Detonation Propagation in a Linear Channel with Discrete Injectors and Side Relief

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1 Introduction

The potential thermodynamic gains associated with pressure gain combustion cycles have resulted in a steady rise in interest in combustors like the pulse detonation engine (PDE) and rotating detonation engine (RDE) [1-3]. While the PDE operates in a manner that requires multiple ignition events and transitions of deflagrations to detonations, the RDE is the realization of a continuously propagating detonation about the circumference of an annular channel [1]. Reactants are supplied axially into the annular channel and continuously refresh the azimuthally propagating detonation structure [2]. It may also be possible to develop more practical engine designs by integrating an aerospike nozzle with the annular shape of an RDE combustor, thus substantially reducing the thruster weight and length [4].

A number of experimental and computational studies have helped to shape the understanding of RDE operation. Voitsekhovskii (1959) reported an experimental facility similar to the modern RDE for studying the propagation of a detonation wave [5]. Also, Sommers & Morrison (1962), Dabora et al. (1965), and Sichel & Foster (1979) examined the propagation of a detonation wave in a thin layer of reactive gas bound by an inert gas [6-8]. More recent numerical studies on the RDE have produced more insightful visualizations of the RDE flowfield [9], and have influenced subsequent approaches that quantify the global thermodynamic efficiency of the RDE cycle [10]. A host of recent investigations have sought to improve RDE understanding in ways that range from providing insight into flow physics, to integration for flight applications [11-13].

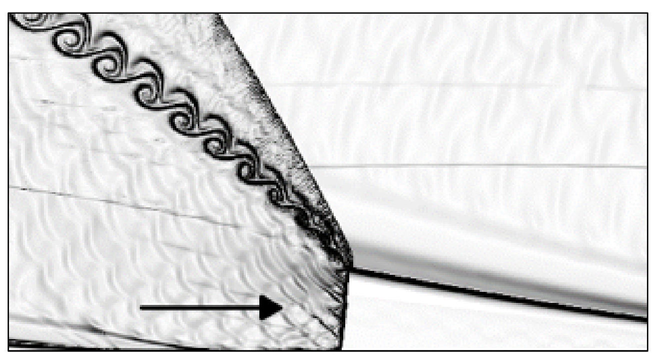

Figure 1. Numerical schlieren of the RDE [9]. Detonation propagates from left to right.

Many challenges still remain before the practical implementation of an RDE system in which the potential benefits can be realized; unwanted deflagration burning, injector mixing, heat transfer losses, and suitable high temperature material are all important issues within the RDE that have yet to be fully addressed [14]. Fundamental experimental studies are needed for the RDE that can fully investigate relevant flow and chemistry features to better understand these loss mechanisms and operating conditions. Numerically, Schwer & Kailasanath [9,11], and Davidenko, Gökalp & Kudryavtsev [13] have studied the fully three-dimensional detonation structure in such RDE models. No experimental data with such details is yet available for comparison or validation of detailed simulation results.

The objectives of this study are to experimentally investigate the nature of a detonation wave propagating across transversely injected reactants in a canonical channel set-up simulating an unwrapped RDE configuration and to provide detailed experimental data that can not only increase the fundamental understanding of the RDE flow structure but can also be used for CFD validation. The approach is to simplify the experimental environment by examining the transient propagation of a detonation wave in cross-flowing reactants through a novel linear channel facility instead of the annular RDE arrangement. Studying the detonation wave propagation in a straight channel allows for the use of high-quality optical measurements that are much more difficult in a curved annulus.

2 Experimental Setup

The Linear Model Detonation Engine (LMDE) facility is shown in Fig. 2, with dimensions normalized by recessed tube diameter **d** and channel width (Y direction) of 3**d**. Design of the LMDE integrates elements of the AFRL's 6-inch RDE [15] and the NRL's premixed microinjection system [16]. In the current configuration the non-crosshatched regions of Fig. 2 (for $Z \geq 0$) represent optically accessible regions of the combustor that allow for imaging of evolving flow structures. Tubes used for reactant injection ($Z < 0$) are not visualized in the current LMDE configuration. Confinement of reactant species is provided on the sides by the quartz windows and below by the injection plane.

