Experimental Research on the Detonation in Gaseous Mixtures with Suspended Aluminum Particles

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Abstract The experiments have been performed in a horizontal detonation tube having a 13-m-long test section with 224 mm internal diameter. The suspended aluminum particles are spherical with a diameter range of 1–50 μm, using a particle concentration of 300 g/m^3 approximately. It is found that the single-front and double-front detonation waves can propagate in a mixture of $\varphi = 1.0$ H_2–air and aluminum particles which react with water vapor produced by gaseous detonation. The pressure records show that the detonation structure is double front when using 50 or 30 μm aluminum particles and that single front when using 20, 10, or 1 μm ones. However, these single-front detonation waves don't have the same properties. The detonation velocity using 1 μm particles is increased by 3.3% from the value of the baseline gas detonation as the heat release between particles and gases starts before the sonic surface and supports the shock, while the 10 and 20 μm ones start behind the sonic surface, so the detonation velocities cannot be increased. The single-front structure displayed in pressure records using 10 and 20 μm particles is because of the delay of the second front which is too short to distinguish in the pressure records.

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1 Introduction

As a fuel additive or a powder fuel in some power engines, metal particles take advantages of high density and high enthalpy of combustion [1]. To have a deeper understanding of the combustion process of metal particles and provide a theoretical basis for taking advantage of metal particles in the high-velocity and high-temperature gas with complex chemistry, the hybrid detonation experiments of gaseous mixtures with suspended aluminum particles have been proposed.

Detonation in gas-particle mixtures can be classified into three main categories, depending upon the different chemical properties of the components [2]:

1. "Heterogeneous detonations": all the combustible is contained in the solid particles, and the oxidizer is in the gaseous phase.
2. "Hybrid detonation": the combustible is contained in both solid and gaseous components.
3. "Dusty detonation": the solid particles are inert and do not participate in chemical reactions, chemical reactions just between the gaseous phase.

Hybrid detonation experiments have been carried out in gaseous mixtures with suspended aluminum powder by Veyssiere [3, 4] and Zhang [2]. Veyssiere performed experiments in a vertical tube with 6 m length and 69 mm internal diameter, while Zhang did in a horizontal one with 10 m length and 80 mm internal diameter. In the experiments, micron-sized aluminum powder was chosen, and the hydrogen-air or acetylene-air gaseous mixtures were oxygen-rich mostly. From their experimental results, it is uncovered that hybrid detonation structures are various according to the sequence of heat release, which comes from both gaseous reactions and reactions between particles and gases, behind the leading shock front. The hybrid detonation structure exists in three states. In the first case, only one discontinuity front exists, and the detonation is supported by the energy released both by gaseous reactions and particle-gas reactions, so it is called "single-front detonation." In the second case, the particles remain inert upstream of the CJ plane, and the reactions with gases occur downstream of the CJ plane, so the detonation front is supported only by the energy released from gaseous explosives. That is called "pseudo gas detonation." In the third case, two detonation fronts exist: the first one is supported by gaseous reactions and the second one by reactions between particles and gaseous products, so it is "double-front detonation."

In order to have a deeper understanding of the combustion process of metal particles and provide a theoretical basis for taking advantage of metal particles in the high-velocity and high-temperature gas with complex chemistry, the hybrid detonation experiments of gaseous mixtures with suspended aluminum particles have been proposed. The experiments have been performed in a horizontal detonation tube having a 13-m-long test section with 224 mm internal diameter.

