Mg and IPN/RDX/Al). Unlike the premixed combustible gas mixtures where a quenching diameter can be a few millimeters, the orifice diameter for the quenching of flames in this case can be of the order of one meter. Both turbulent mixing quenching and sonic choking quenching have been observed. Under fuel lean conditions in the donor chamber, the quasi-steady explosion pressure can undergo very little reduction when comparing the flame quenching cases with the flame transmitted cases. Thus, caution must be taken for the pressure loading even when flames are quenched.

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