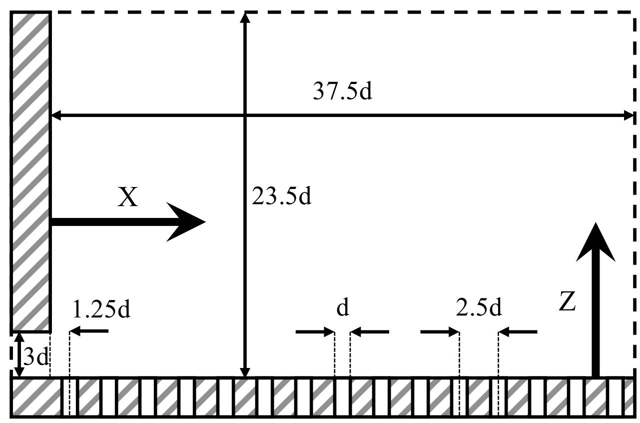

Figure 2. Cross-section view of the LMDE test section. Dimensions normalized by diameter of recessed pre-mixing tube (**d** = 2.54 mm).

Reactant flow propagates in the Z direction, simulating RDE inflow. Fuel and oxidizer species are partially premixed within each of the fifteen recessed cylindrical tubes (L/D of 11.25) at a depth of 10**d** relative to the bottom of the LMDE channel as illustrated in Fig. 2. Independent solenoid control for reactant species allows for control over the height of the partially premixed reactant layer just prior to detonation transit.

A pre-detonator with internal diameter of 4.3**d** and L/D of 42 generates a detonation that propagates in the positive X direction into the reactive cross-flow within the LMDE. A transition piece converts the circular cross-section to a square one with side measuring 3**d**. The pre-detonator operates using a stoichiometric mixture of hydrogen and oxygen, with fill times restricted to mitigate contamination in the LMDE. An electric spark from an automotive ignition system using an iridium tipped spark plug initiates combustion. Dynamic pressure transducers, sampled at 750 kHz with a National Instruments cDAQ-9188 system, positioned 65**d** and 25**d** upstream of the LMDE measure the detonation speed as 2830 m/s.

Optical measurements were made using a Phantom v2512 camera and CAVILUX Smart pulsing diode laser. Position of the wave front is measured relative to the exit of the pre-detonator in the X direction as indicated in Fig. 2. Wave speed in the X direction is estimated using the frame rate of the camera and a central finite differencing scheme.

3 Experimental Results and Discussion

Initial experiments were conducted without reactive cross-flow to establish baseline behavior of the pre-detonator discharge into the LMDE facility. In these experiments the detonation transitions to a strong blast wave upon entering the LMDE channel, Fig. 3a. Pre-detonator discharge occurs from left to right. An incident curved shock structure leads the material interface between pre-detonator exhaust and the gas compressed by the incident shock. Between the incident shock and the material interface, shocklets are observed anchored to the recessed tubes used for reactant injection.

Experiments conducted with cross-flow present yielded successful detonations, Fig. 3b. The reactive cross-flow is visualized to the right of the detonation structure with a height of 8-9**d**. Variation in cross-flow height is piecewise sinusoidal and due to the discrete injection of reactants; cross-flow height is greatest directly above injection locations and shorter elsewhere. The cross-flow shape gives way to the shape of the material interface, which is distinct from the incident shock at X/**d** of zero. The non-uniformity of the initial cross-flow likely accelerates the growth of the Richtmyer-Meshkov instability that forms after the detonation transit. The incident shock and material interface curve to meet the detonation structure near an X/**d** of 31. The region between these two structures is populated by weak shock and expansion waves, likely the result of flow deflection off of the irregularly shaped material interface.