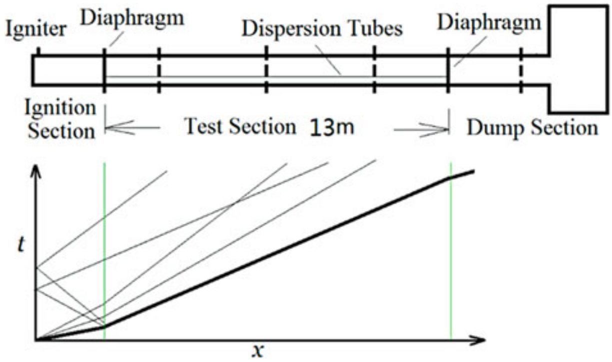


Fig. 1 Schematic diagram of the detonation tube and x-t wave diagram

2 Experiment Conditions

The detonation tube as schematically shown in Fig. 1 consists of three main parts: an ignition section, a detonation test section, and a dump tank. The ignition section is 3 m long, and the detonation test section is 13 m long. Both of them are 224 mm in diameter. The dust was dispersed by turbulent jets before ignition referring to the method of Zhang [5]. The dust dispersion system contains dispersion tubing with a row of 1.0 mm holes 50 mm apart pointing downward to the bottom. Before an experiment beginning, the aluminum powder was placed evenly along the slot on the bottom of the detonation tube. The dust will be dispersed as soon as the gas jets out of the holes, and the blowing gas is inert high-pressure nitrogen.

At the beginning of an experiment, the test section is fulfilled by stoichiometric H_2-air gaseous mixture, and the ignition section is fulfilled by stoichiometric H_2-O_2 for a strong initiation. The suspended aluminum particles are spherical with a diameter range of 1–50 μm, using a particle concentration of 300 g/m^3 approximately. The ignition and dispersion timing sequence is defined by the test to ensure a fairly uniform dispersion.

3 Different Hybrid Detonation Structures

3.1 Single-Front Detonation

When the aluminum particle diameter is 1, 10, or 20 μm, the experimental detonation wave has one single front. Figure 2 displays pressure records using 1 μm particles. The detonation velocity is measured to be 1926 m/s, increased by 3.3% from the value of the baseline gas detonation, and the pressure behind the

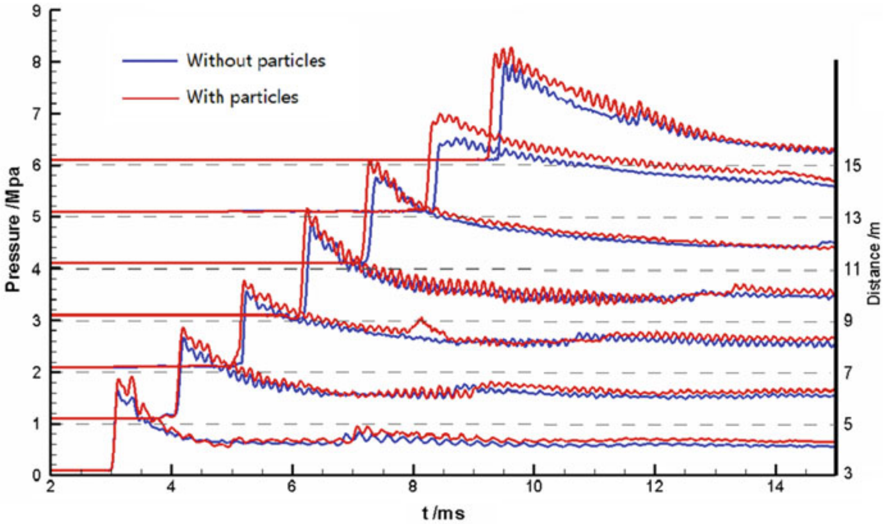


Fig. 2 Pressure records of a detonation in a hybrid H_2-air-aluminum particle mixture (1 μm, 280 g/m^3 aluminum particles, 1.0 Bar, $\varphi = 1.0$ H_2-air)

shock is increased by 10%. In this case, the particles heat release starts before the sonic surface and supports the shock.

The curves using 10 μm and 20 μm are shown in Figs. 3 and 4. They both have only one front but they are not entirely similar with one using 1 μm. The pressures behind the shock are both increased by 40% nearly, but the velocity is decreased a little.

