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Visualization of detonation propagation in a round tube equipped with repeating orifice plates

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ABSTRACT

Self-luminous, high-speed photography was used to visualize fast-flame and detonation propagation through a transparent round tube equipped with repeating orifice plates, in stoichiometric hydrogen-oxygen mixtures at initial pressures up to 60 kPa. Experiments were conducted in a 1.55 m, 7.6 cm inner-diameter plastic tube filled with equally spaced 5.33 cm and 3.81 cm orifice plates (50% and 75% area blockage ratio, respectively). The unprecedented visualization of quasi-detonation propagation in a round tube was used to identify the propagation mechanisms. For both sets of orifice plates, fast-flames were observed below a critical initial pressure. Fast-flame propagation involved the interaction of an uncoupled shock wave and flame with the orifice plates. Detonation propagation involved repeated detonation failure and initiation along the channel length; the limits measured in the 50% and 75% blockage ratio (BR) orifice plates were 7 kPa and 40 kPa, respectively. The orifice diameter-to-detonation cell size ratio (d/λ) corresponding to these limits are 1.4 and 14, respectively. It is proposed that the significant variance in the d/λ at the two limits is attributable to the difference in the detonation propagation mechanism. For the 50% BR orifice plates, near the limit, detonation initiation occurred on the tube wall between orifice plates following reflection of the lead shock wave. Whereas, for the 75% BR orifice plates, detonation initiation at the tube wall was not possible for initial pressures up to 40 kPa. This is the result of a weaker shock wave at the time of reflection due primarily to the larger distance from the orifice edge to the tube wall. Steady propagation of a curved detonation wave was observed for the 50% BR orifice plates for an initial pressure of 50 kPa ($d/\lambda = 25$), or greater; a similar propagation was not observed in the 75% BR orifice plates at initial pressures up to 60 kPa ($d/\lambda = 27$). Numerical simulations carried out using a single-step reaction model demonstrated the key processes involved in detonation initiation at the tube wall and the orifice plate but could not predict quantitatively the critical initial pressure required for detonation propagation measured in the experiments.

1. Introduction

Explosions have plagued the petrochemical industry for decades, with extremely large plant-scale explosions occurring periodically. A desire to understand how these catastrophic events occur in order to prevent them has been the driving force behind the study of deflagrations and detonations. The primary distinction between these two steady combustion waves is how they propagate: detonation waves propagate supersonically, where chemical reaction is initiated by adiabatic shock heating; subsonic deflagrations propagate via the diffusion of mass and heat. Due to the large amount of energy required to directly initiate a detonation wave, detonations usually develop from a deflagration [1]. With the presence of turbulence generating obstacles, a deflagration can accelerate, and under certain conditions, a deflagration-to-detonation transition (DDT) can occur. Flame acceleration is the mechanism by which an industrial explosion develops from a weak ignition source. It is rare, but possible that an industrial explosion can culminate in a detonation wave. In recent years, the study of detonations has evolved past its origins in industrial safety. In attempts to harness the nearly constant volume process efficiency of detonations for propulsion purposes, Pulse Detonation Engines (PDEs) use controlled detonations to generate thrust [2].

Detonation propagation and DDT have been studied extensively in round tubes equipped with repeating orifice plates since the first flame acceleration study conducted by Chapman and Wheeler in 1927 [3]. These experiments have primarily been conducted in opaque metal tubes using non-optical diagnostic techniques [4-6]. Peraldi et al. performed a comprehensive study using various fuels in different diameter tubes and with different blockage ratio

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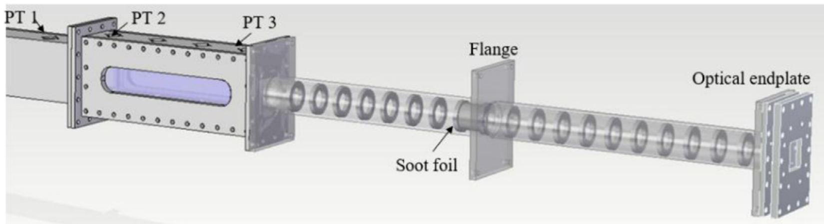

Fig. 1. Schematic showing the last two sections of the square channel and the acrylic round tube equipped with orifice plates and the optically accessible endplate.