The detonation structure is expressed with significant curvature with the leading edge positioned 2-3**d** above the base of the LMDE. Reactant injection is performed with an evolving jet to replicate the flow conditions within an RDE – immediately after detonation transit inflow is impeded by pressure gain, but resumes as unchoked injection as the pressure falls. For different species, in this case hydrogen and oxygen, the inflow velocities differ, resulting in a non-uniform distribution of reactant species in the direction of jet propagation. In addition, the time-varying velocities create time-varying degrees of mixedness between the species. The leading edge of the detonation indicates the relative maximum in cross-flow detonability as a function of these parameters.

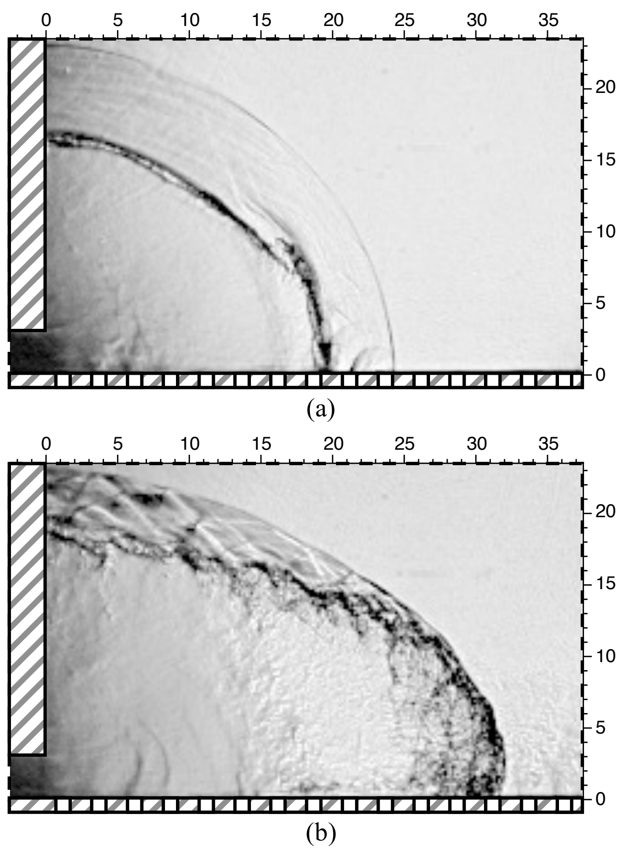

Figure 3. Schlieren image of pre-detonator discharge without cross-flow (a) and detonation propagation in cross-flow of hydrogen-oxygen mixture (ϕ = 1.0) (b).

