Some observations of detonation propagation through a gas containing dust particles in suspension

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Abstract. An experimental study of the influence of low concentration particle suspensions on the propagation of detonation waves in a combustible gaseous mixture is presented. In all cases the particles have an effect on the propagation of the detonation but at certain concentrations, both with inert and combustible particles, a zone of reduced pressure is observed following the detonation front. At the end of this zone there is a sharp pressure increase, which, in some instances, resembles a second shock or detonation front. The paper considers the possible origins of this second pressure rise.

Key words: Detonation, Heterogeneous, Particles, Dust, Aluminium oxide

1 Introduction

The properties of flames and detonation waves propagating into heterogeneous mixtures containing a suspension of combustible particles in a gaseous mixture have been studied for many years. Wolanski (1992) for example reviews basic and applied research on dust-air explosions, providing a general overview of results obtained in the area of ignition, flame propagation and detonation. Corn starch, coal dust and aluminium particles have all been shown to be detonable or enhance the detonation velocity, pressure and temperature of reactive gaseous mixtures.

In other studies, inert particles, such as quartz, sand and aluminium oxide have been shown to significantly reduce the detonation velocity although they could also stabilise marginal detonations (e.g. Sedov et al. 1990).

In contrast, detonation waves propagating into gaseous mixtures containing suspensions of aluminium particles have been shown to exhibit an enhanced double shock front structure Veyssiére et al. (1981–1997) and Khasainov and Veyssiére (1988, 1996), with the second front of these "double-fronted" detonations being attributed to the delayed combustion of the aluminium particles. More recently, Tulis et al. (1996) found that in hybrid mixtures of monopropellant and aluminium powders, aluminium particle size/shape influenced multiple-front detonation propagation characteristics.

When combustible particles are present in gaseous detonation fronts energy release may result both from homogeneous gas phase reactions and also from heterogeneous reactions between the particles and gaseous products. The characteristic times for the two heat releases may differ by an order of magnitude or more. The addition of particles may also influence the gasdynamic flow by their very presence, irrespective of any energy release.

In the present study, in an attempt to distinguish between the pure fluid dynamic effects arising from adding particles to the system and the effects arising from any subsequent combustion, experiments were first conducted using inert aluminium oxide and boron carbide particles. Tests with combustible metallic aluminium and magnesium particles were also conducted. Under certain conditions a secondary pressure rise was observed, irrespective of whether reactive or inert particles were tested. The paper reviews existing work on transient interactions between gas and inert particles to seek possible explanations for the pressure features. Other relevant chemical or gasdynamic processes are also considered.

2 Experimental details

2.1 Experimental apparatus

Figure 1 shows a schematic of the hybrid detonation tube used. It consisted of a 1.14 m long horizontal driver section, a 2.15 m long vertical test section and a particle feed section at the top of the tube. The particle feed section was separated from the test section by a detonation proof ball valve and consisted of a particle reservoir 5 × 10⁻² m in diameter, 5 × 10⁻² m high, with a stainless steel mesh base (7.5–10.5 × 10³ mesh per m). This was vibrated by
Fig. 1. Schematic diagram of the experimental apparatus.

an audio speaker positioned above the reservoir. The optimum frequency was found to be 180–250 Hz. The particle feeder was active when the ball valve was fully open, only then allowing particles to fall into the test section. The ball valve was closed just prior to each test, with a limit switch used to activate the main fuse head ignition unit. The circular driver and test sections were 5 × 10⁻² m in diameter and were separated by a Mylar diaphragm and a 90° bend.

The procedure for conducting an experiment was as follows. The entire tube was first cleaned, a diaphragm fitted and all sections of the tube were placed under vacuum. The test and reservoir section were then filled with 2H₂ + O₂ + 3Ar at a pressure of 26 kPa and the driver section filled with stoichiometric oxy-acetylene to a pressure of 54 kPa.

The ball valve to the particle feed section was then opened manually, activating the particle feed system. Once a steady dust stream was indicated by the optical sensors the ball valve was closed and a detonation initiated directly in the driver section using a Testex fuse head. The driver detonation burst the diaphragm and a detonation was rapidly established in the test section. Detonation pressures and arrival times were recorded in the test section at 0.7 m, 1.04 m and 1.685 m from the bend by Kistler pressure gauges. These were located by diametrically opposing photo diodes to record light emission.

The concentration of the dust in the test section was determined using laser concentration detectors at 0.63 m and 1.77 m from the bend. Suspensions of particles with concentrations between 5 to 30 × 10⁻³ kgm⁻³ were used. The detectors indicated a reasonable degree of uniformity in the falling dust, although some dust did accumulate on the wall.

Pressure and emission data were captured using a custom built transient recorder (up to 10 MHz sample rate) and saved on a personal computer. It was possible to determine the times of the leading edges of the pressure pulses to an accuracy of ±0.2 µs and velocities to ±0.6%.

The calculated CJ detonation velocity, temperature and pressure for the gas mixture alone, without dust, under the above initial conditions are 1877 mₛ⁻¹, 3194 K and 4.7 MPa. The experimental velocity and pressure were slightly higher than the calculated value because the detonation is initially overdriven, but soon settles down to the CJ value. The detonation cell width of this mixture at this initial pressure is of the order of 5 mm.

2.2 Particles studied

The inert particles used in these experiments were supplied as “<10µm” aluminium oxide powder and “<10µm” boron carbide powder by Aldrich. The metallic combustible particles used were “15 µm” aluminium particles supplied by Flurochem. To determine the effective size of the particles under experimental conditions, Malvern particle sizing equipment was used 0.2 m and 2.2 m below the ball valve. Results indicated that a significant proportion of the particles were agglomerating to form large clusters and that the agglomeration process continued as the particles fell down the tube.

Precise ex situ particle size measurements for several test samples were made using a JEOL 840 scanning electron microscope. Samples of the falling particles (under test conditions) were collected on adhesive film at the foot of the test section. The micrographs showed that some of the particles formed large clusters, as large as 150 µm in some cases with aluminium oxide. Each of the particle suspensions in our study should therefore be regarded as a mixture of small particles and large clusters.

Figure 2 shows micrographs of aluminium and boron carbide particles including images of typical particle agglomeration. It was not possible to image aluminium oxide for technical reasons.

3 Results

Figure 3 shows pressure records that illustrate the effect of the presence or otherwise of particle suspensions. The records were all obtained using a gauge located at a recording station approximately 1 m from the end of the bend.