Detonation Propagation in a Linear Representation of a Rotating Detonation Engine

Curtis Metrow and Gaby Ciccarelli
Queen’s University
Kingston, Ontario, Canada

1 Introduction

In recent years, there has been a dramatic increase in research interest concerning Rotating Detonation Engines (RDEs). The detonation mode of combustion offers the potential for high thermal efficiency and power-to-weight ratio [1]. In a RDE, the fuel and oxidizer are injected into an annular combustion chamber through the baseplate. A detonation wave is initiated in a pre-detonator and then transmitted into the combustion chamber where it propagates continuously around the base of the annulus. The high pressure behind the detonation front is significantly larger than the intake pressure, and as a result, the fuel and oxidizer mass flow is arrested. As the products expand behind the detonation wave, the local pressure across the base-plate is reversed and fresh reactants flow into the annulus is re-established just ahead of the detonation wave. Many research groups have constructed RDE prototypes to investigate the effect of fuel and oxidizer injector configuration and combustion chamber parameters on the cycle frequency and detonation wave structure [2], [3], [4].

Numerical studies have been conducted analyzing different aspects of the RDE, such as, area ratio [5], injection hole configuration [6], and wave structure [7]. These simulations do not model actual RDE fuel and oxidizer injection, simulations typically assume pre-mixed fuel-oxidizer injection into the combustion chamber. Recently, 2D simulations were carried out comparing results from separate fuel and oxidizer injection and premixed fuel-oxidizer injection from discrete holes in the base plate [8]. Especially relevant to this study, is the simulation carried out with a wall opposing the injection baseplate that reflected transverse waves, resulting in more detonation cells across the jet height [8].

Detonation wave phenomena is typically studied experimentally by schlieren photography. However, since schlieren photography relies on collimated light transmission, it is not applicable for an annular RDE. Schlieren photography has been used with an optically accessible linear RDE to study the detonation structure through a stratified combustible mixture layer. The stratified layer was produced by the injection of premixed fuel-oxidizer through a linear series of nozzles along the baseplate [9]. The shortcoming of this experiment was that the linear RDE was very short, and the detonation entered the RDE from a small diameter predetonator. As a result, the unsteady detonation propagation observed was representative of the start-up process, but not steady detonation propagation. In this study a linear RDE was developed where the combustor is fed from a similar cross-section detonation channel that transmits a steady CJ detonation wave. The setup can be used to study the effect of fuel-oxidizer injection geometry (nozzle size, spacing and shape), channel width, and fuel-oxidizer jet height on detonation wave structure. Photographic and pressure-time history results from this study are invaluable for validating 2D numerical simulations.

2 Experimental

The apparatus used in this study was comprised of multiple 0.61m long sections, as shown in Figure 1. Unlike the flow-through system used in [9], in this study the channel is completely closed so that the contents can be evacuated. The fifth section, i.e., optical test-section, represents the RDE combustor, and the sixth section was used as a dump tank. The first four sections serve the purpose of generating a planar detonation wave. A flame was ignited by a spark plug located at the endplate. Fence type obstacles (mounted on the top and bottom plates equally spaced at 76 mm) were used to promote flame acceleration and deflagration-to-detonation transition (DDT). The blockage ratio (BR) of the obstacles in sections 1, 2, and 3, are 0.66, 0.5, 0.33, respectively. The fourth section had no obstacles, so the detonation wave stabilized before entering the optical test-section. As shown in Figure 1 a series of four ion probes were mounted on the top channel wall of the third and fourth sections, equally spaced 0.3m apart. The ion probes provided combustion front time-of-arrival data that was used to obtain the combustion front velocity. In all tests it was confirmed that a CJ detonation velocity was achieved in the fourth section.

