Detonation Initiation by Shock Reflection from an Orifice Plate

G. Ciccarelli and B. de Witt
Mechanical and Materials Engineering, Queen's University, Kingston, Canada

Corresponding author G. Ciccarelli: ciccarel@me.queensu.ca

Introduction

It is well known that a flame propagating in a duct filled with obstacles can accelerate to a velocity on the order of the speed of sound in the combustion products and if the conditions are appropriate deflagration-to-detonation transition (DDT) can occur [1]. In the late stages of flame acceleration, just before detonation initiation, the front consists of a leading shock wave followed by a turbulent flame brush. In an obstacle filled tube the primary mechanism for detonation initiation is shock reflection, predominantly off the upstream surface of the obstacle [2]. When a shock reflects off an obstacle with a transverse length smaller than the duct width, expansion waves originating at the obstacle edge traverse the obstacle upstream surface cooling the shock-heated gas thereby slowing the reaction rate and potentially preventing detonation initiation. Chan [2] found that the critical shock Mach number for detonation initiation due to shock reflection from an obstacle varies according to the transverse length of the obstacle. Thomas et al. [3] performed experiments looking at shock reflection induced detonation initiation and showed that initiation only occurs if the chemical induction time is shorter than the time it takes for the expansion waves to traverse the upstream surface of the obstacle. In both the Chan and Thomas investigations an ideal shock wave is generated via a shock tube arrangement. In a tube filled with obstacles a multitude of axial and transverse propagating shock waves exist ahead of the flame. The question is to what extent are the Chan and Thomas ideal shock-obstacle interactions representative of the more complex shock reflection process that occurs in an obstacle array. This paper reports on the investigation of detonation initiation by shock reflection off an obstacle where the shock wave is produced by an accelerating flame in an obstacle field. The shock wave is made to interact with a single obstacle and the critical mixture composition required for successful detonation initiation is found. Using this technique the non-ideal aspects of the shock front which exist ahead of the fast flame propagating in an obstacle field is preserved for the interaction with the obstacle.

Apparatus

Experiments were conducted in a 14.0 cm inner-diameter, 3.05 m long detonation tube. The first 1.36 meters of the tube is filled with orifice plates equally spaced at 15.2 cm followed by a sole "reflector" orifice plate. The length of the transition section between the last "flame acceleration" orifice plate and the reflector orifice plate is varied from 15.2 to 45.6 cm. The orifice plates used to accelerate the flame have a blockage ratio of 0.47 and two different reflector orifice plates were investigated with blockage ratios of 0.6 and 0.87. The blockage ratio (BR) is defined as the ratio of the cross-sectional area of the orifice plate and the tube internal cross-sectional area. A weak electric spark produced by a standard automotive inductive spark ignition system is used to ignite the mixture at the end of the tube. The flame time-of-arrival is measured using ionization probes. Piezoelectric pressure transducers with 1 μs response-time are used to measure the pressure-time history at axial locations within the transition section between the last flame acceleration and reflector plates. The pressure transducer data is also used to calculate the average shock velocity based on the shock time-of-arrival. Tests were performed in mixtures of stoichiometric ethylene-oxygen diluted with nitrogen at room temperature and pressure. Mixture reactivity was varied by changing the ratio of the number of moles of nitrogen to oxygen, defined as β, where β = 3.76 corresponds to air. The accuracy in the measurement of β is 0.05. For each test, the tube is evacuated to a pressure of less than 0.2 kPa. The mixture is prepared by the method of partial pressures within the tube and then circulated for 20 minutes to ensure composition homogeneity.

Results and Discussion

The flame velocity measured down the length of the tube with the 0.87 BR reflector orifice plate and transition section length of 45.6 cm is shown in Fig. 1 for different mixtures. The location of the flame acceleration orifice plates and the reflector orifice plate is denoted on the x-axis by hatch marks. Also shown in Fig. 1 is the average shock velocity measured just before the reflector orifice plate, denoted by solid symbols in the figure. This shock velocity is based on the time-of-arrival at the pressure transducers located at a distance of 1.63 m and 1.78 m from the ignition end. The shock velocity data is offset to the right in order to avoid superposition with the flame velocity data at the same axial location. The flame accelerates up to the last orifice plate at 1.36 m and then for mixtures with a β value of 4.0 or greater the flame velocity drops off very quickly in the smooth-walled transition section. The shock velocity just before the reflector orifice plate is slightly higher than the maximum flame velocity across the last accelerating orifice plate. For the β = 4.0 and 4.2 mixtures detonation initiation does not occur, a high speed flame forms after the reflector plate traveling at roughly the speed of sound in the combustion products. For the β = 3.8 mixture the flame velocity does not drop off in the transition section and remains relatively constant at a velocity of about 50 m/s slower than the shock velocity. For the β = 3.8 mixture a detonation is initiated as a result of the shock interaction with the reflector plate. For the β = 3.5 mixture DDT occurs within the transition section so the "flame" velocity and the shock velocity are identical just before the orifice plate.

