Unconfined Hybrid Detonation Waves

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1 Introduction

Recent large-scale experiments showed that fine aluminum (Al) particles suspended in unconfined air requires a critical charge of 8 kg C4 explosive for initiation of detonation, indicating the insensitivity of Al-air detonation [1]. Combustion of aluminum particles within or behind a gaseous detonation wave, however, may support so called hybrid detonation. Veyssiere reported the first laboratory observation of a detonation wave comprising a "double-shock" when Al particles were suspended in a lean reactive gas mixture in a 69 mm diameter tube [2]. In the same time period, Afanasieva et al. theoretically postulated the existence of double-shock detonations due to two successive energy releases [3]. Khasainov and Veyssiere applied a two-phase ZND model to show that a "steady" double-shock detonation structure can exist, in which the two fronts are stabilized by a generalized CJ condition for the particle-gas mixture at two subsequent phase-frozen sound speed locations [4]. Recent experiments in an 80 mm diameter, 10 m long tube have provided additional conclusive evidence on the self-sustained propagation of double-shock detonation for aluminum particles suspended in various detonable gas mixtures [5-7]. The observed double-shock detonation can quasi-steadily propagate in two modes: either the second shock has the same velocity as the leading shock, or the second shock velocity is less than the leading shock velocity [7]. This behavior was explained as the weak detonation solutions of reactive gases followed by the particle reaction in different time delays and energy release rates. In the present paper, hybrid detonation studies are extended to the unconfined free field conditions in order to investigate the self-maintenance of the hybrid detonation wave propagation without the influence of tube confinement. Experiments for scaling the unconfined hybrid detonation loading are further conducted over a range of charge masses between 3 and 1000 kg.

2 Experimental results and discussion

An unconfined pancake-shape suspension of Al-liquid fuel spray in air was generated through the bursting of a cylindrical dispersal charge, in which a central glass tube filled with C4 was surrounded by an annulus of Al powder saturated with a liquid fuel contained in a polyethylene cylindrical case. Atomized Al particles known as H-2 and supplied by Valimet Inc. were chosen with a mean diameter of 1.6 μm by number and 3.3 μm by mass. A C-H-N-O liquid fuel was used and characterized by a mean detonation cell size of 33 mm in its stoichiometric vapor-air mixture as determined from laboratory detonation tube experiments. Figure 1 displays a dispersal process of 170 kg Al-liquid fuel into a suspension in air where a 15.24 x 15.24 m^2 concrete pad incorporates 1 m interval parallel grooves to permit the installation of ground-level pressure transducers. Detonation of the C4 burster charge dispersed the Al-liquid fuel spray in air to a radius of up to 11-12 m and a height of 3.5-4 m with the suspension touching the ground at a given dispersal time. Detonation of the Al-liquid spray-air cloud was then initiated by a secondary C4 charge near the center of the cloud and propagated cylindrically outwards. The hybrid detonation wave phenomena were recorded using high-speed video cameras, a local pyrometry sensor for the particle temperature and Endevco piezo-resistive pressure transducers radially located on the ground towards the front edge of the concrete pad. Detonation cell sizes were registered using a 1.2 x 0.9 m^2 Al smoke foil installed on the ground at the 6 m radius.

Figure 1. Dispersal of 170 kg Al-liquid fuel spray into air above a 15.24x15.24 m^2 concrete pad (#U8178A).

Figure 2 shows the detonation pressure histories (for the test in Fig. 1) from gauges on the concrete pad along the cloud radius with an average propagation velocity of 1692 m/s, whose maximum deviation is +391 m/s and -346 m/s. The pyrometer recorded a maximum particle temperature of 2800 K. The flame surface of the detonation wave front (see Fig. 3) displays structures about 1 m in scale, indicating the interactions of macroscopic transverse waves generated by the heat release from the nonuniform local particle concentrations as depicted in Fig. 1. This non-uniformity also manifests itself in the detonation velocity and pressure fluctuation shown in Fig. 2. Regardless of this macroscopic non-uniformity effect, the hybrid detonation intrinsically exhibits a detonation cell size of about 20 mm in average as recorded on the smoke foil shown in Fig. 4. The smaller hybrid detonation cell size, with respect to the 33 mm cell size of the vapor-air mixture of the baseline liquid fuel, indicates that the Al particles react considerably within the fuel spray reaction zone and therefore enhance the spray detonation.