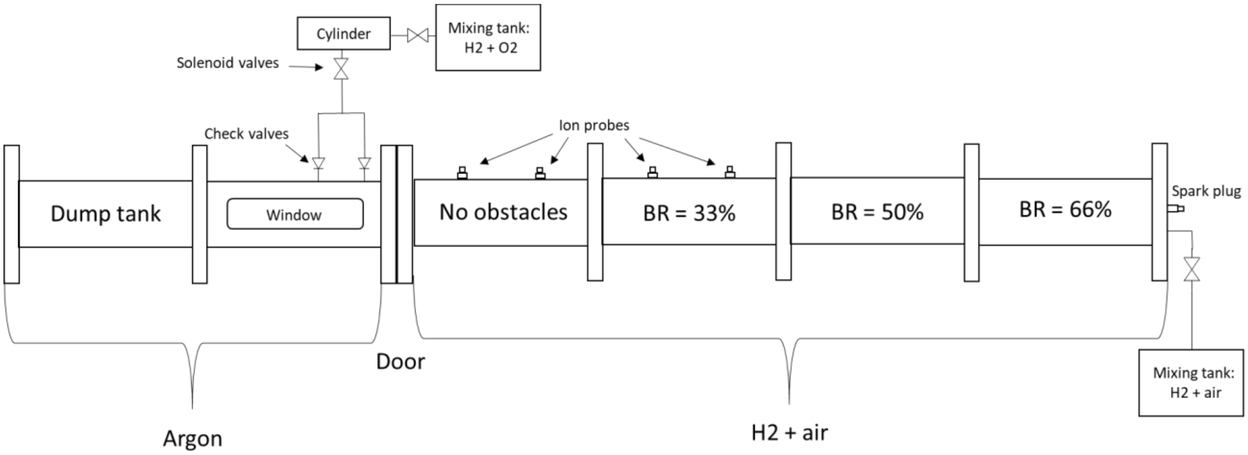

Figure 1: Schematic of the experimental apparatus.

The test-section is 0.61m long with a 63.5mm high and 7mm wide cross-section, and includes a top plate that consists of a plenum with a cover plate that has a linear array of 1.3 mm diameter holes equally spaced at 4.8 mm. The injection holes occupy the first half of the test-section. A solenoid valve initially isolates the plenum from a 250 cc cylinder that is filled with premixed stoichiometric hydrogen-oxygen at 4 bar, see Fig. 1. From the solenoid valve the gas flows through two check valves (0.7 bar gauge opening pressure) on the way to the plenum. The check valve permits evacuation of the plenum up to the solenoid valve but prevents the argon from filling the plumbing upstream of the check valve. The hydrogen-oxygen is distributed to the plenum via four runners from each of the check valves.

The test-section is isolated from the predetonator (first four sections) by a manually operated sliding door that has an aperture similar to the test-section cross-section. Initially the door is left in the open position and the entire channel is evacuated. The door is then closed and the predetonator is filled with stoichiometric hydrogen-air and the test-section and dump tank are filled with argon (simulating the non-reactive exhaust products in a RDE) to 1 atmosphere. The pressure in the predetonator and test-section are balanced by momentarily opening a valve connecting the two. Just prior to ignition, the sliding door is opened, and a stoichiometric hydrogen-oxygen mixture is injected through the holes in the test-section.

A delay generator is used to delay ignition after the solenoid valve is actuated. Varying the delay time for the spark trigger allows the operator to change the hydrogen-oxygen flow time. In this way, the hydrogen-oxygen jet height at the time of detonation wave arrival can be controlled. The schlieren system includes a Photron SAZ camera that records the propagation of the detonation across the injected hydrogen-oxygen stratified layer. The high-speed schlieren images were taken at 240,000 frames per second with a shutter speed of 0.16 μs. The test-section window is 444 mm long, however the camera field-of-view only covers 246 mm due to limitation of the schlieren parabolic mirror.

3 Results and Discussion

Shown in Figure 2 is a schlieren image showing the uniformity of the stoichiometric hydrogen-oxygen jets that extend roughly one-quarter the distance across the channel height just prior to ignition. The images taken from the high-speed video for a combustion test performed with stoichiometric hydrogen-oxygen jets injected into the test-section prefilled with argon at 1 atm and 20°C are presented in Figure 3. The vertical field-of-view (FOV) is 57 mm, the right-edge of the FOV is roughly 71 mm downstream from the door. The images show a curved front that maintains its shape along the length of the FOV. The top part of the front consists of a coupled detonation wave that propagates in the fuel-oxygen layer. The oblique bottom part of the front propagates through the argon, so there is no energy release associated with this part of the front. The oblique shock interacts with the bottom wall producing a reflected wave that trails behind the front. The reflected shock is much steeper because of the high speed of sound in the products. The axial velocity as a function of propagation distance obtained from the video is provided in Figure 4. Note, the steadiness of the velocity down the length of the entire FOV, following a short transient at the start. The average measured velocity of 2000 m/s is significantly lower than the 2800 m/s CJ detonation velocity for stoichiometric hydrogen-oxygen. This velocity deficit can be attributed to strong boundary layer effects (7 mm channel width) and downward lateral expansion of the products, both of which lead to front curvature. Dilution of the hydrogen-oxygen by the argon is believed to play a minor role.

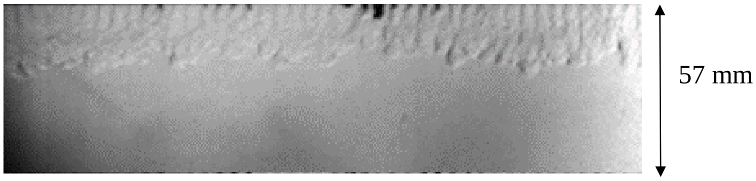

Figure 2: Image showing stoichiometric hydrogen-oxygen jets with the test-section prefilled with argon.