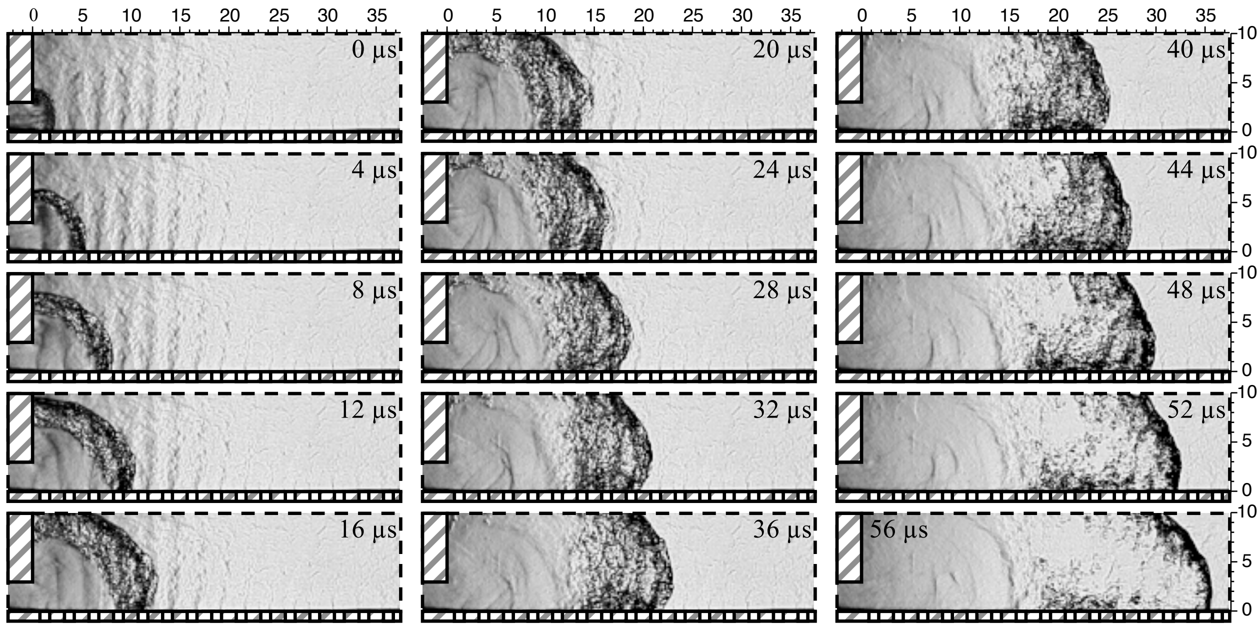

Figure 4. Schlieren images of detonation propagation in cross-flow of hydrogen-oxygen mixture (ϕ = 1.0). The horizontal and vertical scales are the non-dimensional position in the channel X/d and Z/d, respectively.

The detonation transit is examined temporally to investigate variation in propagation behavior with distance from ignition by the pre-detonator, Fig. 4. Images were acquired at 500 kHz, with images shown in increments of 4 µs. The resulting estimates in detonation velocity, Fig. 5, show three distinct regimes of detonation propagation – diffraction, reduced velocity, and acceleration – and indicate the detonation propagation has yet to reach a steady behavior.

Within the pre-detonator the detonation wave is confined on all sides by solid walls; upon exiting the pre-detonator the detonation loses confinement from above and similarly loses triple points to the gaseous confinement layer. The result is a sudden arrest in forward motion of the detonation wave in the first 12 µs of propagation, and mimics the behavior of the blast wave. In the next 22 µs of propagation the detonation moves at a significantly reduced velocity – nearly 50% of the incident detonation speed. In the corresponding schlieren images the detonation structure is curved with a pronounced bulge; the wave structure intersects the base of the LMDE at an oblique angle. The combination of poor mixing, oblique shock angle, and low speed near the base of the LMDE indicate the cross-flow is likely not detonating at this height. The final region of propagation is characterized by a sudden acceleration of the detonation structure to speeds matching that of the incident detonation. In addition, while the bulge of the detonation front still exists, the intersection of the structure with the base of the LMDE occurs at an angle closer to the normal, signifying a greater pressure rise in this region. A greater percentage of the cross-flow reactants are likely detonating in this regime.

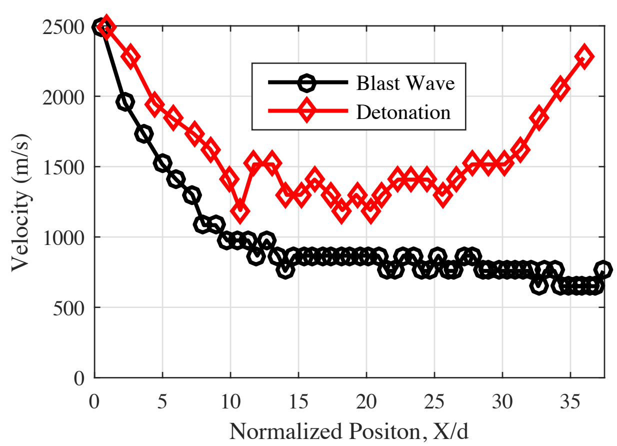

Figure 5. Blast wave and detonation velocities within LMDE channel based off of schlieren images acquired at 500 kHz.

