Effects of Lateral Relief of Detonation in a Thin Channel

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1 Introduction

Conventional engines utilize energy through deflagrating combustion processes, which is combustion at subsonic flame speeds. The idea of harnessing energy from detonations for propulsion is attractive because of the higher energy release rate and the increase in gas pressure. A type of detonation engine that has been receiving a lot of attention lately is the rotating detonation engine, or RDE. In a RDE, a detonation wave circles around an annular chamber and products are continuously exhausted through the back of the chamber.

Typical detonation wave speeds in RDEs have been significantly lower than Chapman-Jouguet (CJ) velocities, ranging from 50-70% of the CJ velocity [1]. This is considerably lower than the predicted detonation wave speed from CFD and shock-tube laboratory measurements, which is typically well above 90% of the CJ velocity [2]. Figure 1 is from Dr. Andrus's work that summarizes the detonation wave speeds relative to the CJ velocities from various experiment and CFD results [3]. This is not an all-inclusive data, but it shows a general discrepancy between experiments and CFDs when it comes to the detonation wave speeds. One of the possible causes is the fact that most CFDs are premixed, while most experiments are non-premixed. That possible cause has been ruled out from Dr. Andrus's premixed RDE work, which showed wave speeds on the order of 50-55% of CJ velocity [4]. There are many other speculations for the cause of lower CJ velocities in RDEs: heat loss, curvature (change in direction), non-stationary gas, partially combusted reactants, heterogeneous mixture, exhaust gas recirculation, and lateral relief (top is unconfined). In order to gain more fundamental understanding of the detonation physics inside a RDE, each of the possible causes need to be investigated. This paper focuses on experimental study of the effect of lateral relief on detonation in a small channel for hydrogen and air mixture, and ethylene and air mixture.

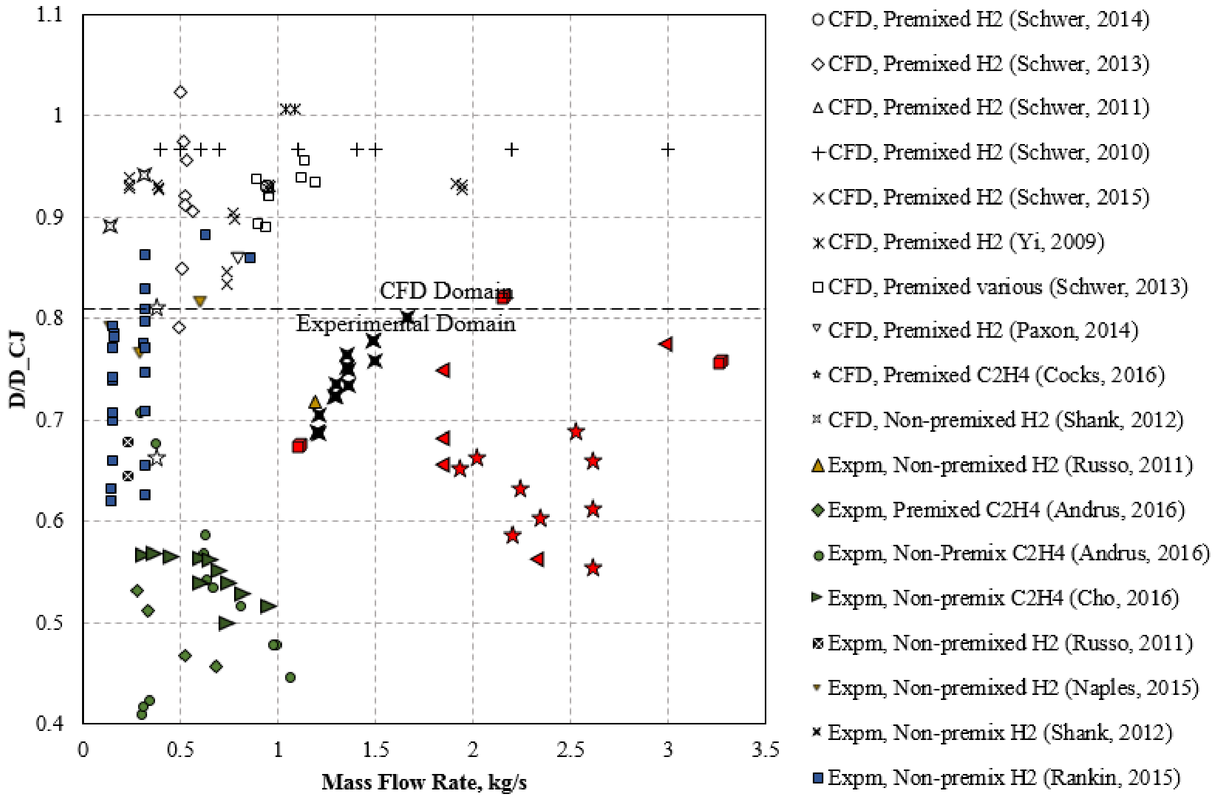

Figure 1. Summary of the detonation wave speed relative to the CJ velocity from various experiments and CFDs, by Andrus [3].