(BR) orifice plates [7]. In this set-up, steady-state propagation was classified according to the average combustion front velocity derived from time-of-arrival measurements taken at regular intervals along the tube. Specifically, the steady propagation regimes were classified as slow-flame, fast-flame and quasi-detonation; where fast-flames typically propagate at a velocity just below the combustion products speed of sound and quasi-detonation waves propagate between this velocity and the CJ detonation velocity. Peraldi et al. proposed a DDT limit criterion that the orifice diameter, *d*, must accommodate at least one detonation cell, where the cell size is given by λ. It has since been established that for higher blockage ratio orifice plates (BR greater than 50%) the DDT limit is typically significantly larger than $d/\lambda = 1$ [8]. Although the data obtained from steel tubes is very important for classifying propagation modes and establishing correlations for the fast-flame and detonation limits, such experiments produce no information concerning the propagation mechanism. Various visualization studies [9–13] have been undertaken using schlieren photography through glass windows in rectangular channels equipped with repeating obstacles to elucidate the propagation mechanism. More recently, soot foils, normally used in unobstructed tubes to record detonation cellular structure, have been installed between orifice plates in round tubes to gain further understanding of detonation propagation [14]. The soot foils revealed that quasi-detonation propagation occurs through a sequence of detonation failure (through the orifice plate) followed by re-initiation before the next orifice plate. Based on the unique soot foil tracks obtained, the investigators speculated that re-initiation took place at the tube wall, at “hot-spots” produced by the reflection of the decoupled detonation shock wave.

High-speed photography has been paramount in establishing the propagation mechanism in rectangular channels, however, schlieren photography cannot be used in a round tube as the curvature of the tube distorts the collimated light. The inapplicability of schlieren, and the complex nature of the combustion, has prevented the use of high-speed photography in round tubes with orifice plates. The exception is in studies using “self-luminous streak photography” (where a narrow slit along the window is used to track the light produced at the combustion front) to obtain detailed velocity measurements, e.g., [15]; however, this approach yielded no insight into the structure of the combustion front. The primary objective of the present research is to use self-luminous high-speed photography to directly visualize detonation propagation in a transparent round tube equipped with repeating orifice plates to determine the propagation mechanism(s). A secondary objective is to compare the effect of the channel cross-section geometry (square versus round) on detonation propagation via a single apparatus.

2. Experimental setup

An optically clear cylindrical channel was connected to a square cross-section combustion channel, as shown in Fig. 1. Premixed stoichiometric hydrogen-oxygen mixtures (prepared by the method of partial pressure in a mixing chamber) were loaded into the combustion channel and ignited at the end of the square channel. Equally spaced fence-type obstacles in the square channel, and orifice plates in the round tube, were used to promote flame acceleration. Two sets of orifice plates were used to study the effect of BR and orifice diameter. The 50% BR orifice plates maintained the same blockage ratio as the square channel, while the 75% BR orifice plates had the same obstacle opening size as the square channel. The average combustion front velocity in the round tube was measured by tracking the combustion front using high-speed video. In the square channel, this velocity was obtained using the shock time-of-arrival at two fast-response piezoelectric pressure transducers (PT 2 and PT 3 in Fig. 1). Two synchronized high-speed cameras were used to observe detonation propagation in the round tube, and in certain experiments soot foils were installed at the end of the cylindrical channel.

The combustion channel consists of three sections: a 3.16 m long aluminum square channel, a 1.55 m long plastic cylindrical channel and an aluminum square cross-section dump tank. For some low pressure tests the dump tank was removed and replaced with an optically accessible endplate, see Fig. 1. The square channel consists of four 61 cm long modular sections and one 63.5 cm long optical section (not used for photography in this study), with a continuous 7.62 cm square interior cross-section. Aluminum fence-type obstacles were installed on the top and bottom of the square channel. The 1.3 cm thick, 1.9 cm high obstacles (BR = 50%) were spaced one channel width apart. The cylindrical channel was composed of two 10.2 cm outer-diameter (OD) segments: a 69 cm long acrylic tube and an 80 cm polycarbonate tube.

Nineteen orifice plates were installed in the cylindrical channel, equally spaced, one-tube diameter apart. A set of optically clear acrylic orifice plates and a set of 6061-Aluminum plates were made for each blockage ratio. The 50% and 75% BR orifice plates had 5.33 cm and 3.81 cm inner-diameters (ID), respectively. The acrylic orifice plates were used with the optical end-flange to allow end-view video to be obtained. The separation distance between orifice plates was maintained by optically clear acrylic spacers that fit tightly into the main tube. The spacers made the inner-diameter of the tube 7.62 cm, equal to the square channel cross-sectional width.

Three model 113A24 PCB piezoelectric pressure transducers were installed in the square channel. The pressure transducers were mounted flush to the inner-surface of the channel and were located 1.73 m, 1.99 m, and 2.45 m from the ignition end of the channel. The first transducer was used to trigger the data acquisition system and camera, and the other two pressure transducers were used to calculate the combustion front velocity in the last segment of the square channel.

Most tests were completed using a 500 mJ automotive capacitive discharge system to ignite the mixtures. A Bosch automotive glow plug (model 0 250 202,127) was used for tests with initial pressures below 7.5 kPa, as the spark plug would not ignite mixtures at these pressures. Two high-speed CMOS cameras were used to obtain self-luminous images: a Photron SA-Z was