

Hybrid Detonations in Aluminum Dust-Gas Mixtures

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INTRODUCTION

Organic or metallic fine particles suspended in detonable gas form a hybrid explosive mixture in which the combustible dust reacts with the oxygen and gaseous detonation products. While a large transverse wave spacing or detonation cell size is inherent to detonations in dust-air mixtures [1], fine particles added to a detonable gas mixture can cause a variety of detonation modes as a result of the interaction between the gas reaction processes and the additional physical processes involved in the mass, momentum and heat transfer between the particles and the gas. The variety and complexity of so called “hybrid detonation” in combustible particles suspended in reactive gases have yet to be thoroughly studied and remain an open area of detonation research. Veyssiere [2] first reported laboratory observation of a detonation wave comprised of a “double-shockfront” structure in a mixture of small concentrations of aluminum particles and lean reactive gases. Using a two-phase ZND model, Khasainov and Veyssiere [3] stated that a “steady” double-shockfront detonation structure can exist in which the first front is stabilized by the CJ condition for the gas containing inert particles and the second front by the generalized CJ condition for the reactive particle-gas mixture. Recently, Veyssiere and Ingignoli [4] observed that, depending on the particle shape and size, addition of aluminum particles can either reduce or increase the detonation cell size of hydrogen-air mixtures. Concerning transition to detonation in hybrid mixtures, Zhang et al. [5] reported that DDT in a mixture of large concentrations of aluminum particles and acetylene-air near a tube end wall can result in a peak pressure of more than twice that produced in the same gas system alone. The present paper is aimed at a more systematic investigation, both numerical and experimental, of the variety of hybrid detonation modes for these multiple time-scale problems.

NUMERICAL SIMULATIONS

The protocol mixture is composed of a lean acetylene-air mixture containing various concentrations of approximately spherical aluminum particles in a size ranging from 0.1 μm to 10 μm . One-dimensional unsteady numerical calculations are performed based on a multiphase fluid dynamics model that was implemented in a second-order Euler code combining the Godunov scheme for the gas-phase and the FCT algorithm for the condensed phase [6]. As a reference point, the acetylene-air detonation is modeled with a global Arrhenius rate law that results in a steady wave structure with a detonation velocity of $D_0 = 1840 \text{ m/s}$, as shown in Figure 1. When large particles and small dust concentrations are used, the detonation wave front remains the same as that for the gas detonation alone. Slow burning of the particles occurs far behind the sonic plane and therefore does not influence the detonation structure and the pressure profile. Reducing the particle size d , combined with an appropriate dust concentration σ , results in various detonation modes as described below.

1. Stable single-front detonation with a small velocity deficit (Figure 2, $d = 10 \mu\text{m}$, $\sigma = 300 \text{ g/m}^3$). The detonation wave propagates stably with a velocity of $D = 1784 \text{ m/s}$ corresponding to a velocity deficit of 3 %. This is due to the momentum and heat transferred from gas to particles before the gaseous sonic plane. Particle ignition occurs far behind the sonic plane and slow combustion of the particles results in a weak compression wave.

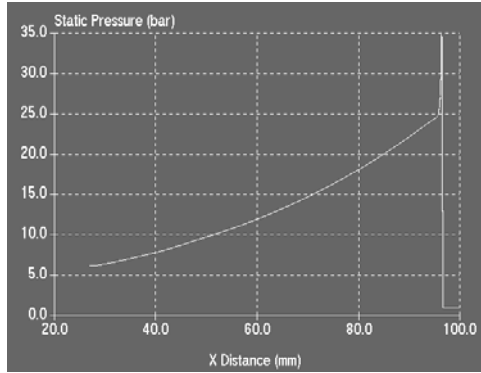


Figure 1. Reference lean C_2H_2 -air detonation.