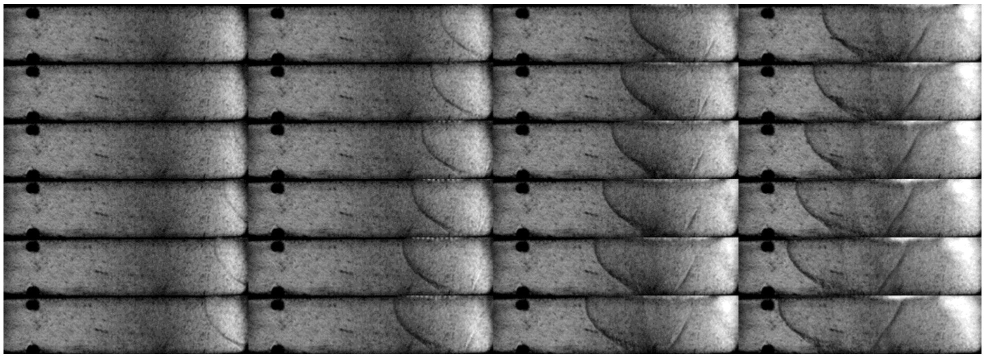

Figure 3: Schlieren images of detonation wave propagating through stratified layer of hydrogen-oxygen

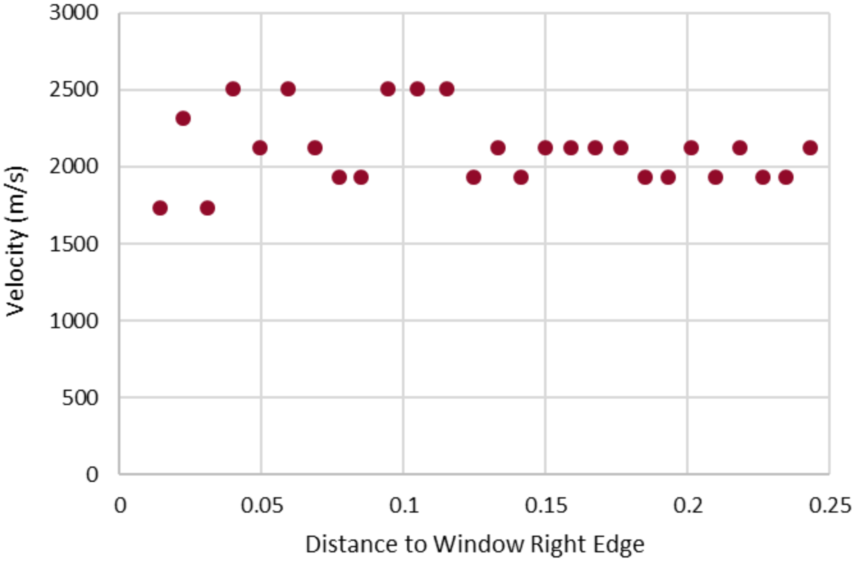

Figure 4: Detonation front velocity along top wall obtained from high-speed video shown in Figure 3.

The Schlieren images show the general shape of the front, however the details of the reaction zone is difficult to discern other than the oblique part of the front appears optically thicker. In order to investigate the structure of the detonation front and the expanding combustion products a 0.5 mm thick sooted aluminum foil was placed against the back window, with the sooted-side facing the camera. In a previous study [10], it was shown that the passage of the shock lofts the very-fine micron size soot particles off the foil where they are quickly heated to the local gas temperature. Soot that is engulfed by the combustion products radiates as a black body and the incandescence is picked up by the camera. Video images taken using this technique for a test under the same conditions as the test in Figure 3 is provided in Figure 5. These images (similar in appearance to OH PLIF) show the location of chemical reaction where the highest temperatures are achieved. The highest intensity light is produced just after the reflected shock next to the bottom wall where the soot is shocked heated a second time.

The images from Figure 6a and b (reproduced from Figures 3 and 4) are from two different tests at the same condition, a comparison is possible because the general features of the structure are reproducible from test to test. The schlieren image shows that in the top half of the channel the front is very thin, typical of a detonation wave. At roughly mid-height the detonation decouples and the bottom half a distinct oblique lead shock wave and trailing contact surface is observed. Based on the image in Figure 6b, the contact surface, highlighted by the incandescing soot particles, is highly turbulent.