3.2 Double-Front Detonation

As shown in Figs. 5 and 6, a double-front structure appears with the aluminum particle size increased to a value. When using 30 μm particles, the first leading shock has a velocity of 1866 m/s close to the value of the baseline, but the pressure after the first shock is a little lower. And the second front has an approximate velocity of 1889 m/s, so the distance between the two fronts is almost constant. The remarkable difference using 50 μm particles is that the second front has a much lower velocity of 1671 m/s.

With the increase of the aluminum particle size, the aluminum particle needs more time for heat transfer, so the reactions between particles and gases begin behind the gaseous sonic plane and cannot influence the first leading shock. Then the particles start chemical reactions in gaseous detonation products. So the first leading shock is only supported by gaseous detonation in the double-front structure, while the second one is supported by particles' combustion.

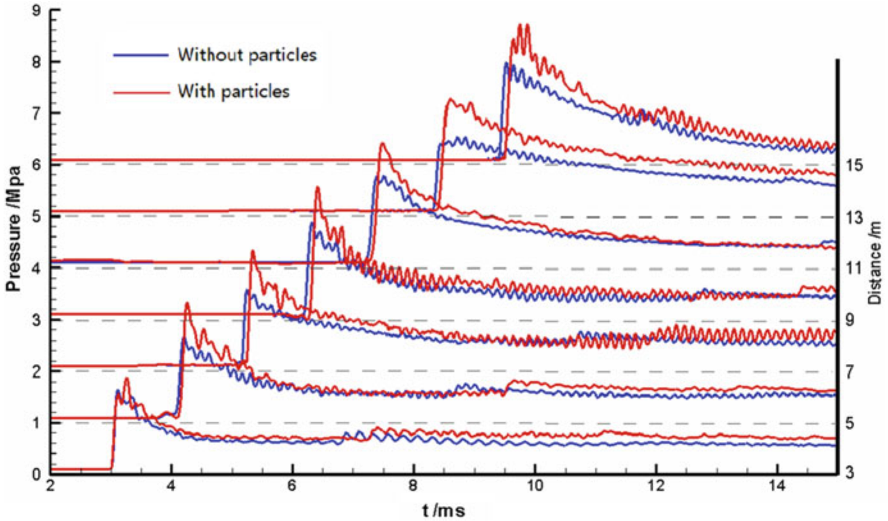


Fig. 3 Pressure records of a detonation in a hybrid H_2-air-aluminum particle mixture (10 μm, 350 g/m^3 aluminum particles, 1.0 Bar, $\varphi = 1.0$ H_2-air)

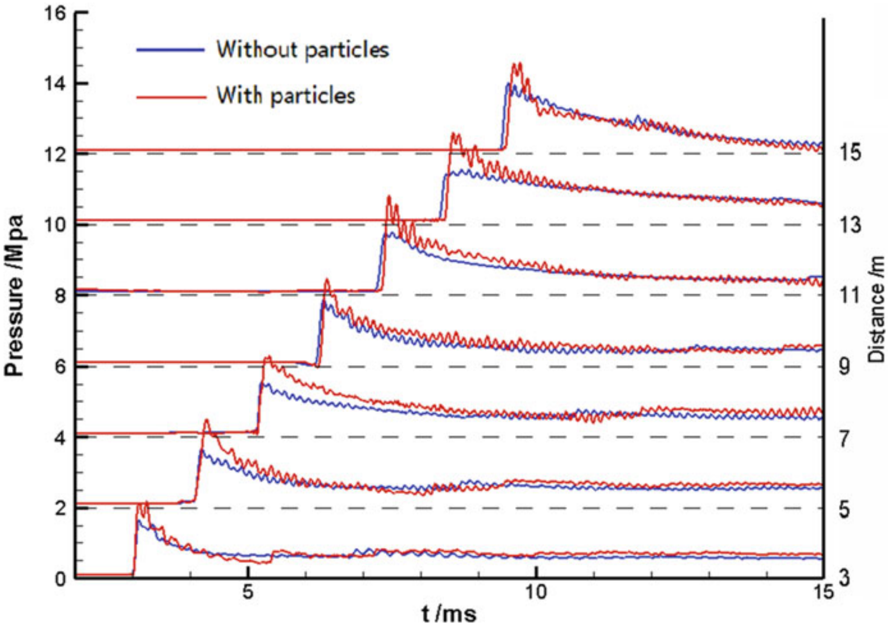


Fig. 4 Pressure records of a detonation in a hybrid H_2-air-aluminum particle mixture (20 μm, 300 g/m^3 aluminum particles, 1.0 Bar, $\varphi = 1.0$ H_2-air)