The critical condition for detonation initiation was determined by varying the mixture composition and measuring the flame velocity along the tube. For mixtures with a value of β ≤ 3.6 DDT occurs before shock reflection, i.e., within the flame acceleration or transition section. A detonation is not initiated from the interaction of the shock wave and the reflector plate for mixtures with β ≥ 4.0. For mixtures with a β between 3.7 and 3.86 a detonation wave is initiated as a result of the shock interaction with the reflector plate. For these mixtures a detonation wave propagates down the length of the tube after the reflector plate. The tests were repeated with a 0.6 BR reflector orifice plate, with the same flame acceleration orifice plates and the same 45.6 cm transition section length. With this lower blockage orifice plate detonation initiation was observed for β < 3.89. This is the same critical mixture composition, to within the measurement accuracy, obtained for the 0.87 BR reflector orifice plate.

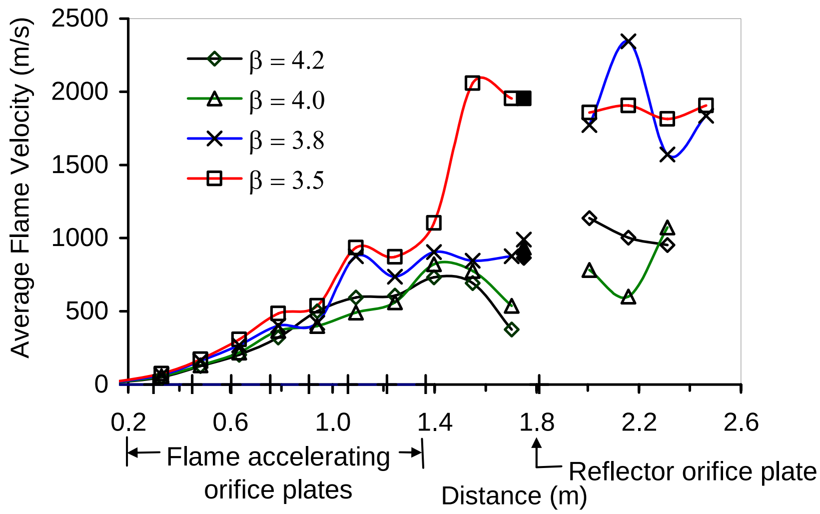
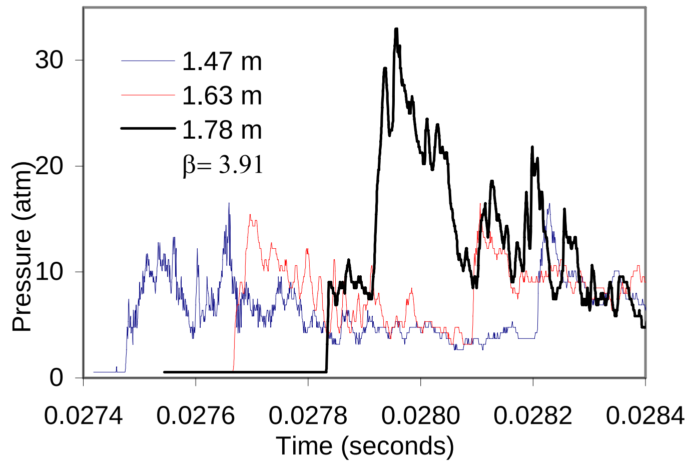
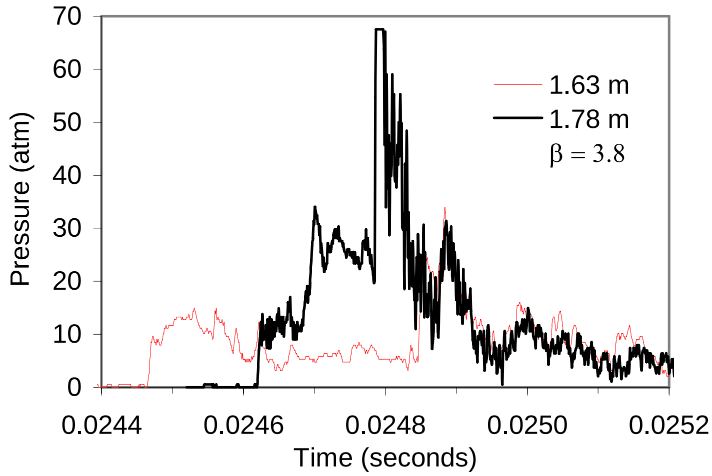


