

Secondary Pressure Waves from Rich Fireballs

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A series of experiments was carried out to investigate the effect of fireball composition on secondary combustion. The fireball was created from a 1.5 liter balloon filled with a propane-oxygen mixture ($1 < \Phi < 3$) and initiated by a detonation (Fig. 1). Two initiation locations (center and bottom) and two initiator strengths (stoichiometric $C_3H_8-O_2$ and $C_2H_2-O_2$) were studied. Two pencil pressure gauges located at 0.6 and 1.2 m and, in some experiments, simultaneous high-speed imaging, were used as diagnostics.

The detonation within the initiator tube diffracts into the balloon, starting a combustion event within the balloon and, ultimately, the balloon membrane ruptures causing mixing of the balloon contents with the surrounding air (Fig. 2). The amount of energy released during the initial combustion event and the secondary reaction depends on the composition of the balloon mixture and the extent of the mixing and reaction of the resulting fireball with the surrounding air. For $\Phi > 1$, the incompletely oxidized products from the primary burn mix with the surrounding air and may be oxidized in a secondary combustion process. For example, at $\Phi = 3$, the initial combustion reaction is approximately $3 C_3H_8 + 5 O_2 \rightarrow 9 CO + 11 H_2 + H_2O$. As the equivalence ratio is increased, an increasing amount of CO and H_2 is produced. When the fireball mixes with the surrounding air, these can be oxidized to CO_2 and H_2O , $CO + \frac{1}{2} O_2 \rightarrow CO_2$, and $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$, releasing energy and creating pressure waves.

The unique feature of the present experiments was a repeatable secondary pressure pulse for sufficiently rich mixtures (see Fig. 3). The secondary pressure rise was observed for all initiation configurations but the nature of the secondary pressure pulse is a strong function of the initial equivalence ratio. For $\Phi = 1$ and 1.5, no secondary pressure waves are observed. An acoustic analysis of the measured pressure histories has been carried out to infer the rate of volume displacement and the total volume displaced by the secondary combustion. The results of the acoustic analysis are in reasonable agreement with both a simplified

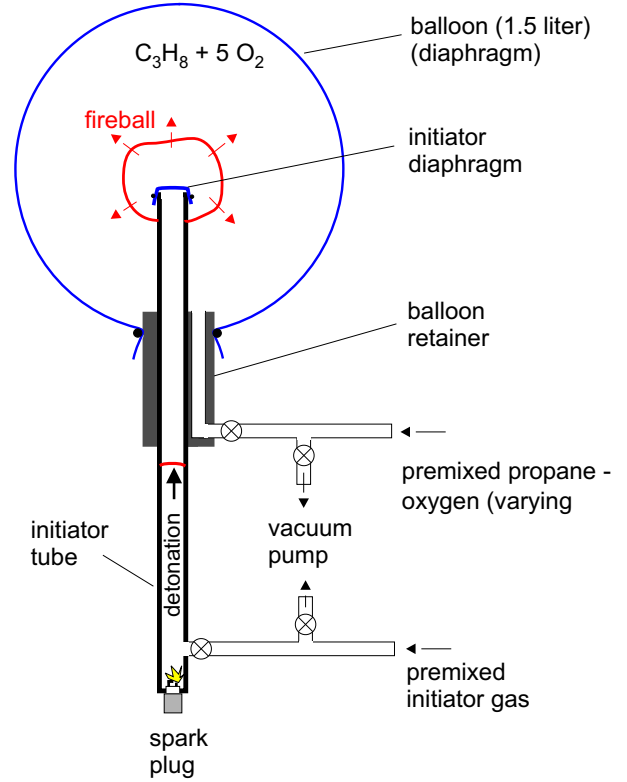


Figure 1: Balloon with initiator tube.

thermodynamic model predicting the total volume displacement assuming constant-pressure combustion for the secondary burn and the analysis of the fireball luminosity of the high-speed images.

