Flame surface enhancement from the head-on interaction with an expansion wave

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1 Background

In recent years, a global hydrogen strategy has emerged to meet increasing demands to reduce carbon emissions and develop a zero-emission fuel. Hydrogen can be stored at pressures reaching 800 bar [1], resulting in accidental releases involving large amounts of gas. The ignition of a fuel-air cloud can lead to a transient during which a flame transitions to a detonation, or deflagration-to-detonation transition (DDT), which can be much more damaging.

As a fuel, hydrogen behaves differently than hydrocarbons. The characteristic reaction time of hydrogen mixtures is shorter, and the mass diffusivity is higher. This results in thinner flames with higher surface areas due to the flame wrinkling caused by hydrodynamic and thermo-diffusive instabilities. Lab-scale shock tube experiments have shown that hydrogen mixtures are prone to DDT. Pinos & Ciccarelli studied the behaviour of a hydrogen-air mixture propagating through a fully-confined tube in which a bank of obstacles was installed [2]. The flame accelerates as it propagates around the obstacles due to an increase in surface area, eventually culminating in a fast flame which drives shock waves ahead of itself. Transition to a detonation is possible once the flame is accelerated to choked flame conditions [2–5].

Sherman studied flame acceleration through a laterally-vented and fully-confined tube [3]. The inclusion of a large venting ratio (50%) prevented DDT for all studied hydrogen concentrations, regardless of the presence of obstacles. Whereas the addition of 50% venting significantly reduced the flame speeds, the opposite effect was seen for a lower venting ratio of 13%. The flame speeds and peak flame overpressures measured were higher in the lightly-vented configuration than the fully-confined experiments. Additionally, DDT events occurred after the flame travelled around a third of the tube as opposed to occurring near the end of the tube as in the fully confined experiments.

Some explanation of this phenomenon can be provided by the experiments of Laviolette and co-workers, who presented preliminary work into rarefaction wave-flame interactions [6]. A flame was ignited at one end of a shock tube, and interacted with a rarefaction wave. The experimental photographs showed the flame deform during its interaction with the rarefaction wave, and DDT was confirmed to occur later in experiments without rarefaction-flame interactions.

The current paper seeks to study the flame enhancement provided by the interaction with a rarefaction wave, and provide insight into the timescales associated with the flame enhancement. The experimental suite is designed to replicate the rarefaction-induced DDT event observed by Sherman and to isolate the flame enhancement resulting from the flame-rarefaction wave interaction. As such, hydrogen-oxygen-nitrogen mixtures will be studied while varying the nitrogen content to control the reactivity of the mixture. The strength of the rarefaction wave will also be controlled.

2 Experimental Apparatus and Method

A 3.4 m-long shock tube with a rectangular cross-section of 203 mm by 19 mm was used for these experiments. A high-pressure test section, initially filled with a hydrogen-air mixture to a maximum pressure of 17.2 kPa, was separated from the low pressure section, initially filled with ambient air, by the use of a diaphragm. A tungsten wire igniter, similar to that used by Yang & Radulescu [7], was installed vertically in the test section. This tungsten wire allows one to ignite a flat laminar flame. A series of high-frequency piezoelectric PCB pressure transducers were mounted on the top wall of the shock tube to collect pressure data. Z-type Schlieren photography was used to record the evolution of the flow field over a region of 330 mm by 203 mm with an exposure time of 0.468 μs. A schematic of the shock tube can be seen in Figure 1. To visualize the evolution of the flame in absence of rarefaction waves, the diaphragm was replaced by a solid wall.

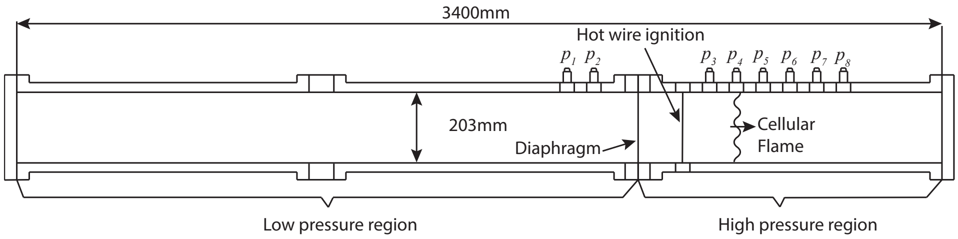

Figure 1: Low-pressure experimental configuration. The tungsten wire igniter is placed at either extremity of the channel, depending on whether the rarefaction wave collides from the fresh or burnt side of the flame. All measurements are in millimeters.