Previous studies of lateral relief on detonation was done by Dabora et al., with mixtures of hydrogen/oxygen in a channel bound by a thin film (25 nm nitrocellulose film), and nitrogen on the other side [5]. The thin film was necessary to break almost instantaneously upon contact with detonation while stopping diffusion of the reactants and inert gas. The authors reported decrease in detonation wave speed on the order of 5-10% for 0.762 cm (0.3 inch) channel. A similar study by Adams looked at the effect of lateral relief for hydrogen/oxygen and methane/oxygen, with hydrogen or helium as boundary gas, separated by a thin nitrocellulose film [6]. The study reported detonation wave speeds that are 83% of CJ velocity for hydrogen/oxygen, and 44% of CJ velocity for methane/oxygen. However, it was unclear to Adams whether the detonation was slow in steady state or under-driven within the test section. Although these are good fundamental studies, fuel mixtures with air in a narrow channel need to be investigated for the air-breathing RDE applications.

The objective of this paper is to study the effect of lateral relief on hydrogen/air and ethylene/air detonation traveling in a narrow channel. The linear narrow channel simulates an “unrolled’ RDE, with the channel width dimension matching the RDE channel gap size of 7.62 mm and 22.86 mm. The equivalence ratio will be varied from 0.95 to 1.7. By studying the effect of lateral relief in a linear RDE, more fundamental understanding of the detonation physics in RDEs will be achieved.

2 Experimental System

Schematics of the experiment system are in Figure 2. A pipe that is 5.05 cm in inner diameter and 114.9 cm in length was used to initiate the detonation. Continuous flow of fuel and air were injected into a static mixer, which was connected at the end of the pipe. The mass flow rate of fuel and air were calculated and monitored with calibrated orifices. For air, an orifice with diameter of 1.6 mm was used, and for fuel, an orifice with diameter of 0.53 mm was used. The air mass flow rate of 4.39 g/s was kept constant for all test conditions, while the fuel mass flow rate was varied to change the equivalence ratio. The mass flow rate was enough to fill the test volume in about 0.5 seconds, which corresponds to about 4 m/s of flow speed through the test section. After over-filling the tube and the thin channel to 4 seconds, a spark plug at the end of the pipe ignited the mixture, and deflagration to detonation transition (DDT) was achieved with a spiral. The spark plug was initiated 0.3 seconds after the valves were closed. The circular pipe transitions to a rectangular channel that has width of 7.62 mm or 22.86 mm and height of 50.8 mm. The rectangular channel continues for 45.7 cm, and it has 4 ion probes to measure the detonation wave speed. This section will essentially be ‘control’, as it allows detonation to propagate in a thin channel without lateral relief. The control section is connected to the ‘experiment’ section, where the effect of lateral relief can be studied. This section has the same channel width and length as the previous control section, but it is 13.5 cm in height. This section has a removable boundary 5.08 cm from the bottom of the channel. This removable boundary is a 5 mm thick Teflon sheet, connected to a linear pneumatic actuator. During the fill cycle, the Teflon boundary is used to keep the reactive mixture from escaping the experiment section. 0.1 seconds before the spark ignition, the boundary is removed, allowing lateral relief to occur as the detonation propagates in this section. The latter half of this section has optical access for visualization of the detonation wave, the oblique shock wave, and the expansion waves. There are 7 ion probe positioned equally along the lower channel section for wave speed measurement. The two ion probes in the control section and two ion probes in the experiment section that were used for speed measurement are identified in Figure 2b. After the experiment section with lateral relief, a 31 cm long extension tube with inner diameter of 5.05 cm is there to minimize any air contamination in the test section.

Two fuels, hydrogen and ethylene, will be tested at various equivalence ratios with air. The channel width for hydrogen will be varied by 7.62 mm or 22.86 mm, while the channel width for ethylene will be 22.86 mm. A summary of the test conditions is on Table 1.