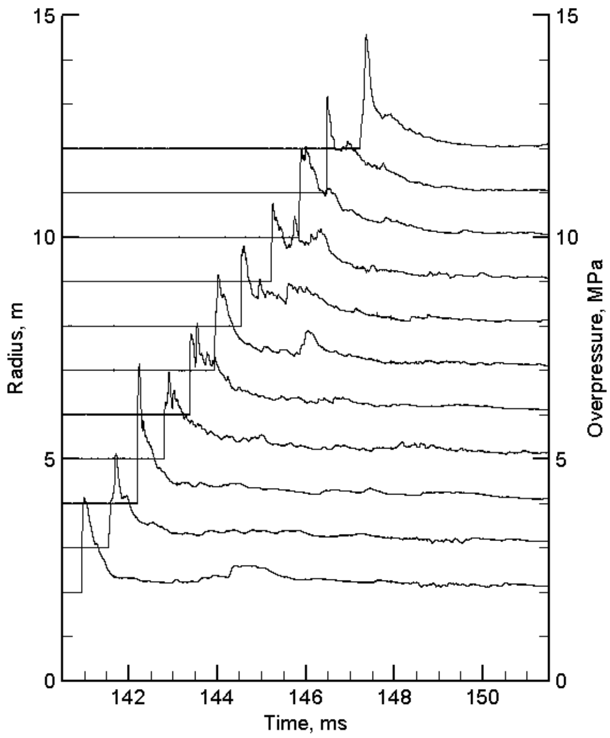

Figure 2. Detonation pressures along the radius on the ground (U8178A).

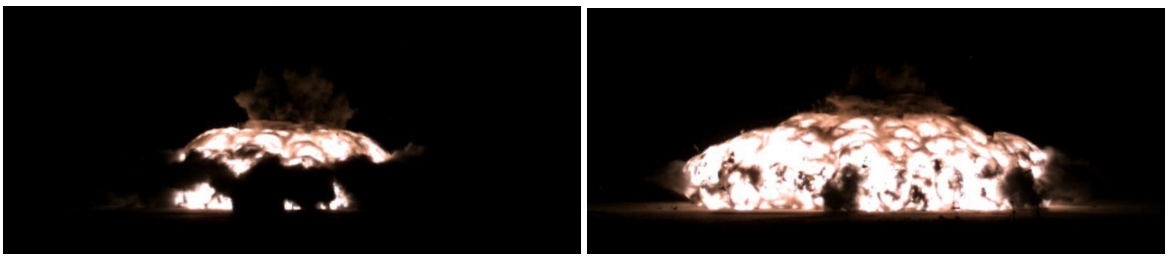

Figure 3. Detonation flame front structure photographed at 6600 frames/s (U8178A).

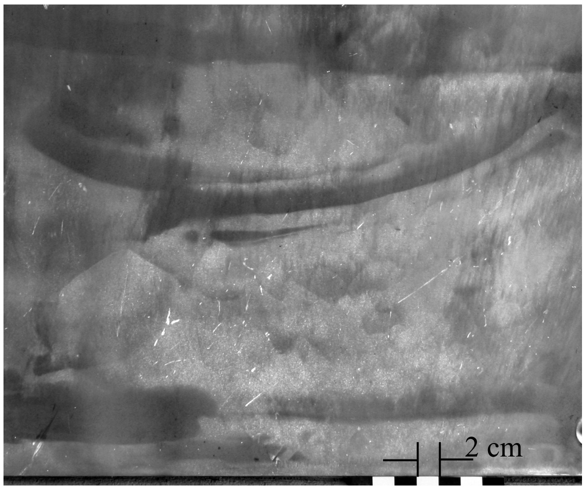

Figure 4. Smoke foil record of detonation cellular structure (U8178A).

In order to study the scaling of the hybrid detonation impulse with charge mass, more than 60 unconfined experiments were conducted over a range of 3 kg to 1000 kg Al-liquid fuel mass. The detonation impulse was obtained by integration of the hybrid detonation pressure history. Figure 5 summarizes the results and indicates a scaling rule where the detonation impulse, *I*, is proportional to the cubic root of the Al-liquid fuel mass, *W*:

$$I \sim W^{1/3}. \qquad (1)$$

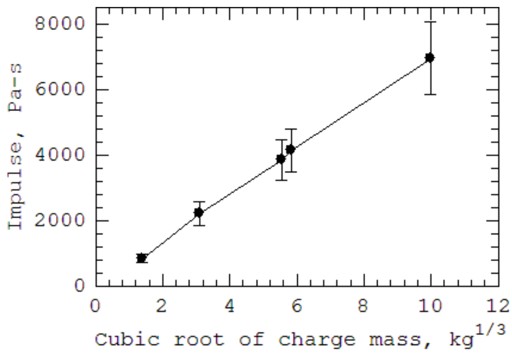

Figure 5. Maximum detonation impulse versus Al-liquid fuel mass.