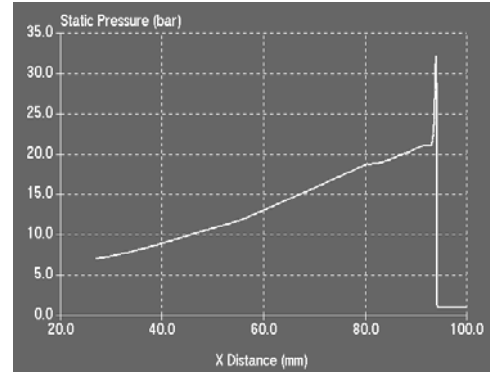


Figure 2. Stable single-front detonation in $10 \mu\text{m}$ Al particles and lean C_2H_2 -air.

2. Unstable detonation with a transient secondary compression (Figures 3, $d = 3 \mu\text{m}$, $\sigma = 300 \text{ g/m}^3$; Figure 4, $d = 10 \mu\text{m}$, $\sigma = 1000 \text{ g/m}^3$). The detonation instability increases and the detonation wave propagates in an oscillatory mode with a larger velocity deficit, due to more momentum and heat losses from the gas to the particles ahead of the gaseous sonic plane. While particle ignition occurs behind the sonic plane, the energy release from the particle combustion is coupled with the unsteady rear flow of the gaseous detonation. Consequently, a transient compression wave is generated behind the detonation front. Within an oscillatory period, the compression wave has an acceleration phase and a deceleration phase. Under conditions of appropriate particle parameters (Figure 4), the acceleration phase can lead to the formation of a shock wave before reverting to the deceleration phase.

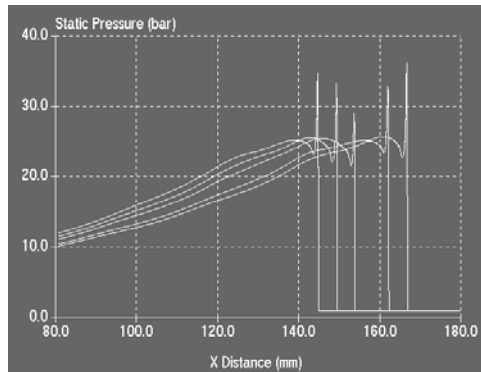


Figure 3. Detonation with a transient secondary compression in $3 \mu\text{m}$ Al particles and lean C_2H_2 -air.

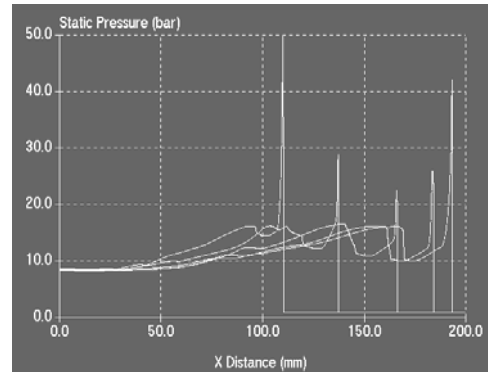


Figure 4. Detonation with a transient secondary compression in $10 \mu\text{m}$ Al particles and lean C_2H_2 -air.

3. Stable detonation with a steady secondary compression (Figures 5 and 6, $d = 1\text{-}2 \mu\text{m}$, $\sigma = 300 \text{ g/m}^3$). While the momentum transferred from the gas to the particles increases due

to a decrease in particle size, the particle ignition occurs ahead of the gaseous sonic plane and the energy release from particle combustion competes with the momentum losses. Hence, the detonation instability decreases and the propagation of detonation becomes steady, when the energy release is balanced with the momentum and heat losses within the gas reaction zone. This occurs in the case of $d = 2 \mu\text{m}$, for which the stable detonation propagates with the same velocity as that for the reference gas alone and the velocity deficit diminishes (Figure 5). Considerable particle combustion is still left behind the sonic plane and causes a steady compression wave behind the detonation front. A further reduction in the particle size causes the detonation velocity and pressure to increase, as shown in Figure 6. The velocity of $D = 1970 \text{ m/s}$ actually results in a velocity increase by 7 %.