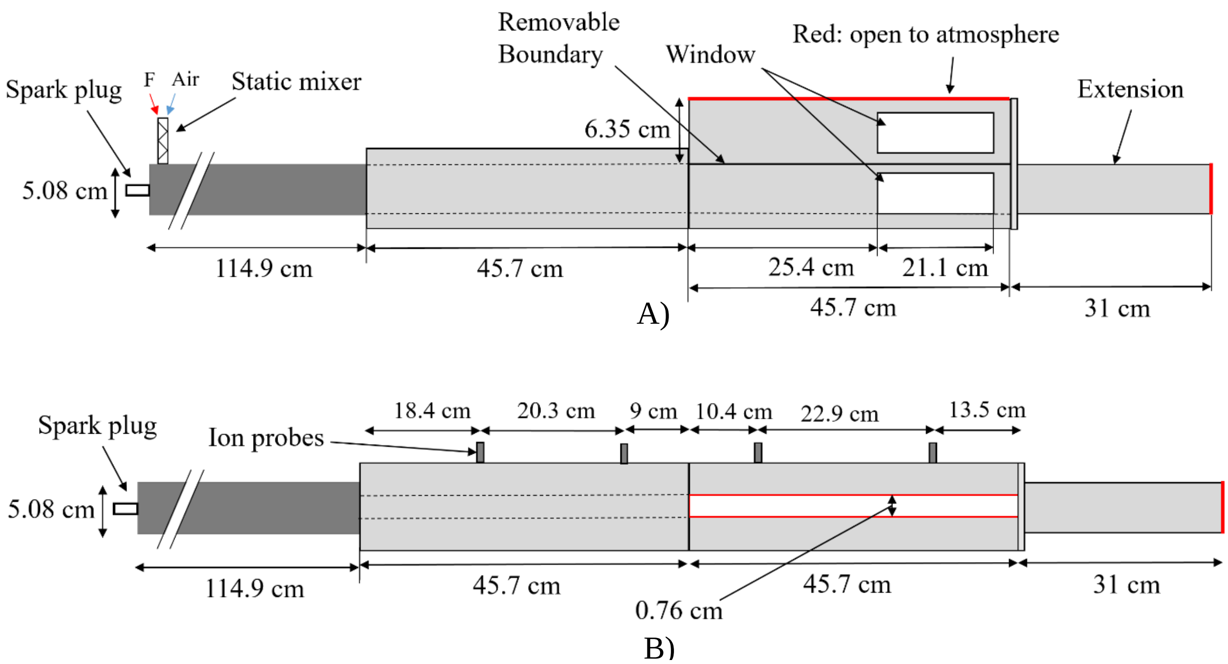

Figure 2. Schematic of the experiment system. A) Front view of the system. B) Top view of the system.

Table 1. Summary of test conditions

Test series	Equivalence Ratio	Fuel	Channel width
1	0.94	Hydrogen	0.76 cm
2	1.07	Hydrogen	0.76 cm
3	1.23	Hydrogen	0.76 cm
4	1.34	Hydrogen	0.76 cm
5	1.54	Hydrogen	0.76 cm
6	1.71	Hydrogen	0.76 cm
11	0.94	Hydrogen	2.29 cm
12	1.07	Hydrogen	2.29 cm
13	1.23	Hydrogen	2.29 cm
14	1.34	Hydrogen	2.29 cm
15	1.54	Hydrogen	2.29 cm
16	1.71	Hydrogen	2.29 cm
21	0.94	Ethylene	2.29 cm
22	1.07	Ethylene	2.29 cm
23	1.23	Ethylene	2.29 cm
24	1.34	Ethylene	2.29 cm
25	1.54	Ethylene	2.29 cm
26	1.71	Ethylene	2.29 cm

3 Results

Preliminary results of test series 1-6 are tabulated in Table 2 and plotted in Figure 3. The detonation wave speed in a thin channel is 3-6% lower than the Chapman-Jouguet detonation wave speed, while detonation in a thin channel with lateral relief are 12-28% lower than the Chapman-Jouguet wave speed. The wave speed deficit is higher for stoichiometric condition and rich conditions, which is similar to the wave speed deficit trend observed in detonation in porous media. Test series 11-16 and 21-16 are in working progress as of this writing.

Table 2. Average and standard deviation of the detonation wave speed measurements.

			No Lateral Relief		**Lateral Relief**		
Fuel	**Equivalence Ratio**	**Channel width (cm)**	**Detonation wave speed (m/s)**	**Percent CJ velocity (%)**	**Detonation wave speed (m/s)**	**Percent CJ velocity**	**Number of tests**
H_2	0.94	0.76	1835± 12.8σ	94.7 ± 0.7σ	Failed	N/A	3
H_2	1.07	0.76	1866 ± 15.5σ	93.7 ± 0.8σ	1439 ± 60.3σ	72.3 ± 3.0σ	15
H_2	1.23	0.76	1929 ± 23.2σ	95.0 ± 1.1σ	1721 ± 64.8σ	84.8 ± 3.2σ	12
H_2	1.34	0.76	1994 ± 13.6σ	97.0 ± 0.7σ	1815 ± 89.2σ	88.3 ± 4.3σ	14
H_2	1.54	0.76	2007 ± 22.8σ	96.2 ± 1.1σ	1818 ± 69.4σ	87.1 ± 3.3σ	14
H_2	1.71	0.76	2040 ± 19.4σ	96.7 ± 0.9σ	1717 ± 82.4σ	81.5 ± 3.9σ	13