3 Modeling

One-dimensional spherical numerical simulations were conducted using a full two-phase fluid dynamics model. The description of the two-phase fluid dynamics model can be found in [1], where a surface kinetic oxidation and diffusion hybrid reaction model is used for Al reaction and a single-step Arrhenius model for gas reaction. In all the calculations, the mesh had a cell size of 50 μm and the initiation was by a sphere of ideal gas with a 1.55 g/cm^3 density, 18.6 GPa pressure, 4260 K temperature and 7.75 kJ/cm^3 internal energy, which was equivalent to a constant volume explosion of a C4 explosive charge. For a sufficiently high energy release rate of Al particles (e.g., with a particle size of d_p = 3.3 μm and a concentration of σ_p = 300 g/m^3 in a ϕ = 0.8 C_2H_2-air mixture), the long-time asymptotic solution yields a steady strong hybrid detonation solution, in which the particle reaction produces a compression wave in the gas reaction zone to increase detonation velocity and pressure (see Fig. 6a). In this calculation, the initiation sphere has a radius of R_I = 2 cm, equivalent to a charge mass of W_I = 52 g. As the energy release rate of Al particles decreases (see Fig. 6b for d_p = 13 μm σ_p = 500 g/m^3 in the ϕ = 0.8 C_2H_2-air mixture), a weak hybrid detonation solution with a double-shock structure can be developed, where the second shock arises at the location of a minimum in the pressure profile at which a generalized CJ point appears. When further decreasing the energy release rate of Al particles (e.g., with d_p = 36 μm and σ_p = 500 g/m^3 in the ϕ = 0.8 C_2H_2-air mixture), the second shock cannot be initiated using an initiation sphere R_I = 2 cm and 4 cm, corresponding to a charge mass of W_I = 52 g and 415 g, respectively. At R_I= 6.25 cm or W_I = 1584 g, the second shock is initiated and asymptotically developed towards a double-shock weak detonation solution as shown in Fig. 6c. Thus, the critical charge mass for initiating the second shock must lie between 415 g and 1584 g.