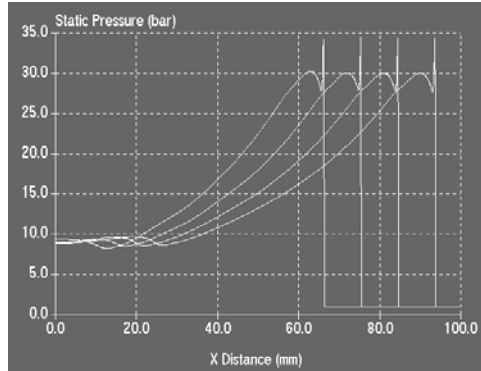


Figure 5. Detonation with a steady secondary compression in $2 \mu\text{m}$ Al particles and lean C_2H_2 -air.

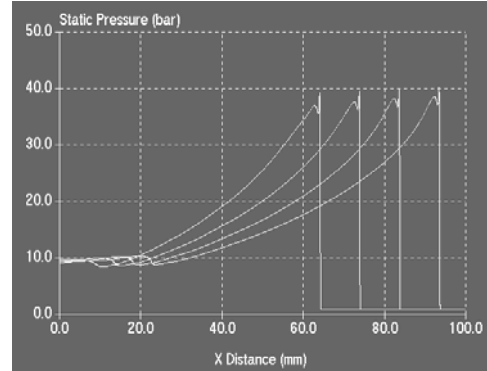


Figure 6. Detonation with a steady secondary compression in $1 \mu\text{m}$ Al particles and lean C_2H_2 -air.

4. Stable single-front detonation with an enhanced velocity. When the particle size is further decreased, combustion of the particles occurs mainly ahead of the gaseous sonic plane. In this case, the detonation front becomes a single shock front followed by the gaseous and particle reaction zone and eventually the gaseous sonic plane. The detonation is stable with an enhanced velocity and shock pressure.

Detailed analysis of the numerical results will also be presented for the flow conditions and propagation mechanisms for these hybrid modes.

EXPERIMENTS

While the numerical simulations illustrate a variety of hybrid detonation modes and their propagation mechanisms, experiments are carried out to examine the existence of these modes via the measurement of pressure histories and detonation cell sizes in a horizontal detonation tube of 8 cm internal diameter. The facility, which is made from Schedule 160 steel pipe capable of sustaining a static pressure of 400 atm at room temperature, consists of a 2 m driver section, a 10 m test section, and a relief section. The test section is equipped with a dispersion system that enables aluminum dust to be suspended in a gaseous mixture [1]. The initiation pulse is produced by detonating a sub-atmospheric stoichiometric acetylene-oxygen mixture in the initiation section, and a circular orifice is used to further adjust the initiation strength. Pressure transducers and ion gauges are located along the test section to measure the pressure history and flame velocity. The detonation cell size is recorded using an aluminum smoke foil mounted cylindrically on the inner surface of a 30 cm long smoke foil section located at the end of the test section. Finally, the relief section is used to avoid undesired pre-compression and the possibility

of subsequent DDT. The experiments are carried out for mixtures of lean acetylene-air and aluminum particles over a range of concentrations. The aluminum particles used are atomized aluminum particles ranging from 1-30 μm . Figure 7 shows a smoke foil record for a mixture of 6.3% acetylene-air and 5 μm mean-size aluminum particles for a concentration of 1000 g/m^3 . The mean detonation cell size is measured to be 5 mm, much smaller than that of the reference gas detonation alone. The complete experimental results for aluminum particle sizes ranging from 1-30 μm with different concentrations will be presented.

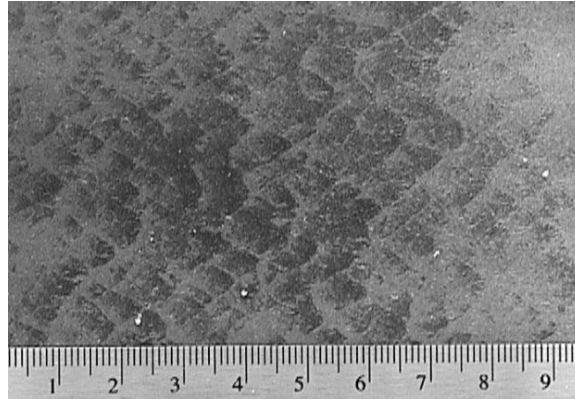


Figure 7. Cellular detonation structure on a smoke foil record for 5 μm Al particles and 6.3 % C_2H_2 – air.

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