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Combustion wave propagation through a bank of cross-flow cylinders

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ABSTRACT

Combustion wave propagation through a bank of 12.7 mm diameter cylinders is investigated in a 76.2 mm tall, 25.4 mm wide channel using high-speed schlieren photography. Two cylinder geometries ("staggered" and "inline") were tested with 50% channel area blockage. The staggered geometry was also tested with 67% blockage. Tests were carried out with hydrogen–air at atmospheric pressure. Flame propagation is highlighted by an initial flame acceleration phase driven by turbulent burning in the cylinder wakes. This is followed by quasi-steady flame propagation characterized by shock-flame interactions. Flame acceleration measured in the staggered and inline cylinder geometry, for the same blockage, was found to be similar despite the different flame pathways. In the fast-flame regime, the quasi-steady flame velocity was also found to be very similar. In the composition range where detonation initiation and failure was observed, often referred to as the quasi-detonation regime, the average velocity was significantly higher in the staggered cylinder geometry due to the higher frequency of detonation initiation.

1. Introduction

Flame acceleration in a duct with flow-path obstructions has been studied for many years in the context of industrial explosions [1] and recently in connection with the design and operation of pulse detonation engines [2,3]. Traditionally these studies are carried out in tubes equipped with equally spaced orifice plates [4–6], or rectangular channels with fence-type obstacles on the top and bottom surfaces [7–9]. These geometries are convenient for controlling the flow perturbations by varying the obstruction blockage area and spacing. Following weak ignition at one end of the channel the flame accelerates and eventually reaches a quasi-steady velocity, typically measured across several consecutive obstacles. The following propagation regimes have been identified based on the final average front velocity: low-speed turbulent deflagration, high-speed turbulent deflagration, quasi-detonation and Chapman-Jouguet (CJ) detonation regimes [5]. A slow-speed deflagration propagates at a subsonic (relative to the reactants) velocity, typically below 200 m/s; high-speed deflagrations propagate at a velocity just below the combustion products sonic velocity; quasi-detonations propagate at a velocity between the combustion products speed of sound and the CJ detonation velocity. Dorofeev et al. proposed that the transition from the slow to high-speed deflagration regimes is governed primarily by the density ratio across the flame [6,10]. Transition from high-speed deflagration to quasi-detonation occurs when the orifice opening diameter, d, is greater than the detonation cell size, λ (i.e., $d/\lambda \geqslant 1$) [5,11], or the gap between the fence-type obstacle pair (core flow area height) is larger than the cell size [12]. Another DDT criterion was proposed by Dorofeev et al. [13] that uses the geometric length-scale L that takes into account the obstacle opening and spacing, $L/\lambda \geqslant 7$. For a tube of inner-diameter D, with orifice plates spaced at S, the length-scale $L = ½(S + D)/(1 - (d/D))$. The numerator represents the average length-scale of the volume between obstacle and the denominator represents the obstacle area blockage ratio for a rectangular cross-section channel with obstacles. Finally, transition from the quasi-detonation regime to the CJ detonation regime occurs when the obstacle minimum transverse opening size is an order of magnitude larger than the mixture cell size. This is equivalent to the critical tube diameter criterion, that can be interpreted as the limit where detonation propagation is unaffected by the degree of lateral confinement [14].

A round tube equipped with orifice plates represents a geometry that is very conducive to flame acceleration but is not representative of industrial piping configurations. A more prototypical geometry involves a bank (or matrix) of cylinders, typical of piping in a chemical processing plant. An idealization of such a geometry is shown schematically in Fig. 1. Ogawa et al. [15] simulated flame acceleration and DDT in an unconfined (open-sided) obstructed space similar to that shown in Fig. 1, with ignition at the bottom left corner. The two-dimensional, compressible, Navier–Stokes

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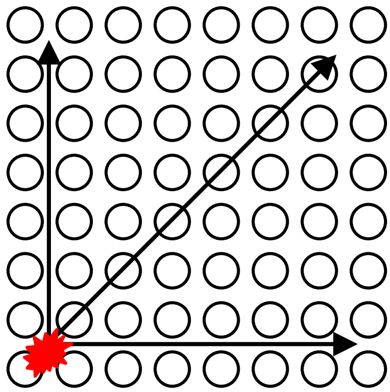

Fig. 1. Schematic showing flame propagation direction in a space filled with a matrix of cylinders.

equations were solved along with a one-step Arrhenius reaction model. Ogawa et al. found that flame propagation depended on the direction of propagation within the matrix of cylinders. These results showed that initially the flame propagated faster in the horizontal and vertical directions compared to along the diagonal direction. It was posited these results were found because the horizontal and vertical directions provide an unobstructed flow path since the cylinders are in line, whereas propagation along the diagonal direction (staggered cylinder geometry) presents a more obstructed path with no line-of-sight open path for the flame. The simulation also showed that once compression waves form ahead of the flame, flame acceleration was more rapid in the diagonal direction due to the interaction of the reflected waves and the trailing turbulent flame. Additionally, it was found that DDT always occurred in the direction with more obstruction.

