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Effect of orifice plate spacing on detonation propagation

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ABSTRACT

Experiments were carried out to measure the detonation propagation limits in a 10 cm inner-diameter tube equipped with equally spaced orifice plates. The limits were established based on the successful transmission of a detonation wave from the obstacle-free first-half into the obstacle-filled second-half of the tube. The effect of the orifice plate spacing was studied for hydrogen, ethylene and acetylene-air mixtures at atmospheric pressure and temperature. Experiments were carried out with 63.5 mm and 76.2 mm diameter orifice plates, spaced at 1.5 and 2 times the tube inner-diameter. The results were compared to previously reported data obtained at a plate spacing equal to one-tube inner-diameter. By increasing the plate spacing the quasi-steady detonation velocity, measured at the end of the orifice plate filled section, approached the theoretical Chapman-Jouguet detonation velocity. The results show that for the 76.2 mm orifice plates, with 1.5 and 2 tube diameter spacing, the detonation propagation limits correspond to the condition $d/\lambda > 1$, where d is the orifice plate diameter and λ is the detonation cell width. The same correlation was found for the larger blockage 63.5 mm orifice plates with 1.5 and 2 tube diameter spacing. This is in contrast to previous results obtained by Cross and Ciccarelli (2015) for the same 63.5 mm orifice plates at one tube inner-diameter spacing that correlated the propagation limits with $d/\lambda > 2$. Large wave velocity fluctuations were observed for the two-diameter orifice plate spacing for mixtures near the propagation limits. These velocity fluctuations, measured by ion probes spaced at a distance larger than the orifice plate spacing, are indicative of a galloping detonation wave.

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1. Introduction

Industrial gas explosions typically involve the accidental release of a gaseous fuel into the atmosphere and the subsequent ignition leading to the generation of a compression wave. In the worst case scenario, the flame accelerates, as a result of flame-path obstructions, leading to deflagration-to-detonation (DDT). This produces shock overpressure up to 20 bar inside the fuel-air cloud, and a shock wave outside the cloud that decays in strength with propagation distance. A comprehensive investigation of flame acceleration and DDT in an obstacle laden geometry was performed by Peraldi et al. (1986). The geometry used in the study was a closed-ended round tube filled with equally spaced orifice plates with a weak spark ignition source at one end. Three different size tubes, with similar blockage ratio (BR) orifice plates (roughly 43%), were used. This geometry has subsequently been used by many investigators to study the influence of orifice plate blockage ratio (BR) (Kuznetsov et al., 2012), orifice plate spacing (Gu et al., 1988) and initial temperature (Ciccarelli et al., 1996) on flame acceleration and DDT.

If conditions are favorable, the flame can accelerate to a maximum quasi-steady velocity equal to the speed of sound of the combustion products (calculated based on an isobaric heat addition process). This so-called choked-flame can propagate at this velocity indefinitely, or transition to a combustion wave propagating at a velocity between the speed of sound of the combustion products and the Chapman-Jouguet (CJ) detonation velocity, commonly referred to as a quasi-detonation. The experiments performed by Peraldi et al. (1986) showed that the quasi-detonation propagation regime corresponds to the condition $d/\lambda \geq 1$, where d is the orifice plate diameter and λ is the detonation cell size. It has since been shown that the critical d/λ, at the DDT limits, increases from unity with increasing BR (Ciccarelli and Dorofeev, 2008). Dorofeev et al. [5] proposed a DDT criterion that takes into account the obstacle spacing, S, i.e., $L/\lambda > 7$ where L is a characteristic macroscopic length-scale. For a tube with inner-diameter, D, filled with orifice plates, the length-scale is defined by $L = 1/2(S + D)/(1 - d/D)$. Note, the first

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part of this expression represents the average size of the chamber enclosed by the tube wall and two adjacent orifice plates. The denominator takes into account the fact that experiments have shown that DDT occurs more readily for smaller blockages (larger *(1-d/D)*, yielding smaller *L*). Gu et al. (1988) performed DDT experiments in a 15 cm inner-diameter tube with 0.50 BR orifice plates spaced at one-half, one and two-tube diameters. For a plate spacing of one or two-diameters the DDT limit was found to follow the $d/\lambda = 1$ critical condition, while for the half-tube diameter spacing the value of d/λ was between 4 and 10, depending on the type of fuel.

In the classical obstacle-laden tube DDT experiment, as described above, flame acceleration leads to onset of DDT and then a detonation wave propagates through the rest of the channel. In such experiments the initial DDT event is required for the subsequent propagation of the detonation wave, and therefore the limits reported are for the initial DDT. There is no distinction made between the *DDT* and detonation *propagation* limits, as is also the case in a smooth tube. As discussed above, in the quasi-detonation regime a detonation wave repeatedly undergoes a cycle of detonation failure and re-initiation, which is responsible for the lower measured average velocity. Since the initial DDT results from the interaction of a fast-flame (shock-flame structure) with an obstacle, and detonation propagation (in the quasi-detonation regime) occurs through subsequent detonation initiations governed by the interaction of a decoupled detonation wave (consisting of a leading shock wave and trailing flame), there is no reason why the DDT and propagation limits should be the same.