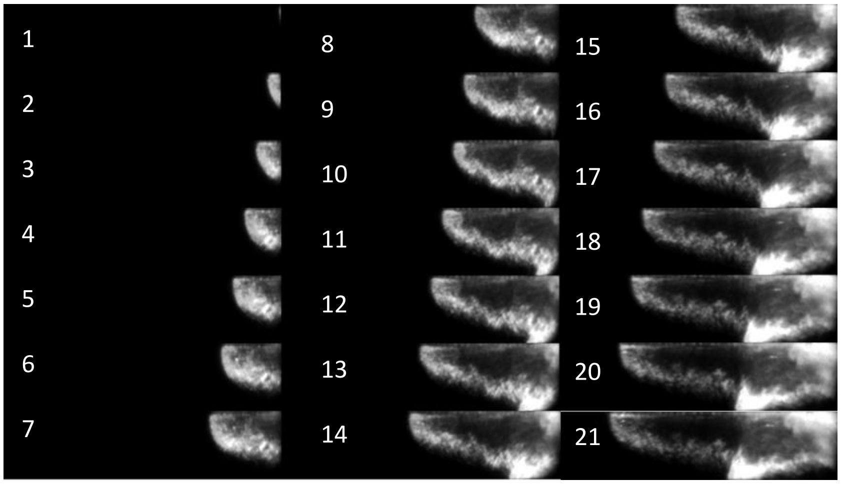

Figure 5. Video of combustion front propagating across a soot foil placed on back window

A photo of a segment of the soot foil obtained from the test in Figure 5 is provided in Figure 6c. The soot foil clearly shows the cellular structure of the detonation wave that propagates in the top portion of the channel, consistent with the schlieren images shown in Figure 6a. A magnified image showing the details of the cellular structure is provided in Figure 6d. The finest cells are located closest to the top wall where the lead shock and reaction zone is smooth and almost perpendicular to the top-wall (see Figure 6a and 6b). A typical cell is highlighted in Figure 6d that measures 2 mm in height, which is on the order of the cell size reported in the literature for stoichiometric hydrogen-oxygen [11]. The cells increase in size in the curved part of the detonation front and there are no cells in the bottom half of the channel. The curved part of the detonation wave is most likely the result of dilution of the head of the hydrogen-oxygen jet by the argon. The results in Figure 4 and 5 correspond to experiments carried out with the minimum hydrogen-oxygen layer height that resulted in detonation propagation. Based on the measured 2 mm cell size there are roughly 3 detonation cells across the channel width, which is well above the propagation limit of one cell. Based on Figure 6d there are about 10 cells across the hydrogen-oxygen layer height. Future experiments will be carried out to measure this propagation limit for different channel widths in order to check the universality of this criterion. Experiments will also be performed with the channel prefilled with nitrogen, instead of argon, to investigate the effect of the hydrogen-oxygen jet mixing with the background inert gas.

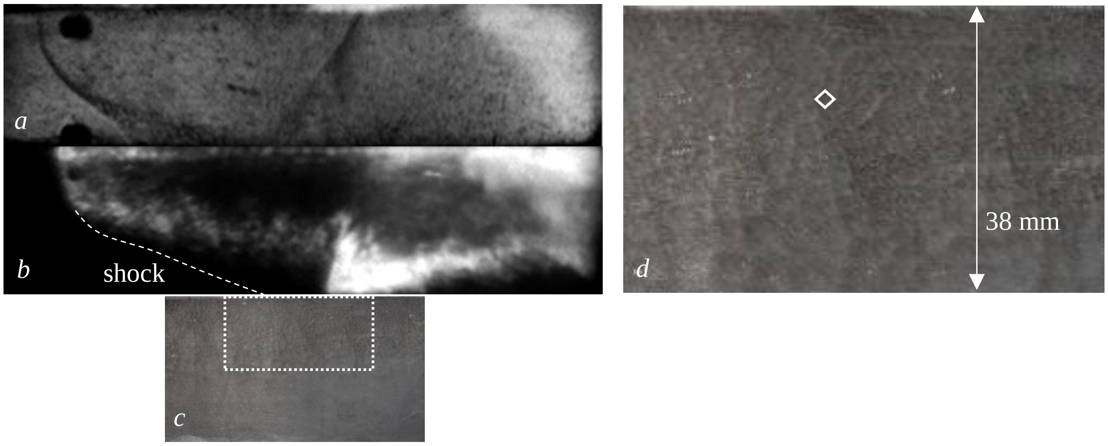

Figure 6. Schlieren (a) and soot incandescence (b) images showing the combustion front structure. A photo showing the cellular structure left on the soot foil (c), where (d) is a 2x magnification of dotted box in (c).

4 Conclusions

A linear representation of a RDE was constructed that allows the generation of a stratified layer of hydrogen-oxygen above argon in a narrow optically accessible channel. A planar CJ detonation wave was transmitted into the optical channel and the subsequent combustion front propagation was visualized via high-speed photography. The detonation cellular structure was captured using the soot foil technique. Regular photography of the detonation front propagation over the soot foil also permitted visualization of the detonation front and the edge of the laterally expanding contact surface separating the products and argon. The results from this well controlled experiment could be used to verify 2D simulations like that reported in [8].

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