Transmission of a Combustion Front into Porous Media

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1 Introduction

The propagation of a combustion front in porous media has been investigated extensively in connection with the design of burners and explosion safety devices. In particular, low-speed flame propagation in porous media has been studied by Babkin [1], and high-speed flame and detonation propagation has been studied by Pinaev [2]. These studies have shown that there are several steady-state combustion regimes ranging from flame propagation at roughly the laminar flame speed up to the Chapman-Jouget (CJ) velocity for detonation waves [3]. The flame propagation regimes include slow constant pressure flames propagating at less than 5 m/s and high velocity flames propagating at hundreds of meters per second with a corresponding local pressure rise. For "detonation waves" it was shown that the front can propagate over a wide range of velocities from half of the CJ velocity up to the CJ velocity [3]. The combustion front propagation velocity has been correlated with the mixture reactivity, i.e., laminar flame velocity for flames and the detonation cell size for detonation waves, and the porous media characteristic pore dimension.

The transient development of the combustion front leading up to the steady-state condition has received little attention in the literature. This paper reports on the investigation of the interaction and transmission of a flame, or detonation wave, from free-space into porous media. Specifically a flame is initiated at the top end of a vertical oriented tube that has a layer of ceramic spherical beads at the bottom end of the tube. The length of the free space above the beads is varied in order to generate various combustion wave conditions ranging from laminar flames to detonation waves. In some tests an array of orifice plates is located in the free space in order to produce either a fast flame or detonation wave at the bead face. From a practical standpoint the results can be used to devise an approach to mitigate the generation of extremely high pressures at the tube endplate resulting from the "pressure piling" phenomenon.

2 Experimental setup

Experiments were performed in a vertically oriented 61.0 cm long, 7.62 cm inner-diameter steel detonation tube, housing two sets of diametrically opposed instrumentation ports spaced at one tube diameter (see Fig 1 for port identification numbering). Piezoelectric pressure transducers and ionization probes were employed on either side, such that the explosion front shockwave and reaction zone could be tracked down the length of the tube. A flame was ignited at the top endplate by a centrally mounted sparkplug that operates via a standard automotive ignition system, while the bottom endplate measured the reflected shock pressure by a centrally mounted pressure transducer. Nitrogen diluted stoichiometric ethylene-oxygen mixtures were prepared in a separate mixing chamber by the method of partial pressures, after which they were downloaded into the pre-evacuated detonation tube. In most tests, four 30 percent blockage ratio orifice plates, spaced at one tube diameter, were located at the ignition end of the tube and a layer of ceramic spherical beads was located at the bottom end. Three different bead diameters, *d*, were used: 3 mm, 6.35 mm, and 12.7 mm. The test parameters included the nitrogen dilution β, defined as the ratio of the number of moles of nitrogen to oxygen, and the mixture initial pressure in the tube.

