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Advancements on the propagation mechanism of a detonation wave in an obstructed channel

Mark Kellenberger*, Gaby Ciccarelli

Department of Mechanical and Materials Engineering, Queen's University, Kingston, Ontario K7L 3N6, Canada

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ABSTRACT

Utilising a recently developed technique, involving high-speed schlieren photography shot through a soot-coated glass sheet, new details of the propagation of combustion waves in obstructed channels have been revealed. In this study, a channel equipped with 50% blockage ratio obstacles was used to examine the repeated detonation initiation and failure processes responsible for the large CJ detonation velocity deficits observed in the quasi-detonation regime. Using a combination of simultaneous schlieren images, soot foil records, and average velocity measurements, experiments were carried out in mixtures of stoichiometric hydrogen–oxygen at initial pressures between 9 kPa and 30 kPa in a 3.66 m long, 7.62 cm by 2.54 cm rectangular cross-section channel. Results indicate continuous detonation propagation through the core of the channel for sufficiently reactive mixtures, while fast-flame propagation occurred for weaker mixtures which do not exhibit detonation initiation at the obstacle face. Two unique propagation modes, one symmetrical and one asymmetrical about the channel centreline, were found to occur at the DDT limit that resulted in average combustion wave velocities between that of the fast-flame and product speed of sound. Local detonation initiation at the obstacle face, following shock reflection, was found to be governed by both the incident shock strength and the distance between the lead shock and trailing flame. For sufficient shock strength and shock-flame spacing, the resulting detonation waves produce a shock interaction at the channel centreline that results in the formation of an axially propagating over-driven detonation that decays in strength with distance. For these quasi-detonations, the average wave velocity over many obstacles is governed by the frequency of these detonation initiation events. These centreline detonation initiation events were typically symmetrical across the channel width, producing a bell-shaped cellular region on the soot foil. However, asymmetrical detonation initiation events, originating at one sidewall, were also observed that produced a narrow vertical band of fine cells resulting from the head-on collision of the detonation wave propagating transversely through the compressed gas region between the lead shock and flame.

1. Introduction

Understanding the mechanism of flame propagation in a channel equipped with obstacles is important for predicting the evolution of a gas explosion in a congested volume. Flame acceleration in an obstacle laden channel can lead to quasi-steady propagation modes. Of interest is the determination of the propagation mechanism of a fast-flame and detonation wave [1], as well as the development of a criterion that can be used to predict the transition from one mode to the other. Many processes in the chemical industry require the use of combustible gases, making the understanding of how they behave when ignited important in the design of facilities where they are used to ensure property and personnel safety. Some of the earliest work on this dates back to Mallard and Le Chatelier [2], who studied the problem of explosions in mines and described the spontaneous transition from deflagration to detonation. Chapman and Wheeler [3] pioneered the study of flame acceleration and deflagration-to-detonation transition (DDT) in tubes containing obstacles. Later, Shchelkin [4] noted detonation speeds as low as 30% [5] of the Chapman and Jouguet (CJ) detonation wave speed in a tube equipped with a spiral-shaped obstacle [6,7]. Detonations of this nature in obstructed channels (exhibiting large CJ detonation velocity deficits) are referred to as quasi-detonations [8].

Following the Three Mile Island nuclear accident, interest in the potential of hydrogen explosions at nuclear facilities lead to studies investigating flame acceleration and DDT of hydrogen mixtures in obstructed geometries. The majority of these tests adopted a

* Corresponding author.
E-mail address: mark.kellenberger@queensu.ca (M. Kellenberger).

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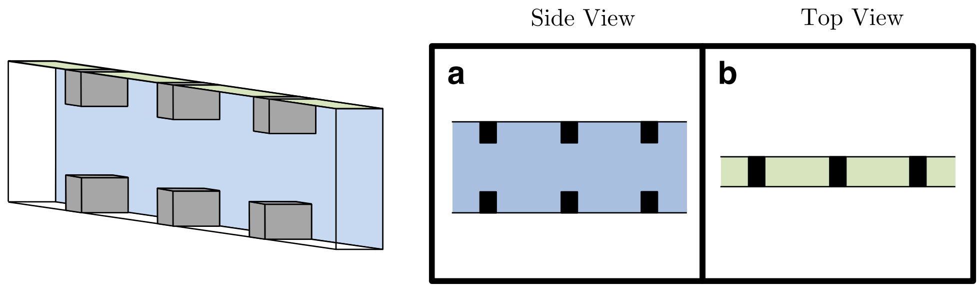

Fig. 1. Schematic showing the simultaneous high-speed schlieren video views and soot foil orientations for the combustion channel setup used in this study. (For interpretation of the references to colour in this figure, the reader is referred to the web version of this article).

repeating orifice plate obstruction field of varying obstacle spacings and orifice diameters. A comprehensive study undertaken by Peraldi et al. in such a geometry proposed a basic criterion that the minimum obstacle opening d must be as large as the detonation cell size λ for a detonation wave to propagate [9]. This criterion has been shown to be applicable for low blockage obstacles (on the order of 40%) but is very conservative for high blockage obstacles where the DDT limit can be as high as $d/\lambda = 7$ [10,11]. Results of these studies are based on average velocity measurements, using time-of-arrival instrumentation, over several obstacle spacings and thus do not give detailed information regarding the mechanism responsible for the onset of detonation. Recently, Rainsford and Ciccarelli [12] obtained self-luminous high-speed video of quasi-detonation propagation in a clear acrylic tube equipped with repeating orifice plates and identified several different detonation propagation mechanisms. Unfortunately, the use of a round tube does not allow for schlieren visualisation of shock waves.

