Shock in Reactive Cross-Flow under Partial Confinement

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1 Introduction

Rotating detonation engines (RDE) and pulse detonation engines (PDE), as examples of pressure gain combustion, hold the potential for an increase in thermodynamic efficiency over constant pressure combustion engines [1-3]. PDEs must purge, refill, and initiate a detonation every operating cycle, which means they are limited to operating tens or hundreds of times per second [2]. In contrast, the RDE only requires an ignition source at startup and then operates continuously with detonation waves cycling around the annular channel thousands of times per second [3]. Although a great deal of work has been done in the development of these engines, there is a distinctive lack of experimental data regarding the flow structures within an RDE during ignition and continuous operation.

The objectives of this study are to investigate a blast wave propagating across transversely injected reactants and to increase our understanding of RDE ignition and operation. Our approach is to simplify the physics contained in the RDE flow problem by lessening the experimental complications introduced by the annulus configuration. Studying blast waves in a partially confined geometry instead of an annulus would provide a tremendous advantage in one's ability to obtain high-quality flow visualization by allowing optical access to the flow structures previously locked away by optical aberrations caused by the annulus.

2 Experimental Setup

A PDE, with cross-section shown in Figure 1, produces detonations in a hydrogen-oxygen mixture at flowrates of 23.4 mg/s and 186 mg/s, respectively. The inner tube diameter is 0.43" and the tube length, relative to the ignition source, is 16.4". Detonation wave speeds within the PDE tube are nominally 2420 m/s (85% Chapman-Jouguet, CJ, velocity). A decaying blast wave is formed when the detonation exits the confinement of the PDE tube.

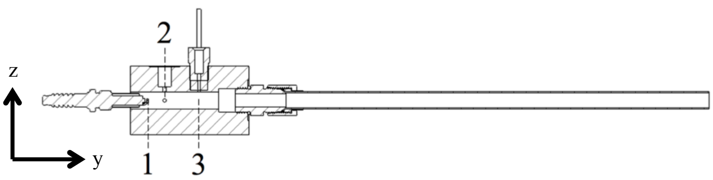

Figure 1. Cross-section view of the PDE. Positions 1, 2, and 3 correspond to the spark ignition source, location of gas injection, and an upstream Kistler transducer placement, respectively. Flow is in the positive Y-direction. The X, Y, and Z-axes form a right-handed coordinate system.

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Downstream of the PDE exit a reactive cross-flow is supplied through the Linear Model Detonation Engine (LMDE). The LMDE is a two-dimensional representation of an RDE with the reactive cross-flow, so named for its perpendicular trajectory relative to the blast wave propagation direction, simulating the RDE inflow used to sustain the transversely propagating detonation wave.

Table 1: LMDE Flow Conditions

Continuous Flow Conditions	Symbol	Value
Atmospheric Temperature	T_{air}	298 K
Atmospheric Pressure	P_{air}	14.7 psi
Hydrogen Flow Rate	$\dot{m}_{H2}$	0.290 g/s
Oxygen Flow Rate	$\dot{m}_{O2}$	2.29 g/s
Helium Flow Rate	$\dot{m}_{He}$	0.858 g/s
Hydrogen-Oxygen Equivalence Ratio	ϕ_{LMDE}	1.0
Helium Dilution (Total Molar)	D_{He}	50%

In particular the LMDE combines attributes of the AFRL's 6-inch RDE [4] and the NRL's premixed microinjection system [5]. Fifteen recessed premixing tubes of diameter 0.10” combine hydrogen, oxygen, and helium into one jet of reactants – in Figure 1 the reactive cross-flow moves in the positive Z direction. Flow conditions for the LMDE are summarized in Table 1.

A flat plate is positioned atop the LMDE and the exit of the PDE tube rests at one end of the LMDE, as shown in Figure 3, to form the partially confined geometry for the blast wave. In this configuration the LMDE behaves as two-dimensional RDE without confinement from annular channel walls.

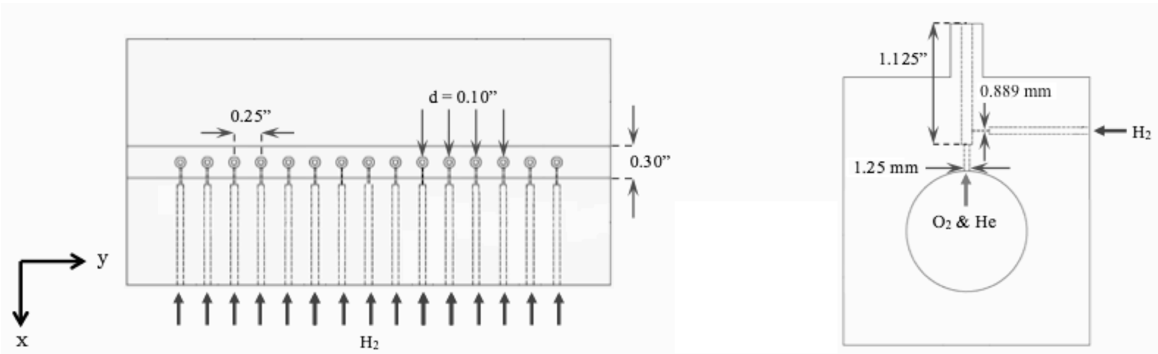


Figure 2. University of Maryland LMDE Geometry. Left: View of the LMDE looking down into the XY plane. Right: View of the LMDE looking end on at the XZ plane.