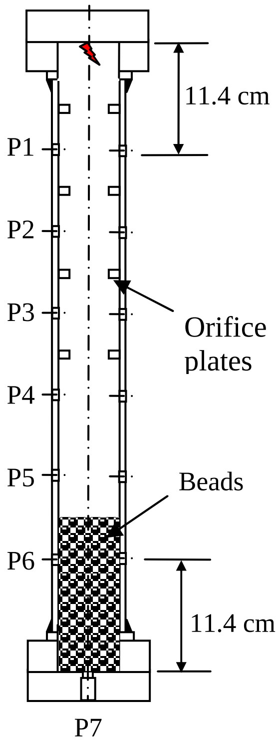

Figure 1. Detonation tube

3 Explosion propagation through porous media

In order to characterize the combustion front propagation through the porous media tests were performed with the tube filled with beads up to a level 3 cm from the top endplate, where the spark plug is located. A laminar flame is ignited in the free space above the beads and expansion of the combustion products produces a flow in the porous media. Flame propagation through the tube filled with 12.7 mm beads for a β= 1 mixture at different initial pressures is provided in Fig. 2. In all cases the flame accelerates to a supersonic velocity that is generally lower than the CJ detonation velocity for the mixture. The distance required for the flame to reach steady-state decreases as the initial pressure increases, and hence reactivity increases. This flame acceleration is similar to that observed in obstacle laden tubes. Once the flame enters the beads the hot combustion products are convected via a jet into the downstream pore where turbulent mixing with the unburned gas occurs, and after a short induction time, rapidly burn. The jet mixing enhanced volumetric burning leads to increased jet velocities and further enhancement of the burning rate in the subsequent pore. This feedback mechanism leads to flame acceleration through the beads. A similar feedback flame acceleration mechanism exists for flames propagating in obstacle laden tubes where the flow disturbance caused by the obstacle leads to flame area enhancement. The main difference is that in a porous media the heat and momentum losses are much more significant. It has been found that in porous media the flame accelerates until it reaches a steady-state velocity which depends on the porosity and reactivity of the mixture. It is believed that at this velocity strong jet mixing of the cold unburned gas with the burned gas in some pores leads to local quenching at the reaction front. In the limiting case a detonation wave can form if the cell size, λ, is on the order of the pore size, δ, which is taken to be δ= *d*/3 [3].

The steady-state combustion velocity for the four nitrogen dilutions is presented in Fig. 3 normalized with the computed CJ detonation velocity. The left most data point for each β value in Fig. 3 represents the lowest pressure for which ionization probe signals were obtained. For the β= 2 and β= 3 mixtures the combustion front does not quite achieve steady-state in the length of the tube so the flame velocity measured at the end of the tube is plotted. The measured combustion front velocity approaches the CJ detonation velocity as the initial pressure increases and the nitrogen dilution decreases. This is consistent with the finding of Makris et al. [3] who argued that the CJ velocity is attained when the pore size equals the critical tube diameter, i.e., δ= 13λ. Using the cell size data available from the Shepherd detonation data base [4]; β= 3 at 90 kPa δ/λ= 1.0; β=2 at 80 kPa δ/λ= 1.5; β=1 at 70 δ/λ= 4.2. It should also be pointed out that Makris et al. [3] established that for a combustion front velocity of less than half the CJ velocity the propagation mechanism is convective rather than detonative. Based on the results in Fig. 3 only the β=1 and β=2 mixtures support detonation waves in 12.7 mm beads.

4 Flame acceleration and interaction with bead layer and solid surface

Experiments were first performed with only the four orifice plates in place in order to characterize the flame acceleration in the tube and the peak pressures generated at the endplate. The flame acceleration down the length of the tube for β=1 mixtures at various initial pressures is shown in Fig. 4. For a β=1 mixture the CJ detonation velocity is roughly 2100 m/s and the isobaric speed of sound is about 1000 m/s. DDT is observed for initial pressures of 50 kPa and above, and the DDT run-up distance decreases with increased initial pressure. For the 50 kPa and 60 kPa tests DDT occurs after the last orifice plate located at 0.305 m from the ignition end. For an initial pressure of 40 kPa a “choked flame” is established before the end of the tube.