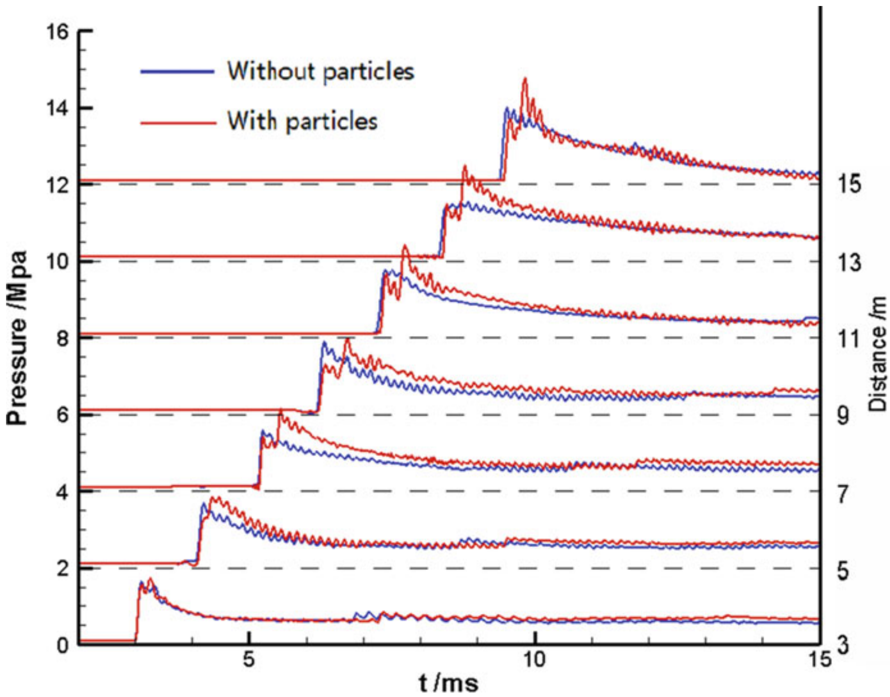


Fig. 5 Pressure records of a detonation in a hybrid H_2-air-aluminum particle mixture (30 μm, 300 g/m^3 aluminum particles, 1.0 Bar, $\varphi = 1.0$ H_2-air)

4 Ignition Delay of the Aluminum Particles

The particles heat release does not take place closely after the shock as gas, so the structure of hybrid detonation is multiplex. It is important that the sequence of heat release comes from both gaseous reactions and reactions between particles and gases.

A quantitative numerical model for steady hybrid detonations in gaseous mixtures with particles in suspension was used to predict the detonation structure numerically [6, 7]. The main assumptions and the method of solution are described in detail in the references. By solving a system of ordinary differential equations and fulfilling the equivalent CJ condition for non-ideal detonations, Fig. 7 gives the numerical results of the ignition delay of aluminum particles with different diameters assuming that the ignition temperature is 933 K or 1350 K. With the increase in particle size, the heat transfer slows down. The 2 μm aluminum particles only need a few millimeters to reach the ignition temperature behind the gaseous shock, while 50 μm aluminum particles need 0.34 m to 933 K or 0.78 m to 1350 K. The sonic plane is only about 1 mm behind the gaseous shock by the calculation