A shadowgraph technique with a C-type arrangement was used to obtain images of interactions between the PDE-generated blast wave and the LMDE cross-flow in the YZ plane. Images were acquired in single-shot mode using a camera linked to an IDT-Provision software package. A high-accuracy controller is employed to ensure synchronization between PDE operation and LMDE cross-flow height.

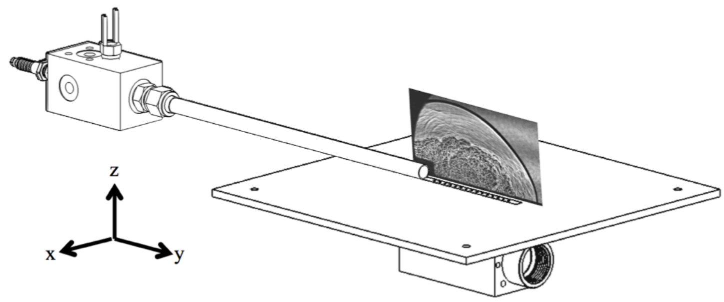


Figure 3. Diametric view of the PDE and LMDE assembly. Blast waves and cross-flows propagate in the positive Y and Z directions, respectively. Shadowgraph images are of the YZ plane as shown.

Kistler dynamic pressure transducers were used in conjunction with a National Instruments cDAQ-9188. Three Kistlers positioned just after the exit of the PDE tube, spaced along the Y-axis and next to the cross-flow jet, were used to measure average blast wave speeds. The Kistler sensors have a range of ±100 psi and were sampled at 750 kHz. The measured values were sent via a TCP/IP connection to a desktop computer operating a LabView control panel. This interface subsequently wrote the data to a text file for use by post-processing software.

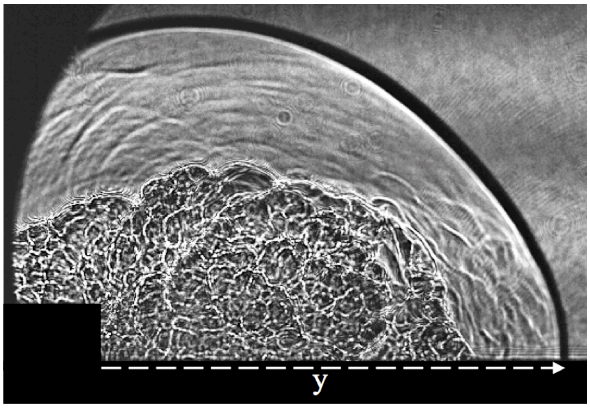


Figure 4. Blast wave traversing the LMDE surface without cross-flow present.

3 Results and Discussion

A. Blast Wave Propagation without Cross-Flow

Blast wave structures were visualized without a cross-flow present to establish a baseline for subsequent comparison. Minimizing PDE fill time mitigates reactant spillage in the Y-direction along the top of the LMDE. Image acquisition occurs relative to the PDE ignition trigger.

Figure 4 shows a typical shadowgraph image of a blast wave (YZ plane) without cross-flow. The largely hemispherical blast wave is characterized by a sharp shock front that precedes the region of combustion within the blast wave. This combustion region produces pressure waves that catch up to the shock and reinforce it. These pressure waves appear as ripples in the region between the shock front and the combustion region.

From these shadowgraph images the position of the forward shock in the Y-direction is measured relative to the exit of the PDE. Figure 5 compares the forward position of the blast wave without cross-flow to the relative time when images were acquired. Image acquisition occurs in a 1 ms window prior to the camera trigger with the exact time determined by a synch signal independent of the controller.

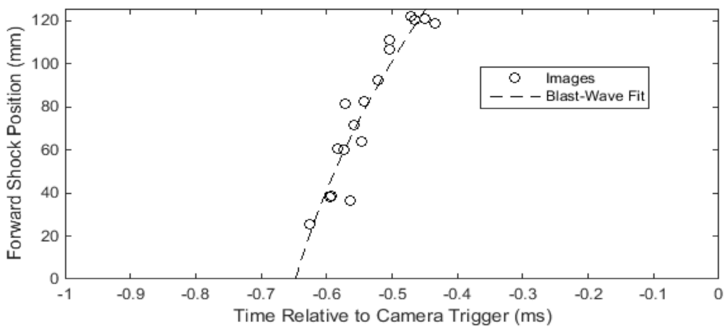


Figure 5. Forward position of the blast wave correlated with the relative image acquisition time.