A second experimental setup was developed to study flame-rarefaction wave interactions at higher initial pressures due to the pressure limitations of the low-pressure shock tube detailed above. This setup consists of a 295 mm diameter steel tube as designed by Armstrong [8], used as an expansion vessel. Attached to one extremity of this tube is an atmospheric-pressure shock tube with a rectangular cross-section of 102 mm by 19 mm, and a length of 660 mm. Windows in the test section allows flow field visualization using the same Z-type Schlieren as used for the low-pressure experiments, and the pressure history was obtained by installing a series of pressure sensors along the top and bottom walls. A schematic of the shock tube can be seen in Figure 2.

Prior to each experiment, the entire shock tube was emptied to a pressure of 80 Pa. Subsequently, the low-pressure section was filled with air to the experimental pressure, before filling the high-pressure section with the reactive mixture. The reactive mixture was prepared using the method of partial pressures, after emptying the mixing tank to a pressure lower than 40 Pa.

2.1 Diaphragm Rupture Mechanism

A diaphragm installed between a low-pressure and a high pressure shock tube section was ruptured to generate the rarefaction wave in the high-pressure medium. To produce ideal planar waves from this rupture, the diaphragm must have a reasonably short characteristic rupture time and a spatially-even rupture pattern. The pressure loading on the diaphragm during experiments is commonly used as a rupture technique in large-scale experiments, such as those of Sherman [3] and Pekalski [9]. During

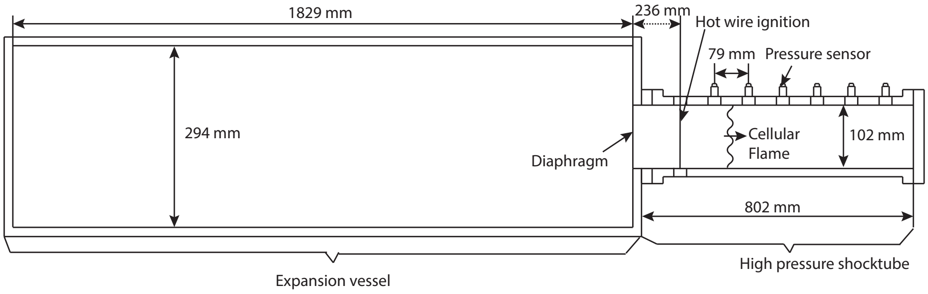

Figure 2: High-pressure experimental configuration. The tungsten wire igniter is placed at either extremity of the channel, depending on whether the rarefaction wave is generated on the fresh or burnt side of the flame. All measurements are in millimeters.

preliminary work, this method was found to function well at high pressures and for smaller diaphragms, but spatially uneven rupture patterns were common in low pressure experiments with large aspect ratio diaphragms.

To generate planar expansion waves at low pressures, 0.33 mm-thick chemically-strengthened thin glass diaphragms were used. A pneumatic piston-actuated plunger-type mechanism was used to strike the diaphragm. The glass was struck at eight points along the height of the channel to ensure spatial uniformity when the diaphragm shatters. Thompson & Loutrel have previously used thin glass diaphragms with dense fluids, and commented that the characteristic burst time of such diaphragms are significantly shortened when studying gases due to the fluid penetration of the fragment screen [10]. They also commented that their addition of a mechanical plunger to actuate the shattering of the diaphragms overcame spatial unevenness in the fracture pattern.

3 Preliminary Results

A series of experiments were performed to validate the proposed experimental method and apparatus. The sequence of frames corresponding to the flame ignition is shown in Figure 3, showing the growth of the flame at different points in the tube. The reactive mixture is $2H_2$ + O_2 + $3.76N_2$, at initial conditions of $P = 17.2$ kPa and $T = 293$ K. The flame is initially ignited at multiple points along the tungsten wire and subsequently preferentially grows along the wire. After having grown the height of the channel, the flame propagates through the channel with two large cells. By the third frame, the flame flattens as it wrinkles and generates more cells. The flame periodically generates more cells as it flattens, resulting in a vertical wrinkled flame in the second and third frames. Finally, the flame evolves into a cellular v-shaped tulip flame as it approaches the end-wall of the shock tube. The generated flame is deemed to be sufficiently flat for these experiments, and qualitatively resembles the flame generated by Yang & Radulescu to study shock-flame interactions [7]. The flame initiation and initial flame growth is also seen to be reproducible between subsequent experiments.