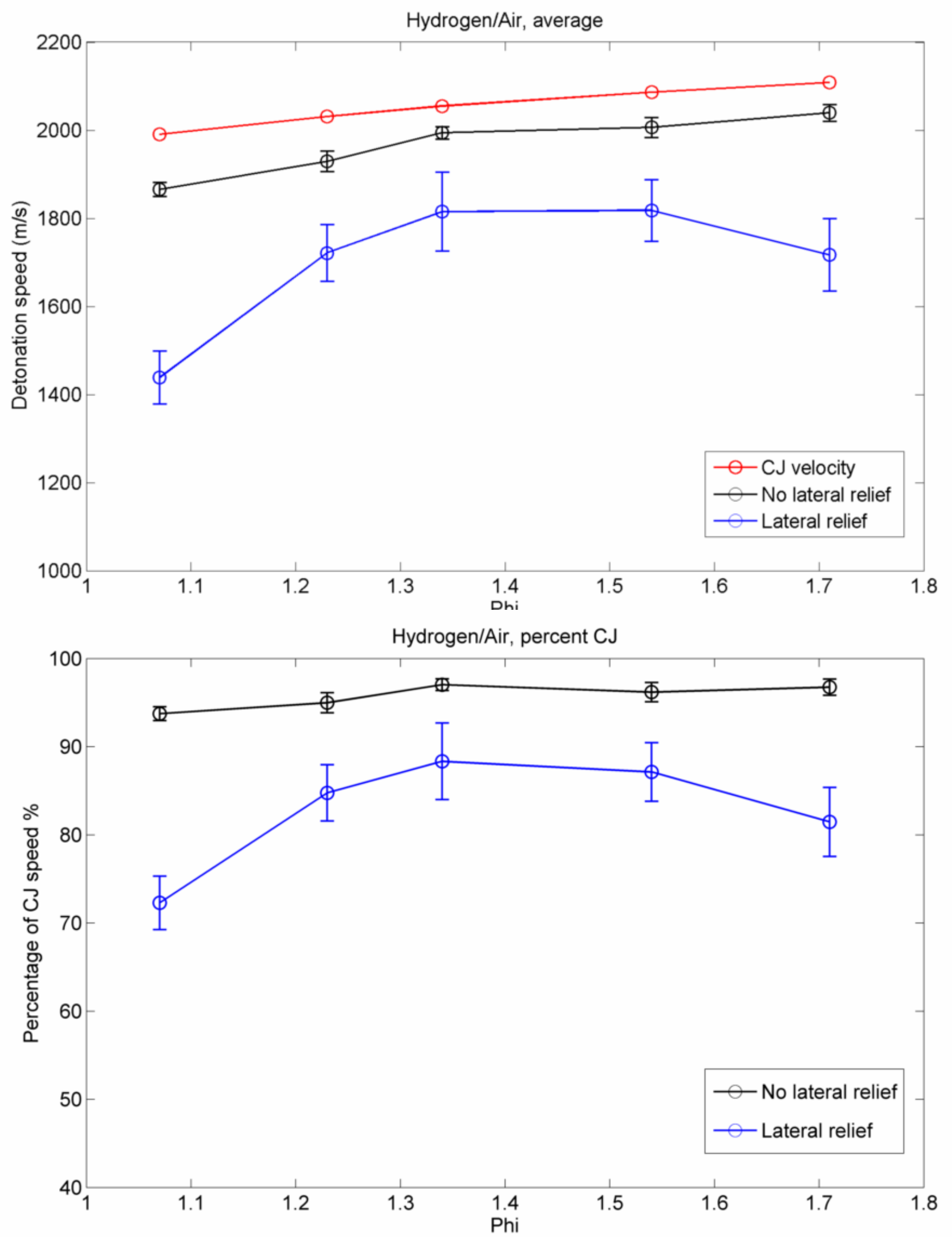

Figure 3. Top: Detonation wave speed as a function of equivalence ratio for theoretical CJ velocity, detonation in a thin channel, and detonation in a thin channel with lateral relief. Bottom: Detonation wave speed as a percentage of theoretical CJ speed for detonation in a thin channel, and detonation in a thin channel with lateral relief.

Acknowledgement

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