Experimentally, it is more convenient to study flame propagation phenomenon in a confined geometry where the flame front can be considered roughly planar. In order to capture the differences between flame propagation in the horizontal and diagonal directions in the unconfined geometry shown in Fig. 1, confined experiments can be carried out with "staggered" and "inline" cylinder geometries, as shown in Fig. 2a and c, respectively. Chao and Lee performed experiments in a 300 mm square cross-section channel with staggered 3.4 cm diameter cylinders where the final steady combustion front velocity was reported [16]. Steady-state propagation regimes were found to be slightly different from those observed in a circular tube equipped with an array of orifice plates with the same blockage ratio. Large flame velocity oscillations were observed that did not correspond to the frequency associated with the cylinder spacing.

In the present study, flame acceleration in a channel equipped with a matrix of cylinders is studied. The effect of the cylinder pattern and the cylinder spacing on the rate of flame acceleration and the final steady velocity is investigated. Schlieren photography is used to capture the evolving combustion front structure and to measure the flame and shock velocity. The scale is not prototypical of a congested industrial piping environment; however the flame propagation mechanism is expected to be similar. The results obtained from the experiments can be used for the validation of computational codes that are used to simulate large-scale explosions. Consideration must be taken for phenomena that are influenced by the smaller scale of the experiment, e.g., in the experiment the flame and detonation wave thickness is closer to the cylinder gap spacing, and flame instabilities could be suppressed due to the small gap spacing. The phenomenon observed in the experiment can also be considered a two-dimensional representation of explosion front propagation through a porous medium [17].

2. Experimental

Experiments were performed in a 25.4 mm wide and 76.4 mm high cross-section channel. The channel consists of three 610 mm long modules. For all the experiments, the last module, farthest away from the ignition point, was empty in order to guard against the endplate reflected shock wave influencing flame acceleration in the first two modules that were equipped with cross-flow cylinders. The optical module, shown in Fig. 3, is equipped with acrylic windows on the front and back sides to permit schlieren photography. The window's horizontal field-of-view is 435 mm long and provides a full view of the channel height. The three setups investigated included two staggered tube geometries with BR = 0.67 and 0.5, as well as an inline tube geometry with BR = 0.5, shown schematically in Fig. 2. Blind holes (12.7 mm diameter and 12.7 mm deep) were drilled into both acrylic windows corresponding to the cylinder patterns in Fig. 2. The 12.7 mm diameter cylinders spanned the channel width and were held in place by insertion into the window blind holes on either end. A single-pass schlieren system is used for visualization, where high-speed video was taken using a Photron S-5 camera operated at 70,000 frames per second. The diameter of the parabolic mirrors permits a video field-of-view of 254 mm diameter, roughly equal to half the window length. An automotive spark ignition system was used to ignite the mixture at one end of the channel. In order to observe the initial flame propagation, the spark plug was advanced past the edge of the window. In this arrangement, the spark plug was mounted at the end of a block that extended back

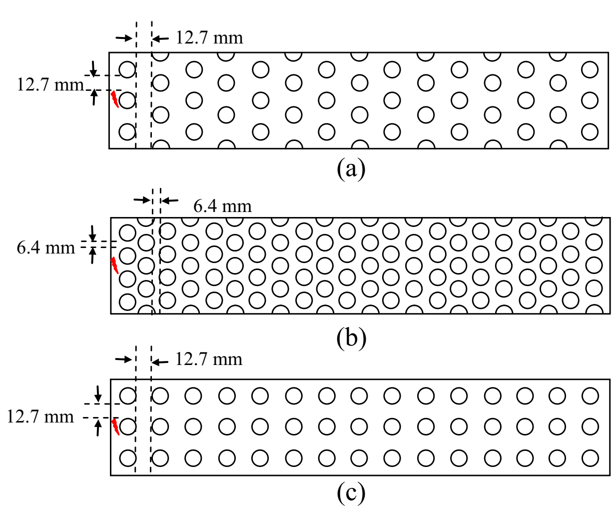

Fig. 2. Schematic of the 12.7 mm diameter cylinder patterns used in the tests; (a) staggered 0.5 BR, (b) staggered 0.67 BR, and (c) inline 0.5 BR.

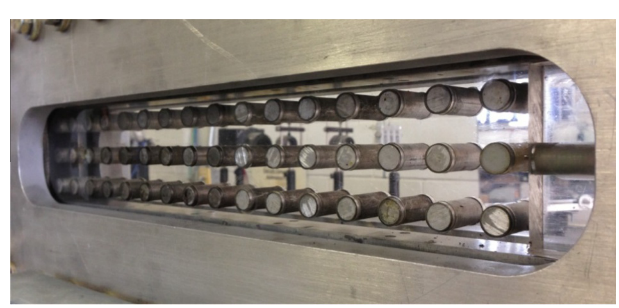

Fig. 3. Photograph of optical channel equipped with 12.7 mm diameter inline cylinders.

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