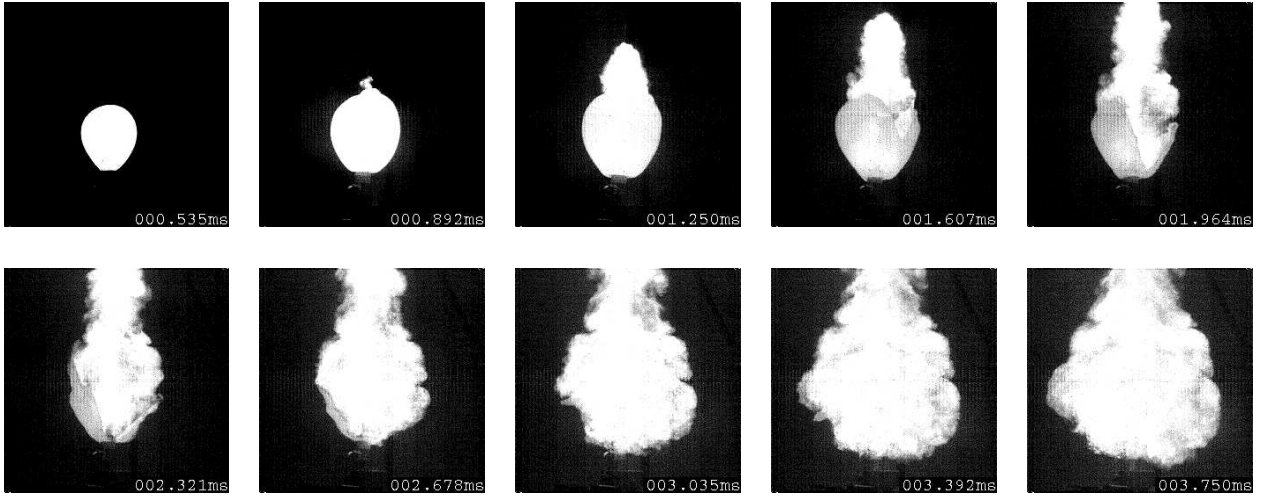


Figure 2: Shot 103, frames 5 to 34, interframe time: $356 \mu\text{s}$, $\Phi = 2.5$.

We have compared our results for peak pressure and impulse with those of previous studies on blast waves from high explosive (Baker et al., 1980) and fuel-air detonation (Dorofeev et al., 1995) by using the Sachs method of scaling with the dimensionless variables described in AMC (1974):

$$\bar{R} = R \left(\frac{p_0}{E} \right)^{\frac{1}{3}}, \quad \bar{p} = \frac{p}{p_0}, \quad \bar{I} = \frac{I c_0}{p_0^{\frac{2}{3}} E^{\frac{1}{3}}}, \quad (1)$$

where R is the distance from the charge, p_0 is the surrounding pressure, E is the energy equivalent of the charge, p is the blast wave peak pressure, and I is the impulse calculated by integrating either the positive or negative phase of the blast pressure trace. Here, only the positive phase is considered.

To carry out the scaling analysis, it is necessary to define an equivalent explosion energy release. The procedure followed in high explosives, Baker et al. (1980), or detonation of fuel-air mixtures, Dorofeev et al. (1995), is to compute equivalent energy by multiplying the mass of mixture with the heat of combustion, which is calculated as the difference in enthalpy between the reactants and products at standard temperature (25°C) and pressure (1 atm). In fact, it is known that only a fraction of the heat of combustion goes into producing the blast wave since the products are still quite hot after expanding to atmospheric pressure but before mixing with the surrounding air. This effect is particularly important for fuel-oxygen mixtures which are highly dissociated and much less efficient at creating blast waves than fuel-air mixtures. To account for this, we use the difference in energy between the CJ state and the isentropically expanded products at ambient pressure. This is similar to the method used for computing the blast energy equivalent for pressurized vessels (see the discussion on pp. 185–199 of AIChE, 1994). For a stoichiometric propane-oxygen mixture, the revised procedure predicts an energy content of 3.1 MJ/kg as compared to 10 MJ/kg predicted by using the conventional heat of combustion technique. By contrast, the energy

content of a stoichiometric propane-air mixture is predicted to be 1.3 MJ/kg as compared to 2.8 MJ/kg predicted by the conventional method. The revised method predicts that 31% of the propane-oxygen mixture’s chemical energy can be converted to mechanical work versus 46% for the propane-air mixture.

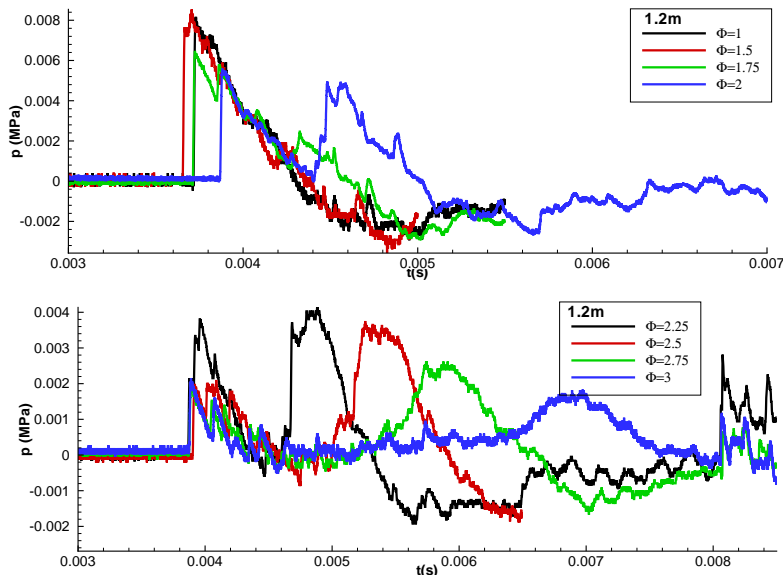


Figure 3: Pressure traces obtained from the pencil gauges at 1.2 m.