An ideal blast wave follows the form [6]:

$$x(t) = A\left(t - t_0\right)^{2/5} - x_0$$

Fitting for A, t_0, and x_0 with the shadowgraph images yields the curve in Figure 5. The average shock speed across the LDME surface is 630 m/s without cross-flow. Variations in deflagration to detonation transitions within the PDE tube contribute to error in timing measurements.

Additional velocity estimates are made by Kistler dynamic pressure transducer measurements taken at positions of 0.5", 2", and 3.5" along the Y-axis relative to the exit of the PDE tube. The shock front produces a sharp rise in the dynamic pressure transducers, and the average speed between two adjacent sensors is inferred by the time delay between this signal rise.

For the baseline configuration without cross-flow the average shock speed without cross-flow is 868 m/s for 12.7mm ≤ Y ≤ 50.8 mm and 571 m/s for 50.8mm ≤ Y ≤ 88.9 mm with standard deviations of 14% and 6.2%, respectively. The fit applied in Figure 5 estimates the average velocity in these ranges as 792 m/s and 606 m/s, respectively, both of which fall within the standard deviations of the Kistler measurements. Pressure transducer estimated velocities, based off of physical flow measurements, are assumed to be more accurate.

B. Blast Wave Propagation with Cross-Flow

A consistent cross-flow is established by calibrating the height of the gases in time relative to the controller commands, and then staggering the triggering of the gases such that each species – hydrogen, helium, and oxygen – independently reach the desired height when the blast wave traverses the LMDE in the positive Y direction. The cross-flow jet velocity in all test cases is small – on the order of tens of meters per second – relative to the detonation wave speed within the PDE, 2420 m/s (Mach number ~4.5 relative to unburned stoichiometric mixture).

Two different cross-flow mixtures are considered – one comprised entirely of a stoichiometric hydrogen-oxygen mixture, and another stoichiometric hydrogen-oxygen mixture that includes 50% helium in molar composition. Cross-flow heights are normalized by the characteristic detonation cell sizes (λ) for the mixtures – for the former the cell size is 1.39 mm [7] and for the latter the cell size is 2.12 mm [7-10]. Measurements were made for each mixture at cross-flow heights of 5λ, 10λ, 15λ, and 20λ. Average velocities are normalized by the speed of sound within the cross-flow, a_{CF}. Results are summarized in Table 2.

Table 2: Blast Wave Cross-Flow Interaction Properties from Kistler Measurements

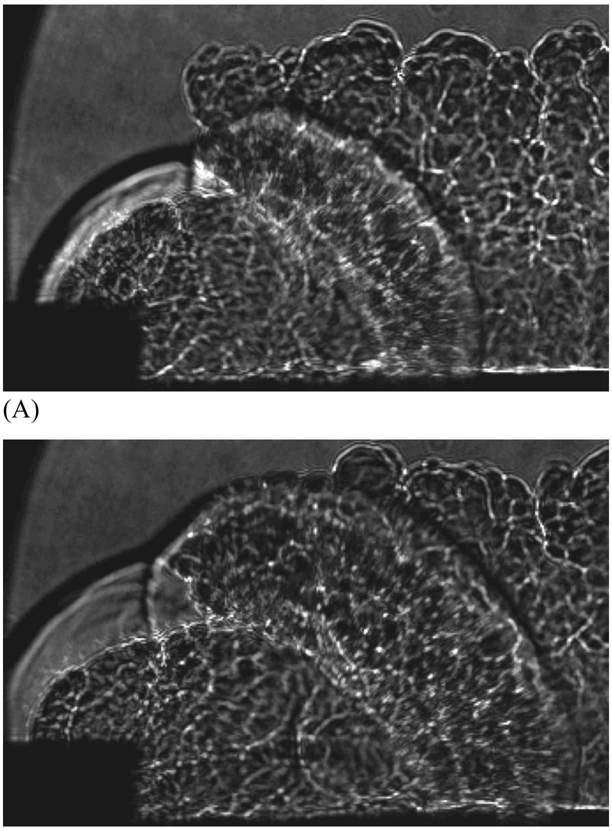
	a_{CF} (m/s)	$\bar{U}_{1\text{-}2}$ (m/s)	$\bar{M}_{1\text{-}2}$	$\pm\sigma_{1\text{-}2}$	$\bar{U}_{2\text{-}3}$ (m/s)	$\bar{M}_{2\text{-}3}$	$\pm\sigma_{2\text{-}3}$
Baseline	344	841	2.4	14%	625	1.8	5.8%
H_2-O_2							
5λ	535	875	1.6	5.8%	603	1.1	3.9%
10λ	535	866	1.6	6.5%	617	1.2	6.1%
15λ	535	950	1.8	20%	573	1.1	10%
20λ	535	891	1.7	17%	594	1.1	5.4%
H_2-O_2-He							
5λ	677	773	1.1	7.3%	778	1.1	8.4%
10λ	677	771	1.1	8.5%	751	1.1	7.4%
15λ	677	858	1.3	6.5%	810	1.2	7.1%
20λ	677	860	1.3	4.0%	739	1.1	6.3%