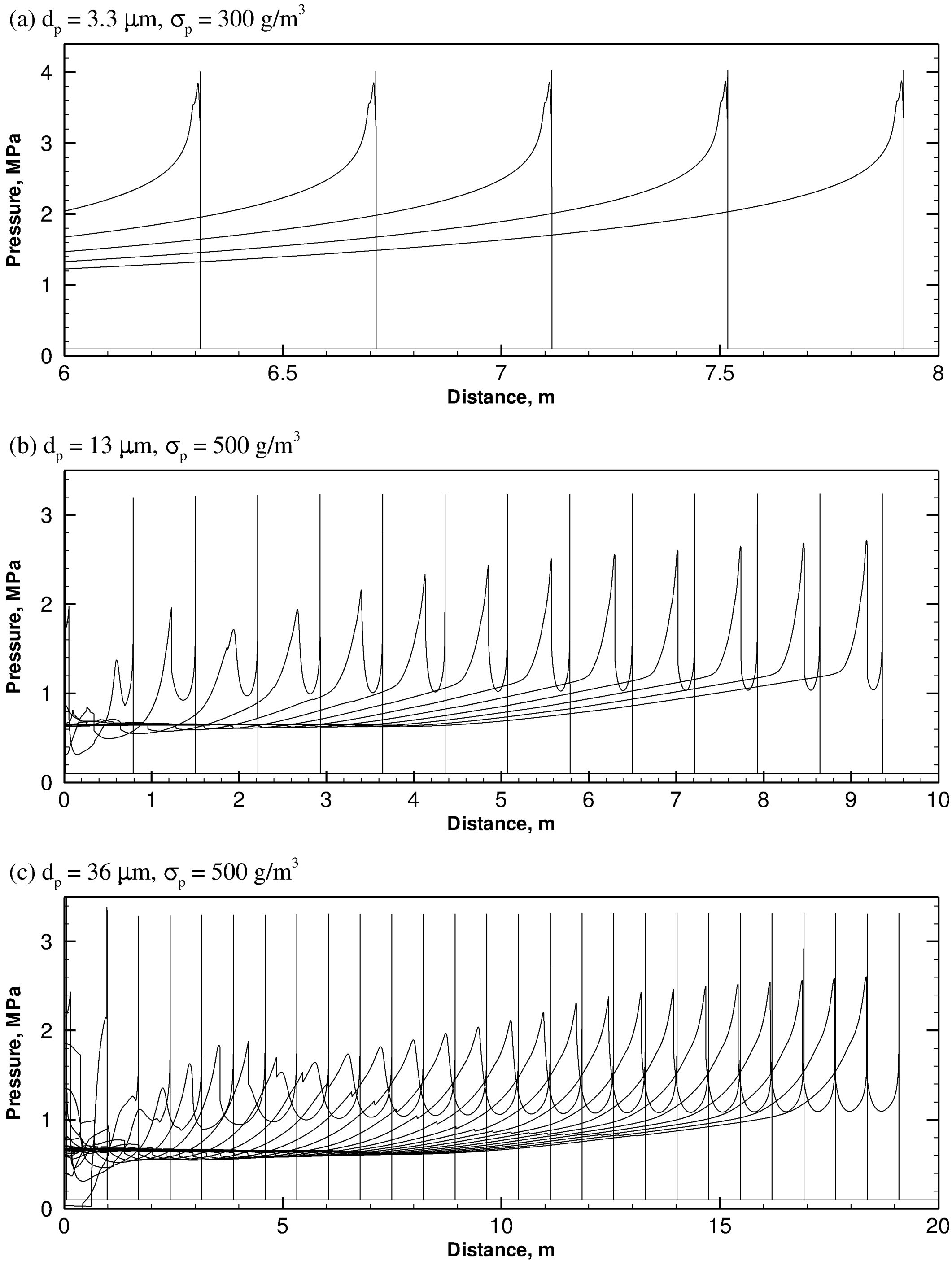

Figure 6. Numerical solution of a hybrid detonation wave in a mixture of C_2H_2-air (ϕ = 0.8) and Al particles: a) a strong hybrid detonation solution with d_p = 3.3 μm and W_I = 52 g, b) a weak hybrid detonation solution with d_p = 13 μm and W_I = 52 g, and c) a weak hybrid detonation solution with d_p = 36 μm and W_I = 1584 g.

The phenomena of the strong and weak hybrid detonation solutions obtained from the spherical numerical simulations are in agreement with that observed and analyzed in the planar geometry [7], except that the spherical hybrid detonation requires a much stronger initiation. By comparing the results of Fig. 6b and Fig. 6c, a critical charge mass to initiate the second shock in the spherical cloud of C_2H_2-air and Al particles seems to be correlated with the Al particle size by:

$$W_I \sim d_p^n \tag{2}$$

where $n \approx 3$. More calculations must be conducted to achieve a firm conclusion.

4 Conclusion

Hybrid detonation in an unconfined large-scale Al-liquid fuel spray suspended in air has been experimentally demonstrated in which the energy release of Al particles (1.6 μm mean diameter by number and 3.3 μm by mass) within the detonation zone of the liquid spray reduces the cell size and enhances the detonation. This phenomenon is in agreement with that observed in the previous confined tube studies and referred as a strong solution of hybrid detonation in the analysis [7]. The impulse of unconfined hybrid detonation scales with the cubic root of Al-liquid fuel mass observed over a wide range of fuel masses from 3 kg to 1000 kg. In contrast to the laboratory tube observation in Al-reactive gas mixtures, the double-shock weak detonation solutions have not been apparent in the experiments of the unconfined Al-liquid fuel spray in air when increasing the Al particle size in a range from 1.6 μm to 13.2 μm mean diameter by number (or 3.3 μm to 36 μm mean diameter by mass). One-dimensional spherical numerical simulations in Al-reactive gas mixtures using a full two-phase fluid dynamics model indicate that a double-shock weak detonation solution can exist only when the initiation charge mass is sufficiently large above a critical mass at which the rate of the Al energy release can support the formation and subsequent propagation of the second shock. This critical mass seems to be proportional to a power of the Al particle diameter.

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