The pressure and impulse measurements indicate that the explosions of the rich propane-oxygen mixtures have some unusual characteristics in the near-to-intermediate field measurement locations used in this study. For nearly stoichiometric mixtures, $\Phi = 1$ and 1.5, the leading blast wave peak pressures and impulses are comparable with the previously-measured gaseous and high explosive blasts when the energy content E_1 of the balloon alone is used to formulate Sachs scaling variables. This is consistent with a detonation being initiated in the balloon at these equivalence ratios. The peak pressure of the leading wave rapidly decreases below the energy-equivalent reference blast values as the equivalence ratio is increased. This is consistent with a much slower initial combustion process than detonation for $\Phi > 2$. At $\Phi = 3$, the peak blast pressure is only 15% of the reference blast pressure, consistent with a flame speed of 60 m/s.

For all intermediate equivalence ratios, $2.75 > \Phi > 1$, the Sachs-scaled impulse agrees well with the predictions on the basis of the energy in the balloon alone. This is consistent with a nonideal explosion resulting in a pressure decay following the leading blast that is slower than the reference case and also for $2.5 > \Phi > 1.75$, a significant contribution from the secondary combustion. Although the impulse is as expected on the basis of the balloon contents alone, the augmentation due to mixing and combustion with the surrounding air is still lower than what could be achieved if all the fuel was rapidly and completely oxidized. From a purely thermodynamic point of view, at least a factor of two increase in the impulse over the values obtained in this study for $3 \leq \Phi \leq 2$ may be possible for the richest cases.

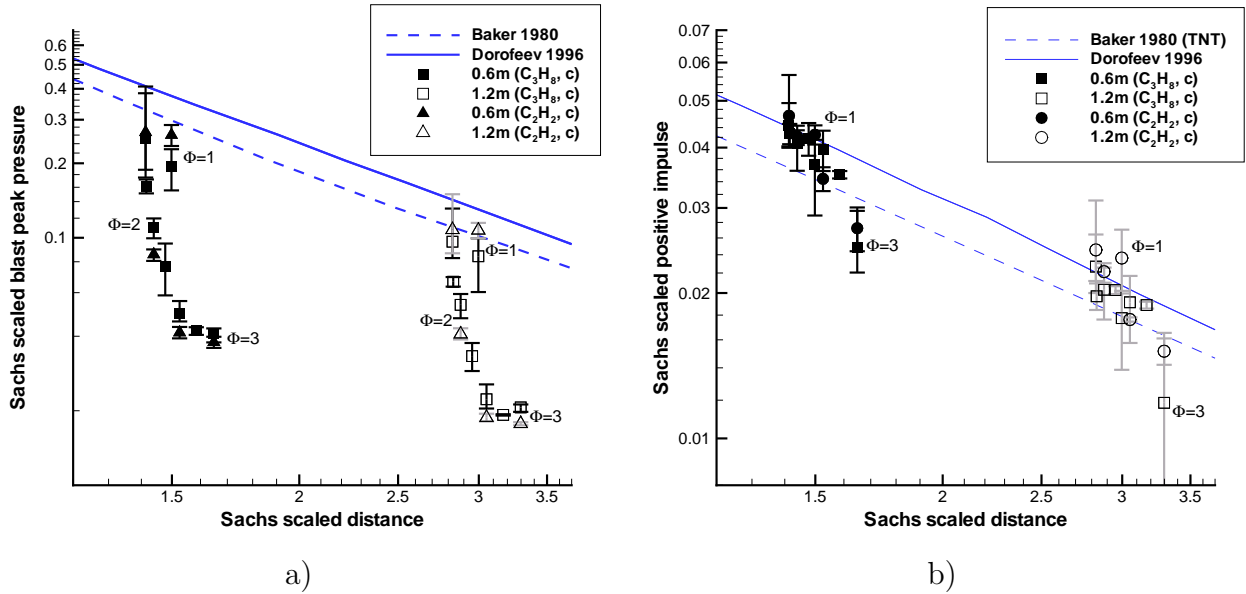


Figure 4: a) E_1 -Sachs-scaled peak pressure and b) E_1 -Sachs-scaled impulse for both initiator mixtures versus Sachs-scaled distance. Center initiation location.

Acknowledgment

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