Flame-rarefaction interaction experiments are conducted using an initial pressure ratio of 10 across the diaphragm, with a reactive mixture of $2H_2$ + O_2 + $3.76N_2$. The initial pressures in the shock tube are of 17.2 kPa and 1.7 kPa, separated by a thin polyethylene film with a thickness of 0.03 mm. This diaphragm has a rupture overpressure around 31 kPa, and no plunger-type mechanism is used to time the rupture. The rupture time can be determined from time-of-arrival data using the pressure sensors mounted in the low-pressure section. Frames from these experiments are shown in Figure 4, with the rarefaction wave originating from the burnt side of the flame. A flame initially propagates from right to left through the frame with an average speed around 16 m/s, when measured along the top wall. At much later times, after the rupture of the diaphragm, the flame is seen propagating through the field-of-view in the opposite direction at a speed around 91 m/s. In the last three frames, one sees the flame deformation caused by the interaction with the expansion wave. One sees the reversal of the flame cells into cusps. This was previously identified as a flame enhancement mechanism for shock-flame interactions by Yang & Radulescu [7]. Recent numeric simulations of flame-rarefaction interactions by Yang and co-workers has also suggested flipping of flame cells when the expansion wave originates from the burnt side of the flame [11]. Additionally, a reversal of the v-shape flame is observed, suggesting a global deformation of all the features of the flame resulting from this interaction. However, the longer timescales involved with flipping the tulip flame prevents further investigation due to the presence of the reflected rarefaction wave. We are currently repeating these experiments using an undiluted hydrogen-oxygen mixture to reduce the characteristic flame thickness, which in turn reduces the characteristic flame time that governs the flipping of the flame cells.

The presence of non-idealities in these experiments are important and prevent detailed analyses of the flame enhancement. Notably, the initial use of the self-actuating overpressure diaphragm rupture technique for low-pressure experiments with a high-aspect ratio diaphragm were found to be very limiting. Spatially-uneven rupture patterns, the long rupture time relative to the pressure equilibration time, and the high ductility of the plastic diaphragms affected the reproducibility within runs of experiments, and limited observations to individual experiments. The plunger-type mechanism combined with brittle thin glass diaphragms is promising for low-pressure expansion wave generation.

4 Summary

An experimental method to study the interaction between a rarefaction wave and a flame was detailed. A flame is reproducibly ignited by the tungsten wire igniter, which develops into a vertical winkled flame. The preliminary experiments have shown the flame deformation caused by its interaction with a rarefaction wave. Notably, the flipping of flame features at all scales was observed when studying the interaction of a rarefaction originating from the burnt side of the flame. Despite this, the flame enhancement caused by the interaction cannot yet be quantified. Improvements to the apparatus, particularly the diaphragm rupture mechanism and the design of a high-pressure installation to study a wider range of pressures, was detailed. The experimental suite implementing these improvements is currently underway.

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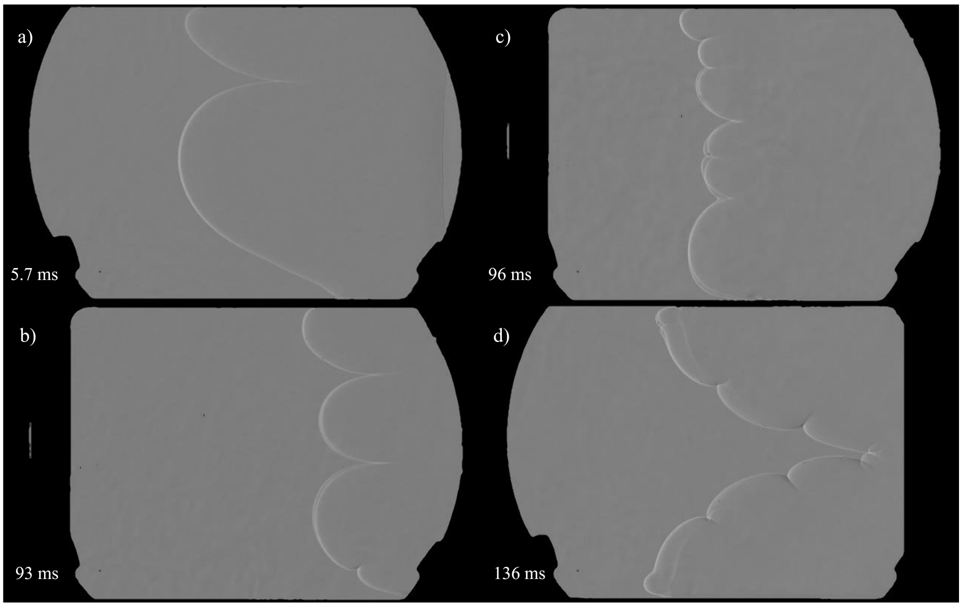