Fitting of image positions to the blast wave theory is not performed for these cases. Blast wave theory assumes the energy deposition to the flow occurs instantaneously. If the cross-flow is successful in sustaining the forward speed of the shock structure then the assumptions of this theory break down.

In all cases the blast wave speed decreases between the two measurement regions. Increasing wave speeds, or even a decrease in the deceleration of the blast wave front, between these two regions would indicate additional driving of the leading shock through the combustion of the reactive cross-flow and the shedding of additional pressure waves. These preliminary results indicate that for the partially confined geometry, where the cross-flow is only confined from below, a cross-flow in excess of 20λ is required to drive a blast wave or to sustain a detonation. The increase in the standard deviation of the velocity measurements for the H_2-O_2 for cross-flow heights of 15λ and 20λ suggest statistical outliers that may be the driving of the blast wave by the reactive cross-flow in these cases.

In the absence of a sufficiently reactive material the detonation structure decays from a CJ detonation to a weak shock in 10's of mm. The length over which this deceleration occurs is mixture dependent and correlates with the density of the cross-flow, or lack thereof; during the baseline case with no cross-flow the shock remained strong beyond the length of the data acquisition, in the cross-flows composed of H_2-O_2 the deceleration took nearly 100 mm, and in the H_2-O_2-He cross-flows the deceleration occurred over the first 50 mm.

For RDE operation the implication is twofold – the ignition source must be linked to the combustion annulus by reactive material, and any shock waves generated by the detonation wave passing over an injector orifice (or other geometric irregularity) that propagate in the opposite direction of the detonation wave will quickly dissipate in intensity. The later implication proposes that such generated pressure waves contribute minimally as an RDE thermodynamic cycle loss mechanism.



(A)

(B)

Figure 9. Blast wave structure for a cross-flow of stoichiometric hydrogen and oxygen with helium at a height of 20λ.

For both the H_2-O_2 and H_2-O_2-He cross-flow, the shock front in some cases reaches higher velocities than in the baseline case because of the higher speed of sound in the cross-flow. At the interface with the cross-flow the accelerated shock front outpaces the shock front in quiescent air, and a second shock is transmitted into the quiescent air to resolve the pressure mismatch, as seen in Fig. 9A and 9B. If the reactive cross-flow had a density greater than the surrounding gas then this secondary shock structure would instead propagate into the cross-flow. The twice-shocked region in the reactive cross-flow could serve as a local hot-spot, an area of high pressure and temperature capable of auto ignition that might aide in RDE ignition.

4 Summary and Conclusions

An experimental study is underway to investigate the nature of a blast wave propagating across a reactive cross-flow in a partially confined geometry. A shortened and smooth bore PDE fires a blast wave into a flow field propagating perpendicular to the axis of the PDE tube. Several experiments were performed using various combinations of hydrogen, oxygen, and helium as reactive cross-flow mixtures.

The cross-flow height and composition at the time of the wave arrival were examined for possible effects on shock wave cross-flow interaction using shadowgraph visualization and dynamic pressure measurements. The results were compared to the baseline blast wave propagation in the absence of cross-flow. In this paper the cross-flow mixtures were composed of either stoichiometric hydrogen-oxygen or stoichiometric hydrogen-oxygen diluted with 50% helium by mole fraction. The following observations were made:

1. Four different cross-flow heights, 5λ, 10λ, 15λ, and 20λ, were tested for two different cross-flow compositions. In each case the blast wave forward shock decayed in intensity. The reactive cross-flow height required to sustain a blast wave in the partially confined geometry exceeds 20λ for both mixtures.
2. Pressure waves shed into a low-density region quickly attenuate in intensity. In RDEs this implies shocks reflected off of irregular annulus features are unlikely to serve as a significant thermodynamic cycle loss mechanism.
3. In cases where the shock is propagating parallel to the cross-flow/quiescent gas interface the shock front is mismatched due to discontinuous speeds of sound in the gasses. A second shock is transmitted into the material with the lower speed of sound to resolve the pressure discrepancy. The region of the flow that is twice shocked can act as a detonation ignition source for certain cross-flow mixtures.

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