Cross and Ciccarelli (2015a) performed experiments to measure the DDT and “detonation propagation limits” for hydrogen-air and ethylene-air. The DDT limits were measured in the traditional fashion, similar to those performed by Peraldi et al. (1986), the detonation propagation limits were measured based on the transmission of a CJ detonation wave from a smooth tube into an orifice plate filled tube of the same inner-diameter. The experiments were carried out with 0.44 BR orifice plates spaced at one-tube diameter. The results indicated that the DDT and propagation limits were similar and followed the criterion $d/\lambda > 1$ proposed by Peraldi et al. (1986). A follow-up set of experiments were carried out in the same tube with different BR orifice plates, with the same one-tube diameter plate spacing (Cross and Ciccarelli, 2015b). The results showed that both the DDT and propagation limits narrowed with increasing BR; for 0.75 BR orifice plates the propagation lean and rich limit for hydrogen-air correlated with $d/\lambda > 4$ and $d/\lambda > 6$, respectively. The results also showed that the DDT limits narrowed more than the propagation limits with increasing BR. This is an important finding since it shows that for larger BR plates the DDT limits do not characterize the ability of a steady detonation wave to propagate in a given geometry. In the current study, the effect of orifice plate spacing on the detonation propagation limit was investigated for hydrogen, ethylene and acetylene.

2. Experiments

Experiments were carried out in an apparatus consisting of a 6.1 m long, 100 mm inner-diameter tube. As shown in Fig. 1, the second half of the tube contained equally spaced 76.2 mm diameter orifice plates. The orifice plates spacing is maintained by four circumferential equally-spaced 12.7 mm outer-diameter and 9.5 mm inner-diameter tubes slid over 6 mm threaded rods that pass through all the orifice plates, see Cross and Ciccarelli (2015b) for details. The detonation wave was initiated at the end of the smooth tube via an oxygen-acetylene driver. The oxygen and acetylene is mixed during transport to the detonation tube. The tube is evacuated to below 0.5 kPa, the test gas mixture is introduced to roughly 95 kPa followed by loading of the driver gas mixture to a test pressure of 101 kPa. The initial temperature for all the tests is roughly 20 °C. Ignition of the driver gas is via a capacitive discharge spark across two electrodes. The average wave velocity was obtained from flame time-of-arrival measurements deduced from ionization probe signals. The ionization probes were distributed at a spacing of 0.610 m, except for the three at the end of the tube that were 0.305 m apart. The average velocity based on the last two ionization probes in the smooth tube section of the tube, were used to verify the existence of a steady CJ detonation wave before the orifice plates.

The test mixture was prepared by the method of partial pressures in a separate mixing chamber equipped with an air driven magnetic drive stirrer. The mixture constituents were added to the mixing chamber and mixed for 20 min. Gases were supplied from standard compressed gas cylinders. Mixtures of hydrogen-air and ethylene air were used in the tests.

3. Results

Experiments were carried out with two orifice plate sizes, 76.2 mm and 63.5 mm with various plate spacing.

3.1. Velocity data for 76.2 mm diameter orifice plates (BR = 0.44)

The velocity measured down the tube for two hydrogen-air mixtures (30% and 18% hydrogen) and for three orifice plate spacing is provided in Fig. 2. The data corresponding to one and one-half and two-tube diameters ($S = 1.5D$ and $S = 2D$) are new data and the $S = D$ spacing data is from Cross and Ciccarelli (2015a). The average velocity is measured based on the transit time between consecutive ion probes, the data point is assigned to a distance equal to the average distance from the spark. The calculated CJ detonation velocity for the two mixtures is shown for reference. The first data point ($x = 2.44$ m) represents the detonation velocity measured in the smooth part of the tube, just before the orifice plate section. The second velocity data point ($x = 3.05$ m) is based on the transit time between the ion probes 0.305 m before and after the first orifice plate and therefore has no significance. For all the tests, the detonation velocity measured before the first orifice plate is very close to the calculated CJ value. For the 30% hydrogen mixture (stoichiometric composition) tests the velocity drops slightly by about 10% after the detonation enters the orifice plate section (downstream of $x = 3.05$ m) and stabilizes to a quasi-steady velocity below the CJ value. For the 18% hydrogen mixture the velocity drops more dramatically upon entering the orifice plate section, stabilizing for the $S = D$ spacing and with some large wavelength velocity oscillations for the larger plate spacing.

The average velocity measured in this study for hydrogen-air mixtures over the last 0.61 m of the obstacle section is plotted in Fig. 3 for a $S = 1.5D$ and $S = 2D$ spacing. The average is based on the last two velocity measurements, obtained from the last three the ion probes that are 0.305 m apart. Also shown for comparison, is the $S = D$ spacing data reported by Cross and Ciccarelli (2015a), where the average is also based on the last two velocity measurements. The error bars represent the maximum and minimum measured velocity.

The measured average velocity approaches the theoretical CJ detonation velocity with increased obstacle spacing, i.e., the detonation velocity deficit decreases with increased orifice plate spacing. This trend was also observed by Gu et al. (1988) in DDT experiments performed in an orifice plate filled tube. For 30% hydrogen-air and $S = 2D$ plate spacing, the detonation velocity at the end of the tube is 6% below the CJ detonation velocity. The detonation velocity deficit at the end of the smooth part of the tube, just before the orifice plate section, was 1%. Therefore, even for the

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