Figure 1. Flame velocity history for different mixtures

The shock wave development within the transition section can be seen in the pressure-time histories shown in Fig. 2. Three pressure time histories recorded in the transition section for a test with a 0.87 BR reflector orifice plate and β= 3.91 mixture are provided in Fig. 2a. These pressure signals are characteristic of tests not resulting in detonation initiation after shock reflection. The first pressure transducer location in the transition section is at 1.47 m for which the measured pressure time-history is representative of conditions that exists within the orifice plate array. The rise-time to the peak pressure is relatively slow (38 μs) and the signal has a high frequency component associated with a train of compression waves. The low frequency oscillation in the pressure signal after the initial rise is due to the reverberation of a transverse wave produced by the interaction of the shock front and the last few flame acceleration orifice plates. The time-of-arrival of the reflected shock wave from the reflector orifice plate is 1.15 ms after the initial pressure rise. The rise-time to the peak pressure progressively decreases in the next transducers, reaching a value of 2 μs for the last one at 1.78 m located just before the reflector plate. At 1.78 m the pressure signal is close to a step-type pressure time-history corresponding to a steady, planar shock wave produced via the shock tube method used by Thomas et al. [3]. The average post shock pressure measured at 1.78 m is roughly 10 atm which is consistent with the average velocity of 941 m/s based on the measured time-of-flight of 162 μs for the shock between 1.63 m and 1.78 m. The reflected shock wave with peak pressure roughly three times the incident shock pressure, arrives at the pressure transducer located at 1.78 m roughly 80 μs after the passage of the incident shock wave. The pressure time histories recorded at 1.63 m and 1.78 m characteristic of tests resulting in detonation initiation is given in Fig. 2b for a β = 3.8 mixture. The only difference from the pressure signals recorded for the β = 3.91 mixture shown in Fig. 2a is the large spike in pressure corresponding to the detonation wave arriving just after the reflected shock wave.



(a)



(b)

Figure 2. Pressure time histories for a (a) β = 3.91 and (b) β= 3.8 mixture

Additional experiments were performed with a transition section length of 30.5 cm and 15.2 cm with the 0.87 BR reflector plate. With the reflector plate moved closer to the last flame acceleration plate the shock front structure becomes less "ideal" and closer to the structure that exists in the flame acceleration section. The results from these tests are summarized in Fig. 3 along with the results obtained for the two blockage ratio reflector orifice plates with the 45.6 cm transition section length. The critical mixture β decreases from 3.86 to 3.57 as the transition section length is decreased from 45.6 cm to 15.2 cm.

As the shock front propagates in the transition section it strengthens as the train of compression waves coalesce, shock velocity measurements indicate an average increase of about 50 m/s over the last 30.5 cm of the transition section. There is a corresponding decrease in the chemical induction time for the reflected gas state which is more favourable for detonation initiation with respect to the quenching effect of the expansion waves across the reflector orifice plate face. The calculated reflected shock state chemical induction time for tests performed with a transition section length of 30.5 cm and 45.6 cm are shown in Fig. 4. The induction time is obtained via a transient, constant volume, combustion calculation using the Konnov [4] mechanism with the initial conditions taken to be the reflected shock state corresponding to the measured average shock velocity just before the reflector plate. The scatter in the induction time data is due to the variability in the strength of the shock wave produced as a result of flame acceleration for the same mixture. Note the induction time is very sensitive to the reflected shock temperature. A difference in the shock velocity of 50 m/s results in an order of magnitude difference in the induction time. The 30.5 cm transition section induction data is shifted to the left relative to the 45.6 cm data, thus the lower critical β is the direct result of a weaker shock wave at the end of the shorter transition section.

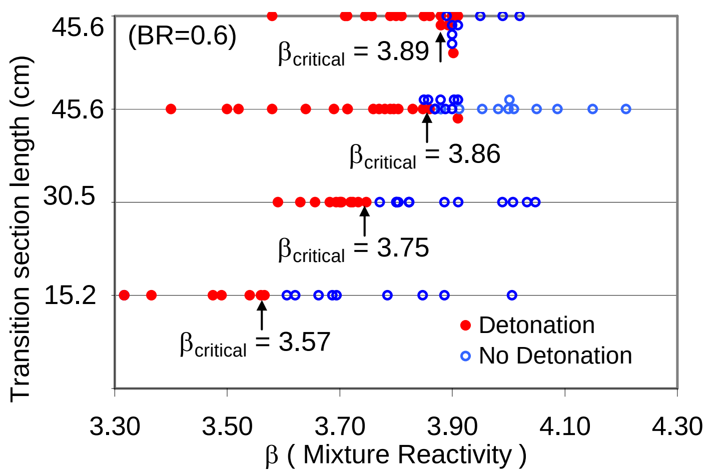


Figure 3. Critical mixtures for detonation initiation for BR= 0.87 reflector except where noted