Figure 3: Experimental frames showing the ignition and propagation of the flame, with timestamps taken from the moment of first ignition at the centre of the wire. The field of view changes between frames to show the flame evolution throughout the tube.

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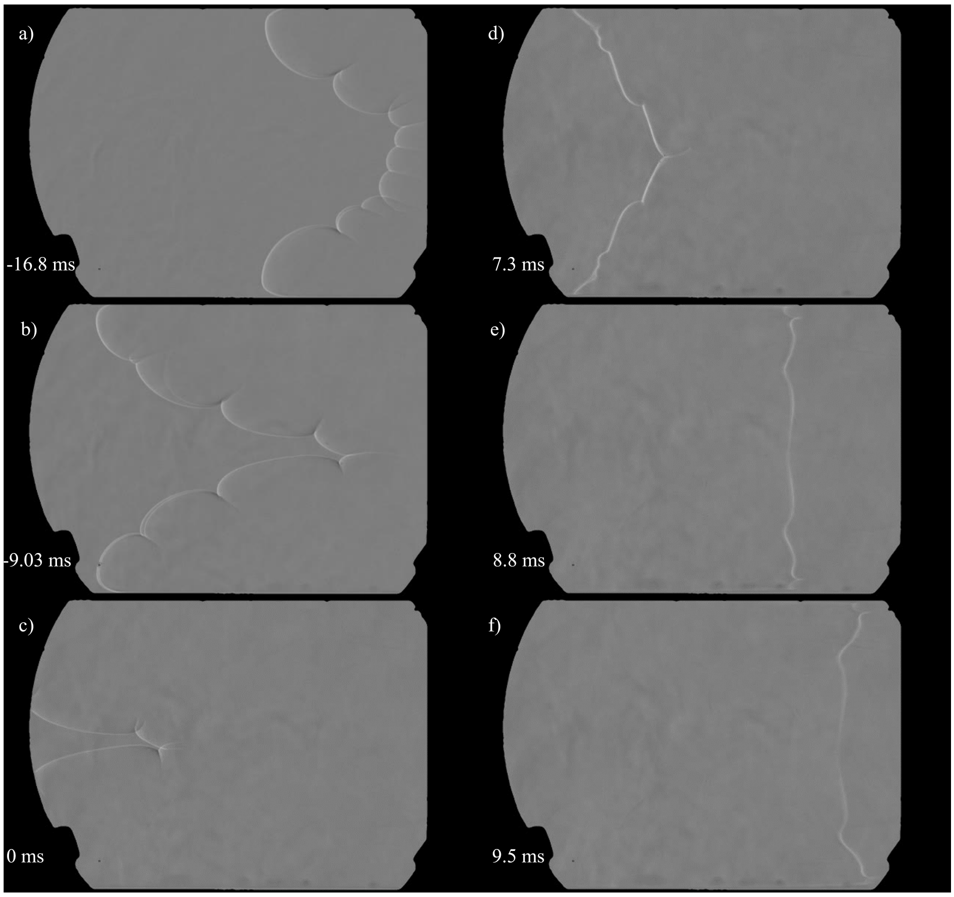

Figure 4: Low-pressure experiments, with a reactive gas pressure of 17.2 kPa and an inert gas pressure of 1.7 kPa, for a pressure ratio of 10. A wrinkled flame propagates from right to left through the frame at an average velocity around 16 m/s when measured along the top wall. The flame is seen propagating across the field of view at a velocity around 91 m/s due to the expansion-driven flow acceleration.