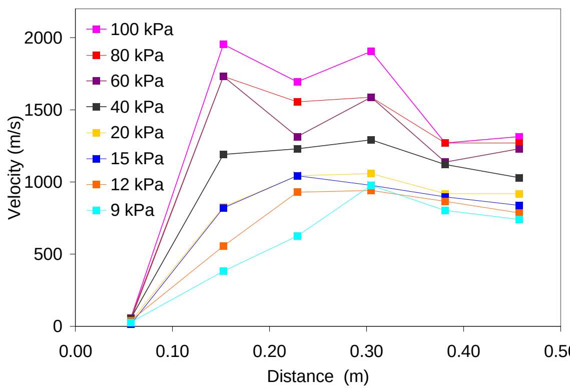

Figure 2. Flame velocity for β=1 and d=12.7 mm beads

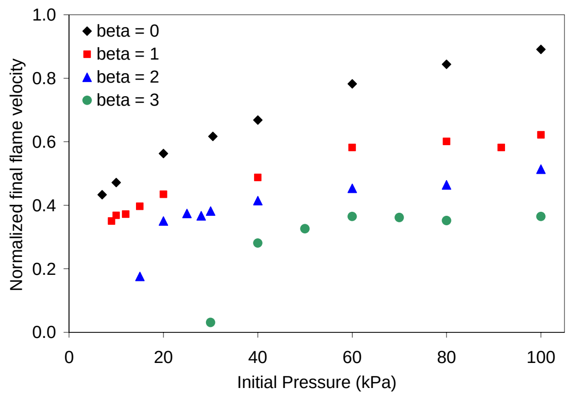

Figure 3. Final flame velocity in 12.7 mm beads

Plotted in Fig. 5 is the normalized peak pressure recorded at the endplate (P7). For the β=1 mixtures at an initial pressure of 50 kPa or above DDT occurs and a detonation wave reaches the endplate. As consequence the peak pressure recorded at P7 corresponds to roughly the reflected CJ detonation pressure. For initial pressures below 50 kPa, pressures significantly higher than the reflected CJ pressure are recorded. For these mixtures the shock propagating ahead of the flame reflects off the endplate, raising the pressure and temperature of the end gas. After a short induction time this gas explodes producing a detonation wave in the already pre-compressed gas. For the β= 0 mixtures DDT occurs for all initial pressures so the peak pressure is on the order of the reflected CJ detonation pressure. For the β= 2 mixture DDT does not occur so a shock wave reaches the end plate. For initial pressures of 40 kPa and less the end gas does not react whereas for initial pressures of 60 kPa and above there is reaction of the end gas producing reflected CJ magnitude pressures. For the β= 3 mixture the peak pressure corresponds to the reflection pressure of a weak shock with no end gas reaction.

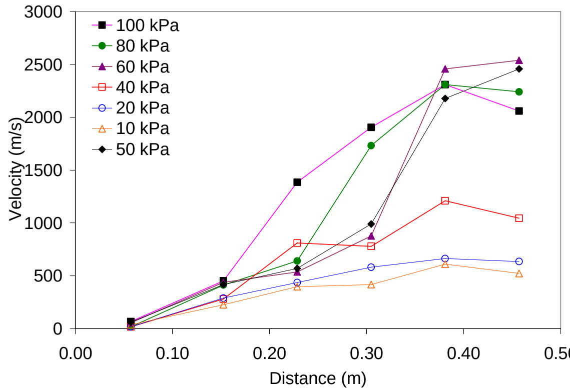

Figure 4. Flame velocity for β=1 orifice plates no beads

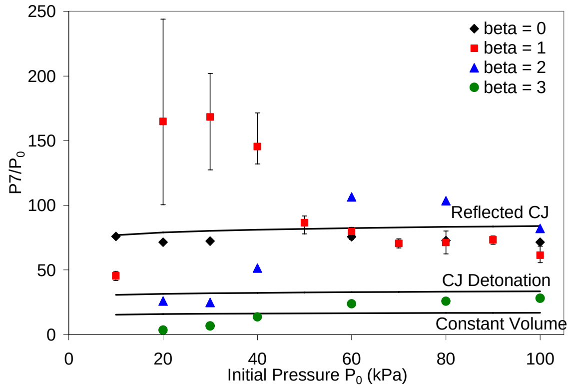

Figure 5. Peak end plate pressure no beads

Experiments were then performed with a 15 cm layer of beads at the bottom of the tube. As seen in Fig. 1, for this configuration P6 and P7 are located in the bead layer and P5 is 3.81 cm above the bead surface. Analysis of the P5 and P6 pressure transients provides information concerning the reflection and transmission characteristics of the interaction. The normalized peak pressures recorded for β=1 mixtures over the full range of initial pressures is provided in Fig. 6 for the 3 mm beads, and in Fig. 7 for the 12.7 mm beads. For the β=1 mixture, depending on the initial pressure, the combustion front incident on the bead layer, located 0.46 m from the ignition end, can either be a detonation wave or a shock flame complex (see Fig. 4). It is clear that the beads provide a buffer for the endplate as the peak pressure recorded at P7 with beads present is significantly lower than with no beads (see Fig. 5 for no bead values). This is especially true for the 3 mm beads where the peak P7 pressure is lowered to between the constant volume and CJ detonation pressure. For the larger porosity 12.7 mm bead layer the peak pressure recorded at P6 is significantly larger than that recorded for the 3 mm bead layer and.