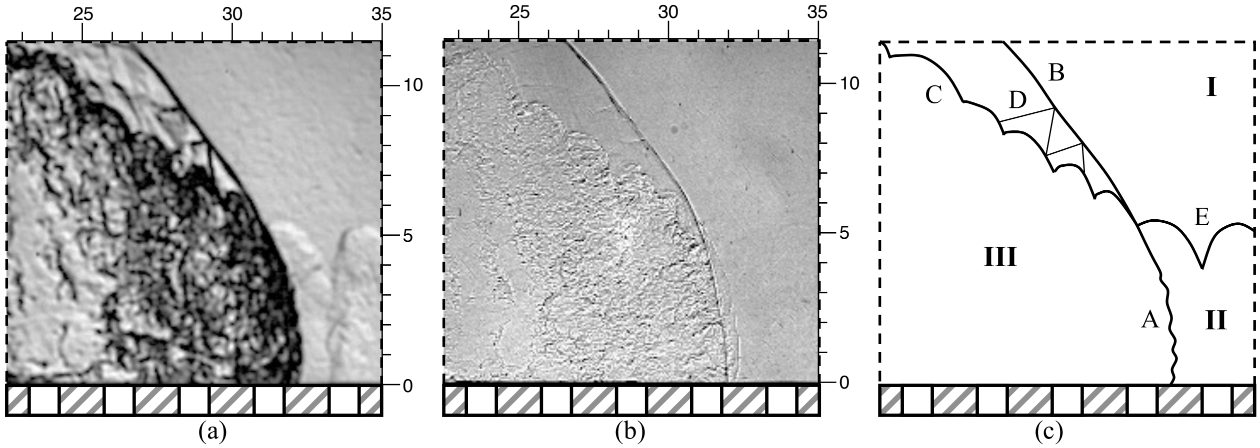

Figure 6. Schlieren (a), shadowgraph (b), and annotated illustration (c) of detonation in cross-flow of hydrogen-oxygen mixture ($\phi = 0.8$).

The detonation transit is imaged in the region of sudden acceleration at a higher resolution to observe flow features, Fig. 6. Key flow regions are the background confinement gas (I), the reactant cross-flow (II), and the combusted products (III). Structures include the detonation front (A), an oblique shock (B), the material interface between combustion products and shocked background gas (C), shocks and expansion fans reflecting off of the material interface (D), and the material interface between the cross-flow and the background gas (E). The irregularities in the detonation front appear to be cellular structures, although the mechanism that maintains them in the LMDE configuration requires further investigation.

4 Concluding Remarks

An experimental study is in progress to study detonation waves propagating across an array of reactant jets discharged into a narrow channel. The principal objective was to gain better understanding of the fundamental flow structure and the physical processes that occur inside an RDE combustor. Preliminary results indicate the detonation propagates as a curved structure with peak propagation occurring in the middle of the cross-flow and is likely a function of inflow velocity and mixing characteristics. Three regimes of propagation have been identified – diffraction, reduced velocity, and acceleration – with images acquired during the acceleration regime to visualize key detonation structures.

In this paper, we present the results from one of the cases where partially-premixed hydrogen-oxygen jets are injected into the oxygen-enriched air background. Since the partially-premixed reactant jets evolve inside the channel, they also mix with the background gas resulting in highly non-uniform reactant mixture along the jet height. At the same time, there are discretely spaced reactant jets along the wave propagation direction, possibly creating a discontinuous pathway of detonable mixture. As a result, even in such a simple configuration as that considered in this paper, the flowfield becomes quite complicated.

The wave and flow structures were characterized using two simultaneously applied high-speed visualization techniques and dynamic pressure measurements. It was shown that the detonation wave speed was not constant across the channel passage, suggesting the wave was still in the transient stage of development. Furthermore, the wave speed fluctuated substantially, suggesting possible effects of non-uniform reactant mixture. The present results highlighted that the mixing within the reactive mixture as well as the mixing between the reactant jets and the previous cycle products should play a critical role for sustaining and stabilizing detonation wave propagation inside an RDE combustor.

Acknowledgments

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