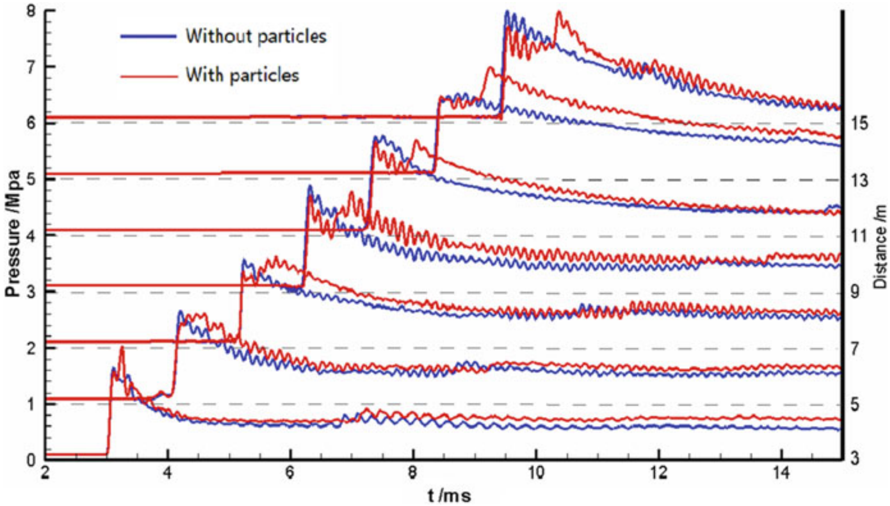
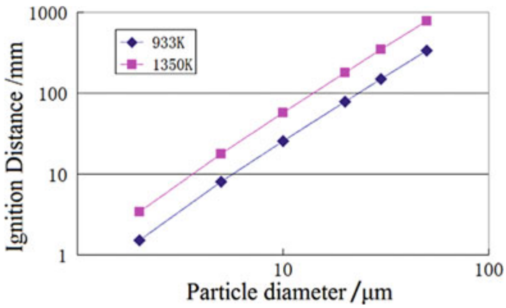


Fig. 6 Pressure records of a detonation in a hybrid H_2-air-aluminum particle mixture (50 μm, 275 g/m^3 aluminum particles, 1.0 Bar, $\varphi = 1.0$ H_2-air)

Fig. 7 Ignition delay of aluminum particles with different diameters



result in these cases. As a result, only when the aluminum particle size is small enough, the ignition can occur before the gaseous sonic plane.

When the diameter is 1 μm, the particles heat release starts before the sonic surface and supports the shock, so the detonation velocity and the pressure behind the shock are both increased. While the 10–50 μm ones start behind the sonic surface, the detonation velocities cannot be increased. The larger the particles, the longer they reach the ignition temperature; thus a second shock wave supported by a late energy release can propagate with 30 μm or 50 μm aluminum particles. Based on the experimental results and calculation analysis, the single-front structure but not a double-front one displayed in pressure records using 10 and 20 μm particles is because of the delay of the second front which is too short to distinguish in the pressure records. A variety of cases are summarized in Table 1.

Table 1 Different hybrid detonation structures

Particle diameter/μm	Detonation structure in pressure records	Ignition position
1	Single front	Before the sonic surface
10		Behind the sonic surface
20		
30	Double front	
50		

5 Conclusion

It is found that the single-front and double-front detonation structures can propagate in a mixture of $\varphi = 1.0$ H_2-air and aluminum particles which react with water vapor produced by gaseous detonation. The pressure records show that the detonation structure is double front when using 50 or 30 μm aluminum particles and single front when using 20, 10, or 1 μm ones. However, these single-front detonation waves don't have the same properties. When the diameter is 1 μm, the particles heat release starts before the sonic surface and supports the shock, so the detonation velocity and the pressure behind the shock are both increased from the value of the baseline gas detonation, while the 10 and 20 μm ones start behind the sonic surface, so the detonation velocities cannot be increased. The single-front structure displayed in pressure records using 10 and 20 μm particles is because of the delay of the second front which is too short to distinguish in the pressure records.

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