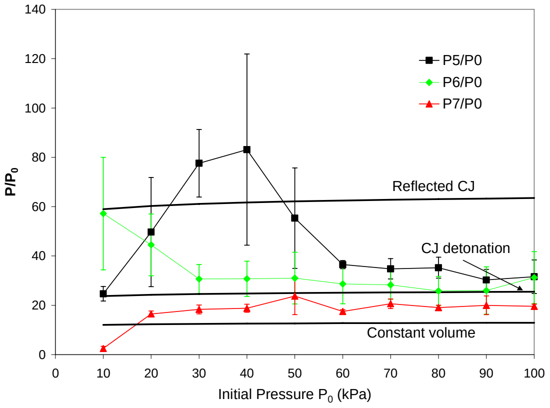

Figure 6. Normalized peak pressure for β=1 mixture for tube with 15 cm layer of 3 mm beads

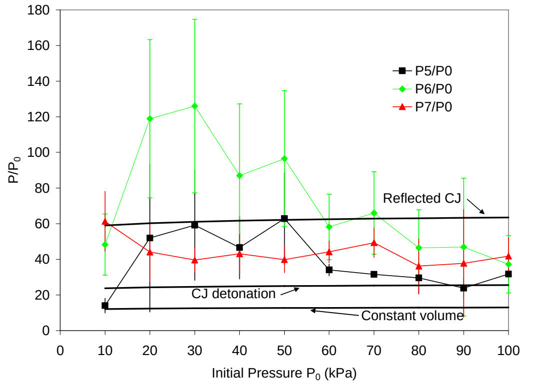

Figure 7 Normalized peak pressure for β=1 mixture for tube with 15 cm layer of 12.7 mm beads

the peak pressure recorded at P5 is slightly lower. This is because for the 3 mm beads for pressures below 50 kPa a detonation is initiated after the precursor shock reflects of the bead surface. Figure 8 shows the pressure traces recorded for a β=1 mixture at an initial pressure of 20 kPa. The P5 pressure transient indicates the passage of the inert shock that precedes the flame, followed by a large 2 MPa pressure spike propagating back through the products. This pressure front is associated with detonation initiation at the bead surface following shock reflection. For the more porous 12.7 mm bead layer the precursor shock is transmitted into the bead layer producing a convective flow in the bead. When the flame reaches the bead layer a large explosion occurs near P6 generating the pressures shown in Fig 6. A comparison of the peak P5 pressure for the different beads and a solid reflecting surface positioned at 0.46 m is provided in Fig. 9. The results indicate that the 3 mm bead surface produces a peak pressure at P5 closer to that of a solid surface compared to the 12.7 mm bead surface, which produces a much lower peak P5 pressure. The smaller 3 mm beads perform the best in terms of dampening the shock energy that is transmitted into the bead layer and onto the end plate and also produces a peak pressure ahead of the bead surface that is significantly smaller than the P7 end plate pressure when no beads are present.

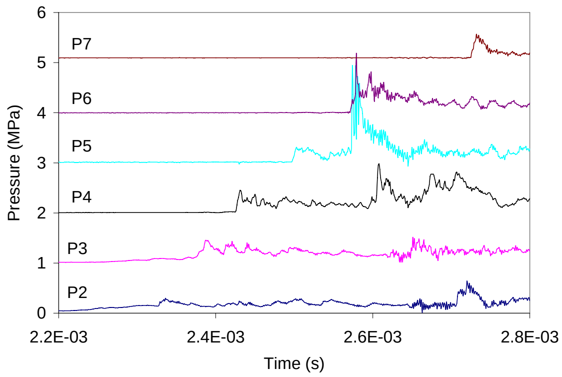

Figure 8. Pressure transients for β=1 mixture for tube with 15 cm layer of 3 mm beads

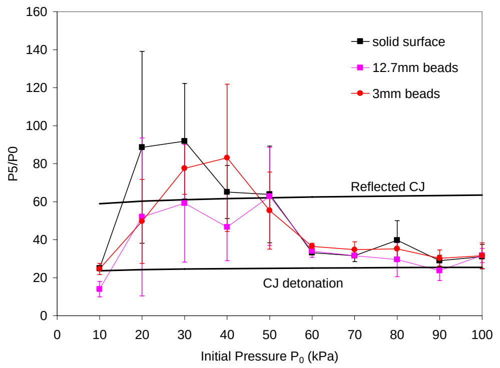

Figure 9. Normalized peak P5 for β=1 mixture for for tube with 15 cm layer of beads and solid surface

References

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