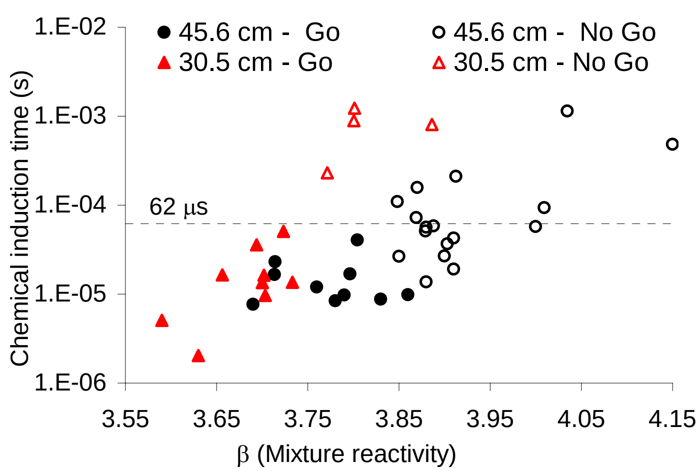


Figure 4. Calculated induction time based on reflected shock state for 0.87 BR reflector orifice plate, expansion time shown as dashed line

The characteristic expansion time for the reflected shocked gas upstream of the orifice plate can be calculated based on the width of the orifice plate divided by the local speed of sound. Over the β range of interest the reflected gas temperature does not vary much, so the expansion time is roughly constant. For the 0.87 BR reflector orifice plate the expansion time is 62 μs, shown as a dashed line in Fig. 4. It is evident from Fig. 4 that in general, detonation initiation occurs (solid symbols) in experiments where the induction time is less than the expansion time, thus corroborating the findings of Thomas et al. [3]. For the 15.2 cm transition section length the measured critical β of 3.57 corresponds to the DDT limit in the array and thus there is no detonation initiation at the reflector plate. This can be attributed to the very slow pressure rise time of 38 μs, see Fig 2a, relative to the 62 μs expansion time.

The calculated induction time for the 0.6 BR experiments is provided in Fig 5, the corresponding reflector plate expansion time is 33 μs. Experiments were performed with a transition section length of 45.6 cm. The critical mixture was found to be β= 3.89. From Fig. 5 the critical mixture calculated induction time is of the same order as the expansion time.

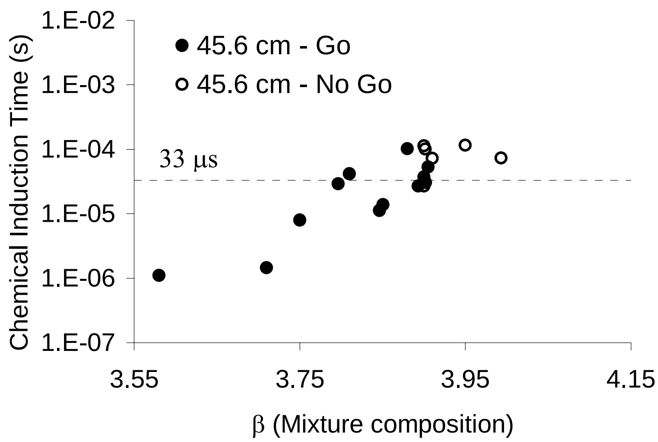


Figure 5. Calculated induction time based on reflected shock state for 0.6 BR reflector orifice plate, expansion time shown as dashed line

Conclusions

Flame acceleration in the orifice plate section resulted in the formation of a shock wave ahead of the flame that reflects off the reflector orifice plate. As the shock propagates in the transition section between the last flame acceleration orifice plate and the reflector orifice plate the sock pressure increases as the pressure rise time decreases. The critical mixture composition for detonation initiation due to shock reflection is found to be roughly the same for the 0.6 and 0.87 BR reflector orifice plates tested. It is shown that for a 30.5 cm and 45.6 cm long transition section, at the critical condition the reflected shock state induction time equals the time it take for an expansion wave to sweep across the orifice plate face. For the 15.2 cm long transition section shock reflection detonation initiation is not observed. It is hypothesized that initiation does not occur because the shock front is not fully developed, i.e., the shock front pressure rise time is on the order of the reflector plate expansion time.

Acknowledgments

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