A rectangular channel geometry (with flat windows) allows for an optically accessible channel for high-speed schlieren video, providing unprecedented access to the combustion phenomena (including shock waves and reaction zones) involved in the fast-flame and quasi-detonation regimes. Rectangular channels employ the use of fence-type, two-dimensional obstacles. Urtiew and Oppenheim [13] first used a stroboscopic laser schlieren system to visualise the DDT process in an unobstructed rectangular channel. The earliest study using high-speed schlieren, recorded with a film-based drum camera, in a channel equipped with obstacles was performed by Teodorcyk et al. [14,15]. They showed that propagation in the quasi-detonation mode is characterised by repeated detonation initiation (following shock reflection off the obstacle upstream surface and channel walls) and detonation failure cycles, leading to a sub-CJ average velocity. Kellenberger and Ciccarelli [16] revealed that quasi-detonation propagation is governed by the shock-obstacle interaction. In these experiments, high-speed schlieren was used to measure the explosion front velocity in a 7.6 cm tall by 2.5 cm wide channel equipped with equally spaced fence-type obstacles mounted on the top and bottom channel walls. The average steady-state centreline velocity for stoichiometric hydrogen–oxygen at an initial pressure in the range of 8–30 kPa was obtained. Based on the average centreline shock velocity, and the details of the shock/flame (and detonation) interaction with the obstacles, five propagation modes were identified. The main differentiators between modes was whether ignition occurred at the obstacle face following shock reflection, and whether a detonation was initiated at the centreline of the channel following collision of the transverse shock waves produced by the local explosions at the top and bottom obstacles. The resolution of the schlieren images were not sufficient to identify the nature of the “local explosion” initiated at the obstacle face and at the channel centreline.

Recently, high-speed schlieren systems have been used in combination with soot foils to investigate DDT in obstructed channels [17–19]. The soot foil technique is typically used to record the detonation wave cellular structure that consists of a “fish-scale” pattern of lines corresponding to the trajectories of the detonation front triple-points. This provides information that cannot be obtained from schlieren video alone, however until recently direct coupling of shock structures captured on video and triple-point tracks recorded on soot foils during detonation initiation was not possible. A simultaneous schlieren and soot foil technique [20] has recently been demonstrated by the authors that enables schlieren imaging through a sooted glass sheet. This technique directly couples shock waves captured on video to soot foil tracks, overcomes line-of-site integration limitations of conventional schlieren, and enables incandescing of soot lofted from the foil to act as a tracking medium for flames and hot spots.

The objective of this study is to obtain new details on the propagation mechanisms of a quasi-detonation wave by extending the knowledge gained in previous studies through the use of a simultaneous soot foil and schlieren photography technique.

2. Experimental

To determine the behaviour of the supersonic combustion waves in the present study, experiments were conducted in a 7.62 cm tall, 3.66 m long channel consisting of five equal length sections. The width of the channel was 2.54 cm, giving the cross-section a narrow rectangular shape. The entire length of the channel was equipped with 0.5 blockage ratio (BR) fence-type obstacles along the top and bottom channel walls, spaced one channel height apart and extending across the entire channel width. The channel was equipped with an optical section, beginning 2.46 m from the point of ignition, to allow access for schlieren photography at up to 175,000 frames per second (fps) with a Photron SA5 high-speed camera through 3.18 cm thick, 44.4 cm by 7.62 cm acrylic windows. The single-pass schlieren setup consisted of a 35 W xenon arc lamp light source and two 25.4 cm diameter $f/12$ parabolic mirrors. The unique design of the combustion channel permitted a top-down view, as well as a conventional side-view, enabling complex three-dimensional wave behaviours to be deciphered. The camera views used in this study are shown schematically in Fig. 1. In addition to the schlieren visualisation, a simultaneous soot foil technique was employed to obtain a physical record of combustion wave propagation on the channel wall. This was accomplished by lightly sooting a 2.2 mm thick sheet of glass above a kerosene lamp and placing it on the inside of the acrylic window. Details of the simultaneous schlieren and the glass soot foil technique can be found in Kellenberger and Ciccarelli [20]. Some tests included soot-foils (including using aluminium substrate) on multiple channel walls to help determine the three-dimensional behaviour of combustion wave propagation. High-speed piezoelectric pressure transducers (PCB 113A24) were flush-mounted along the top wall 30.48 cm apart, capturing pressure-time histories at 3 MHz in the channel optical section. Stoichiometric hydrogen–oxygen mixtures were used in all tests at an initial temperature of